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Implementation of the crustal scarcity indicator into life cycle assessment software

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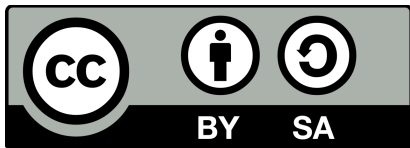
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Cover: Round Mountain open pit gold mine, aerial photo from 2008. Located in Round Mountain, Big Smokey Valley, Nevada. Picture by Uncle Kick-Kick (Patrick Huber) obtained from Wikimedia Commons (2020-10-05):

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SUMMARY

This report provides a detailed description of how the crustal scarcity indicator (CSI) is implemented into the life cycle assessment (LCA) software OpenLCA. The original characterization factors for the CSI, called crustal scarcity potentials (CSPs), were designed to be paired with life cycle inventory data formulated as the amount (mass) of elements extracted from the crust. However, some inventory data is not formulated in terms of mass of elements extracted. For example, data in the Ecoinvent database – the world's largest LCA database – can also be expressed in terms of the amount of mineral extracted, the amount of rock extracted, or the amount of ore extracted. In order to implement the CSI into OpenLCA in a way that captures such non-element flows, we construct five categories of inventory data for material flows extracted from the crust. Type A flows are flows of elements, such as lead or tin, which the original CSPs can be paired with. Type B flows are flows of minerals, such as kieserite or stibnite. Type C flows are flows of rocks and groups of minerals, such as basalt or olivine. Type D flows are ores, like copper ore. Type A flows are paired with the CSPs of the respective element types. However, for type B, C and D flows, new CSPs were calculated based on their respective content of different elements. These new CSPs can be found in Appendix A-D. In addition, type E flows are those that are too vaguely formulated in the Ecoinvent database, for example as general metal or ore, making it impossible to derive CSPs. In the concluding discussion, we show that this implementation gives the CSI a wider coverage of different inventory flows than other existing mineral resource impact assessment methods implemented in different packages for OpenLCA. The implementation might thus be considered a guidance for a more all-encompassing implementation of other mineral resource impact assessment methods as well.

SAMMANFATTNING

Denna rapport innehåller en detaljerad beskrivning av hur jordskorpan knapphetsindikator (JKI), en metod för miljöpåverkansbedömning, kan implementeras i mjukvaran OpenLCA för livscykelanalys (LCA). De ursprungliga karaktäriseringsfaktorerna för JKI, kallade jordskorpan knapphetspotentialer (JKP), togs fram för att kombineras med livscykelinventeringsdata formulerad i termer av mängd (massa) grundämne utvunnet ur jordskorpan. Somliga inventeringsdata är dock formulerade på andra sätt. Inventeringsdata från databasen Ecoinvent – världens största LCA-databas – kan till exempel även vara uttryckta i termer av mängd mineral utvunnen, mängd bergart utvunnen eller mängd malm utvunnen. För att kunna implementera JKI i OpenLCA på ett sätt som även inkluderar sådana icke-grundämneshöjden skapades fem kategorier av inventeringsdata för materialflöden utvunna ur jordskorpan. Typ A-flöden är grundämneshöjden, såsom bly eller tenn, som de ursprungliga JKP:erna kan kombineras med. Typ B-flöden är flöden av mineraler, såsom kieserit eller stibnit. Typ C-flöden är flöden av bergarter och grupper av mineraler, såsom basalt eller olivin. Typ D-flöden är malmer, såsom kopparmalm. Typ A-flöden kan kombineras direkt med respektive grundämne bland de ursprungliga JKP:erna. För typ B-, C- och D-flöden behöver nya JKP:er beräknas baserat på deras respektive innehåll av olika grundämnen. Dessa nya JKP:er återfinns i bilagor A-D. Typ E-flöden utgörs av sådana flöden som är alltför vagt formulerade, till exempel som generell metall och malm, för att det ska vara möjligt att beräkna JKP:er. I det avslutande avsnittet visas att denna implementering av JKI täcker in fler inventeringsflöden än andra existerande miljöpåverkansbedömningsmetoder för materialresurser i OpenLCA. Denna implementering kan därför tjäna som vägledning för en mer omfattande implementering av andra miljöpåverkansbedömningsmetoder för materialresurser i LCA.

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1. INTRODUCTION

The assessment of mineral resources has been much discussed in the life cycle assessment (LCA) field. The discussions have included how to best assess the impacts of mineral resource extraction from different perspectives and even what a mineral resource impact is to begin with (Dewulf et al., 2015; Finnveden, 2005; Sonderegger et al., 2017; Steen, 2006). Recently, a task force of the Life Cycle Initiative, hosted by the United Nations Environment Programme and the Society for Environmental Toxicology and Chemistry, provided recommendations for which mineral resource impact assessment methods to use in different situations (Berger et al., 2020), see Table 1. Subsequently, some of the authors of this report, together with colleagues, developed a new mineral resource impact assessment method called the crustal scarcity indicator (CSI) (Arvidsson et al., 2020). The main rationale behind the method is to provide a long-term perspective on mineral resource scarcity, to a higher degree than what existing mineral resource impact assessment methods are capable of, including those in Table 1. The idea is to provide assessment results which are relevant also for decisions with >100-year implications.

Although the CSI itself has already been described in a journal publication (Arvidsson et al., 2020), its exact implementation into LCA software is not trivial. This is because of the varying quality and formats of life cycle inventory (LCI) data, a challenging situation which applies to any mineral resource impact assessment method – not just the CSI. In this report, the implementation of the CSI into LCA software is described. First, a description of the CSI is provided, after which the aim of the report is described in more detail. Next, a detailed description of the implementation itself is provided. The report ends with a concluding discussion, including a comparison with the implementation of other mineral resource impact assessment methods into LCA software.

1.1 The Crustal Scarcity Indicator

The developed CSI is based on characterization factors called crustal scarcity potentials (CSP), which are calculated as:

$$CSP_i = \frac{1/C_i}{1/C_{Si}} \quad (\text{Eq. 1})$$

where C is the crustal concentration (in ppm), i is an element and Si stands for silicon, which serves as the reference element to which all other elements are related. As can be seen, the crustal concentration C is the only input parameter in the calculation of the CSPs. Since crustal concentration measurements have remained relatively stable over time (Drielsma et al., 2016), it also makes the CSPs stable over long time periods. The reason for selecting the crustal concentration as the only input parameter is because it has been shown (or at least suggested) to correlate with a number of important resource metrics in the long term, including reserves and mineral ore deposits. Please read Arvidsson et al. (2020) for a further description of these correlations.

The CSPs can be applied in life cycle impact assessment (LCIA) of resource extraction by multiplying the mass of element i extracted from the crust (m_i , in kg) by the corresponding CSP of element i according to the following equation:

$$CSI = \sum_i m_i \times CSP_i \quad (\text{Eq. 2})$$

Table 1. Recommended mineral resource impact assessment methods for different questions according to Berger et al. (2020). ADP=abiotic resource depletion, SOP=surplus ore potential, LIME=life-cycle impact assessment method based on endpoint modelling, CEENE=cumulative exergy extraction from the natural environment, GeoPolRisk= geopolitical-related supply risk.

How can I quantify the relative...	Recommended method
... contribution of a product system to the depletion of mineral resources?	ADP with ultimate reserves
... contribution of a product system to changing mineral resource quality?	None
... consequences of the contribution of a product system to changing mineral resource quality?	SOP (interim)
... (economic) externalities of mineral resource use?	LIME2 endpoint (interim)
... impacts of mineral resource use based on thermodynamics?	CEENE (interim)
... potential mineral availability issues for a product system related to mid-term physico-economic scarcity of mineral resources?	ADP with economic reserves (suggested)
... potential accessibility issues for a product system related to short-term geopolitical and socio-economic aspects?	ESSENZ (interim) and GeoPolRisk (suggested)

Table 2. Crustal scarcity potentials (CSPs) for all 76 included 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	2,100
Os	6,900,000,000	I	400,000	Nb	35,000	Zr	2,100
Rh	4,700,000,000	Ta	400,000	B	26,000	V	2,000
Re	1,500,000,000	Ho	370,000	Pb	26,000	Cl	1,200
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	6,600	Na	12
Bi	1,600,000	As	110,000	Pr	5,800	Mg	10
Sb	1,400,000	Dy	79,000	Rb	5,800	Ca	6.2
Tm	1,000,000	Gd	76,000	N	5,100	Fe	5.4
Lu	940,000	Hf	76,000	Ni	4,800	Al	3.4
Tl	570,000	Sm	74,000	Zn	3,900	Si	1

Since the CSPs are based on crustal concentrations and reflect potential crustal scarcity, they should only be paired with LCI data (i.e. m_i) reflecting extraction of elements from the crust. LCI data reflecting extraction of elements from the sea or the atmosphere should thus *not* be used in the calculation of the CSI.

CSPs have been calculated for 76 of the currently 118 elements of the periodic table. However, three groups of elements were deliberately excluded:

1. **Elements exclusively produced in the technosphere**, which are thus not extracted from the crust, mainly radioactive elements (some synthetic ones and some that exist in nature as well) with very low annual productions, sometimes as low as a few ng/year or less.
2. **Noble gases**, which are not considered parts of the crust, although pockets of noble gases and other gases might be trapped in the crust.
3. **Hydrogen and oxygen**, which are considered inexhaustible and therefore irrelevant from a long-term global scarcity point of view.

Data on crustal concentrations is obtained from the most recent standard reference by Rudnick and Gao (2014) for most elements. If crustal concentrations were given for the corresponding oxide instead of the pure element (which was the case for the elements silicon, titanium, aluminum, iron, manganese, magnesium, calcium, sodium, potassium and phosphorous), the concentration of the pure element was calculated based on its molar shares of the respective oxide. For carbon, rhodium and tellurium, data was not available in Rudnick and Gao (2014) and therefore instead obtained from an older source (Wedepohl, 1995). Table 2 shows the CSPs for all included elements. They are presented with two significant numbers, since that matches the significant numbers of most crustal concentration 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.

1.2 Aim of the Study

When conducting an LCA, it is important that the LCI data and the implementation of selected LCIA methods fit well together. The original CSPs were developed to be paired with inventory data m_i which represents the amounts of elements extracted (see Eq. 2), thus making a good fit with such flows (Figure 1a). However, LCI data as available in existing LCA databases are not always formulated in such a way. Rather, there exist several different ways to name a material flow extracted from the crust. Sometimes, mineral names are used without providing the constituent elements, such as “4.5 kg chalcopyrite” (a copper-containing mineral with the chemical structure CuFeS_2). Other times, vaguer terms such as “copper ore” are used, where the only given information is that the material flow extracted must contain some minable amounts of copper. However, there are surely also other elements in the ore besides copper. Copper ore and other ore flows thus do not fit well with the original CSPs (Figure 1b). There are a number of such challenging situations that can arise due to the varying LCI data variants that exist for material flows extracted from the crust. The aim of this study is to enable a comprehensive implementation of the CSI into the OpenLCA software by developing new CSPs that can be paired with the non-elemental flows in the Ecoinvent database.

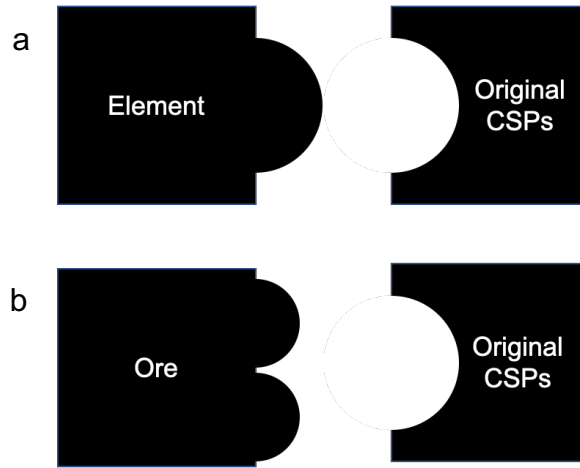


Figure 1. Illustration of the compatibility between the original crustal scarcity potentials (CSPs) and (a) LCI data formulated as flows of elements (good fit) and (b) LCA data formulated as flows of ores (poor fit).

2. IMPLEMENTATION

For the implementation of the CSI into OpenLCA, we identify a number of types of material flows representing extraction from the crust. These types are called type A, type B, type C, type D and type E flows, respectively. The implementation of type A flows is straightforward as they refer directly to flows of elements extracted from the crust, which is what the original CSPs in Table 2 were designed to be paired with. However, flow types B, C and D are not formulated as amounts of elements extracted from the crust. Therefore, the flow types B, C and D are the main focus of this report and will be described in detail below. Specifically, we consider the flows present in the Ecoinvent database (version 3.6) (Wernet et al., 2016), which is the currently largest LCA database in the world. However, the implementation might also be relevant for other databases and data sources. For example, the CPM database (Swedish Life Cycle Center, 2020) also contains non-elemental flows. In a unit process called “Copper ore mining” in that database, material resource flows extracted include, for example, bauxite (a rock), bentonite (a clay), dolomite (a mineral) and iron ore.

The overarching approach is to develop new CSPs based on the elemental composition of the respective flows containing mixtures of elements, i.e. creating a list of new CSPs which expands on the list of original CSPs in Table 2. However, all new CSPs are based on the 76 original, elemental CSPs reported in Table 2. An alternative approach would have been to modify the LCI data, turning it all into flows of elements which can be paired with the original CSPs. However, most LCI data in contemporary LCA databases are under the purview of the various organizations providing the data, making such an approach unfeasible for anyone not working directly with such an organization.

Unfortunately, there were some flows for which new CSPs could not be derived, since they were too ambiguous. Two examples are “metals” and “ore mined”. Depending on the type of metal and ore, the CSP of such flows might differ many orders of magnitude. Considering the lack of any specific information about these flows, estimating reasonable CSPs for them was deemed impossible. They have therefore been categorized as type E flows, which are defined as material resource flows so ambiguous that reasonable CSPs cannot be estimated. All type E flows can be found in Appendix E. A motivation for why a reasonable CSP could not be estimated is provided for all type E flows in Appendix E.

