Supplementary information for :

Byproduct-to-host ratios for assessing the accessibility of mineral resources

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<https://doi.org/10.1021/acs.est.4c05293>

## Summary

21 pages, 2 figures, 1 table.

Table of contents

[Calculation of global production as host (figure 2 in manuscript) 3](#_Toc147330598)

[General methodology 3](#_Toc147330599)

[Determine the host element(s) in a deposit 3](#_Toc147330600)

[Data processing 5](#_Toc147330601)

[Data harmonization 5](#_Toc147330602)

[Choice of recovery rate data as function of data availability 6](#_Toc147330603)

[Additional information on data sources for calculation of Htb ratios 8](#_Toc147330604)

[Byproducts of fossil fuels 8](#_Toc147330605)

[Crude oil 8](#_Toc147330606)

[Coal 8](#_Toc147330607)

[Natural Gas 9](#_Toc147330608)

[Byproducts of host metals 9](#_Toc147330609)

[Aluminium byproducts 9](#_Toc147330610)

[Bismuth (Bi) 10](#_Toc147330611)

[Tungsten (W) 10](#_Toc147330612)

[Phosphate rocks (P) 10](#_Toc147330613)

[Platinum group elements (PGMs) 10](#_Toc147330614)

[Hafnium (Hf) 11](#_Toc147330615)

[Niobium (Nb) and tantalum (Ta) 11](#_Toc147330616)

[Lead-zinc (Pb-Zn) deposits 11](#_Toc147330617)

[Vanadium (V) deposits 11](#_Toc147330618)

[Tin-dominant deposits 11](#_Toc147330619)

[Cobalt (Co) 12](#_Toc147330620)

[Copper byproducts 12](#_Toc147330621)

[Rare earth elements (REEs) 13](#_Toc147330622)

[Lithium (Li) 14](#_Toc147330623)

## Calculation of global production as host (figure 2 in manuscript)

The left side of figure 2 (in manuscript) shows the global production of an element from deposits where it is defined as host. It is calculated as follows :

Where is the total production (in 2021 here) taken from literature (see data in supporting information 5) and  is calculated as follows:

Where is the quantity of element h in deposit i, is the ensemble of sites where the element h is designed as host and is the ensemble of sites where the quantity of the element h is reported, whether it is the host or not. We assume that this value is the best proxy of the share of global production of the element as host.

## General methodology

## Determine the host element(s) in a deposit

We calculate the contribution of each element in a deposit to the mine revenues, for « mineral resources » category, by multiplying the quantity of each element by its 2010-2018 arithmetic average market price. It is determined as follows:

Where and are respectively the revenue, the quantity and the 10 years average market price of element i. is the list of elements that have a reported quantity for the given deposit. Market price of elements are available in supporting information 2.

There is no standard definitions of host, co-product or byproduct and clear boundary between these three status (Mudd et al. 2017a). Nassar et al. (2015) suggested that « a metal needs to contribute no more than 20% of revenue to be considered a by-product and otherwise should be considered a coproduct ». Therefore, elements contributing to more than 20% to total revenues are considered as potential coproduct. Ideally, we should consider mine operation cost, also called cost of sales. By substracting the cost of sales to the revenues from one potential co-product, we would have been able to answer to Nassar et al. (2015) question: « can a metal be profitably mined on its own under the current cost structure? ». We did not consider cost of sales to determine the number of coproducts due to lack of data and time.

### Data harmonization

Une image contenant texte, capture d’écran, Police, carte de visite

Description générée automatiquement

**Figure 1.** Harmonization steps to include data for a given deposit where complementary information comes from e.g. two different references. We used “Sentence Transformers” (ST) machine learning tool (Reimers and Gurevych 2019) and adapted the code of (Agez 2023) to identify deposits having a potential unperfect match (e.g. Galeno in list A vs El Galeno in list B). Using ST allows, for each mine names in list A, to have a list of e.g., 5 mines from B that have a degree of similarity between 0 (none) and 1 (close to perfect match) with mine of list A. We manually rechecked the ST output mapping of mine names having a degree of similarity above 0.8, within the same country and having the same primary commodity (the host element).

## Choice of recovery rate data as function of data availability

The total recovery rate of an element e (e.g. aluminum, copper, indium) extracted from a deposit is calculated with the most representative data. Figure 6.2 presents the decision-tree for the choice of data to calculate the total recovery rate.

