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LCIA OF IMPACTS ON HUMAN HEALTH AND ECOSYSTEM

A crustal scarcity indicator for long-term global elemental resource assessment in LCA

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Abstract

Purpose How to assess impacts of mineral resources is much discussed in life cycle assessment (LCA). We see a need for, and a lack of, a mineral resource impact assessment method that captures the perspective of long-term global scarcity of elements.

Method A midpoint-level mineral resource impact assessment method matching this perspective is proposed, called the crustal scarcity indicator (CSI), with characterization factors called crustal scarcity potentials (CSPs) measured as kg silicon equivalents per kg element. They are based on crustal concentrations, which have been suggested to correlate with several important resource metrics (reserves, reserve base, reserves plus cumulative production, and ore deposits), thereby constituting proxies for long-term global elemental scarcity.

Results and discussion Ready-to-use CSPs are provided for 76 elements, through which the CSI can be calculated by multiplying with the respective masses of elements extracted from Earth's crust for a certain product. As follows from their crustal concentrations, the three platinum-group metals iridium, osmium, and rhodium have the highest CSPs, whereas silicon, aluminum, and iron have the lowest CSPs.

Conclusion An evaluation of the CSPs and the characterization factors of four other mineral resource impact assessment methods in LCA (the abiotic depletion, the surplus ore, the cumulative exergy demand, and the EPS methods) were conducted. It showed that the CSPs are temporally reliable, calculated in a consistent way, and have a high coverage of elements in comparison. Furthermore, a quantitative comparison with the characterization factors of the four other methods showed that the CSPs reflect long-term global elemental scarcity comparatively well while requiring a minimum of assumptions and input parameters.

Recommendations We recommend using the CSI for assessments of long-term global elemental scarcity in LCA. Since the CSI is at the midpoint level, it can be complemented by other mineral resource impact assessment methods (both existing and to be developed) to provide a more comprehensive view of mineral resource impacts in an LCA.

Keywords Life cycle assessment · Life cycle impact assessment · Resource use · Abiotic resource depletion · Material footprint

1 Introduction

Natural resource is one of three generally accepted areas of protection in life cycle assessment (LCA) (Finnveden et al. 2009). However, how to best construct mineral resource impact assessment methods for LCA depends on the perspective taken on mineral resources (Steen 2006; Dewulf et al. 2015; Sonderegger et al. 2017). Consequently, there is no single, unambiguously "correct" way of aggregating mineral resources based on their impacts (Guinée and Heijungs 1995). In the recent work by the Life Cycle Initiative's task force on mineral resources, Sonderegger et al. (2020) define four general groups

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of mineral resource impact assessment methods in LCA: (1) depletion methods, which quantify the decrease in resource stocks due to extraction; (2) future efforts methods, which quantify the additional societal efforts required in the future as a result of current extraction; (3) thermodynamic accounting methods, which quantify the exergy lost due to mineral extraction; and (4) supply risk methods, which consider the criticality of mineral resources in terms of supply disruption. These four types of methods are based on different perspectives and provide answers to different questions. As a complementary perspective to this typology, we suggest that it is fruitful to make distinctions along both the temporal and spatial dimension, thus separating short-term (e.g., 1–10 years) from long-term (e.g., > 100 years) and regional from global perspectives. We see a specific need for a mineral resource impact assessment method that captures the perspective of long-term global elemental scarcity, which like most life cycle impact assessment (LCIA) methods would aim at capturing an important economic externality not necessarily internalized in current market prices. We have seen a lack of a method covering this perspective in LCA studies on emerging and evolving technologies containing scarce metals. For example, Peters et al. (2016) found that manganese dominated the mineral resource impacts of a sodium-ion battery and considered this to be caused by a high overestimation of manganese by the mineral resource impact assessment method ReCiPe 2008. Manganese is relatively common in Earth's crust (about 800 ppm) but still received a higher mineral resource impact than the rarer nickel (about 60 ppm). Therefore, they suggested that the method does not allow for drawing sound conclusions about mineral resource impacts for manganese-containing batteries and omitted mineral resource impacts from the study. Similarly, in an LCA study of a lithium-sulfur battery (Arvidsson et al. 2018), the abiotic depletion method from 2001 (based on ultimate resources) highlighted the abundant element sulfur, and not, e.g., the 25 times rarer lithium in the crust, as the main contributing element. This result was considered unreasonable from a long-term global elemental scarcity point of view, and abiotic depletion method results were therefore omitted from the study. In a third example, Nordelöf et al. (2019) found little guidance in long-term minimization of mineral resource impacts when assessing permanent magnet electric traction motors based on neodymium, cobalt, and strontium, respectively. This was partly due to one variant of the abiotic depletion method (recommended by the ILCD handbook) failing to capture long-term elemental scarcity. Neodymium and cobalt are approximately 10–20 times rarer than strontium, but the methods' characterization factor for strontium was 7 times higher than for cobalt and 300 times higher than for neodymium. A final example is an LCA study of a laptop, where André et al. (2019) identified, among other things, a notably high characterization factor for tin in the ReCiPe 2008 method. While silver is approximately 30 times rarer than tin in the crust, tin was considered having 4 times as high impact according to that method.

Considering these cases of mineral resource impact assessment methods failing to capture potential long-term global elemental scarcity, we developed a new method for LCA that matches this perspective. The aim of this paper is to present this method, which is called the crustal scarcity indicator (CSI) and is measured as kg of silicon equivalents (kg Si eq). Relating it to the mineral resource impact assessment typology by Sonderegger et al. (2020), the CSI is a depletion method marked by its long-term global perspective on elemental scarcity in Earth's crust.[1]

2 Method

The structure of this paper follows a four-step approach. First, the background to and development of the CSI are described. Second, to show that the CSI captures long-term global elemental scarcity better than existing mineral resource impact assessment methods, the CSI is evaluated together with four other methods against three criteria. The first criterion is temporal reliability (Brown 1996), meaning that characterization factors (CFs) can be reproduced to similar values if updated, thus being stable over time. This is important from a long-term perspective, since temporally unstable CFs will result in fluctuating assessments of long-term scarcity. The second criterion is methodological coherence, meaning that CFs are calculated using the same general method for different elements. This is important since long-term global scarcity should preferably be captured in the same way for different elements. The third criterion is practical applicability in terms of providing CFs for as many relevant elements as possible. This is a general merit for a mineral impact assessment method (Berger et al. 2020), but particularly so from a long-term perspective since it is difficult to a priori establish which elements are of future interest and which are not.

There currently exist several different mineral resource impact assessment methods in LCA (Sonderegger et al. 2020). The methods evaluated in this paper (in addition to the CSI) are the abiotic depletion method (van Oers and Guinée 2016; Guinée and Heijungs 1995; van Oers et al. 2020), the surplus ore method (Vieira et al. 2017), the cumulative exergy demand (CExD) (Bösch et al. 2006), and the environmental priority strategies in product development (EPS) method (Steen 2016; 1999). The abiotic depletion is considered since it is a depletion method with a number of endorsements. The variant based on reserve bases is interim recommended as midpoint method for resource depletion by the ILCD handbook (European Commission-Joint Research Centre 2011).