Before going into the type A, B, C and D flows, it could be worth describing some underlying geological terms that underpin these types. These terms correspond to different aggregation levels for materials extracted from the crust, ranging from the least aggregated level (i.e. elements) to the most aggregated level (i.e. rocks). *Elements* are the substances present in the periodic table of the elements, currently amounting to 118, with hydrogen being the first and oganesson being the 118th. In the crust, most elements do not occur as native elements (with a few exceptions, such as gold, silver, platinum and carbon as graphite or diamond) but in the form of *minerals*. Minerals are naturally occurring, homogeneous, solid crystalline chemical compounds, usually formed by inorganic processes (Rankin, 2011). Since minerals are homogeneous, with distinct chemical structures, it means they have the same chemical and physical characteristics down to its smallest unit structure. Most minerals are either oxides, sulfides, carbonates, halides, hydroxides, sulfates, phosphates, borates or silicates (Rankin, 2011). Some mineral names refer to groups of minerals rather than specific chemistries, which is referred to as *mineral groups*. An example is vermiculite, which includes different magnesium-, iron- and aluminium-containing silicates (Anthony et al., 2020). Mixtures of different minerals are referred to as *rocks* (Rankin, 2011). *Rocks* can be classified into igneous rocks, sedimentary rocks and metamorphic rocks based on how they are formed. Rocks can furthermore form clay, silt, sand and gravel due to weathering processes. If elements, minerals or rocks occur in concentrated deposits, such that they might be profitable to mine, they can be referred to as *ores* (Rankin, 2011). Figure 2 provides a graphical illustration of the relationships between these geological terms.

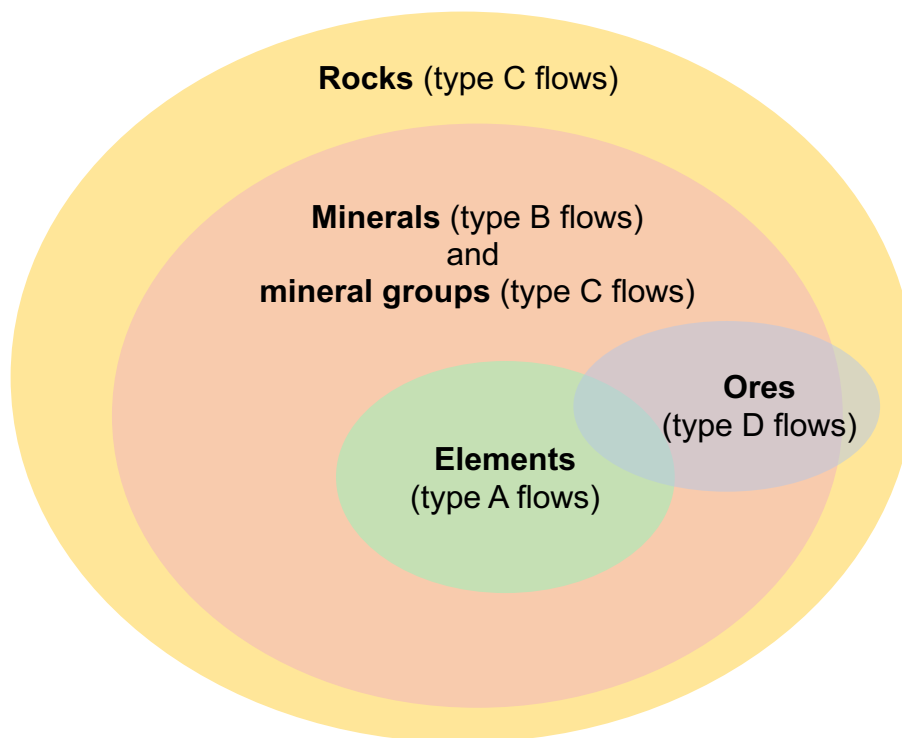


Figure 2. Venn diagram showing the relationships between the terms used: element, mineral, mineral group, rock and ore. Their respective flow types (type A, B, C and D flows), as defined for the implementation described in this report, are also shown in parentheses. Type E flows are not depicted in the figure but can be any unspecified type of mineral resource flow extracted from the crust, i.e. either of elements, minerals, mineral groups, rocks and ores.

2.1 Type A Flows: Elements

Type A flows constitute the most convenient types of material flows when considering the pairing of LCI data with the CSPs. They are often formulated as “element” or “element, in ground” (with or without first letter capitalized), corresponding to the element level in Figure 2. Examples include “gallium” and “Germanium”. Sometimes, formulations more detailed regarding the medium (e.g. mineral or ore) in which the element is present can be found, such as in “element, in ore”, “element, in crude ore” or “element, in sulfide”. An example is “Aluminium, 24% in bauxite, 11% in crude ore”. Sometimes, the chemical symbol is used to designate the element instead of the full name, such as “Pt” for platinum. An example flow with several chemical symbols is “Pt, Pt 2.5E-4%, Pd 7.3E-4%, Rh 2.0E-5%, Ni 2.3E+0%, Cu 3.2E+0% in ore”.

The main point about these type A flows is that they are formulated in terms of the amount of one specific element extracted from the ground, i.e. from the crust. They thus constitute direct quantifications of the parameter m_i in Eq. 2. This means that data formulated in this way can be used directly in Eq. 2. Type A flows are thus LCI data which can be paired with the CSPs in Table 2. A table with all type A flows in the Ecoinvent database (version 3.6) can be found in Appendix A, together with their corresponding CSPs.

A special case to note is the flow “Lithium, 0.15% in brine”. Lithium is today mainly extracted from brines, such as in the Salar de Atacama in Chile (Kushnir and Sandén, 2012). The brine itself is liquid and typically pumped up to the Earth’s surface. However, the lithium in brines originates from the weathering of a source rock below (Bradley et al., 2013) and is therefore here considered an extraction from the crust.

2.2 Type B Flows: Minerals with Distinct Chemical Structures

Sometimes, LCI data is provided in terms of a certain amount of mineral extracted, without information about which the constituting elements are. Examples of this include “Borax”, “Pyrite” and “Zirconia, as baddeleyite”. Such material flows are here referred to as type B flows. These do not correspond directly to m_i in Eq. 2 and can thus not be paired with the CSPs in Table 2. Fortunately, minerals have distinct chemical structures that can be used to calculate CSPs adapted to the specific minerals. Consider a fictional mineral with the chemical composition $A_xB_yC_z$. A, B and C are elements, whereas x , y and z are their respective molar coefficients. The CSP of 1 kg of this mineral ($CSP_{A_xB_yC_z}$) can be calculated according to:

$$CSP_{A_xB_yC_z} = \frac{M_A}{M_{A_xB_yC_z}} \times x \times CSP_A + \frac{M_B}{M_{A_xB_yC_z}} \times y \times CSP_B + \frac{M_C}{M_{A_xB_yC_z}} \times z \times CSP_C \quad (\text{Eq. 3})$$

where M_A , M_B , M_C and $M_{A_xB_yC_z}$ are the molar masses of the respective element or mineral. CSP_A , CSP_B and CSP_C are the CSPs of the respective elements in the mineral, i.e. elemental CSPs like the ones shown in Table 2.

To take a specific example, the mineral pyrite has the chemical structure FeS_2 . The molar masses of iron, sulfur and pyrite are approximately 56 g/mol, 32 g/mol and 120 g/mol, respectively. The molar coefficients are 1 for Fe and 2 for S. The CSP of iron is 5.4 kg Si eq/kg and the CSP of sulfur is 700 kg Si eq/kg. The CSP of pyrite, CSP_{FeS_2} , can then be calculated as:

$$CSP_{FeS_2} = \frac{M_{Fe}}{M_{FeS_2}} \times 1 \times CSP_{Fe} + \frac{M_S}{M_{FeS_2}} \times 2 \times CSP_S = \frac{56}{120} \times 1 \times 5.4 + \frac{32}{120} \times 2 \times 700 \quad (\text{Eq. 4})$$

Although these calculations can be tedious, they are in principle straight forward given the existence of a distinct chemical structure for the mineral. Note that since oxygen and hydrogen are not included in the CSI, they can be considered to have CSPs equal to zero and therefore do not contribute to the CSP of a mineral. Appendix B contains a list of all minerals (i.e. type B flows) in the Ecoinvent database (version 3.6), as well as their corresponding CSPs calculated based on chemical structures as described in this section. The chemical structures used in the calculations are provided in Appendix B as well. The main source used for obtaining chemical structures was the open-access online *Handbook of Mineralogy* by Anthony et al. (2020).

Note that there are some material flows extracted which are commonly referred to as “minerals”, but at a closer look, they in fact consist of a mixture of different minerals or represents a group of several minerals. The relevant examples from the Ecoinvent database are the following:

- **Feldspar** is a group of silicate minerals, mainly albite ($\text{NaAlSi}_3\text{O}_8$) and microcline (KAlSi_3O_8) (Bulatovic, 2015).
- **Olivine** is a group of minerals which includes both forsterite (Mg_2SiO_4) and fayalite (Fe_2SiO_4) as well as the range in between ($(\text{Mg}, \text{Fe})_2\text{SiO}_4$), with varying magnesium and iron contents (Cressey and Howie, 2005).
- **Vermiculite** is also a group of different minerals with varying contents of magnesium, iron, aluminium and silicon ($(\text{Mg}, \text{Fe}^{3+}, \text{Al})_3(\text{Si}, \text{Al})_4\text{O}_{10}(\text{OH})_2 \cdot 4\text{H}_2\text{O}$) (Anthony et al., 2020).
- **Albite** is a group of minerals with varying contents of sodium, calcium, aluminium and silicon (Anthony et al., 2020).
- **Nepheline** is a group of minerals with varying sodium and potassium content (Anthony et al., 2020).

Since these “minerals” do not have distinct chemical structures that can be used for calculating their CSPs, they were not included in the type B category, but instead in regarded as type C flows, described in Section 2.3.

Another special case is chemical compounds, such as “TiO₂, 54% in ilmenite, 18% in crude ore” and “Magnesium chloride”. These are sometimes not specified as minerals, although there might exist minerals with the same chemical structure in some of these cases (such as rutile and anatase for TiO₂), but in other cases not. Regardless of this, all such chemical compounds have been considered type B flows in this report, since they have distinct chemical structures in the same way as the minerals.

2.3 Type C Flows: Rocks and Mineral Groups without Distinct Chemical Structures

Material flows of rocks and mineral groups, consisting of several minerals, have been categorized as type C flows here. Examples of this category includes “Basalt” (an igneous rock), “Diatomite” (a sedimentary rock), “Gravel” (a loose aggregation of rock fragments), “Sand, unspecified” (finely divided rock and mineral particles), “Clay, unspecified” (fine-grained soil materials that develops plasticity when wet) and “Gangue” (commercially valueless rock materials around ores). Similar to the type B flows, the type C flows also do not correspond directly to m_i in Eq. 2 and can therefore not be paired with the original CSPs in Table 2. In addition, such rocks and mineral groups do not have distinct chemical structures that can be used as described for type B flows in Section 2.2. Instead, their specific elemental compositions must be obtained from reported measurements. For example, consider the fictitious rock *hypotheticite*, with an assumed measured composition of 40%

element A, 40% element B and 20% element C. The CSP of *hypotheticite* can then be calculated as:

$$CSP_{\text{hypotheticite}} = 0.4 \times CSP_A + 0.4 \times CSP_B + 0.2 \times CSP_C \quad (\text{Eq. 5})$$

Note again that since oxygen and hydrogen do not have CSPs, they do not contribute to the CSP of materials in which they are constituents. Consequently, oxygen and hydrogen will therefore not be considered in the elemental composition of rocks and mineral groups.

To take a real example, consider the rock basalt, which is present in the Ecoinvent database (version 3.6) as the flow “Basalt”. It consists of 17.26% silicon, 5.51% aluminium, 2.65% iron, 2.51% calcium, 2.37% magnesium, 1.2% sodium, 0.59% titanium and 0.08% potassium (Shrivastava et al., 2016). Its CSP can thus be calculated as:

$$CSP_{\text{basalt}} = 0.1726 \times CSP_{\text{Si}} + 0.0551 \times CSP_{\text{Al}} + 0.0265 \times CSP_{\text{Fe}} + 0.0251 \times CSP_{\text{Ca}} + 0.0237 \times CSP_{\text{Mg}} + 0.012 \times CSP_{\text{Na}} + 0.0059 \times CSP_{\text{Ti}} + 0.0008 \times CSP_{\text{K}} \quad (\text{Eq. 6})$$

Note that the sum of the constituent elements in the Eq. 6 do not add up to 100%. This is because the rock also contains oxygen and hydrogen for which the CSPs are zero and not included. In addition, when doing composition measurements, there is often something called “loss of ignition” (LOI). The LOI is a measure of the total volatiles in a rock, such as water, carbon dioxide, fluorine, chlorine and sulfur (Lechler and Desilets, 1987). The mass of the LOI is, as the name suggests, lost when doing elemental composition measurements and can be as high as 20% in some composition data. Since the composition of the LOI varies, and since several of the components listed by Lechler and Desilets (1987) are not included in the CSI (e.g. the oxygen and hydrogen in water as well as gases trapped in rocks), the content of the LOI was not considered in the CSPs of type C flows. This also contributes to the compositions of some of those flows not adding up to 100%.

Apart from LOI, there might also be trace elements, such as lanthanides and actinides, found in the rocks. But the shares of these trace elements are likely to vary highly between locations and are neither consistently nor regularly reported in the literature. Hence, they are not included in the calculations.

A list of type C flows can be found in Appendix C, along with their elemental compositions as well as underlying references and assumptions. As can be seen there, the type C flows generally consist of relatively abundant elements, such as silicon and aluminium. This generally gives them relatively low CSPs (often <10 kg Si eq/kg) compared to many of the type B flows. This is expected, since the compositions of type C flows are generally similar to ordinary rock. Exceptions are coal, oil and even more so, platinum group metals (PGM).

Unfortunately, not all type C flows are as convenient as basalt when it comes to acquiring elemental composition data. These less well-defined type C flows require some assumptions, often due to them representing a wider group of materials, as described in the subsections below.