Une image contenant texte, capture d’écran, Police, diagramme

Description générée automatiquement

**Figure 2.** Decision-treeof data used to calculate the recovery rate of elements along a generic supply chain. VEIN = Vein-type deposit. Blue boxes are data used to calculate the total recovery rate (equation 3 in Methods). Green boxes are documents where input data is stored and red diamond are questions where decisions are taken for each deposit having key characteristics (grey boxes).

# Additional information on data sources for calculation of BtH ratios

## Byproducts of fossil fuels

### Crude oil

#### Vanadium (V) in oil fly ash

We calculated an average amount of vanadium per kg of crude oil as follow :

Where M means mass (in kg) and is the density (kg/liter). is the average of values reported in Table 2 of Bakkar et al. (2023) and Jung and Mishra (2018); since « Burning heavy fuel oil yields about 3 kg of ash per kiloliter of oil » (Mofarrah and Husain 2013); since « most of the ash (~90 %) is fly ash (FA) » (Mofarrah and Husain 2013) and oil density equals 1.01 kg/liter.

Unfortunately, there is no dataset covering the distribution of vanadium concentration in crude oil refineries worldwide which explains while we only included a single V-Crude oil ratio in this dataset.

### Coal

#### Germanium (Ge) in coal fly ash

Two estimates of germanium content in coal fly ash were identified in the literature : the first comes from US recoverable coal reserves where « more than 252 billion short tons coals [67] are estimated to contain 1.7 Mt Ge [36] » (Patel and Karamalidis 2021). The « mineral resources » estimate for germanium in coal considered as the amount of coal where Ge content is between 8 and 200 ppm, as indicated by Frenzel et al. (2014). We estimate that 851.14 Gt coal contain germanium between 8 and 200 ppm using data from Frenzel et al. (2014). We assumed an average concentration of Ge in those 851.14 Gt of 104ppm. The economic reserves of Ge in coal equals 9860 Mt coal with Ge>200 ppm on the basis of the distribution of Ge content in Table 10 of Frenzel et al. (2014). We assumed a conservative concentration of Ge of 200ppm for the ore reserves.

### Natural Gas

#### Helium

The possibilities of commercial extraction of He from natural gas is when the concentration is above 0.15% (Yakutseni 2014). Helium content distribution in natural gases in the world is reported in figure 2 of Yakutseni (2014) : 3% of natural gas reserves have He concentration above 0.3% and 1% of natural gas reserves have He concentration above 3%.

## Byproducts of host metals

### Aluminium byproducts

#### Scandium from red mud

We calculate the ratio of scandium content in red mud, which is a residue generated during the processing of bauxite through Bayer process (Botelho Junior et al. 2021), relatively to aluminum content in alumina as follow :

Where kg Sc/kg Al2O3 since table 1 of (Petrakova et al. 2015) indicates 90g Sc/t red mud (which is within the range of content of Scandium in bauxide resiudes in China, which is between 55 and 116 g/t (China is by far the biggest producer bauxite in the world) indicated in the Table 5 of the review of Botelho Junior et al. (2021)).

Where is between 1.25 tred mud / tAl2O3 (average of minimum values of Wei et al. (2022) and Petrakova et al. (2015)) and 2.75 tred mud / tAl2O3 (average of maximum values of Wei et al. (2022) and Petrakova et al. (2015)). We consider the average of this two values, which equals 2 tred mud / tAl2O3. From Wei et al. (2022) : "Approximately, 1.0–2.5 tonnes of red mud is produced from per tonne of alumina generation rest with the nature and operating conditions of the bauxite (Wang et al. 2018)". From Petrakova et al. (2015) : "Bayer process of alumina production involves generation of considerable mud tonnage (1,5 - 3t of red mud per 1 t of alumina)".

Scandium recovery rate from bauxite with different leaching agents and processes range between 35% and 93.3% (Botelho Junior et al. 2021). We consider the mean of recovery rate values reported in Table 6 of Botelho Junior et al. (2021).