[1] A note on the terms "rarity" and "scarcity," which are often used to denote the lack of availability of a resource, can be made here: rarity generally refers to how unusual resources are in nature, whereas scarcity generally refers to the unavailability of resources demanded by society (Ljunggren Söderman et al. 2014). There can be many reasons for scarcity, e.g., trade embargos and high demand, but the further we look into the future, scarcity will likely be conditional on rarity, i.e., the fundamental (un)availability of resources in nature.

The variant based on ultimate reserves is recommended by the Life Cycle Initiative's task force on mineral resources for assessing the "contribution of a product system to the depletion of mineral resources" (Berger et al. 2020). The variant based on economic reserves is suggested by the same task force for assessing the "potential availability issues for a product system related to mid-term physico-economic scarcity of minerals" (Berger et al. 2020). However, only the variant based on ultimate reserves is included in the comparison because it has the most long-term perspective of the variants due to the consideration of ultimate reserves. The surplus ore method is considered since it is part of the most recent version of the frequently used ReCiPe package of impact assessment methods (Huijbregts et al. 2016) and since it is the future efforts method given interim recommendation by the Life Cycle Initiative's task force on mineral resources for assessing "consequences of the contribution of a product system to changing mineral resource quality" (Berger et al. 2020). The CExD is considered since it is a widely used thermodynamic accounting method included in the ecoinvent database (Bösch et al. 2006), which is the largest LCA database in the world. The EPS method is a future efforts method considered since it has an explicit long-term perspective when it comes to elemental resources (Steen 2016). These four methods thus represent three out of four types of mineral resource impact assessment outlined by Sonderegger et al. (2020). Since supply risk methods have a short-term perspective, typically 10 years (Sonderegger et al. 2020), no such method is included in the comparison.

Third, we conduct a quantitative comparison of the CFs of the developed CSI with the CFs from the other four methods, outlining and discussing differences, similarities, and relevance for long-term global elemental scarcity. CFs for the abiotic depletion method were obtained from van Oers et al. (2020) (5-year moving averages from 2015[2]), the CFs for the surplus ore method from Huijbregts et al. (2016) (hierarchist values), the CFs for the CExD from the ecoinvent database (version 3.3, as implemented in OpenLCA version 1.6.3), and the CFs for the EPS method from Steen (2016).

Fourth, we conduct a small, hypothetical case study to illustrate the developed CSI method and further compare it with the abiotic depletion, surplus ore, CExD, and EPS methods.

3 The crustal scarcity indicator

The developed CSI method is based on average crustal concentrations of elements. What renders crustal concentrations relevant from an elemental scarcity perspective is that they have been shown to be proxies for a number of important resource metrics. One such metric is the global reserves R of an element, which is the share of a resource that could be economically extracted at the time when the reserve assessment is conducted (Gordon et al. 2007). A linear proportionality between the crustal concentration C and global reserves R was first suggested by McKelvey (1960), and subsequent research has largely confirmed this relationship (Mookherjee and Panigrahi 1994). A roughly linear relationship was also shown by Mookherjee and Panigrahi (1994) between crustal concentrations and the reserve base B, which is the share of a resource that meets certain criteria for mining, such as grade, quality, and depth.[3] A more recent variant of McKelvey's curve considered the relationship between crustal concentrations and the sum of the reserves R and cumulative consumption U (Rankin 2011; Nishiyama and Adachi 1995). Again, a roughly linear proportionality was found.

For rare elements specifically, often defined as having crustal concentrations < 0.1% (Henckens et al. 2016), an additional proportionality between crustal concentrations and an important resource metric might exist. According to Skinner (1976), the distribution of crustal concentrations of abundant elements (e.g., iron) can be described by a unimodal, one-hump, bell-shaped curve, effectively representing the concentration distribution in common rock (supplementary material (SM), Fig. S1). Rare elements, on the other hand, have crustal concentrations described by a bimodal curve, with a larger hump representing their concentrations in common rock, where rare elements have incidentally substituted more abundant ones (Fig. 1). However, it is the smaller hump that is of main interest, since it consists of the distribution of highly concentrated ores available to humanity, formed by different geological processes (or meteorite impacts). The implication of the bimodal curve is that once the concentrated ores in the smaller hump have been extracted, humanity will hit the "mineralogical barrier" and be forced to extract rare elements from common rock at very high energy input and economic costs (Skinner 1976).[4] Although the bimodal curve should be regarded as a hypothesis of which a complete verification would require extensive drilling tests, "it is thought to be highly probable in concept by many economic geologists/geochemists" (Gordon et al. 2007). The exact value of the stock M of concentrated elements present in the small hump cannot be known for sure until the last ore has been found. However, it has been hypothesized that it is proportional to the crustal concentrations of each element (Skinner 1976; Henckens et al. 2016).

[2] We notice from van Oers et al. (2020) that the CFs for other ADP variants from 2015 (20-year moving average and cumulative) are generally within the same order of magnitude as the 5-year moving average.

[3] In addition, even clearer linear relationships for the reserve bases of certain groups of metals and their upper crustal concentrations can be derived (Mookherjee and Panigrahi 1994).

[4] Such a scenario, when all mineral deposits have been extracted, has been referred to as "Thanatia" (Calvo et al. 2018).

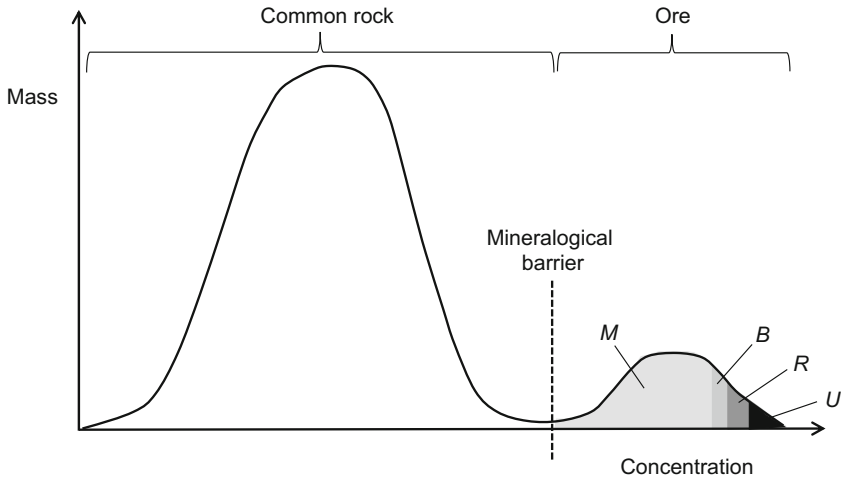

Fig. 1 Schematic illustration of the bimodal mass-concentration curve showing the distribution of rare element concentrations in the crust. The large hump represents the concentration of rare elements in common rock, and the smaller hump represents highly concentrated ores. The mineralogical barrier is the point at which the concentrated ores in the smaller hump have been extracted. *M*, mass of the element under the smaller hump (including *B*, *R*, and *U*); *B*, reserve base (including *R*); *R*, reserves; and *U*, cumulative consumption. Note that the magnitudes of *B* and *R* are not dictated by concentration alone - deposit size, depth, overburden, mineralogy, etc. are all factors in their estimation. Adapted from Skinner (1976), Gordon et al. (2007) and Henckens et al. (2016)