Clay

Flows representing clays extracted from the ground are called “Clay”, “Clay, unspecified”, “Clay, ball”, “Clay, fire” and “Clay, bentonite”. In general, the term clay is quite broad and there are many types of clays which can be categorized in different ways (Mukherjee, 2013; Velde, 1992). For the flows “Clay” and “Clay, unspecified”, we approximate them as typical pure clays, which effectively

means kaolin clays with the chemical structure $2\text{SiO}_2 \cdot \text{Al}_2\text{O}_3 \cdot 2\text{H}_2\text{O}$ (Weems, 1903), which translates to an elemental composition of 15% silicon and 21% aluminium. This element composition was used to calculate the CSP of clay in the same way as for other type C flows, as described at the start of Section 2.3. Since “Clay, ball” and “Clay, fire” consist mainly of the same kaolin ($2\text{SiO}_2 \cdot \text{Al}_2\text{O}_3 \cdot 2\text{H}_2\text{O}$) mineral (United States Environmental Protection Agency, 1985), they were also approximated in this way. Regarding “Clay, bentonite”, bentonite clay is synonymous to the clay mineral smectite (Velde, 1992). The composition of smectite as reported by Herron and Matteson (1993) was therefore assumed to represent the elemental composition of this flow.

Feldspar

No general elemental composition can be identified for the flow “Feldspar”. We therefore approximate feldspar as an equal (50%-50%) mixture of the minerals albite ($\text{Na}_2\text{O} \cdot \text{Al}_2\text{O}_3 \cdot 6\text{SiO}_2$) and microcline ($\text{K}_2\text{O} \cdot \text{Al}_2\text{O}_3 \cdot 6\text{SiO}_2$), which are the two most important feldspar minerals from an industrial point of view (Bulatovic, 2015).

Fuller's earth

Fuller's earth is any clay material with the capacity to decolorize oil or other liquids if it improves the commercial value of such oils or liquids (Hosterman and Patterson, 1992). It is generally composed of attapulgite or bentonite (Hosterman and Patterson, 1992). Therefore, it is here approximated as the flow “Clay, bentonite”.

Gangue

There are two gangue flows: “Gangue” and “Gangue, bauxite”. Gangue is a term to describe commercially unprofitable materials, such as quartzite and silicates (Lassner et al., 2000), effectively equal to common rock. The CSPs of the gangue flows were therefore approximated as common rock, specifically the reference bedrock described in Section 2.4 and Table 3.

Granite

Regarding the flow “Granite”, the exact composition of granite varies. Haldar and Tišljär (2014a) write that the two main compositions of granite are quartz (SiO_2 , 20-40%) and K-feldspar (KAlSi_3O_8 , 50-80%). We therefore approximate granite as 30% SiO_2 and 70% KAlSi_3O_8 , corresponding to an element composition of 35% Si, 9.8% K and 6.8% Al.

Gravel

Regarding the flow “Gravel”, gravel used in construction typically consists of ordinary stones without any significant amounts of rare elements. The CSP of gravel was therefore approximated as common rock, specifically the reference bedrock described in Section 2.4 and Table 3.

Inert rock

It is here assumed that the flow “Inert rock” refers to some general rock without any notable content of rare elements. The CSP of inert rock is therefore approximated as the reference bedrock described in Section 2.4 and Table 3. The flow “rock, inert” is considered synonymous to the flow “Inert rock” and thus treated in the same way.

Lava

There is a flow called “lava”. Lava consists of molten rock, often in the form of common rock types, such as basalt and granite (McCall, 2013). It is therefore approximated as the reference bedrock described in Section 2.4 and Table 3.

Metamorphous rock

There are a metamorphous rock flow called “Metamorphous rock, graphite containing”. In geology, “metamorphous rock” is more often referred to as “metamorphic rock” and this means rock that has undergone solid-state recrystallization (metamorphism) due to e.g. high heat and pressure (Haldar and Tišljär, 2014b). Metamorphic rocks consist partly of new minerals which require high heat and/or pressure to be formed, and partly of minerals previously present in the rock and stable enough to survive the metamorphism. Metamorphic rocks include both very common rocks, such as gneiss, and more special rocks, like milky-white marble. However, with metamorphic rocks being very common, for example making up 12% of the global land cover (Wilkinson et al., 2009), its average composition is most likely similar to that of the crust. Therefore, the flow “Metamorphous rock, graphite containing” was approximated as the reference bedrock described in Section 2.4 and Table 3. We note that the specification “graphite containing” in the flow names might suggest some sort of graphite-rich metamorphic rock. However, since no quantification (or indication) of the graphite content is present in the flow names, there is not enough evidence to assume a high-graphite metamorphic rock. Such metamorphic rocks do exist, however, an example being graphite schist with graphite as dominant mineral (Haldar and Tišljär, 2014b).

Natural aggregate

Natural aggregates means crushed stone, sand and gravel (Wilburn and Goonan, 1998). Therefore, same as for gravel and stone, the CSP of natural aggregates is approximated as common rock, specifically the reference bedrock described in Section 2.4 and Table 3. The flow “Aggregate, natural” is considered synonymous to “Natural aggregates” and thus treated in the same way.

Sand, gravel and stone

The flow “Sand, gravel and stone, extracted for use” has a very broad flow name, containing resources which have been modelled differently in this report. Sand has been modelled based on elemental composition report by Hasdemir et al. (2016). Gravel has been approximated as reference bedrock and so has stone. Therefore, since the majority of the components in this flow have been approximated as reference bedrock, this whole flow is also approximated as reference bedrock described in Section 2.4 and Table 3. It can furthermore be noted that the CSP of sand and the reference bedrock are quite similar: 2.1 and 2.8 kg Si eq/kg, respectively.

Shale

Regarding the flow “Shale”, shale consists mainly of clay minerals, such as illite, kaolinite, smectite, quartz and feldspar (Dayal, 2017; Speight, 2013). Since a specific shale composition in terms of specific element composition is difficult to obtain, we approximate these flows as “Clay, unspecified” due to the high content of clay minerals.

Stone

The flow “stone” is assumed to refer to some ordinary rock-type stone and is therefore approximated as reference bedrock described in Section 2.4 and Table 3.

2.4 Type D Flows: Ores

Ores is a fourth category of extracted material flows in the Ecoinvent database (version 3.6). Examples of this include “copper ore”, “copper ore (1.2%)” and “Zinc, Lead, Silver, ore (8,54% Zn, 5,48% Pb, 94 g/t Ag)”. In these cases, the flow refers to the entire ore being extracted. However, the composition of that ore is not made fully clear. Sometimes, as in “copper ore”, the composition is not specified at all, except for the stated presence of the main element mined (copper, in that case). In other cases, as in “copper ore (1.2%)”, one part of the composition, i.e. the 1.2% copper, is made clear. Often, this component constitutes a minority of the ore’s entire elemental content. In yet other cases, several parts of the ore are made clear, as in “Zinc, Lead, Silver, ore (8,54% Zn, 5,48% Pb, 94 g/t Ag)”. However, in none of these cases is the whole composition (100%) of the ore made clear. Therefore, in order to estimate a reasonable content of the whole ore, we applied the following procedure:

1. Estimate the **amount of the main element** (such as copper in copper ore) using current average ore grades, unless the amount is already stated in the flow name. (In some cases, the grade had to be recalculated from an oxide grade, such as V_2O_5 grade, to a pure elemental grade.)
2. Estimate **amounts of other elements** likely to be present in conjunction with the main element, e.g. sulfur in copper ores, based on likely mineral compositions.
3. Add the **amounts of other elements stated in the flow name**, as well as estimated **amounts of other elements** likely to be present in conjunction with those elements based on likely mineral composition.
4. Assume the rest of the ore composition to be **average rock** (as calculated in Eq. 8).

A generic equation for the CSP of type D flows can thus be written as follows:

$$CSP_{\text{type D flow}} = X \times CSP_{\text{main element}} + \sum_i Y_i \times CSP_{\text{other (likely) element } i} + (1 - X - \sum_i Y_i) \times CSP_{\text{average rock}} \quad (\text{Eq. 7})$$

where X is the percentage of the main element in the ore (sometimes given in the flow name, sometimes estimated) and Y_i is the percentage of some other element i either stated in the flow name or likely to also be part of the ore (based on likely mineral composition).

According to step 4 above, as well as for Eq. 7, a value for the CSP of “average rock” is required in order to cover for the part of the ore that is not clear from the flow name and cannot be inferred in other ways. We therefore constructed a theoretical material flow extracted called “reference bedrock”, which is used for this purpose. The CSP of this reference bedrock flow is calculated as a mixture of the ten most common elements in the crust according to their respective crustal concentrations. These elements are silicon, aluminium, iron, calcium, magnesium, sodium, potassium, titanium, manganese and phosphorous. Their respective crustal concentrations can be seen in Table 3. When summing up the concentrations in the third column of Table 3, it can be seen that these ten elements account for 99.74% of the Earth’s crust. Based on the relative shares of the ten elements in the 99.74% of the crust, also listed in Table 3, the CSP of the reference bedrock (abbreviated RB) can be calculated as:

$$CSP_{\text{RB}} = 0.28 \times CSP_{\text{Si}} + 0.084 \times CSP_{\text{Al}} + 0.052 \times CSP_{\text{Fe}} + 0.046 \times CSP_{\text{Ca}} + 0.028 \times CSP_{\text{Mg}} + 0.023 \times CSP_{\text{Na}} + 0.015 \times CSP_{\text{K}} + 0.0042 \times CSP_{\text{Ti}} + 0.00078 \times CSP_{\text{Mn}} + 0.00044 \times CSP_{\text{P}} \approx 2.8 \text{ kg Si eq/kg} \quad (\text{Eq. 8})$$

This CSP for the reference bedrock (CSP_{RB}) is used as the CSP of average rock ($CSP_{\text{average rock}}$) in Eq. 7, i.e. $CSP_{\text{average rock}} = CSP_{RB}$. In the subsections below, the steps 1-4 outlined above are described for all ores present in the Ecoinvent database (version 3.6).

Table 3. Crustal concentrations of the ten most common elements in Earth’s crust, their respective shares of the crustal mass and their respective shares of the mass of these ten elements. Crustal concentrations were calculated from Rudnick and Gao (2014) based on the corresponding oxides (e.g. SiO_2 for Si).

Element	Crustal concentration (ppm)	Share of crustal mass	Share of the mass of these ten elements
Si	2,800,000	28%	28%
Al	84,000	8.4%	8.4%
Fe	52,000	5.2%	5.2%
Ca	46,000	4.6%	4.6%
Mg	28,000	2.8%	2.8%
Na	23,000	2.3%	2.3%
K	15,000	1.5%	1.5%
Ti	4,200	0.42%	0.42%
Mn	770	0.078%	0.078%
P	440	0.044%	0.044%

As a last general note on the reporting of ore extraction in the Ecoinvent database, and that these flows are assumed to contain a certain amount of reference bedrock, it is important to clarify that much mining operations imply excavation of large amounts of additional bedrock before even reaching the ore body, as well as around the ore to make it available for mining. Such excavated bedrock can also be referred to a “gangue”, as defined in Section 2.3, but it is not a part of the ore flows discussed here. Consequently, there is a difference between bedrock surrounding ores (not included in the type D flows) and the reference bedrock which is a part of the ore body mixtures (included in the type D flows as in Eq. 7).

Chromium ore

There is one chromium ore flow in the Ecoinvent database (version 3.6), called “Chromium ore”. The only chromium mineral of economic importance and industrial use is chromite ($FeCr_2O_4$) (Miller-Ihli, 1992). It is here assumed that the ore is a typical high-chromium ore with concentrations ranging from 46 to 55% of Cr_2O_3 (Miller-Ihli, 1992). The average value of 50.5% is used here, which translates to 23.5% chromium. The CSP of the chromium ore is calculated based on this chromium content, the accompanying iron as per the $FeCr_2O_4$ structure, and the rest (excluding the chromium, iron and oxygen shares) is assumed to be reference bedrock:

$$CSP_{\text{Chromium ore}} = 0.235 \times CSP_{Cr} + 0.235 \times \frac{0.5 \times M_{Fe}}{M_{Cr}} \times CSP_{Fe} + (1 - 0.235 - 0.235 \times \frac{0.5 \times M_{Fe}}{M_{Cr}} - 0.235 \times \frac{2 \times M_O}{M_{Cr}}) \times CSP_{RB} \quad (\text{Eq. 9})$$

Note that although oxygen does not have a CSP, it “takes up space” from the reference bedrock, thereby reducing the CSP of the chromium ore somewhat due to a reduced amount of reference bedrock needed.

Copper ore

Several different types of copper ore flows are present in the Ecoinvent database (version 3.6). If the flow name only says “Copper ore”, it is assumed that the concentration of copper is 0.62%, which was the global average copper concentration in mined ores around 2012 (Mudd and Weng,

2012). In addition, it is assumed that the copper is mined in the form of the mineral chalcopyrite (CuFeS_2), which is one of the economically most important copper minerals (Mudd and Weng, 2012). Corresponding amounts of iron and sulfur are therefore added based on the molar relationships in the CuFeS_2 molecular structure. The rest of the material is assumed to be the reference bedrock defined above:

$$CSP_{\text{Copper ore (sulfidic)}} = 0.0062 \times CSP_{\text{Cu}} + 0.0062 \times \frac{M_{\text{Fe}}}{M_{\text{Cu}}} \times CSP_{\text{Fe}} + 0.0062 \times \frac{2 \times M_{\text{S}}}{M_{\text{Cu}}} \times CSP_{\text{S}} + \left(1 - 0.0062 - 0.0062 \times \frac{M_{\text{Fe}}}{M_{\text{Cu}}} - 0.0062 \times \frac{2 \times M_{\text{S}}}{M_{\text{Cu}}}\right) \times CSP_{\text{RB}} \quad (\text{Eq. 10})$$

The exact same procedure was applied for the flow “Copper ore, sulfidic”, since CuFeS_2 is a sulfidic copper mineral.

If the concentration of copper was given in the flow, as in “Copper ore (1.2%)”, then this concentration was used instead of 0.62% in Eq. 10. Again, corresponding amounts of iron and sulfur based on the CuFeS_2 molecular structure are added. The rest of the material is assumed to be the reference bedrock defined above.