#### Gallium (Ga) from bauxite

35 active bauxite mines from the dataset of Shulte et al. (2014) that were reporting both tonnage, aluminium or alumina and gallium content were selected and included in the mineral reserves dataset (ResV). Table S1 of Qi et al. (2023) reports the gallium content (in ppm) in 150 karst and laterite bauxite deposits worldwide. Among the 150 deposits of Qi et al. (2023), 26 were already included in our dataset. However, no estimates of either “Ore Reserves” or “Mineral Resources” tonnage were identified for each of the 124 remaining deposits so could not be included in our dataset. The absence of mineral resources estimates for African bauxite deposits listed in Zainudeen et al. (2023) also prevented us from adding operational sites in Sierra Leone, Ghana, Mozambique, Tanzania or Ivory Coast.

We used the gallium recovery function as function of gallium concentration in bauxite from figure 3 of Frenzel et al. (2016). We derived a trend curve for the recovery function (with coefficient of determination R2 = 0.9994) resulting in the following equation:

Where is the recovery rate of gallium in bauxite deposit i and is the concentration of gallium in bauxite deposit i in ppm.

### Iron (Fe)

To the best of our knowledge, there is no global dataset of iron mines worldwide. Rauch (2009) provides a global mapping of in-ground iron content per 1 km2 cell but such data is valid for year 2000 and it is not precised whether these estimates correspond to a mineral reserves estimate or a resource estimate. We identified South African iron deposits thanks to the dataset of Cole (2024) and added them in our dataset by looking for mineral resources estimates provided in mining company reports.

We used the recovery efficiency as function of iron grade in multiple different ores (best data identified to the best of author’s knowledge) from figure S2.2 of Wang et al. (2021), which is defined as follows :

Where is the recovery rate of iron in deposit i and is the concentration of iron in deposit i in %.

### Bismuth (Bi)

Bi is mainly mined as a by-product of Pb and W mining in China (Deady et al. 2022). We included Bi content into two deposits (Broken Hill, Australia and Nui Phao skarn deposit in Vietnam) using Bi grade reported in supporting information of Deady et al. (2022). 28 other deposits have mean Bi content in Deady et al. (2022), however no additional information (tonnage, grade of other elements, deposit type) was found. As a result, the 28 other deposits were not included in the dataset.

### Tungsten (W)

Han et al. (2021) provides a review on 8 tungsten deposits, which allowed us to identify mine names and locations. However, additional research were conducted since both reserves and WO3 grade are not accurately reported in Han et al. (2021). We added 5 deposits from Table 1 of Han et al. (2021) and completed missing information (grade of other elements, status of the deposit) with mining companies reports.

### Phosphate rocks (P)

Morocco has the largest known phosphate rock reserves (Jasinski 2023; Houssini et al. 2023). The OCP group (100% government owned) manages Khouribga and Gantour mining centers (USGS 2021), however only the P2O5 grade (%) is reported and there is no ore reserves or mineral resources estimates (as per JORC code). We included phosphate rock deposits in Brazil thanks to (Silva et al. 2023) and Elandsfontein deposit in South Africa thanks to Cole (2024).

### Platinum group elements (PGMs)

Mudd et al. (2018) is our reference dataset, the most exhaustive dataset on PGMs reserves, from which we refined estimates of elements as for Pd, Pt, Ru, Rh and Ir elements content were not reported (only 4E grade). We completed this dataset with mines study at the country scale : South Africa (Bullock et al. 2023).

We compared the values of contents of four elements (4E) of PGM reported in tables ST1 to ST8 in the most recent exhaustive dataset on PGMs resources estimate by Mudd et al. (Mudd et al. 2018) with the same values reported in the most recent exhaustive dataset on copper resources estimate by Mudd et al. (Mudd and Jowitt 2018). For matching deposits, there is a good agreement between estimates of 4E content in the two datasets. We calculated the ratio of 4E content in matching deposits and obtained a median, 5th percentile and 95th percentile values equal to 100%, 96,9% and 251% with 4 oultliers below 5th percentile (Magazynskraal 3JQ, Zondernaam, Pedra Branca and Denison) and 5 outliers above 95th percentile (Bakubung (Ledig-Frischgewaagd), Maseve-1/1a, Bathopele, Kroondal (PSA) and Platreef (Flatreef-Turfspruit) (ratio = 103704% for the latter)).

### Hafnium (Hf)

We estimated the quantity of Hafnium in 16 sedimentary deposits assuming that Hf content equals 2% of Zr content in the deposit as suggested by Perks and Mudd (2021).