Crustal concentrations have thus been suggested to have roughly proportional relationships with *R*, *B*, *R* + *U*, and (for rare elements) *M* (Fig. 1), thereby potentially correlating with different resource metrics relevant for long-term global elemental scarcity. Even though this correlation is not perfect for all elements and other factors also influence these resource metrics, we thus suggest that average crustal concentrations, a measure of the rarity of elements, is a proxy for potential long-term global elemental scarcity. Crustal concentrations also bring the benefit of being stable over time and possible to estimate at relatively high certainty, which do not apply to the resource metrics with which they correlate. For example, *M* is difficult to know for certain (Skinner 1976), and specific estimations of *R* are only snapshots in time (Drielsma et al. 2016). A mineral resource impact assessment method based on crustal concentrations, called the CSI, is therefore proposed, with CFs called crustal scarcity potential (CSP):

$$\mathrm{CSP}_i = \frac{1/C_i}{1/C_{Si}} \tag{1}$$

where *C* is the crustal concentration (in ppm), and Si is the reference element silicon. The CSPs can be applied in LCIA of resource extraction at the midpoint level by multiplying the mass of element *i* extracted from the crust (m_i, in kg) by the corresponding CSP according to the following equation:

$$\mathrm{CSI} = \sum_i m_i \times \mathrm{CSP}_i \tag{2}$$

It is important to remember that the CSP stands for crustal scarcity potential. It should therefore only be paired with inventory data m_i reflecting extraction of elements from Earth's crust, not from other environmental compartments such as oceans and the atmosphere.

It can be noted that the CSPs are similar to a variant of the abiotic depletion method called "alternative 2" first presented in a report by van Oers et al. (2002), with CFs calculated as:

$$\mathrm{ADP}_{\text{alternative 2},i} = \frac{1/R_i}{1/R_{\mathrm{ref}}} \tag{3}$$

where *R* is the ultimate reserve (i.e., crustal content, in kg), *i* is an element, and "ref" stands for a reference element. This "alternative 2" method has largely fallen into disuse, and the CSI differs from this method in two regards. First, the crustal concentration (*C*) (unit, mass/mass) is applied instead of the parameter for ultimate reserves *R* (unit, mass). Ultimate reserves are obtained by multiplying the crustal concentration by the mass of Earth's crust (Drielsma et al. 2016), and there is thus no point in doing this multiplication by the mass for both the resource *i* and the reference resource because they cancel each other out.[5] The second difference is that silicon instead of antimony is used as reference resource. Antimony was chosen as reference resource for the abiotic depletion method because of alphabetical reasons (van Oers and Guinée 2016). We instead choose silicon since it is the most abundant of the elements included in the CSI. Thereby, the CSPs all obtain values higher than or equal to one, which reduces situations with large negative exponents.

In order for the CSI to have as complete coverage of the elements in the crust as possible, we only exclude three groups

[5] Not explicitly including a number on the weight of all atoms in Earth's crust might also reduce the risk of provoking the misinterpretation that all these atoms should be regarded as an available resource.

of elements either not considered part of the crust or deemed irrelevant for long-term global elemental scarcity (SM, Fig. S2). The first group contains elements which are not at all extracted from Earth's crust but produced in the technosphere, typically radioactive elements of which much less than 1 kg/year is produced worldwide. The second group consists of the noble gases, which are not considered parts of the crust and therefore not included in sources of crustal concentration data (Rudnick and Gao 2014; McLennan 2001; Wedepohl 1995).[6] The third group consists of hydrogen and oxygen, which are effectively inexhaustible and therefore irrelevant from a long-term global scarcity point of view, to the extent that crustal concentration data is often not provided for these two elements separately.

Data on crustal concentrations is available from the most recent standard reference by Rudnick and Gao (2014). Their average crustal concentration data is derived from estimates for the upper, middle, and lower crusts mixed in proportions of 31.7%, 29.6%, and 38.8%, respectively. The concentration of the upper crust is derived from sampling, the concentration of the middle crust is modeled as a mixture of different minerals, and the concentration of the lower crust is based on seismic data. Based on crustal concentration data provided by Rudnick and Gao (2014), we calculate CSPs for each included element using Eq. (1). In cases when crustal concentrations were given for the corresponding oxides (silicon, titanium, aluminum, iron, manganese, magnesium, calcium, sodium, potassium, and phosphorous), the concentrations of the pure elements were calculated based on their molar shares of the respective oxides. For carbon, rhodium, and tellurium, data was not available in Rudnick and Gao (2014) and instead obtained from an older source (Wedepohl 1995). Table 1 provides the CSPs listed with two significant numbers, which match the significant numbers in most of the input data. In accordance with their inverse crustal concentrations, the three platinum-group metals iridium, osmium, and rhodium have the highest CSPs, whereas silicon, aluminum, and iron have the lowest CSPs.

4 Evaluating the crustal scarcity indicator vs four other methods regarding long-term global elemental scarcity

The CSI and the four other mineral resource impact assessment methods clearly have global rather than regional scopes (i.e., all CFs provided apply to the whole world), but to which degree they de facto have long-term perspectives is less clear. Here, the CSI and the other methods are evaluated based on the criteria for long-term global elemental scarcity specified in Section 2; see Table 2 for a summary.

Regarding the temporal reliability of the CSI, estimates of average global crustal concentrations have remained relatively similar since the early 1900s (Drielsma et al. 2016). Regarding methodological coherence, the simplicity of Eq. (1) and the availability of crustal concentration data for all relevant elements avoid the need for any special, incoherent treatment of specific elements. Regarding practical applicability, CSPs are provided for 76 elements.

The CFs of the abiotic depletion method, called abiotic depletion potentials (ADPs), relate the extraction of a resource to its ultimate reserves (Guinée and Heijungs 1995):

$$\mathrm{ADP}_i = \frac{DR_i / R_i^2}{DR_{Sb} / R_{Sb}^2} \tag{4}$$

where DR is the annual global extraction rates (in kg/year) of resource i, R is the ultimate reserves (= crustal content, in kg) of i, and Sb is the reference element antimony. Most extraction rates change notably over time, in particular for byproduct metals (Drielsma et al. 2016). In the latest update of the ADPs, average extraction rates over a few years were applied, a 5-year updating was recommended and the use of cumulative ADPs (based on the sum of global production up to a certain year) was proposed (van Oers et al. 2020). These measures improve the temporal reliability of the ADPs, but they might still vary considerably over longer time periods as extraction rates change. All ADPs are calculated in the same way, giving the abiotic depletion method a high methodological coherence, and 76 ADPs are currently provided.