Sometimes, the material flow extracted also contains one or several precious metals in addition to copper, specifically gold and silver, for example “Copper, Gold, Silver, ore (1.7% Cu, 0.7 g/t Au, 3.5 g/t Ag)”. In these cases, the copper was again considered along with the corresponding iron and sulfur as per the CuFeS_2 molecular structure. In addition, the specified amounts of gold and silver were considered. Although those precious metals might also coexist with some other elements, such as silver together with sulfur in sulfide ores (Butterman and Hilliard, 2004), we did not consider those since they would be a comparatively minor contribution to the CSP of the ore considering the comparatively high CSPs of gold and silver. In addition to the copper, iron, sulfur, silver and gold contents, the remaining content was assumed to be reference bedrock. This approach is used for all ores where copper coexist with gold and/or silver. An example equation is here provided for the specific flow “Copper, Gold, Silver, ore (1.7% Cu, 0.7 g/t Au, 3.5 g/t Ag)”:

$$CSP_{\text{Copper,Gold,Silver,ore (1.7\% Cu, 0.7 g/t Au, 3.5 g/t Ag)}} = 0.017 \times CSP_{\text{Cu}} + 0.017 \times \frac{M_{\text{Fe}}}{M_{\text{Cu}}} \times CSP_{\text{Fe}} + 0.017 \times \frac{2 \times M_{\text{S}}}{M_{\text{Cu}}} \times CSP_{\text{S}} + 0.0000007 \times CSP_{\text{Au}} + 0.0000035 \times CSP_{\text{Ag}} + \left(1 - 0.017 - 0.017 \times \frac{M_{\text{Fe}}}{M_{\text{Cu}}} - 0.017 \times \frac{2 \times M_{\text{S}}}{M_{\text{Cu}}} - 0.0000007 - 0.0000035\right) \times CSP_{\text{RB}} \quad (\text{Eq. 11})$$

A final copper ore case is the flow “Copper-Molybdenum-Gold-Silver ore (1.13% Cu, 0.02% Mo, 0.01 g/t Au, 2.8 Ag)”. We here used the approach described above for copper (including the corresponding iron and sulfur), gold (no additional elements) and silver (no additional elements). For molybdenum, we added both the molybdenum itself and a corresponding amount of sulfur as per the mineral molybdenite (MoS_2), which is effectively the only molybdenum mineral suitable for industrial production (Polyak, 2016). The remaining content is again assumed to be reference bedrock:

$$CSP_{\text{Copper-Molybdenum-Gold-Silver ore (1.13\% Cu, 0.02\% Mo, 0.01 g/t Au, 2.8 Ag)}} = 0.0113 \times CSP_{\text{Cu}} + 0.0113 \times \frac{M_{\text{Fe}}}{M_{\text{Cu}}} \times CSP_{\text{Fe}} + 0.0113 \times \frac{2 \times M_{\text{S}}}{M_{\text{Cu}}} \times CSP_{\text{S}} + 0.00000001 \times CSP_{\text{Au}} + 0.0000028 \times CSP_{\text{Ag}} + 0.0002 \times CSP_{\text{Mo}} + 0.0002 \times \frac{2 \times M_{\text{S}}}{M_{\text{Mo}}} \times CSP_{\text{S}} + \left(1 - 0.0113 - 0.0113 \times \frac{M_{\text{Fe}}}{M_{\text{Cu}}} - 0.0113 \times \frac{2 \times M_{\text{S}}}{M_{\text{Cu}}} - 0.00000001 - 0.0000028 - 0.0002 - 0.0002 \times \frac{2 \times M_{\text{S}}}{M_{\text{Mo}}}\right) \times CSP_{\text{RB}} \quad (\text{Eq. 12})$$

Iron ore

There is one material flow referring to the extraction of an unspecified iron ore in the Ecoinvent database (version 3.6), named “Iron ore”. Most of the current iron ore production is in the form of hematite (Fe_2O_3) (Jankovic, 2015). Ore grades are 25-30% in the United States (Tuck and Ghalayini, 2019) and 10-35% in China (Tuck et al., 2017). Based on these values, 25% is used here, which is the average number of 25, 30, 10 and 35%. This enables the calculation of the CSP of iron ore, involving only the iron content and the additional reference bedrock:

$$CSP_{\text{Iron ore}} = 0.25 \times CSP_{\text{Fe}} + (1 - 0.25 - 0.25 \times \frac{3/2 \times M_0}{M_{\text{Fe}}}) \times CSP_{\text{RB}} \quad (\text{Eq. 13})$$

Note that although oxygen does not have a CSP, it “takes up space” from the reference bedrock, thereby reducing the CSP of the iron ore somewhat due to a reduced amount of reference bedrock needed.

Lead ore

There are two type D lead ore flows included in the Ecoinvent database (version 3.6): “lead ore” and “lead, zinc ore (4.6%, 0.6%)”. In the first case, since the ore grade of the flow is not specified, a generic grade must be used. An average ore grade of 3.4% lead in lead-zinc ores is reported by Calvo et al. (2016) and used here. The most important lead mineral is galena (PbS) (Anthony et al., 2020). Zinc is also associated with sulfur, being mainly mined as the mineral zinc sulfide sphalerite (ZnS) (Brugger, 2016). For both lead ore flows, the amount of lead is first added, then zinc (if present), then the corresponding amounts of sulfur as per PbS and ZnS , and finally reference bedrock is added to account for the rest of the material:

$$CSP_{\text{Lead ore}} = 0.034 \times CSP_{\text{Pb}} + 0.034 \times \frac{M_S}{M_{\text{Pb}}} \times CSP_S + (1 - 0.034 - 0.034 \times \frac{M_S}{M_{\text{Pb}}}) \times CSP_{\text{RB}} \quad (\text{Eq. 14})$$

$$CSP_{\text{Lead, zinc ore (4.6\%, 0.6\%)}} = 0.046 \times CSP_{\text{Pb}} + 0.006 \times CSP_{\text{Zn}} + \left(0.046 \times \frac{M_S}{M_{\text{Pb}}} + 0.006 \times \frac{M_S}{M_{\text{Zn}}}\right) \times CSP_S + (1 - 0.046 - 0.006 - 0.046 \times \frac{M_S}{M_{\text{Pb}}} - 0.006 \times \frac{M_S}{M_{\text{Zn}}}) \times CSP_{\text{RB}} \quad (\text{Eq. 15})$$

Manganese ore

There are two manganese ore flows in the Ecoinvent database (version 3.6), called “Manganese ore” and Manganese ore (R.O.M.). The abbreviation “R.O.M.” stands for “run of mine” and refers to an ore in a natural, unprocessed state. Thus, all these three flows were considered effectively synonymous. The main manganese mineral mined is pyrolusite (MnO_2) (Habashi, 2002). The average global ore grade in 2019 was calculated at 33.29% based on data in a bar diagram on page 21 in a report from the International Manganese Institute (2019). The CSP for manganese ore can thus be calculated by considering the manganese as per the average grade and adding reference bedrock to account for the material not consisting of manganese or oxygen:

$$CSP_{\text{Manganese ore}} = 0.3329 \times CSP_{\text{Mn}} + (1 - 0.3329 - 0.3329 \times \frac{2 \times M_0}{M_{\text{Mn}}}) \times CSP_{\text{RB}} \quad (\text{Eq. 16})$$

Molybdenum ore

The only flow representing an ore including molybdenum, but no other metals, in the Ecoinvent database (version 3.6) is the unspecified “Molybdenum ore”. As mentioned above, the main

molybdenum mineral mined is molybdenite (MoS_2) (Polyak, 2016). Molybdenum ore grades are generally in the range of 0.01-0.25% (International Molybdenum Association, 2018). The average value of 0.13% is used here. Corresponding amount of sulfur as per the molecular structure MoS_2 is added and the rest of the ore is assumed to consist of the reference bedrock defined above:

$$CSP_{\text{Molybdenum ore}} = 0.0013 \times CSP_{\text{Mo}} + 0.0013 \times \frac{2 \times M_S}{M_{\text{Mo}}} \times CSP_S + (1 - 0.0013 - 0.0013 \times \frac{2 \times M_S}{M_{\text{Mo}}}) \times CSP_{\text{RB}} \quad (\text{Eq. 17})$$

Nickel ore

One nickel ore flow present in the Ecoinvent database (version 3.6) is called "Nickel ore". Typical ore grades range between 1.5 and 3% (Crundwell et al., 2011), with the average value of 2.25% being used here. Most nickel is mined in the form of pentlandite, with the approximate chemical structure $\text{Ni}_{4.5}\text{Fe}_{4.5}\text{S}_8$ (Crundwell et al., 2011). Consequently, corresponding amounts of iron and sulfur were added, as well as reference bedrock to account for the rest of the mass:

$$CSP_{\text{Nickel ore}} = 0.0225 \times CSP_{\text{Ni}} + 0.0225 \times \frac{M_{\text{Fe}}}{M_{\text{Ni}}} \times CSP_{\text{Fe}} + 0.0225 \times \frac{8/4.5 \times M_S}{M_{\text{Ni}}} \times CSP_S + \left(1 - 0.0225 - 0.0225 \times \frac{M_{\text{Fe}}}{M_{\text{Ni}}} - 0.0225 \times \frac{8/4.5 \times M_S}{M_{\text{Ni}}}\right) \times CSP_{\text{RB}} \quad (\text{Eq. 18})$$

Another nickel ore flow has another ore grade specified in its flow name: "Nickel ore, 1.6%". For this flow, the same calculation as in Eq. 18 is conducted, but with the ore grade 1.6% used instead of the average.

Phosphate and phosphorus ore

There are two phosphorous-containing ore flows in the Ecoinvent database (version 3.6): "Phosphate ore" and "Phosphorus ore (29% P_2O_5)". Starting off with the second one, we assume this flow is extracted as 29% phosphorous pentoxide (P_2O_5), corresponding to 12.66% phosphorous, and the rest is reference bedrock. The CSP of the phosphorous ore is thus calculated as:

$$CSP_{\text{Phosphorus ore (29% } \text{P}_2\text{O}_5)} = 0.1266 \times CSP_P + (1 - 0.1266 - 0.1266 \times \frac{2.5 \times M_O}{M_P}) \times CSP_{\text{RB}} \quad (\text{Eq. 19})$$

For the phosphate ore flow, we assume the exact same calculation, since 29% phosphorous pentoxide seems to be a reasonable, medium grade for phosphate rock (Haldar, 2018).

Tin ore

The only tin ore among the type D flows considered is simply called "Tin ore". Ore grades for tin vary in the wide range of 0.01-5%, but an ore grade of 1% seems to roughly reflect a typical current ore grade (International Tin Association, 2020). The principal tin ore is cassiterite (SnO_2) (Anthony et al., 2020). Since this ore only contains tin and oxygen, and oxygen does not have a CSP, there is no need to add other elements besides the tin itself and the reference bedrock:

$$CSP_{\text{Tin ore}} = 0.01 \times CSP_{\text{Sn}} + (1 - 0.01 - 0.01 \times \frac{2 \times M_O}{M_{\text{Sn}}}) \times CSP_{\text{RB}} \quad (\text{Eq. 20})$$

However, note again that although oxygen does not have a CSP, it “takes up space” from the reference bedrock, thereby reducing the CSP of the tin ore somewhat due to a reduced amount of reference bedrock needed.

Titanium ore

Titanium is a bit of a special case since it typically seems to be mined as more or less pure mineral, meaning that “titanium ore” effectively equals “titanium mineral”. While both ilmenite (FeTiO_3) and rutile (TiO_2) are mined titanium minerals, ilmenite is clearly dominating by more than a factor of ten (Jin and Berlin, 2007; Kang et al., 2019). Indeed, ilmenite is sometimes referred to as titanium ore (Kang et al., 2019). Therefore, the CSP of titanium ore is here approximated as that of ilmenite:

$$CSP_{\text{Titanium ore}} = CSP_{\text{Ilmenite}} \quad (\text{Eq. 21})$$

Being a mineral, ilmenite is a type B flow, which CSP can be found in Appendix B.

Tungsten ore

Only one tungsten ore flow is present in the Ecoinvent database (version 3.6): “Tungsten ore”. Ore grades range between 0.06 and 1.2% (Leal-Ayala et al., 2015), and an average value of 0.63% is used here. The most commonly mined tungsten mineral is scheelite (CaWO_4) (Lassner et al., 2000). The CSP of tungsten ore is therefore calculated by first adding the tungsten contribution, then the calcium as per the CaWO_4 chemical structure, then filling up with reference bedrock:

$$CSP_{\text{Tungsten ore}} = 0.0063 \times CSP_W + 0.0063 \times \frac{M_{\text{Ca}}}{M_W} \times CSP_{\text{Ca}} + (1 - 0.0063 - 0.0063 \times \frac{M_{\text{Ca}}}{M_W} - 0.0063 \times \frac{4 \times M_O}{M_W}) \times CSP_{\text{RB}} \quad (\text{Eq. 22})$$

As stated earlier, the oxygen content is considered since it reduces the content of reference bedrock in the ore, although the oxygen itself does not contribute to the CSP of the tungsten ore.

Uranium ore

One uranium ore flow in Ecoinvent (version 3.6) is called “Uranium ore, 1.11 GJ per kg”. A typical uranium ore grade is 0.15% U_3O_8 , corresponding to 0.13% uranium (Norgate et al., 2014), and the economically most important uranium-bearing mineral is uraninite (UO_2) (Eriksson et al., 2004). The CSP of uranium ore is thus calculated as follows, with reference bedrock making up the rest of the ore not consisting of uranium and oxygen in uranite:

$$CSP_{\text{Uranium ore}} = 0.0013 \times CSP_U + (1 - 0.0013 - 0.0013 \times \frac{2 \times M_O}{M_U}) \times CSP_{\text{RB}} \quad (\text{Eq. 23})$$

Vanadium ore

There is one vanadium ore, called “Vanadium ore”, in the Ecoinvent database (version 3.6). Vanadium is mined in the form of vanadium pentoxide (V_2O_5). An average grade was calculated to be 0.607% V_2O_5 based on Kelley et al. (2017), which corresponds to 0.34% vanadium. Consequently, the CSP of vanadium ore can be calculated as:

$$CSP_{\text{Vanadium ore}} = 0.0034 \times CSP_V + (1 - 0.0034 - 0.0034 \times \frac{5/2 \times M_O}{M_V}) \times CSP_{\text{RB}} \quad (\text{Eq. 24})$$

Zinc ore

Several zinc ores exist among the material flows present in the Ecoinvent database (version 3.6). Some are unspecified zinc-only flows, specifically “Zinc ore” and “Zinc ore, sulfide”. Others have a specific ore grade set, for example “Zinc ore, 8%”. Zinc is mainly mined as the mineral zinc sulfide sphalerite (ZnS) (Brugger, 2016). Ore grades normally range between 5 and 15% (Wang, 2016), thus the average of 10% is used here unless the ore grade was specified in the flow name. We also note that the generic 10% ore grade is similar to most specified ore grades in some flow names, such as 8% and 12.6%. In the cases with non-specified ore grades, the CSP of zinc ore was calculated as follows, using the generic 10% ore grade, adding sulfur as per the ZnS chemical structure and finally adding the reference bedrock to account for 100% of the ore content:

$$CSP_{Zinc\ ore} = 0.1 \times CSP_{Zn} + 0.1 \times \frac{M_S}{M_{Zn}} \times CSP_S + (1 - 0.1 - 0.1 \times \frac{M_S}{M_{Zn}}) \times CSP_{RB} \quad (Eq. 25)$$

In cases where the zinc ore grade is specified, that specified value was used instead of 10% in Eq. 25.