### Niobium (Nb) and tantalum (Ta)

We used the Nb and Ta grade in Table 3 of the most exhaustive review of Nb and Ta grade by Mackay and Simandl (2014) to calculate the total content (multiplying grade by tonnage of the deposit) and include the content of Nb and Ta in deposits included in our dataset.

### Lead-zinc (Pb-Zn) deposits

We included 10 lead-zinc deposits from Tables 5 and 6 of Mudd et al. (2017b) while 9 were already included in our dataset (with Ag, Pb, Zn content already reported).

### Vanadium (V) deposits

We included 14 vanadium deposits in our dataset: two from the review of Simandl and Paradis (2022) and eight identified thanks to the supporting information of Owens et al. (2022) where we found tonnage and grade estimates data from mining companies reports. We also included four African deposits (Abenab, Tete Mafic Complex, Tin Edia and Merela Project) for which both tonnage and grade estimate are reported, out the 76 deposits listed in Table 1 of Boni et al. (2023).

### Tin-dominant deposits

Cassiterite is the main ore mineral of tin (Lehmann 2021), and more than 65% of the world's cassiterite reserves are situated in China, Indonesia, Myanmar, and Australia (Jeon et al. 2022). We identified 14 deposits where tin is the host metal. However, none of them is in China, Indonesia, Myanmar and Peru, reported as the countries with the largest ore reserves by USGS (USGS 2023). 3 deposits among the top 15 undeveloped CRIRSCO-compliant tin resources by tin content reported by International Tin Association (ITA 2020), namely Manono, Cinovec, Nazareth are included in our dataset. However, Deputatskoe, Syrymbet, Pyrkakaysky, Tigrinoe, Redmoor, Achmmach, Odinokoe, Tellerhauser, Gottesburg, Sherlovogorskaya, Rentails and Verkhneye deposits could not be included due to lack of mineral resources estimates for other elements, which is necessary to derive BtH ratios.

The most recent review of tin-dominant deposits of Lehmann (2021) identifies Sinclair et al. (2014) as the most detailed database of tin deposits as of today. In Sinclair et al. (2014), 6 potentially operating mines are reported (no end year) and 5 are closed. However, we did not find either tonnage or metal grades for operating mines (Molodezni, Pravourmi, Tayozhny, Lermontovka and Vostok) so we could not include them in our dataset. Our dataset suffers of major data gaps regarding tin-dominant deposits in currently dominant extracting countries like China, Indonesia, Myanmar and Peru.

### Potash (K) deposits

Only the USGS provide an open-access dataset of evaporite-related potash resources worldwide (Orris et al. 2014) where 228 mines are reported with 67 being active or under development. Despite providing relevant information like the name and country of the mine, the deposit type (e.g. potash-bearing brine, stratabound potash-bearing salt) and the status of the mine in 2014, tonnage and elements grade are missing. Data gaps attempted us to include those 67 active/under development mines in our dataset.

### Cobalt (Co)

Our main data source for Co-dominant deposit is the table 3 of Dehaine et al. (2021). It provides the status, type, main commodity, tonnage and Co grade. The content of Co in 22 deposits were already reported by Mudd et al. (2018).

### Copper byproducts

#### Rhenium (Re)

The Re grade data of Werner et al. (2023) was used to calculate Re content in 556 deposits where Re was not already reported. We used data from tables 1 and S6 of Werner et al. (2023). Table 1 of Werner et al. (2023) reports Re grade for 211 deposits (8 have Re grade equal to zero) “with sufficient information reported in the scientific, technical or corporate literature to record Re resources” (Werner et al. 2023). Table S6 of Werner et al. (2023) reports Re content by extrapolating Re content from Mo content using regression analysis in Mo-containing deposits.

We used Werner et al. data rather than Brainard (2023) data since the latter aggregated granular mine level raw data to the national level due to subscription licensing of multiple data. We could not compare rhenium content at the mine level of Brainard (2023) versus Werner et al. (2023).

#### Tellurium (Te)

To the best of existing knowledge, there is no global estimate of tellurium in different deposits, especially its main one: copper porphyry (CP) deposits. Tellurium is mostly recovered at copper electrolytic refining stage (Moats et al. 2021; Nassar et al. 2022). However, there is a knowledge gap on tellurium content in CP deposits. It could be filled by following Werner et al. (2017) data collection methodology and Frenzel (2023) guidance for statistical analysis, which consists on establishing loglinear regression between the concentration of the metal of interest, per deposit type, and the concentration of another element use as reference. Then, it is possible to extrapolate the content of the element of interest in deposits with similar characteristics (same ore type or reporting the content of the element used as reference). Filling this gap would enable to know with confidence the average ratio of tellurium relatively to copper or molybdenum in those deposits.