The CFs of the surplus ore method, called surplus ore potentials (SOPs), quantify the increased amount of ore required for obtaining the same amount of metal due to decreasing ore grades from increased extraction (Huijbregts et al. 2016). For a mineral resource i, the SOP is calculated as:

$$\mathrm{SOP}_i = \frac{\mathrm{ASOP}_i}{\mathrm{ASOP}_{Cu}} \tag{5}$$

where ASOP is the absolute SOP, and Cu is the reference resource copper. An ASOP for mineral resource i is calculated as (Vieira et al. 2017):

$$\mathrm{ASOP}_i = \frac{\int_{CME_i}^{MME_i} OP_i(ME_i)\,dME_i}{R_i} \tag{6}$$

where OP_i is the inverse ore grade of i, ME_i is the amount of i extracted (in kg), MME_i is the maximum cumulative amount of i that can become extracted in the future (in kg), CME_i is the current cumulative amount of i extracted (in kg), and R_i is the reserves (in kg). The maximum cumulative amount is equal to the reserves plus the current cumulative amount extracted: $MEE_i = R_i + CME_i$. The parameter OP_i is derived based on a

[6] Note, however, that noble gases and other gases can be trapped in the crust, see, e.g., Strutt (1939).

Table 1 Crustal depletion potentials (CSPs) for 76 elements in order of highest value

Element	CSP (kg Si eq/kg)	Element	CSP (kg Si eq/kg)	Element	CSP (kg Si eq/kg)	Element	CSP (kg Si eq/kg)
Ir	7,600,000,000	Tb	470,000	Th	51,000	Cr	2100
Os	6,900,000,000	I	400,000	Nb	35,000	Zr	2100
Rh	4,700,000,000	Ta	400,000	B	26,000	V	2000
Re	1,500,000,000	Ho	370,000	Pb	26,000	Cl	1200
Ru	470,000,000	Mo	350,000	Ge	22,000	Sr	880
Au	220,000,000	Br	320,000	Ga	18,000	S	700
Pd	190,000,000	W	280,000	Li	18,000	P	650
Pt	190,000,000	Eu	260,000	Y	15,000	Ba	620
Te	57,000,000	U	220,000	La	14,000	F	510
Hg	9,400,000	Sn	170,000	Nd	14,000	Mn	370
In	5,400,000	Be	150,000	Sc	13,000	C	140
Ag	5,100,000	Yb	150,000	Co	11,000	Ti	67
Cd	3,500,000	Cs	140,000	Cu	10,000	K	19
Se	2,200,000	Er	130,000	Ce	6600	Na	12
Bi	1,600,000	As	110,000	Pr	5800	Mg	10
Sb	1,400,000	Dy	79,000	Rb	5800	Ca	6.2
Tm	1,000,000	Gd	76,000	N	5100	Fe	5.4
Lu	940,000	Hf	76,000	Ni	4800	Al	3.4
Tl	570,000	Sm	74,000	Zn	3900	Si	1

log-logistic cumulative grade-tonnage relationship (Vieira et al. 2012). By including price-based allocation of byproduct elements (Huijbregts et al. 2016), the SOPs become time-sensitive since market prices of metals are highly fluctuating over time (Drielsma et al. 2016). The surplus ore method is furthermore methodologically incoherent regarding how the SOPs are calculated: only 18 SOPs are calculated using the proposed method, whereas the other 42 are extrapolated based on price (Huijbregts et al. 2016). In addition, all rare earth elements are given the same SOP, as are a number of platinum-group metals (iridium, osmium, and ruthenium). The practical applicability of the SOP is relatively high with 60 available values, although the majority of these are extrapolated based on price.

Table 2 Five mineral resource impact assessment methods are evaluated as high, medium, or low by the criteria defined in Section 2. In brief, temporal reliability is about being reproducible over time, methodological coherence is about calculating all characterization factors using the same general method, and practical applicability is about the number of characterization factors provided

Method	Temporal reliability	Methodological coherence	Practical applicability*
Crustal scarcity indicator	High (due to time-independent parameter)	High (because all values are calculated in the same way)	High: 76
Abiotic depletion	Medium (due to moving average or cumulative extraction rates)	High (because all values are calculated in the same way)	High: 76
Surplus ore	Low (due to current prices)	Low (due to price extrapolation and group values)	Medium: 60
Cumulative exergy demand	Low (due to current prices)	Low (due to all values being based on one copper ore)	Low: 32
EPS	Low (due to backstop technology costs)	Medium (due to varying number of some elements extracted together)	High: 71

* Assessed as the number of elemental CFs provided

For calculating CFs for the cumulative exergy demand (CExD), the following equation is applied (Bösch et al. 2006):

$$CF_{CExD,i} = \frac{0.63}{C_{ore,i}} \tag{7}$$

where $CF_{CExD,i}$ is the cumulative exergy demand of element i in an ore (in MJ/kg), and $C_{ore,i}$ is the concentration of the element in the ore (in kg/kg). The number 0.63 MJ/kg ore is the median chemical exergy of 14 ores described by Finnveden and Östlund (1997) and specifically represents a certain Swedish copper sulfide ore. The CExD makes use of current prices for byproduct element allocation (Bösch et al. 2006), which results in CFs varying over time. A notable methodological incoherency in the CExD is that all CFs are based on the ore exergy of 0.63 MJ/kg from a certain copper ore, which would strictly only be correct to use for copper from such an ore. The CExD furthermore has the lowest practical applicability of the evaluated indicators, providing only CFs for 32 elements.

In the EPS method, elements are assessed in terms of environmental load units (ELU) reflecting the extraction cost from a backstop technology (Steen 2016), which is taken to be acid leaching of elements from ordinary rock for most elements (Steen and Borg 2002). Although the EPS method has a clear long-term perspective on elemental resources, it thus contains assumptions about specific future backstop technologies for element extraction. The costs related to such technologies might change over time, for example in terms of input materials and electricity costs. An assumption is also made regarding how many elements will be extracted together from leaching in the future: one for iron and aluminum, ten for all others (Steen 2016). The reason for this is the high crustal concentrations of iron and aluminum compared with most other elements, but whether this assumption will become realized is uncertain and it creates a methodological incoherency between some elements. The practical applicability of the EPS indicator is high, with 71 CFs provided.