In a number of other flows, the zinc ore was also specified to contain other elements with varying ore grades, namely copper, lead and/or silver, as in for example “Zinc, Lead, Silver, ore (8,54% Zn, 5,48% Pb, 94 g/t Ag)”. In all these cases, the ore grades of all metals (zinc, copper, lead and silver) are provided, thereby making the use of generic ore grades (such as 10% for zinc) unnecessary. In all these cases, the CSP of the zinc/copper/lead/silver ores are calculated as:

$$CSP_{Zinc/copper/lead/silver\ ore} = g_{Zn} \times CSP_{Zn} + g_{Cu} \times CSP_{Cu} + g_{Pb} \times CSP_{Pb} + g_{Ag} \times CSP_{Ag} + \left(g_{Zn} \times \frac{M_S}{M_{Zn}} + g_{Cu} \times \frac{2 \times M_S}{M_{Cu}} + g_{Pb} \times \frac{M_S}{M_{Pb}} \right) \times CSP_S + g_{Cu} \times \frac{M_{Fe}}{M_{Cu}} \times CSP_{Fe} + (1 - g_{Zn} - g_{Cu} - g_{Pb} - g_{Ag} - \left(g_{Zn} \times \frac{M_S}{M_{Zn}} + g_{Cu} \times \frac{2 \times M_S}{M_{Cu}} + g_{Pb} \times \frac{M_S}{M_{Pb}} \right) - g_{Cu} \times \frac{M_{Fe}}{M_{Cu}}) \times CSP_{RB} \quad (Eq. 26)$$

where g_i stands for ore grade of element i , which is set to zero if the element is not stated in the flow name. As can be seen in Eq. 26, we first add the four main metals (i.e. those of the four elements present in the ore). Second, corresponding amounts of sulfur is added as per the chemical structures ZnS, CuFeS₂ and PbS. Third, the corresponding amount of iron is added as per the chemical structure CuFeS₂. Finally, reference bedrock is added to account for 100% of the ore.

2.5 Software Implementation

The starting point for our implementation is the Ecoinvent version 3.6 database (Wernet et al., 2016). Specifically, we use the flows listed in three resource categories: “in ground”, “land” and “unspecified”. Further, we select “mass” as the relevant flow type for our calculations as the CSPs are calculated per unit mass equivalents (i.e. kg Si eq/kg). This results in a total of over 800 flows which are sub-divided into type A to E as described in Section 2. Those not included in the CSI, such as radioactive elements, are not further considered. Regarding the software for the implementation, we have chosen OpenLCA, which is an open-source LCA software, in order to show how the implementation is done. The implementation procedure thus assumes that the user has OpenLCA installed, along with Ecoinvent version 3.6 database already imported. The rest of the practical implementation is described as a stepwise procedure below.

Step 1: Open an active database and navigate to “Impact assessment methods” (Figure 3). Right click on the “Impact assessment methods” and select “New LCIA method”. A new window opens

prompting the user to enter a name and provide the description. Enter details as necessary and click on “Finish”.

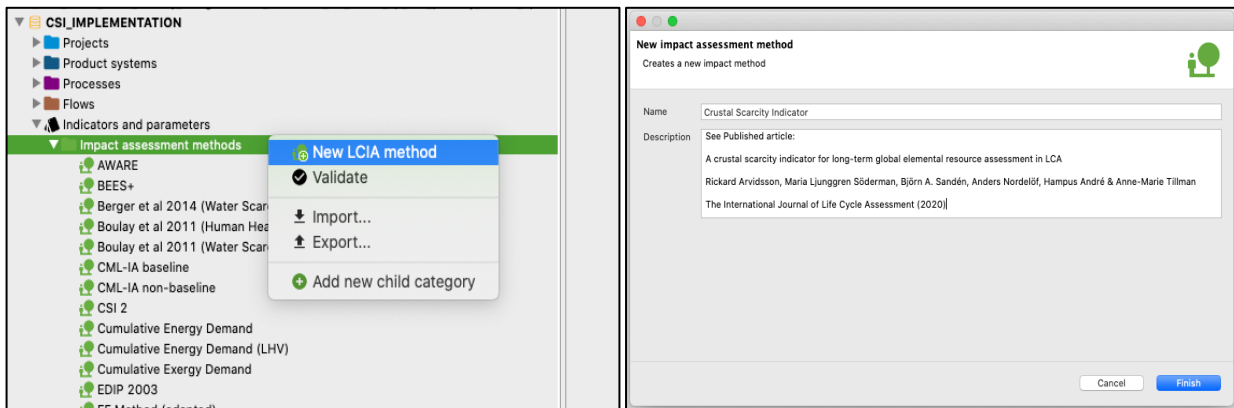


Figure 3. Step 1 of the practical implementation.

Step 2: A blank window opens with only the details about the name and description from the previous step. When this new window opens, OpenLCA assigns it a unique identifier called the universally unique identifier (UUID). Simultaneously, under the “Last change” section, a time stamp is created to alert the user of the last time edits were made to the file. There is also the added possibility to select a “Version” number if future updates to the CSI are foreseen. At the bottom of the screen, multiple tab options are activated, such as: “General information”, “Impact factors”, “Normalization and weighting”, “Parameters” and “Shape files (beta)”. While still in the “General information” tab (Figure 4), click on the plus sign, which will automatically add a “New impact category”. Double click on “New impact category” and change the name to “Crustal Scarcity Indicator”. In the reference unit, enter “kg Si eq”.

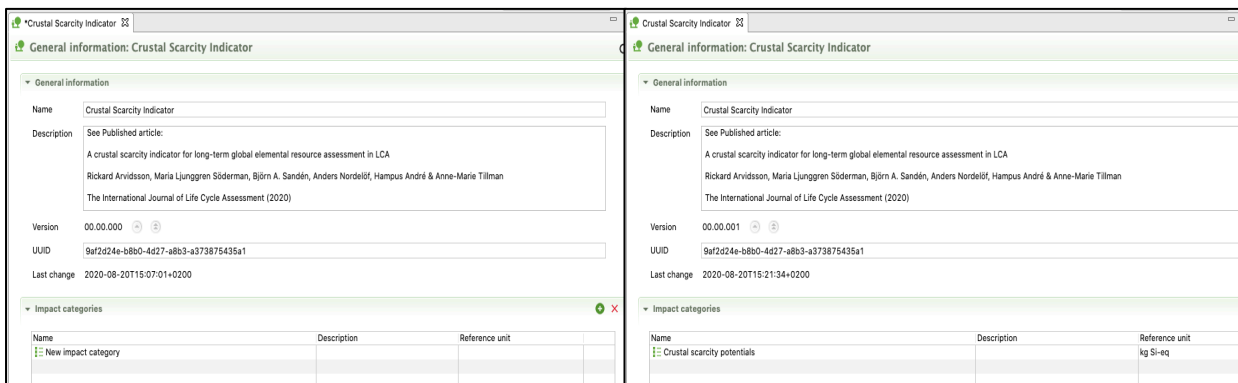


Figure 4. Step 2 of the practical implementation.

Step 3: Next, click on the “Impact factors” next to the “General information” tab where a window with no data in it opens up. Here, the column heading names are: “Flow”, “Category”, “Flow property”, “Factor”, “Unit” and “Uncertainty” (Figure 5). Click on plus and a new window prompting the user to enter “Flows” appears. Here, navigate to the Ecoinvent 3.6 flows > Elementary flows > Resource. Multiple select: “in ground”, “land” and “unspecified”, and then click “OK”.

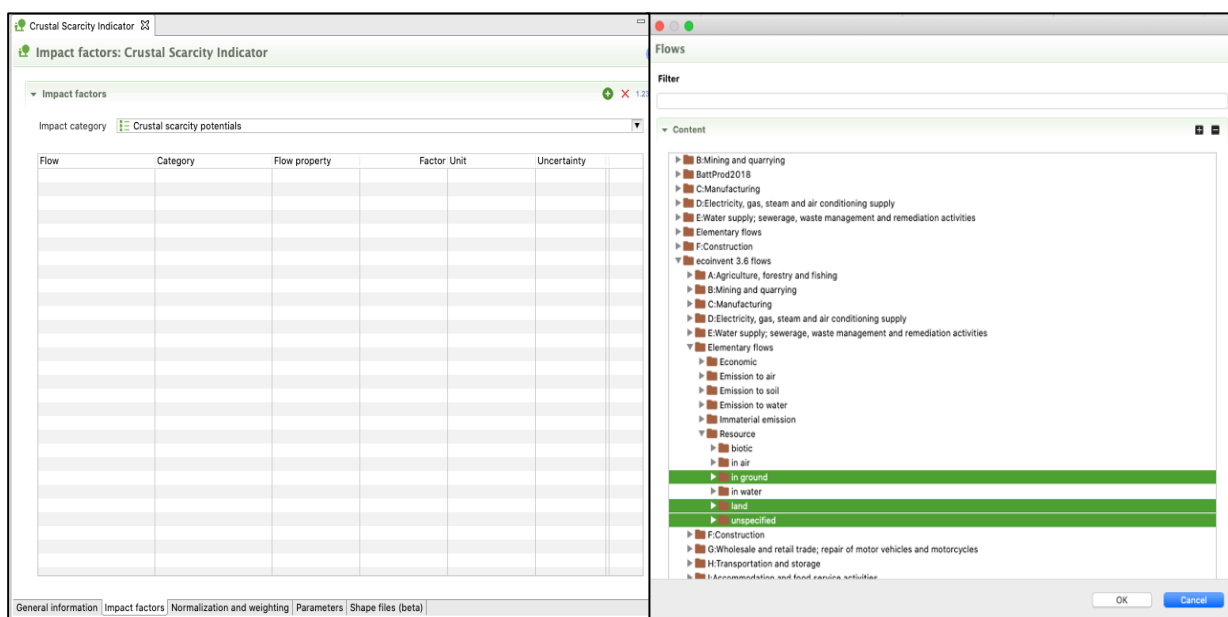


Figure 5. Step 3 of the practical implementation.

Step 4: Rows with all the elementary flows corresponding to these resource categories (“in ground”, “land” and “unspecified”) appear. The “Flow property” includes multiple types, such as mass, volume, area, etc. Click on “Flow property” which will rearrange all the flows based on the flow property. Retain only mass flows by selecting all non-mass flows and removing them from the list. This is done by right clicking on the selected “non-mass” flows and then clicking on “Remove selected” (Figure 6).

Flow	Category	Flow property	Factor	Unit	Uncertainty
Energy, from oil	Resource/unspecified	Energy	1.0	kg Si-eq/MJ	none
Energy, from oil sand (10% bitumen)	Resource/unspecified	Energy	1.0	kg Si-eq/MJ	none
Biomass, feedstock	Resource/unspecified	Energy	1.0	kg Si-eq/MJ	none
Energy, primary, from geothermal	Resource/unspecified	Energy	1.0	kg Si-eq/MJ	none
Energy, gross calorific value, in biomass...	Resource/unspecified	Energy	1.0	kg Si-eq/MJ	none
Energy, recovered	Resource/unspecified	Energy	1.0	kg Si-eq/MJ	none
Energy, from coal	Resource/unspecified	Energy	1.0	kg Si-eq/MJ	none
Energy, primary, from wind power	Resource/unspecified	Energy	1.0	kg Si-eq/MJ	none
Energy, unspecified	Resource/unspecified	Energy	1.0	kg Si-eq/MJ	none
Energy, from oil sand (100% bitumen)	Resource/unspecified	Energy	1.0	kg Si-eq/MJ	none
Energy, gross calorific value, in biomass, r...	Resource/unspecified	Energy	1.0	kg Si-eq/MJ	none
Energy, primary, from geothermal	Resource/in ground	Energy	1.0	kg Si-eq/MJ	none
Energy, from uranium	Resource/in ground	Energy	1.0	kg Si-eq/MJ	none
Energy, unspecified	Resource/in ground	Energy	1.0	kg Si-eq/MJ	none
Energy, from coal	Resource/in ground	Energy	1.0	kg Si-eq/MJ	none
Energy, from peat	Resource/in ground	Energy	1.0	kg Si-eq/MJ	none
Energy, from coal, brown	Resource/in ground	Energy	1.0	kg Si-eq/MJ	none
Energy, from oil	Resource/in ground	Energy	1.0	kg Si-eq/MJ	none
Energy, from sulfur	Resource/in ground	Energy	1.0	kg Si-eq/MJ	none
Energy, from gas, natural	Resource/in ground	Energy	1.0	kg Si-eq/MJ	none
Energy, geothermal, converted	Resource/in ground	Energy	1.0	kg Si-eq/MJ	none
Erosion Resistance	Resource/land	Erosion Resistance (Occ.)	1.0	kg Si-eq/kg	none
Erosion Resistance	Resource/land	Erosion Resistance (Transf.)	1.0	kg Si-eq/kg/a	none
Nuclear energy	Resource/in ground	Gross calorific value	1.0	kg Si-eq/MJ	none
Groundwater Replenishment	Resource/land	Groundwater Replenishment (Occ.)	1.0	kg Si-eq/(mm*m2)	none
Groundwater Replenishment	Resource/land	Groundwater Replenishment (Tra...	1.0	kg Si-eq/(mm*m2)/a	none
Water, cooling, well, in ground	Resource/unspecified	Mass	1.0	kg Si-eq/kg	none
Oil, crude, feedstock, 42 MJ per kg, in ground	Resource/unspecified	Mass	1.0	kg Si-eq/kg	none
Gas, mine, off-gas, process, coal mining/kg	Resource/unspecified	Mass	1.0	kg Si-eq/kg	none
Oil, brown, 8 MJ per kg, in ground	Resource/unspecified	Mass	1.0	kg Si-eq/kg	none
Oil, crude, 41 MJ per kg, in ground	Resource/unspecified	Mass	1.0	kg Si-eq/kg	none
Coal, feedstock, 26.4 MJ per kg, in ground	Resource/unspecified	Mass	1.0	kg Si-eq/kg	none
Chromium ore, in ground	Resource/unspecified	Mass	1.0	kg Si-eq/kg	none
Ruthenium, in ground	Resource/unspecified	Mass	1.0	kg Si-eq/kg	none
Cobalt	Resource/unspecified	Mass	1.0	kg Si-eq/kg	none
Oil, crude, 42.6 MJ per kg, in ground	Resource/unspecified	Mass	1.0	kg Si-eq/kg	none

Figure 6. Step 4 of the practical implementation.