#### Selenium (Se)

To the best of our knowledge, there is no publicly available dataset on selenium content in copper deposits. Stifner et al. (2023) suggested that “The weighted ratio of the quantity of selenium to the produced tonnage of metallic copper was found to be just over 3% in terms of both reserves and resources”. Their analysis is based on a 700 copper deposits dataset (Weber 2022), however they do not disclose transparently how they obtained this value. This lack of transparency on data attempted us to include additional Se content in our dataset.

### Rare earth elements (REEs)

We identified 7 reviews of REEs reserves estimates with variable level of data reporting, which are presented in Table 1.

Table 1. Identified reviews of REEs deposits worldwide with/without tonnage and grade estimates.

|  |  |  |  |
| --- | --- | --- | --- |
| **Relevant information provided** | **Number of deposits covered** | **Spatial coverage** | **Reference** |
| Tonnage, TREO%, Status, name of host and byproducts | 25 | World | (Hellman and Duncan 2014) |
| Tonnage, %LREO, %HREO, Th (ppm), U(ppm) | 267 | World | (Weng et al. 2015) |
| Tonnage, status, % individual REO | 49 | World except China | (Paulick and Machacek 2017) |
| Status, % individual REO | 21 operating | World | (Nassar et al. 2023) |
| Tonnage, status, % individual REO | 146 (77 with tonnage value) | World | (Liu et al. 2023) |
| Tonnage, %TREO | 24 | Murmansk region, Russia | (Kalashnikov et al. 2016) |
| Tonnage, status, % individual REO | 7 (operating or exploration) | Murmansk region, Russia | (Kalashnikov et al. 2022) |

We used the dataset of Liu et al. as our reference dataset by including the 77 sites where tonnage is reported and 2 sites from Nassar et al. (2023) not reported by Liu et al. (2023). We completed the data collection by looking for mineral resources estimates in each of the 79 deposits to identify either host or byproduct elements not reported in sources presented in Table 1, as only individual REO grade was reported.

We considered the recovery rate at mining/benefeciation of Nassar et al. (2023) as it was only the source reporting this value at the deposit level (in their Table S1).

### Lithium (Li)

Peer-review articles gathering deposits locations and resources estimates : first screening with old studies of Gruber et al. (2011), GrosJean et al. (2012), Mohr et al. (2012) and Kesler et al. (2012), as well as reviews focus on contient brines of Munk et al. (2019), Sanjuan et al. (2022) and Vera et al. (2023).

Grosjean et al. did not include three Australian deposits : the Mount Cattlin, Mount Marion, Wodgina, Bald hill and Pilgangoora (Altura and Pilbara Minerals) deposits, that we identified thanks to Geosciences Australia and Tabelin et al. (2021). We completed with recent reviews of lithium deposits : Quebec (Ibarra-Gutiérrez et al. 2021), brines in China and Argentina (Lucrecia López Steinmetz et al. 2018; Zhu et al. 2023). Pastos Grandes and MSB Blanco in Maricunga salar in Argentina were not reported in Zhu et al. (2023) and Lucrecia Lopez Steinmetz et al. (2018) but added in our dataset thanks to Ibarra-Gutierrez et al (2021).

Regarding brines, we calculated brines volume using Gruber et al. (2011) formula :

Where A is the area of the aquifer (m2), D the depth of the aquifer (m) and P the porosity in % (brine fraction of the aquifer).

We used Gruber et al. (2011) values for A, D and P for Salar de Uyuni, Salar de Atacama and the Li, Mg, K densities from Table 1 of Zhu et al. (2023) as those latter were more recent than those of Gruber et al.

We identified Rittershoffen, Insheim and Bruchsal geothermal operating sites in Germany from Kölbel et al. (2023) but that we could not include since the brine volume is not provided in the grey or scientific literature. Dead sea, Israel and Great Salt Lake, USA are not included in the dataset as it seems unlikely these resources to be extracted due to enormous volume of water to be processed to extract Li, as already mentionned by Gruber et al. (2011).

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