5 Quantitative comparison of crustal scarcity potentials vs characterization factors from four other methods

In Fig. 2, CSPs are plotted against the corresponding ADPs. There is some correlation between these two sets of CFs, and it is possible to distinguish three groups of elements previously identified in the literature: (1) geochemically abundant elements (Skinner 1976), sometimes called rock-forming elements (Izatt et al. 2014), with low impact (e.g., silicon and iron); (2) a large group of rare elements (Skinner 1976) with higher impact (e.g., lithium and copper); and (3) a small group containing the rarest precious metals (Izatt et al. 2014) with high impact (e.g., gold and platinum[7]). However, there is not a complete correlation between the CSPs and the ADPs. The ADPs contain a multiplication of two parameters, $1/R_i$ and DR_i/R_i, where the first of these parameters is effectively equivalent to the CSP. The second parameter is thus responsible for the differences between the CSPs and the ADPs. Notably, some elements with very different CSPs have similar ADPs (examples in dashed boxes in Fig. 2). Two examples of large differences are the elements gallium and carbon, where the ADPs are not aligned with a long-term elemental scarcity perspective. Gallium has a similar ADP as the abundant element iron (left dashed box in Fig. 2). However, gallium and iron have very different CSPs, meaning very different crustal concentrations. The explanation for the low ADPs of gallium despite its low crustal concentration is the comparatively low extraction rate (i.e., low DR_{Ga}/R_{Ga}). Similarly, gallium can be compared with copper and lead in Fig. 2: although the crustal concentrations of these three elements are comparable (as evident from their CSPs), the ADPs differ notably because of the lower current extraction rate of gallium. Carbon has a similar ADP as a number of rare elements, including germanium and holmium, while their CSPs differ considerably (right dashed box in Fig. 2). The reason for the high ADPs of carbon is a high production relative to its crustal concentration (i.e., high DR_C/R_C), possibly stemming from its large use in energy production. The ADPs thus overestimates or underestimates impacts relative to their crustal concentrations because of the inclusion of the DR_i/R_i parameter. The risk of underestimation was also noted by Sonderegger et al. (2020), who mention that several mineral resource impact assessment methods have not included the current annual production in their CFs since doing so "may underestimate future risks of mineral supply shortages for minerals that are not yet used in large volumes." Conversely, future risks of mineral supply shortages can be overestimated by a current use of large volumes, as in the case of carbon. Although the DR_i/R_i parameter might not be helpful for capturing long-term elemental scarcity in an LCIA context, it should be noted that it can be of interest from a different point of view: for estimating "how long time it will take until an element is depleted" by relating the current extraction to the ultimate (or some other) reserve. From this perspective, $1/R_i$ corresponds to the impact indicator, while the extraction rate DR_i in fact corresponds to the life cycle inventory (LCI) data on the extraction of i in an "LCA" with a functional unit corresponding to the full global economy. Such a quotient can be used to continuously assess the sustainability of global mineral demand.

Figure 3 shows the CSPs plotted against the corresponding available SOPs. The results resemble those in Fig. 2—it is possible to distinguish the three groups of abundant, rare, and rarest elements, but the SOPs give some rare elements similar impacts as the most abundant ones, including iron and silicon (dashed box in Fig. 3). This goes for a range of rare elements, including zinc, lead, cadmium, antimony, and neodymium. As mentioned in Section 3, all rare earth elements are given the same impact and so are a number of platinum-group metals (iridium, osmium, and ruthenium). That is why these can be found along two respective vertical lines in Fig. 3. A notable outlier on the SOP axis is cesium, which is given the highest SOP of all elements included, even higher than those of platinum and gold. From a long-term elemental scarcity perspective, it seems questionable that cesium of all elements should have highest resource impact. Indeed, cesium is positioned much lower on the CSI axis as per its crustal concentration, roughly on the same level as arsenic and tin.

Figure 4 shows the CSPs from this study plotted against the corresponding available CFs from the CExD. Note that

[7] The position of the precious metal rhodium on the ADP axis is surprisingly low. It might even be the result of a typo, so that the ADP of rhodium should be 1.8×10^3 instead of 1.83×10^{-3} kg Sb equivalents per kg as reported by van Oers et al. (2020).

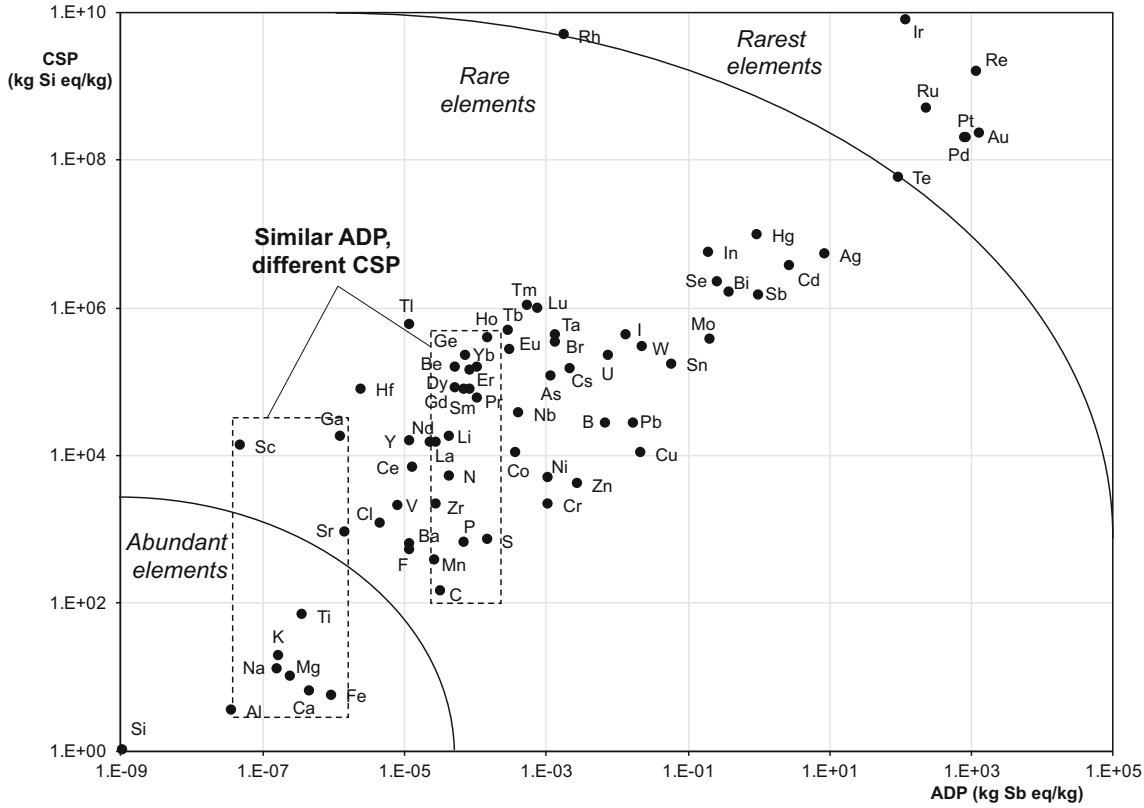

Fig. 2 Crustal scarcity potentials (CSPs) plotted against abiotic depletion potentials (ADPs). Some examples of elements with similar ADPs but different CSPs are highlighted in dashed boxes