Step 5: This leaves the user with only the flows relevant for implementation in the CSI. However, the “Factors” in the table, i.e. the characterization factors, here specifically the CSPs, are all assigned value 1 – which is incorrect. For the final step in the implementation of the CSI, these “Factors” have to be manually changed to the correct CSP values as provided in the Appendix A, B, C and D of this report (Figure 7). This is a tedious process due to the high number of flows and hence has to be conducted carefully. Note that if a flow name ends with “in ground” (e.g. “Basalt, in ground”), it should have the same CSP as the flow with the same name apart from “in ground” (i.e. “Basalt”). Once all the CSP values have been entered in the “Factor” column, save the implemented method.

Flow	Category	Flow property	Factor	Unit	Uncertainty
Gas, natural, 30.3 MJ...	Resource/unspecified	Mass	1.0	kg Si-eq/kg	none
Silver, 3.2ppm in sulfi...	Resource/unspecified	Mass	1.0	kg Si-eq/kg	none
Copper, Cu 0.38%, A...	Resource/unspecified	Mass	1.0	kg Si-eq/kg	none
Rhodium, Rh 1.6E-7...	Resource/unspecified	Mass	1.0	kg Si-eq/kg	none
Silver, Ag 9.7E-4%, A...	Resource/unspecified	Mass	1.0	kg Si-eq/kg	none
Silver, Ag 4.8E-5%, A...	Resource/unspecified	Mass	1.0	kg Si-eq/kg	none
Molybdenum, 0.022...	Resource/unspecified	Mass	1.0	kg Si-eq/kg	none
Gold, Au 6.7E-4%, in...	Resource/unspecified	Mass	1.0	kg Si-eq/kg	none
Gallium, in ground	Resource/in ground	Mass	1.0	kg Si-eq/kg	none
Molybdenum, 0.022...	Resource/unspecified	Mass	1.0	kg Si-eq/kg	none
Gangue, bauxite, in g...	Resource/in ground	Mass	1.0	kg Si-eq/kg	none
Molybdenum, 0.025...	Resource/unspecified	Mass	1.0	kg Si-eq/kg	none
Lead, Pb 0.014%, Au...	Resource/unspecified	Mass	1.0	kg Si-eq/kg	none
Laterite, in ground	Resource/in ground	Mass	1.0	kg Si-eq/kg	none
Zinc, Zn 0.63%, Au 9...	Resource/unspecified	Mass	1.0	kg Si-eq/kg	none

Flow	Category	Flow property	Factor	Unit	Uncertainty
Aluminium	Resource/in ground	Mass	3.4	kg Si-Eq/kg	none
Aluminium	Resource/unspecified	Mass	3.4	kg Si-Eq/kg	none
Aluminium, 24% in ba...	Resource/in ground	Mass	3.4	kg Si-Eq/kg	none
Aluminium, in ground	Resource/in ground	Mass	3.4	kg Si-Eq/kg	none
Anhydrite, in ground	Resource/in ground	Mass	170.0	kg Si-Eq/kg	none
Antimony	Resource/in ground	Mass	1400000.0	kg Si-Eq/kg	none
Antimony	Resource/unspecified	Mass	1400000.0	kg Si-Eq/kg	none
Antimony, in ground	Resource/in ground	Mass	1400000.0	kg Si-Eq/kg	none
Arsenic	Resource/in ground	Mass	110000.0	kg Si-Eq/kg	none
Arsenic	Resource/unspecified	Mass	110000.0	kg Si-Eq/kg	none
Barite, 15% in crude ore	Resource/in ground	Mass	460.0	kg Si-Eq/kg	none
Barium	Resource/in ground	Mass	620.0	kg Si-Eq/kg	none
Barium	Resource/unspecified	Mass	620.0	kg Si-Eq/kg	none
Barium, in ground	Resource/in ground	Mass	620.0	kg Si-Eq/kg	none
Basalt, in ground	Resource/in ground	Mass	620.0	kg Si-Eq/kg	none
Basalt, in ground	Resource/in ground	Mass	1.5	kg Si-Eq/kg	none
Beryllium	Resource/in ground	Mass	150000.0	kg Si-Eq/kg	none

Figure 7. Step 5 of the practical implementation.

Step 6: Once the CSI method is implemented in OpenLCA, it can easily be shared with other users. For this, navigate on the right bar to “Crustal Scarcity Indicator” and right click. Then select “Export” (Figure 8). This will prompt the user to select the dataset that needs to be exported and to select the type of export file. Select “JSON-LD” and click next. Then navigate and select the “Crustal Scarcity Indicator” and enter the export location under the “To file”. Click “Finish”. This creates a zip file in the given directory location. For a new user, this file can be imported just like in the first screenshot (Figure 3), where instead of selecting “New LCIA Method” click on “Import” and select the location where the zip file is saved.

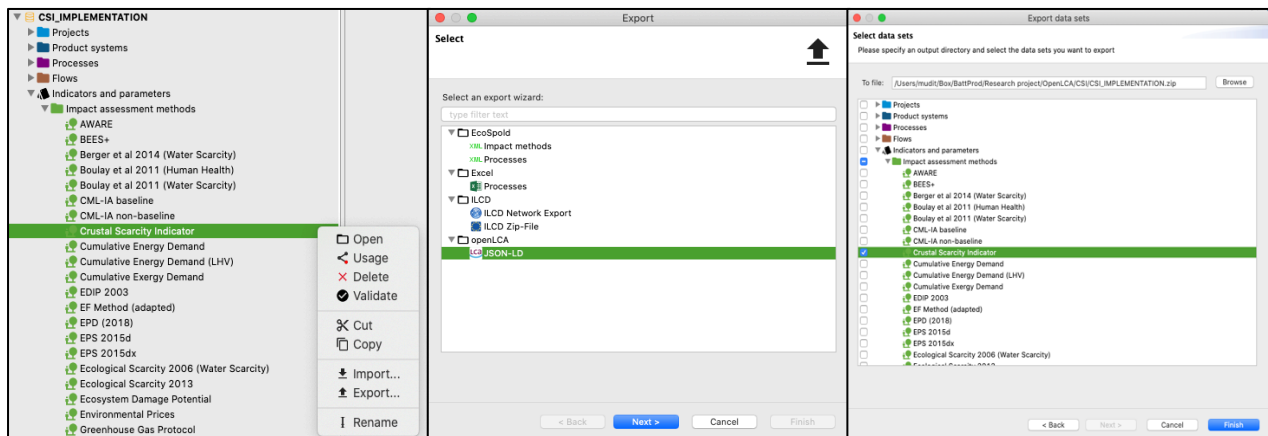


Figure 8. Step 6 of the practical implementation.

3. CONCLUDING DISCUSSION

In this concluding section, we first discuss pros and cons of the implementation of the CSI as described in this report. We then compare this implementation to that of other mineral resource impact assessment methods in OpenLCA.

3.1 Pros and Cons of the Implementation

Type A flows of elements are the type of flows that the CSI was initially developed for and they can therefore be paired with the original CSPs in Table 2. For type B and type C flows, new CSPs reflecting the elemental composition of minerals, mineral groups and rocks need to be calculated. Such calculations are relatively straight forward and relies on established data on the elemental composition of such materials. Possible exceptions are the general type C flows, such as clay and gangue, for which many different types exist. Here, the specific elemental composition of such flows had to be approximated (Section 2.3). Still, the approximate compositions probably reflect relatively well the compositions of most types of clay, gangue and other general type C flows.

For type D flows, however, the calculation of new CSPs to be paired with the LCI data is less straight forward. This is because the LCI data for type D flows is incomplete. It only reports parts of the ore content, as in “copper ore (1.2%)”. As a consequence, the rest of the ore composition must be estimated or assumed, which is considered the least straight forward step in the implementation of the CSI into OpenLCA. This means that in order to create a good fit between LCI data and the CSPs as illustrated in Figure 1a, the LCI data is effectively made to have an artificially higher resolution in terms of ore composition than it actually has in the database. An important aspect of the implementation of CSPs for type D flows is that the estimation of likely ore grades makes these CSPs less long-term than other CSPs, since ore grades change (albeit slowly) over time. Since a main rationale behind the CSI is to capture a long-term perspective (Arvidsson et al., 2020), the need for estimating ore grades based on current mining practices is considered a weakness in the presented implementation.

However, alternative implementations of type D flows can probably be considered worse: either not considering type D flows at all, or only considering the constituents reported in the LCI data (i.e. the main element and possibly some other elements). Both of these alternatives would lead to an underestimation of the CSPs of type D flows. In the former case, the underestimation would be considerable, whereas in the latter case, it would be less considerable but still notable in several cases, in particular if the main element has a low CSP. Therefore, the approach for implementing type D flows described in Section 2.4 is considered to be the best available option. The adding of constituents not reported in the LCI data for type D flows applied in Section 2.4 is considered reasonable based on generally existing knowledge about the respective ores, although more detailed approaches might be possible as well.

The implementation of type D flows sends a clear message to providers of LCI data: type D flows simply named “nickel ore” or similar are incomplete when it comes to revealing their chemical composition. Preferably, they should instead be reported as the amounts of elements extracted. This would make the LCI data perfectly compatible with not just CSPs, but also with characterization factors from other mineral resource impact assessment methods in the LCA field, such as abiotic depletion potentials and surplus ore potentials, which are also formulated as impact per kg of element (Huijbregts et al., 2017; van Oers et al., 2020).

3.2 Comparison to Other Implementations

We are also interested in how other mineral resource impact assessment methods have been implemented into OpenLCA regarding the main four types of mineral flows extracted defined in this report (type A, B, C and D). We therefore select five random flows from each category and check which characterization factors they have linked to them (in addition to the now-available CSPs, of course). The flows are selected from the Ecoinvent databases (version 3.6) as implemented in OpenLCA (version 1.10) with the OpenLCA LCIA method package (version 2.0) installed. The result can be seen in Table 4. Although we only consider a limited number of flows, there is a clear pattern that the coverage of the flow types among other mineral resource depletion methods is uneven. Type A flows are covered reasonably well, with the exception of more ‘exotic’ elements, such as hafnium, and, for some unknown reason, calcium. Type B flows seem to be much more sparsely covered. Only a few mineral resource impact assessment methods cover the five minerals in Table 4, most notably the Ecological Scarcity and Cumulative Exergy Demand methods. It is particularly notable that minerals with a high content of rare elements, such as the antimony-containing stibnite (Sb_2S_3), are covered by so few methods. For type C flows, brown coal is covered well, probably because of resource concerns related to fossil resources such as coal. But other flows more akin to common rock are covered very sparsely. Again, the Cumulative Exergy Demand method stands out by covering more flows than other methods. However, considering the generally low resource impact per kg of most type C flows (Appendix C), this might not be a very severe problem from a practical point of view. More problematic is probably that type D flows, such as an ore with a zinc content of 12.6% and an ore containing the relatively rare tungsten, are not covered by most mineral resource impact assessment methods. For type D flows, the Cumulative Exergy Demand method does not cover any of the five flows investigated. Instead, the IMPACT2002+ method stands out by covering four of the five type D flows. Although we acknowledge that a complete coverage of such ores is difficult because of their largely unspecified elemental composition (which we have tried to solve as described in Section 2.4), at least the zinc content specified at 12.6% could have easily been accounted for. We must therefore conclude that the implementation of the CSI as described in Section 2 is comparatively comprehensive and covers more relevant material flows extracted than most other mineral resource impact assessment methods implemented into OpenLCA. Its implementation might therefore serve as inspiration also for the implementation of other mineral resource impact assessment methods. In some cases, the exact same equations might be possible to use, just switching the CSPs to the characterization factors of other mineral resource impact assessment methods, such as abiotic depletion potentials (van Oers et al., 2020) and surplus ore potentials (Huijbregts et al., 2017).

Table 4. Characterization factors implemented in the Ecoinvent databases (version 3.6) in OpenLCA (version 1.10) with the OpenLCA LCIA method package (version 2.0) installed for five random flows of each type (type A, B, C and D).

Material flows extracted	Characterization factors implemented
Type A flows	
Calcium	-
Hafnium	Ecological Scarcity 2013 EPS 2015 ReCiPe 2016 (midpoint + endpoint)
Lead, 5.0% in sulfide, Pb 3.0%, Zn, Ag, Cd, In	CML-IA (baseline + non-baseline) Cumulative Exergy Demand Ecological Scarcity 2013 EDIP 2003 EF Method (adapted) Environmental Prices EDP (2018) EPS 2015 ILCD 2011 Midpoint+ IMPACT 2002+ ReCiPe 2016 (midpoint + endpoint)
Potassium	CML-IA (baseline + non-baseline) EF Method (adapted) Environmental Prices EDP (2018) EPS 2015 ILCD 2011 Midpoint+
Rhenium	CML-IA (baseline + non-baseline) Cumulative Exergy Demand Ecological Scarcity 2013 EF Method (adapted) EDP (2018) EPS 2015 ILCD 2011 Midpoint+ IMPACT 2002+ ReCiPe 2016 (midpoint + endpoint)
Type B flows	
Anhydrite	Cumulative Exergy Demand
Colemanite	Ecological Scarcity 2013 EPS 2015
Kieserite	Cumulative Exergy Demand Ecological Scarcity 2013
Magnesite	Cumulative Exergy Demand Ecological Scarcity 2013
Stibnite	Ecological Scarcity 2013 EDIP 2003
Type C flows	
Coal, brown	BEES+ CML-IA (baseline) Cumulative Energy Demand Cumulative Exergy Demand Ecological Scarcity 2013 EDIP 2003 EF Method (adapted) Environmental Prices EDP (2018) EPS 2015 ILCD 2011 Midpoint+ IMPACT 2002+ ReCiPe 2016 (midpoint + endpoint) TRACI 2.1
Laterite	-
Metamorphous rock, graphite containing	Cumulative Exergy Demand
Olivine	Cumulative Exergy Demand
Shale	Cumulative Exergy Demand
Type D flows	
Iron ore	IMPACT 2002+ ReCiPe 2016 (midpoint + endpoint)
Molybdenum ore	IMPACT 2002+
Nickel ore	IMPACT 2002+
Tungsten ore	EDIP 2003 IMPACT 2002+
Zinc ore, 12.6%	EPS 2015

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APPENDIX A – TYPE A FLOWS

Note that if a flow name ends with “in ground”, it should have the same CSP as the flow with the same name apart from “in ground”.