several CExD CFs are available for some elements: copper (11), gold (9), lead (2), molybdenum (7), nickel (4), palladium (2), platinum (2), rhodium (2), silver (7), zinc (2), fluorine (2), and phosphorous (2). These CFs represent ores with different grades and/or byproducts and have thus been plotted as separate values. Considering the price-based allocation, prices of byproducts influence the CExD CFs, and elements can get lower CFs due to the presence of other valuable high-grade elements in the same ore. For example, the molybdenum ores included have the same molybdenum concentration (0.0082%), but different byproducts of different concentrations, giving CExD CFs for molybdenum that vary between 209 and 1447 MJ/kg. Fig. 4 shows that there is a general agreement between the CSPs and the CExD CFs for many elements, for example regarding the high CFs for rhenium, rhodium, palladium, platinum, and gold. Similarly, the abundant metals iron and aluminum have low CFs according to both methods. However, as can be seen in Fig. 4, the CExD CFs give effectively as low impact as for iron and aluminum to a number of other elements: manganese, chromium, and cadmium, as well as the lower ends of the phosphorous, zinc, nickel, copper, and lead value ranges (dashed box in Fig. 4). This defies a long-term elemental scarcity perspective and confirms that this is not the perspective of the CExD. A notable outlier on the CExD CF scale is tantalum, which is given one of the highest values (Fig. 4). It is reported to be present at very low concentrations in extracted ores (160 ppm), which is only 230 times its crustal concentration of 0.7 ppm. Some precious metals present at similarly low concentrations in ores (palladium, 200–730 ppm; platinum, 250–480 ppm; gold, 110–970 ppm) have much lower crustal concentrations (0.0013–0.0015 ppm). The concentration in ores is thus similar for these metals, but the crustal concentration of tantalum is much higher. Since the CExD CFs consider current ore concentrations (Eq. (7)), these metals (including tantalum) are ranked similarly by the CExD, whereas the CSPs consider crustal concentrations (Eq. (1)), for which there is a large difference between tantalum and these precious metals.

Figure 5 shows the CSPs plotted against the corresponding available EPS CFs, showing that they are generally proportional, which confirms that the EPS CFs are approximately proportional to the inverse crustal concentrations as suggested (Steen 2016). Some deviations occur due to smaller differences in concentration data (between different sources as well as between the upper and total crusts) and differences in leaching efficiencies between the metals. However, there are also some larger deviations. For boron, lithium, potassium, and sulfur, the extraction is assumed to be from sea water instead of the crust in the EPS method. Consequently, these EPS CFs are not proportional to crustal concentrations. It can also be noted that the EPS CFs for aluminum and iron are higher than would be expected. For example, they have

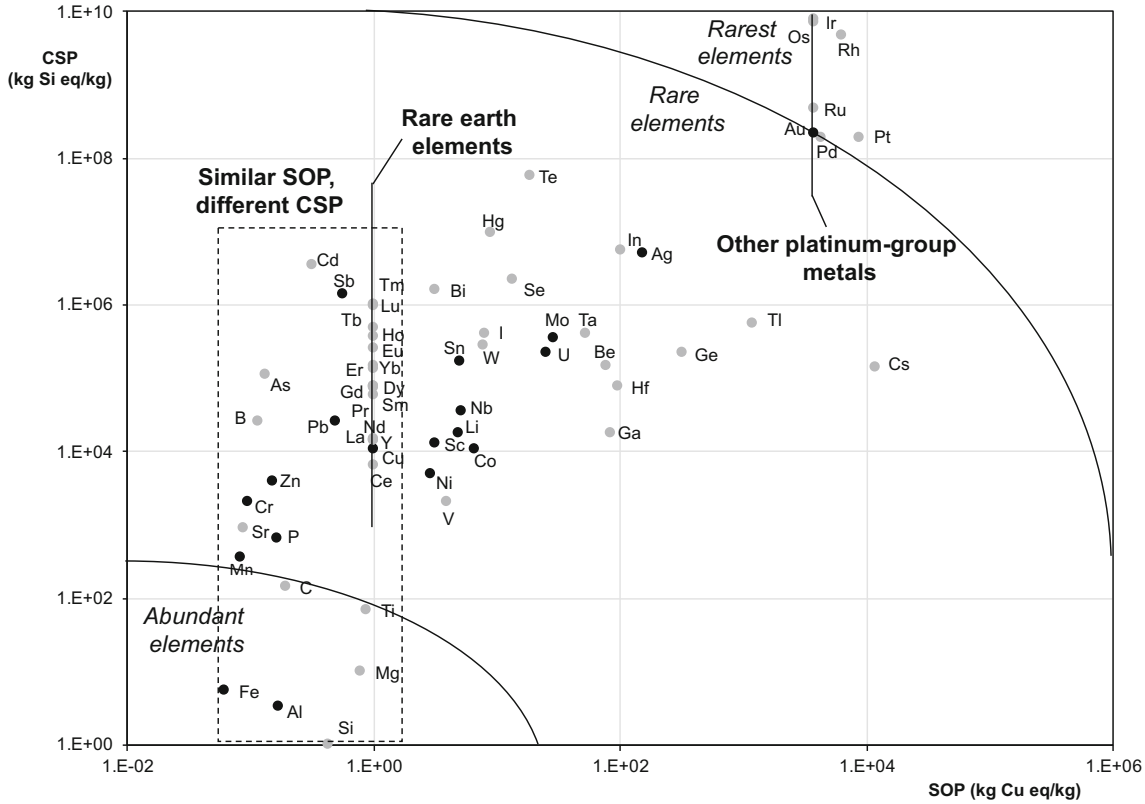

Fig. 3 Crustal depletion potentials (CSPs) plotted against surplus ore potentials (SOPs) from ReCiPe 2016. Two vertical lines contain all rare earth elements and some platinum-group metals, respectively, for which the surplus ore indicator assumes the same impact. Elements for which SOPs are obtained by price extrapolation are shown in gray. Examples of elements with similar SOPs but different CSPs are highlighted in a dashed box

similar EPS CFs as titanium, which is more than ten times as rare. The reason for these higher values is because the EPS method assumes an extraction of ten elements together from ordinary rock for all elements except aluminum and iron, where extraction of one single element is assumed. This makes the extraction costs of aluminum and iron ten times higher relative to their upper crustal concentrations, since they need to cover their own extraction costs completely instead of sharing them with nine other elements. From a long-term global perspective, following, e.g., Skinner (1976), it would perhaps be more reasonable to assign iron and aluminum lower CFs relative to the rarer elements, since both iron and aluminum, with their likely unimodal concentration curves, are much harder to deplete than the rarer elements, with their likely bimodal concentration curves. A final outlier is selenium, where the underlying concentration data differs notably: 0.13 ppm in this study based on Rudnick and Gao (2014) and 50 ppm in the EPS method based on McLennan (2001). However, the 50 ppm value is probably a misquote by McLennan (2001) of Taylor and McLennan (1985), in which the concentration of selenium is rather reported as 0.05 ppm (or 50 ppb), not 50 ppm. Because of this likely misquoted concentration applied in the EPS CF, the cost estimated for selenium becomes lower than the element's CSP suggests due to an artificially higher concentration (50 ppm instead of 50 ppb). It can be concluded that the EPS method generally gives a similar relative ranking of elements as the CSI but includes some additional assumptions and parameters for the calculation of CFs. The CSI thus achieves a similar ranking without any assumptions about backstop technology, need for leaching experiments, and cost estimations.

6 Hypothetical case study

Consider a hypothetical, simplified inventory analysis result of 1 kg iron, 1 kg sulfur, and 1 kg lithium extracted from the crust per some arbitrary functional unit. A partial inventory result for a large pack of lithium-sulfur batteries might look something like this, since lithium and sulfur are used in roughly the same proportions (Arvidsson et al. 2018), and iron (in the form of steel) might be used as packing material. From a long-term global elemental scarcity point of view and a focus on the crust, it seems clear that of these three elements, lithium should be the main concern considering its crustal concentration of 16 ppm. Iron is an abundant metal (50,000 ppm) and sulfur is a relatively common element (400 ppm) in the crust. Fig. 6 shows impact assessment results for this hypothetical

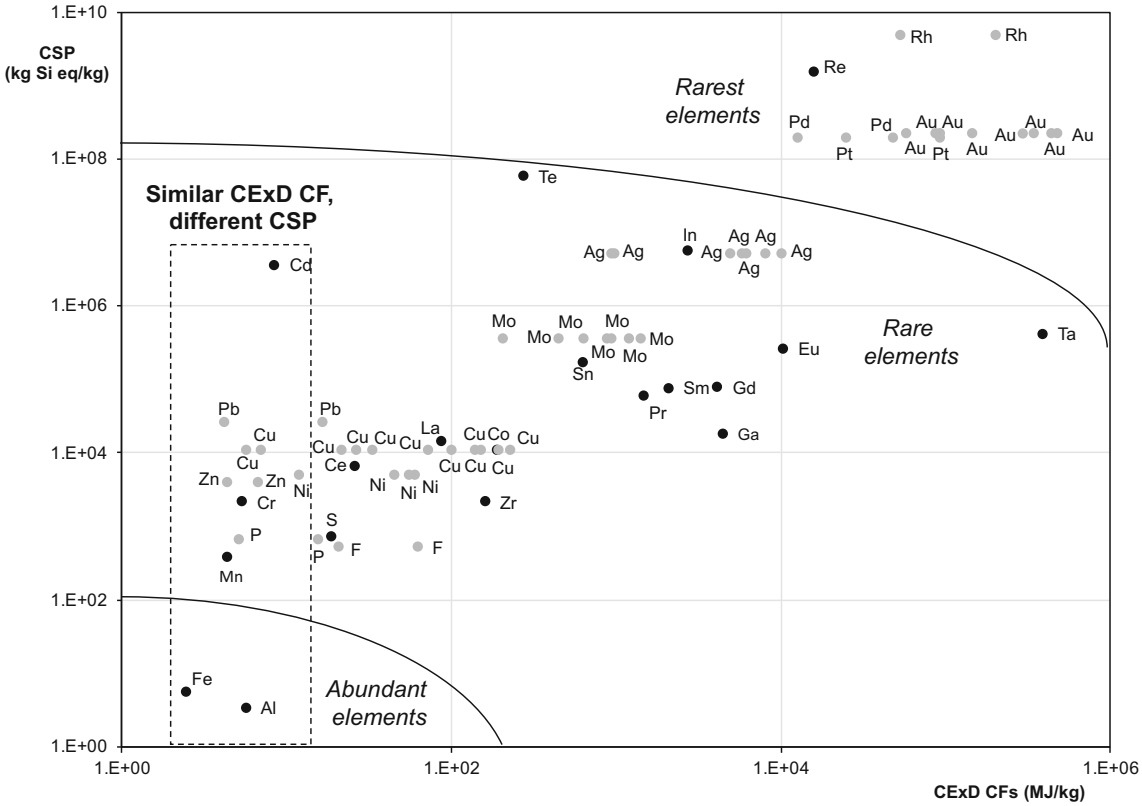

Fig. 4 Crustal depletion potentials (CSPs) plotted against cumulative exergy demand (CExD) characterization factors (CFs). Elements with multiple CExD CFs, reflecting different grades and/or byproducts in ores, are shown in gray. Examples of elements with similar CExD CFs but different CSPs are highlighted in a dashed box

inventory result as assessed by the four methods CSI, abiotic depletion, surplus ore, CExD, and EPS. For the CSI, lithium is indeed the largest contributor. For the abiotic depletion, sulfur is instead the largest contributor, which might be due to the high production of sulfur from desulfurization of fossil fuels relative to its crustal concentration. The surplus ore method also identifies lithium as the largest contributor. However, the surplus ore method does not contain a CF for sulfur, which thus gets a zero contribution for that reason. For the CExD, sulfur becomes the main contributor, but the CExD lacks a CF for lithium, which therefore gets a zero contribution. For the EPS method, iron becomes the main contributor. This is because the EPS method goes beyond the crust and assumes that sulfur and lithium can be extracted in large amounts from sea water in the future. In this hypothetical case study, the CSI both provides CFs for all three elements and highlights the element with the highest long-term crustal scarcity, i.e., lithium.

7 Concluding discussion

From a long-term global elemental scarcity perspective, the CSI has a clear benefit compared with the abiotic depletion, surplus ore, CExD, and EPS methods: it does not include any time-sensitive parameters and thereby provides CFs that better reflect long-term global elemental scarcity. In particular, the economic allocation conducted within the surplus ore and CExD methods, which is based on highly volatile price data, is avoided. Furthermore, it has been suggested that extractions and other interventions should not be part of CFs but belong to the LCI analysis phase of the LCA framework (Finnveden 2005). From this perspective, it is a benefit that the CSI only includes one parameter related to the natural system and not any socio-technical parameters, such as prices and extraction rates. The CSI method thus constitutes a depletion method with several advantages compared with existing depletion methods and other mineral resource impact assessment methods when it comes to capturing long-term scarcity.

The comparison of CFs conducted in Section 5 also showed that three of the other four mineral resource assessment methods (abiotic depletion, surplus ore, and CExD) calculated roughly the same resource impact for some abundant as for some rare elements. Although we acknowledge the different perspectives of these three methods and the CSI, with the other three methods not having an explicit long-term perspective, it still seems questionable to assign the same resource impact to, e.g., the use of iron, silicon, and aluminum and the use of gallium, cadmium, and lead, respectively. The three rarer elements probably face higher risk of depletion,