Material flow extracted	CSP (kg Si eq/kg)
Aluminium	3.4
Aluminium, 24% in bauxite, 11% in crude ore	3.4
Antimony	1,400,000
Arsenic	110,000
Barium	620
Beryllium	150,000
Bismuth	1,600,000
Boron	26,000
Bromine	320,000
Cadmium	3,500,000
Cadmium, 0.30% in sulfide, Cd 0.18%, Pb, Zn, Ag, In	3,500,000
Calcium	6.2
Carbon	140
Cerium	6,600
Cerium, 24% in bastnasite, 2.4% in crude ore	6,600
Cesium	140,000
Chlorine	1,200
Chromium	2,100
Chromium, 25.5% in chromite, 11.6% in crude ore	2,100
Cobalt	11,000
Cobalt, Co 5.0E-2%, in mixed ore	11,000
Copper	10,000
Copper, 0.52% in sulfide, Cu 0.27% and Mo 8.2E-3% in crude ore	10,000
Copper, 0.59% in sulfide, Cu 0.22% and Mo 8.2E-3% in crude ore	10,000
Copper, 0.97% in sulfide, Cu 0.36% and Mo 4.1E-2% in crude ore	10,000
Copper, 0.99% in sulfide, Cu 0.36% and Mo 8.2E-3% in crude ore	10,000
Copper, 1.13% in sulfide, Cu 0.76% and Ni 0.76% in crude ore	10,000
Copper, 1.18% in sulfide, Cu 0.39% and Mo 8.2E-3% in crude ore	10,000
Copper, 1.25% in sulfide, Cu 0.24% and Zn 0.1% in crude ore	10,000
Copper, 1.42% in sulfide, Cu 0.81% and Mo 8.2E-3% in crude ore	10,000
Copper, 2.19% in sulfide, Cu 1.83% and Mo 8.2E-3% in crude ore	10,000
Copper, Cu 0.2%, in mixed ore	10,000
Copper, Cu 0.38%, Au 9.7E-4%, Ag 9.7E-4%, Zn 0.63%, Pb 0.014%, in ore	10,000
Copper, Cu 3.2E+0%, Pt 2.5E-4%, Pd 7.3E-4%, Rh 2.0E-5%, Ni 2.3E+0% in ore	10,000
Copper, Cu 5.2E-2%, Pt 4.8E-4%, Pd 2.0E-4%, Rh 2.4E-5%, Ni 3.7E-2% in ore	10,000
Copper, Cu 6.8E-1%, in mixed ore	10,000
Cu, Cu 3.2E+0%, Pt 2.5E-4%, Pd 7.3E-4%, Rh 2.0E-5%, Ni 2.3E+0% in ore	10,000
Cu, Cu 5.2E-2%, Pt 4.8E-4%, Pd 2.0E-4%, Rh 2.4E-5%, Ni 3.7E-2% in ore	10,000
dysprosium	79,000
Dysprosium	79,000

erbium	130,000
Erbium	130,000
europium	260,000
Europium	260,000
Europium, 0.06% in bastnasite, 0.006% in crude ore	260,000
Fluorine	510
Fluorine, 4.5% in apatite, 1% in crude ore	510
Fluorine, 4.5% in apatite, 3% in crude ore	510
gadolinium	76,000
Gadolinium	76,000
Gadolinium, 0.15% in bastnasite, 0.015% in crude ore	76,000
gallium	18,000
Gallium	18,000
Gallium, 0.014% in bauxite	18,000
Germanium	22,000
Gold	220,000,000
Gold, Au 1.0E-7%, in mixed ore	220,000,000
Gold, Au 1.1E-4%, Ag 4.2E-3%, in ore	220,000,000
Gold, Au 1.3E-4%, Ag 4.6E-5%, in ore	220,000,000
Gold, Au 1.4E-4%, in ore	220,000,000
Gold, Au 1.8E-4%, in mixed ore	220,000,000
Gold, Au 2.1E-4%, Ag 2.1E-4%, in ore	220,000,000
Gold, Au 4.3E-4%, in ore	220,000,000
Gold, Au 4.9E-5%, in ore	220,000,000
Gold, Au 5.4E-4%, Ag 1.5E-5%, in ore	220,000,000
Gold, Au 6.7E-4%, in ore	220,000,000
Gold, Au 6.8E-4%, Ag 1.5E-4%, in ore	220,000,000
Gold, Au 7.1E-4%, in ore	220,000,000
Gold, Au 9.7E-4%, Ag 9.7E-4%, Zn 0.63%, Cu 0.38%, Pb 0.014%, in ore	220,000,000
Gold, Au 9.7E-5%, Ag 7.6E-5%, in ore	220,000,000
Hafnium	76,000
holmium	370,000
Holmium	370,000
indium	5,400,000
Indium	5,400,000
Indium, 0.005% in sulfide, In 0.003%, Pb, Zn, Ag, Cd	5,400,000
Iodine	400,000
Iridium	7,600,000,000
Iron	5.4
Iron, 46% in ore, 25% in crude ore	5.4
Iron, 72% in magnetite, 14% in crude ore	5.4
Lanthanum	14,000
Lanthanum, 7.2% in bastnasite, 0.72% in crude ore	14,000
Lead	26,000
Lead, 5%, in sulfide, Pb 2.97% and Zn 5.34% in crude ore	26,000

Lead, 5.0% in sulfide, Pb 3.0%, Zn, Ag, Cd, In	26,000
Lead, Pb 0.014%, Au 9.7E-4%, Ag 9.7E-4%, Zn 0.63%, Cu 0.38%, in ore	26,000
Lead, Pb 3.6E-1%, in mixed ore	26,000
lithium	18,000
Lithium	18,000
Lithium, 0.15% in brine	18,000
lutetium	940,000
Lutetium	940,000
Magnesium	10
Magnesium, 0.13% in water	10
Manganese	370
Manganese, 35.7% in sedimentary deposit, 14.2% in crude ore	370
Mercury	9,400,000
Molybdenum	350,000
Molybdenum, 0.010% in sulfide, Mo 8.2E-3% and Cu 1.83% in crude ore	350,000
Molybdenum, 0.014% in sulfide, Mo 8.2E-3% and Cu 0.81% in crude ore	350,000
Molybdenum, 0.016% in sulfide, Mo 8.2E-3% and Cu 0.27% in crude ore	350,000
Molybdenum, 0.022% in sulfide, Mo 8.2E-3% and Cu 0.22% in crude ore	350,000
Molybdenum, 0.022% in sulfide, Mo 8.2E-3% and Cu 0.36% in crude ore	350,000
Molybdenum, 0.025% in sulfide, Mo 8.2E-3% and Cu 0.39% in crude ore	350,000
Molybdenum, 0.11% in sulfide, Mo 0.41% and Cu 0.36% in crude ore	350,000
Molybdenum, 0.11% in sulfide, Mo 4.1E-2% and Cu 0.36% in crude ore	350,000
Neodymium	14,000
Neodymium, 4% in bastnasite, 0.4% in crude ore	14,000
Ni, Ni 2.3E+0%, Pt 2.5E-4%, Pd 7.3E-4%, Rh 2.0E-5%, Cu 3.2E+0% in ore	4,800
Ni, Ni 3.7E-2%, Pt 4.8E-4%, Pd 2.0E-4%, Rh 2.4E-5%, Cu 5.2E-2% in ore	4,800
Nickel	4,800
Nickel, 1.13% in sulfide, Ni 0.76% and Cu 0.76% in crude ore	4,800
Nickel, 1.13% in sulfides, 0.76% in crude ore	4,800
Nickel, 1.98% in silicates, 1.04% in crude ore	4,800
Nickel, Ni 2.3E+0%, Pt 2.5E-4%, Pd 7.3E-4%, Rh 2.0E-5%, Cu 3.2E+0% in ore	4,800
Nickel, Ni 2.5E+0%, in mixed ore	4,800
Nickel, Ni 3.7E-2%, Pt 4.8E-4%, Pd 2.0E-4%, Rh 2.4E-5%, Cu 5.2E-2% in ore	4,800
niobium	35,000
Niobium	35,000
Nitrogen	5,100
Osmium	6,900,000,000
Palladium	190,000,000
Palladium, Pd 1.6E-6%, in mixed ore	190,000,000
Palladium, Pd 2.0E-4%, Pt 4.8E-4%, Rh 2.4E-5%, Ni 3.7E-2%, Cu 5.2E-2% in ore	190,000,000
Palladium, Pd 7.3E-4%, Pt 2.5E-4%, Rh 2.0E-5%, Ni 2.3E+0%, Cu 3.2E+0% in ore	190,000,000
Pd, Pd 2.0E-4%, Pt 4.8E-4%, Rh 2.4E-5%, Ni 3.7E-2%, Cu 5.2E-2% in ore	190,000,000
Pd, Pd 7.3E-4%, Pt 2.5E-4%, Rh 2.0E-5%, Ni 2.3E+0%, Cu 3.2E+0% in ore	190,000,000
Phosphorus	650
Phosphorus, 18% in apatite, 12% in crude ore	650

Phosphorus, 18% in apatite, 4% in crude ore	650
Platinum	190,000,000
Platinum, Pt 2.5E-4%, Pd 7.3E-4%, Rh 2.0E-5%, Ni 2.3E+0%, Cu 3.2E+0% in ore	190,000,000
Platinum, Pt 4.7E-7%, in mixed ore	190,000,000
Platinum, Pt 4.8E-4%, Pd 2.0E-4%, Rh 2.4E-5%, Ni 3.7E-2%, Cu 5.2E-2% in ore	190,000,000
Potassium	19
praseodymium	5,800
Praseodymium	5,800
Praseodymium, 0.42% in bastnasite, 0.042% in crude ore	5,800
Pt, Pt 2.5E-4%, Pd 7.3E-4%, Rh 2.0E-5%, Ni 2.3E+0%, Cu 3.2E+0% in ore	190,000,000
Pt, Pt 4.8E-4%, Pd 2.0E-4%, Rh 2.4E-5%, Ni 3.7E-2%, Cu 5.2E-2% in ore	190,000,000
Rh, Rh 2.0E-5%, Pt 2.5E-4%, Pd 7.3E-4%, Ni 2.3E+0%, Cu 3.2E+0% in ore	4,700,000,000
Rh, Rh 2.4E-5%, Pt 4.8E-4%, Pd 2.0E-4%, Ni 3.7E-2%, Cu 5.2E-2% in ore	4,700,000,000
Rhenium	1,500,000,000
Rhenium, in crude ore	1,500,000,000
Rhodium	4,700,000,000
Rhodium, Rh 1.6E-7%, in mixed ore	4,700,000,000
Rhodium, Rh 2.0E-5%, Pt 2.5E-4%, Pd 7.3E-4%, Ni 2.3E+0%, Cu 3.2E+0% in ore	4,700,000,000
Rhodium, Rh 2.4E-5%, Pt 4.8E-4%, Pd 2.0E-4%, Ni 3.7E-2%, Cu 5.2E-2% in ore	4,700,000,000
Rubidium	5,800
Ruthenium	470,000,000
S, bonded, naturally occurring	700
samarium	74,000
Samarium	74,000
Samarium, 0.3% in bastnasite, 0.03% in crude ore	74,000
Scandium	13,000
Selenium	2,200,000
Silicon	1
Silver	5,100,000
Silver, 0.007% in sulfide, Ag 0.004%, Pb, Zn, Cd, In	5,100,000
Silver, 0.01% in crude ore	5,100,000
Silver, 3.2ppm in sulfide, Ag 1.2ppm, Cu and Te, in crude ore	5,100,000
Silver, Ag 1.5E-4%, Au 6.8E-4%, in ore	5,100,000
Silver, Ag 1.5E-5%, Au 5.4E-4%, in ore	5,100,000
Silver, Ag 1.8E-6%, in mixed ore	5,100,000
Silver, Ag 2.1E-4%, Au 2.1E-4%, in ore	5,100,000
Silver, Ag 4.2E-3%, Au 1.1E-4%, in ore	5,100,000
Silver, Ag 4.6E-5%, Au 1.3E-4%, in ore	5,100,000
Silver, Ag 5.4E-3%, in mixed ore	5,100,000
Silver, Ag 7.6E-5%, Au 9.7E-5%, in ore	5,100,000
Silver, Ag 9.7E-4%, Au 9.7E-4%, Zn 0.63%, Cu 0.38%, Pb 0.014%, in ore	5,100,000
Sodium	12
Strontium	880
Sulfur	700
tantalum	400,000

Tantalum	400,000
Tantalum, 81.9% in tantalite, 1.6E-4% in crude ore	400,000
Tellurium	57,000,000
Tellurium, 0.5ppm in sulfide, Te 0.2ppm, Cu and Ag, in crude ore	57,000,000
terbium	470,000
Terbium	470,000
Thallium	570,000
Thorium	51,000
thulium	1,000,000
Thulium	1,000,000
Tin	170,000
Tin, 79% in cassiterite, 0.1% in crude ore	170,000
Titanium	67
Tungsten	280,000
Uranium	220,000
Uranium, 2291 GJ per kg	220,000
Uranium, 451 GJ per kg	220,000
Uranium, 560 GJ per kg	220,000
Vanadium	2,000
ytterbium	150,000
Ytterbium	150,000
Yttrium	15,000
Zinc	3,900
Zinc 9%, in sulfide, Zn 5.34% and Pb 2.97% in crude ore	3,900
Zinc 9%, Lead 5%, in sulfide	3,900
Zinc, 9.0% in sulfide, Zn 5.3%, Pb, Ag, Cd, In	3,900
Zinc, Zn 0.63%, Au 9.7E-4%, Ag 9.7E-4%, Cu 0.38%, Pb 0.014%, in ore	3,900
Zinc, Zn 3.1%, in mixed ore	3,900
Zirconium	2,100
Zirconium, 50% in zircon, 0.39% in crude ore	2,100

APPENDIX B – TYPE B FLOWS

Note that if a flow name ends with “in ground”, it should have the same CSP as the flow with the same name apart from “in ground”.