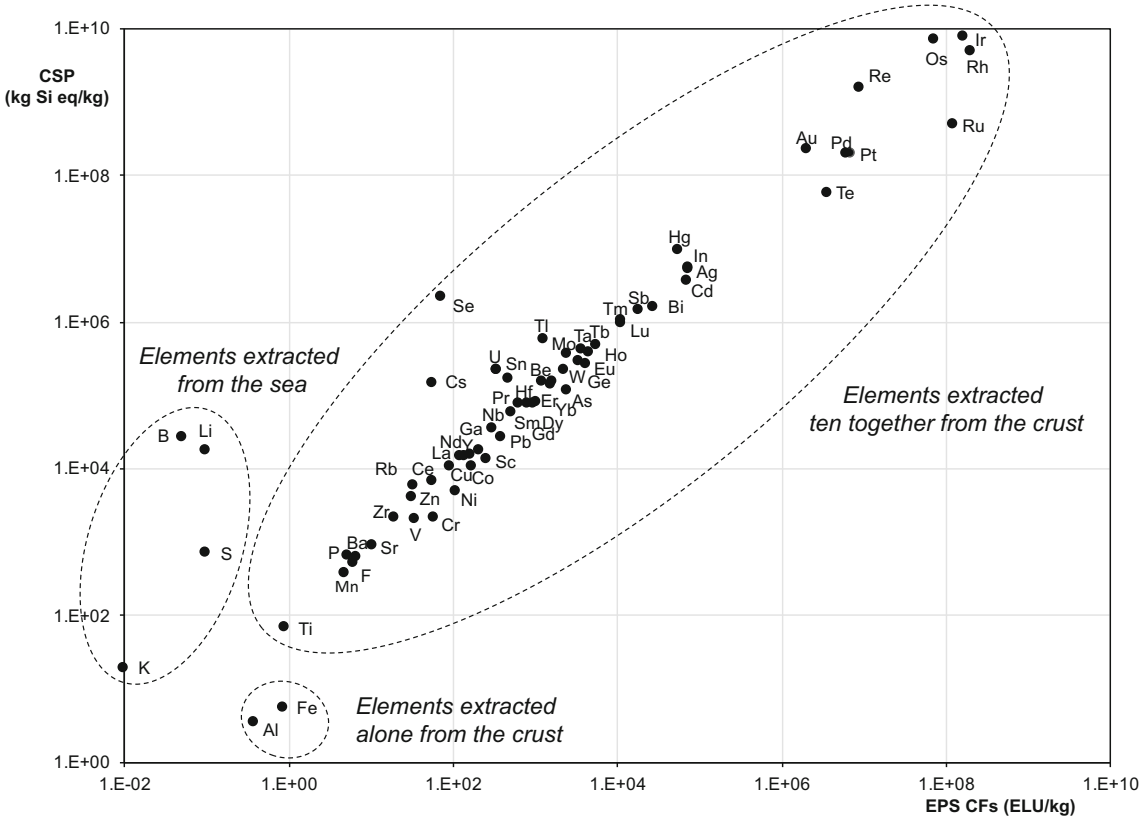

Fig. 5 Crustal depletion potentials (CSPs) plotted against environmental priority strategies in product development (EPS) characterization factors (CFs). Three groups of elements treated differently in the EPS method are highlighted in dashed ovals

require larger efforts for extraction (both now and in the future), result in larger exergy losses when extracted, and face higher supply risks than the three abundant ones. The rarer elements should therefore warrant higher impacts regardless of which of the perspectives outlined by Sonderegger et al. (2020) is preferred. The comparison thus highlight that the relative ranking of elements provided by some mineral resource impact assessment methods is in need of careful scrutiny in relation to the claimed perspectives.

Still, the CSI has a number of limitations. Since the CSI is a midpoint indicator concerned with the long-term global elemental scarcity of the crust, it should, by definition, not be expected to cover all aspects of mineral resource use. It is rather to be seen as a part of a larger "family" of mineral resource impact assessment methods, much as climate change and acidification belong to a "family" of emission-related impact assessment methods. These two emission-related impact categories cover greenhouse gases and acidic emissions, respectively, as well as their impacts, but

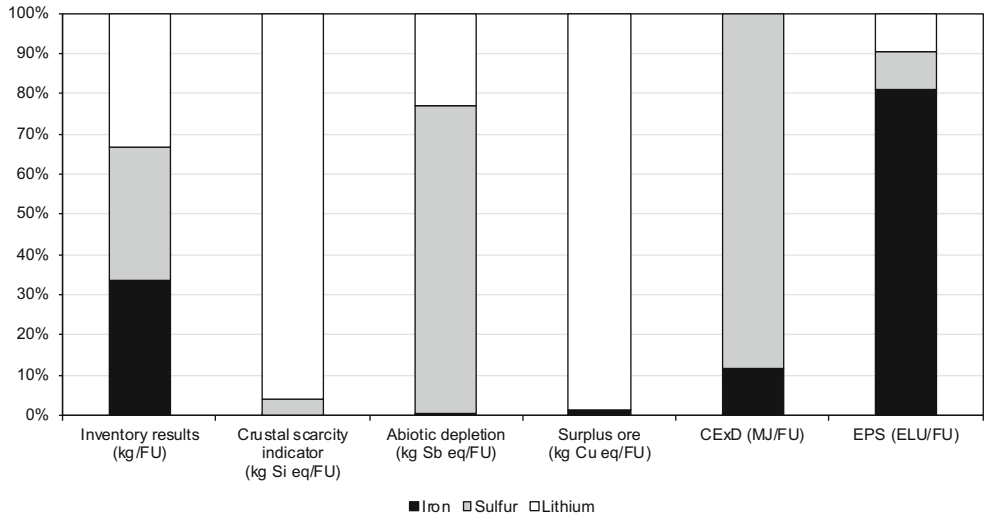

Fig. 6 Results from four mineral resource impact assessment methods given a hypothetical, simplified case study with an inventory of 1 kg iron, 1 kg sulfur, and 1 kg lithium extracted from the crust per some arbitrary functional unit (FU). Note that the surplus ore method does not have a characterization factor for sulfur, and the cumulative exergy demand (CExD) method does not have a characterization factor for lithium, which is why these elements get zero resource impact with these methods

not other emissions or the impacts of other emissions. The CSI thus needs to be complemented by other methods to provide a richer picture of the resource impacts of products, in line with the reasoning by the Life Cycle Initiative's task force on mineral resources that different mineral resource impact assessment methods answer different questions (Berger et al. 2020). Since the CSI targets long-term elemental scarcity, it does not consider specific chemical forms of elements, such as carbon in the form of crude oil and hard coal, or metals in different minerals. In the near term, given the technologies available today, certain chemical constellations (e.g., crude oil and copper sulfide) might be more attractive than others, resulting in higher extraction of these forms. However, given, say, a 100-year time perspective, there is no guarantee that the same forms will remain the most attractive, as exemplified by crude oil extraction being limited at year 1900. Given more short-term interests, however, the scarcity of such specific forms might be of high interest and warrant detailed scrutiny by means of other methods.

As mentioned above, the CSI only considers resources in the crust. For some of the elements in the periodic table, other compartments also constitute important sources now or in the future. For example, in the future, extraction from the sea rather than the crust is a possible backstop technology for lithium (Kushnir and Sandén 2011), in line with the assumption in the EPS method. Nitrogen, on the other hand, is mainly obtained from the atmosphere through the Haber-Bosch process or liquification of air. Considering that other environmental compartments than the crust are or might become important sources of some resources, this could warrant the development of analogous midpoint indicators for these compartments, for example an "oceanic scarcity indicator" and an "atmospheric scarcity indicator."

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