Material flow extracted	Chemical structure of mineral	CSP (kg Si eq/kg)
Anhydrite	CaSO_4	170
Barite	BaSO_4	460
Barite, 15% in crude ore	BaSO_4	460
Bertrandite	$\text{Be}_4\text{Si}_2\text{O}_7(\text{OH})_2$	23,000
Borax	$\text{Na}_2\text{B}_4\text{O}_7 \cdot 10\text{H}_2\text{O}$	2,900
Calcite	CaCO_3	19
Calcium carbonate	CaCO_3	19
Calcium chloride	CaCl_2	770
Celestite	SrSO_4	540
Chrysotile	$\text{Mg}_3(\text{Si}_2\text{O}_5)(\text{OH})_4$	2.8
Cinnabar	HgS	8,100,000
Colemanite	$\text{Ca}_2\text{B}_6\text{O}_{11} \cdot 5\text{H}_2\text{O}$	4,100
Diamond, industrial*	C	140
Dolomite	$\text{CaMg}(\text{CO}_3)_2$	21
Fluorspar	CaF_2	250
Fluorspar, 92%	CaF_2	250
Graphite	C	140
Gypsum	$\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$	130
Ilmenite	FeTiO_3	23
Kaolinite	$\text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4$	0.82
Kaolinite, 24% in crude ore	$\text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4$	0.82
kieserite	$\text{MgSO}_4 \cdot \text{H}_2\text{O}$	160
Kieserite	$\text{MgSO}_4 \cdot \text{H}_2\text{O}$	160
Kieserite, 25% in crude ore	$\text{MgSO}_4 \cdot \text{H}_2\text{O}$	160
Kyanite	Al_2SiO_5	1.3
Magnesite	MgCO_3	23
Magnesite, 60% in crude ore	MgCO_3	23
Magnesium chloride	MgCl_2	900
Molybdenite, 0.24%	MoS_2	210,000
Potashsalt, crude	KCl (assumed based on Orris et al. (2010))	580
Potassium chloride	KCl	580
Pyrite	FeS_2	380
Pyrolusite	MnO_2	230
Rutile	TiO_2	40
Sodium bromide	NaBr	250,000
sodium carbonate	Na_2CO_3	21
Sodium chloride	NaCl	730
Sodium nitrate	NaNO_3	840
Sodium sulfate	Na_2SO_4	160
Sodium sulphate, various forms	Na_2SO_4	160

Spodumene	$\text{LiAl}(\text{SiO}_3)_2$	670
Stibnite	Sb_2S_3	1,000,000
Sulfate	SO_4^{2-}	230
Sylvite	KCl	580
Sylvite, 25 % in sylvinite	KCl	580
Talc	$\text{Mg}_3\text{Si}_4\text{O}_{10}(\text{OH})_2$	2.2
TiO ₂ , 45-60% in Ilmenite	TiO ₂	40
TiO ₂ , 54% in ilmenite, 18% in crude ore	TiO ₂	40
TiO ₂ , 54% in ilmenite, 2.6% in crude ore	TiO ₂	40
TiO ₂ , 95% in rutile, 0.40% in crude ore	TiO ₂	40
Titanium oxide	TiO ₂ (assumed)	40
Trona	$\text{Na}_3(\text{CO}_3)(\text{HCO}_3) \cdot 2\text{H}_2\text{O}$	19
Ulexite	$\text{NaCaB}_5\text{O}_6(\text{OH})_6 \cdot 5\text{H}_2\text{O}$	3,500
Uranium oxide (U ₃ O ₈), 332 GJ per kg, in ore	U ₃ O ₈	190,000
Uranium oxide, 332 GJ per kg, in ore	UO ₂ (assumed)	190,000
Wollastonite	CaSiO ₃	2.4
Zirconia	ZrO ₂	1,600
Zirconia, as baddeleyite	ZrO ₂	1,600

*We here assume the flow regards natural diamond extracted for *industrial purposes*, rather than being *industrially manufactured* diamond, which would not be an elementary resource flow but rather a technospheric product flow.

APPENDIX C – TYPE C FLOWS

Note that if a flow name ends with “in ground”, it should have the same CSP as the flow with the same name apart from “in ground”.

Material flow extracted	Composition (excluding hydrogen and oxygen)	Reference	CSP (kg Si eq/kg)
Aggregate, natural	Reference bedrock 100% (Table 3)	Section 2.3	2.8
Albite	Si 31.71% Al 10.64% Na 8.44% Ca 0.84% K 0.025%	Anthony et al. (2020), recalculated from the corresponding oxides	1.7
Apatite	Ca 39.36% P 18.25% Cl 2.32% F 1.24%	Mineralogy Database (2012)	160
Basalt	Si 17.26% Al 5.51% Fe 2.65% Ca 2.51% Mg 2.37% Na 1.2% Ti 0.59% K 0.08%	Shrivastava et al. (2016)	1.5
Bauxite	Al 23.7% Fe 17.9% Ca 2.6% Ti 2.0% Si 1.4% Na 0.7% Mn 0.02%	Average composition of two bauxites from Greece and Ghana (Vind et al., 2018), recalculated from the corresponding oxides	3.4
Clay	Al 20.7% Si 11.0%	Section 2.3	0.82
Clay, ball	Al 20.7% Si 11.0%	Section 2.3	0.82
Clay, bentonite	Si 26.4% Al 9.1% Mg 2.2% Fe 2.0% Ca 1.3% Na 0.7% K 0.6% Ti 0.15% S 0.02%	Section 2.3	1.4
Clay, fire	Al 20.7% Si 11.0%	Section 2.3	0.82
Clay, unspecified	Al 20.7% Si 11.0%	Section 2.3	0.82
Coal, 18 MJ per kg	C 68.1% N 1.4% S 0.74%	Average based on Yi et al. (2017) (assumed lignite)	170
Coal, 26.4 MJ per kg	C 81.8% N 1.3% S 1.2%	Average based on Yi et al. (2017) (assumed bituminous)	190
Coal, 29.3 MJ per kg	C 81.8% N 1.3% S 1.2%	Average based on Yi et al. (2017) (assumed bituminous)	190
Coal, bituminous, 24.8 MJ per kg	C 81.8% N 1.3% S 1.2%	Average based on Yi et al. (2017)	190
Coal, brown	C 68.1% N 1.4% S 0.74%	Average based on Yi et al. (2017) (brown coal is synonymous to lignite)	170
Coal, brown, 10 MJ per kg	C 68.1% N 1.4% S 0.74%	Average based on Yi et al. (2017) (brown coal is synonymous to lignite)	170
Coal, brown, 8 MJ per kg	C 68.1% N 1.4% S 0.74%	Average based on Yi et al. (2017) (brown coal is synonymous to lignite)	170
Coal, feedstock, 26.4 MJ per kg	C 81.8% N 1.3% S 1.2%	Average based on Yi et al. (2017) (assumed bituminous)	190

Coal, hard, 30.7 MJ per kg	C 86.6% N 1.1% S 0.75%	Average based on Yi et al. (2017) (hard coal is synonymous to anthracite)	180
Coal, hard, unspecified	C 86.6% N 1.1% S 0.75%	Average based on Yi et al. (2017) (hard coal is synonymous to anthracite)	180
Diatomite	Si 47%	Approximated as SiO ₂ based on Antonides (1997)	0.47
Feldspar	Si 31% Al 10% K 7.0% Na 4.4%	Section 2.3	2.5
Fuller's earth	Si 26.4% Al 9.1% Mg 2.2% Fe 2.0% Ca 1.3% Na 0.7% K 0.6% Ti 0.15% S 0.02%	Section 2.3	1.4
Gangue	Reference bedrock 100% (Table 3)	Section 2.3	2.8
Gangue, bauxite	Reference bedrock 100% (Table 3)	Section 2.3	2.8
Garnet, industrial*	Si 19% Fe 17% Al 12% Mg 9%	Assumed 50% almandine (Fe ₃ Al ₂ Si ₃ O ₁₂) and 50% pyrope (Mg ₃ Al ₂ Si ₃ O ₁₂) based on Curry (2017)	2.4
Granite	Si 35% K 9.8% Al 6.8%	Section 2.3	2.4
Gravel	Reference bedrock 100% (Table 3)	Section 2.3	2.8
Inert rock	Reference bedrock 100% (Table 3)	Section 2.3	2.8
Kaolin	Si 26.9% Al 20.0% K 1.50% Fe 0.60% Ti 0.36% Mg 0.36% Ca 0.25% P 0.086%	Yahaya et al. (2017)	1.6
Kaolin ore	Si 26.9% Al 20.0% K 1.50% Fe 0.60% Ti 0.36% Mg 0.36% Ca 0.25% P 0.086%	Yahaya et al. (2017). Although referred to as an ore in this flow name and elsewhere, kaolin is in this context rather to be seen as a mineral group; see further Dill (2016) for a thorough discussion	1.6
Laterite	Fe 18% Si 11% Al 3.4%	Average based on several locations reported by Persons (1970), recalculated from the corresponding oxides	1.2
lava	Reference bedrock 100% (Table 3)	Section 2.3	2.8
Lignite, 11 MJ per kg	C 68.1% N 1.4% S 0.74%	Average based on Yi et al. (2017)	170
Limestone	Ca 40% C 12%	Approximated as CaCO ₃ , which is the main component	19
metallurgical coal	C 81.8% N 1.3% S 1.2%	A type of bituminous coal (Falcon, 2013), therefore assumed same as "Coal, bituminous, 24.8 MJ per kg"	190
Metamorphous rock, graphite containing	Reference bedrock 100% (Table 3)	Section 2.3	2.8
Natural aggregate	Reference bedrock 100% (Table 3)	Section 2.3	2.8
natural pumice	Si 33% Al 8.4% K 3.4% Na 2.7% Fe 2.2% Ca 1.1% Mg 0.29%	Cardarelli (2018), recalculated from the corresponding oxides	1.8

Nepheline	Si 20.36% Al 18.34% Na 8.97% K 4.04% Ca 3.17% Mg 0.03%	Anthony et al. (2020), recalculated from the corresponding oxides	2.9
Oil shale	C 85% N 1.1% S 3%	Stauffer et al. (2008)	200
Oil, crude	C 85% N 1.1% S 3%	Stauffer et al. (2008)	200
Oil, crude, 41 MJ per kg	C 85% N 1.1% S 3%	Stauffer et al. (2008)	200
Oil, crude, 42 MJ per kg	C 85% N 1.1% S 3%	Stauffer et al. (2008)	200
Oil, crude, 42.6 MJ per kg	C 85% N 1.1% S 3%	Stauffer et al. (2008)	200
Oil, crude, 42.7 MJ per kg	C 85% N 1.1% S 3%	Stauffer et al. (2008)	200
Oil, crude, feedstock, 41 MJ per kg	C 85% N 1.1% S 3%	Stauffer et al. (2008)	200
Oil, crude, feedstock, 42 MJ per kg	C 85% N 1.1% S 3%	Stauffer et al. (2008)	200
Oils, unspecified	C 85% N 1.1% S 3%	Stauffer et al. (2008)	200
Olivine	Mg 25.4% Fe 14.6% Si 18.3%	Mineralogy Database (2012)	3.5
Perlite	Si 33.7% Al 7.0% K 3.2% Na 2.7% Fe 1.1% Ca 1.1% Mg 0.31%	Average based on several countries reported by Maxim et al. (2014), recalculated from the corresponding oxides	1.7
PGM, 4.7E-4% Pt, 3.1E-4% Pd, 0.2E-4% Rh, in crude ore	Pt 58.75% Pd 38.75% Rh 2.5%	Proportions of the three PGMs in 1 kg assumed the same as the proportions of the percentage numbers in the flow name	300,000,000
Phonolite	Si 26.8% Al 10.28% Na 5.90% K 4.44% Fe 3.73% Ca 1.99% Mg 0.657% Ti 0.378% Mn 0.132%	Brooker et al. (2001), recalculated from the corresponding oxides	3.3
Pumice	Si 33% Al 8.4% K 3.4% Na 2.7% Fe 2.2% Ca 1.1% Mg 0.29%	Cardarelli (2018), recalculated from the corresponding oxides	1.8
Rock, inert	Reference bedrock 100% (Table 3)	Section 2.3	2.8
Sand, gravel and stone, extracted for use	Reference bedrock 100% (Table 3)	Section 2.3	2.8
Sand, quartz	Si 36% Al 5.0% Ca 4.0% K 2.4% Fe 1.3% Na 0.83% Mg 0.75% S 0.084%	Assumed same as "Sand, unspecified"	2.1

Sand, unspecified	Si 36% Al 5.0% Ca 4.0% K 2.4% Fe 1.3% Na 0.83% Mg 0.75% S 0.084%	Average based on several sands as reported by Hasdemir et al. (2016), recalculated from the corresponding oxides	2.1
Shale	Al 20.7% Si 11.0%	Section 2.3	0.82
Silt	Si 62% Al 5% K 3.5% Na 2.2%	Approximated as 50% quartz and 50% feldspar, which are the two dominating components (Verkhovets et al., 2006)	1.5
Slate	Si 26% Al 9.1% Fe 4.9% K 3.1% Mg 1.5% C 1.4% S 1.2% Na 0.91% Ca 0.71% Ti 0.46% Mn 0.077% P 0.031%	Nanz (1953), recalculated from the corresponding oxides	13
Steatite	Si 30% Mg 19%	Approximated as the mineral talc due to the high talc content in steatite	2.2
stone	Reference bedrock 100% (Table 3)	Section 2.3	2.8
Sylvinite	Cl 54.8% K 23.6% Na 21.6%	Average composition with 55% NaCl and 45% KCl based on Fernández-Lozano and Wint (1997)	660
Tripoli	Si 43% Ca 0.93% Na 0.52% Mg 0.18% Al 0.12% Fe 0.10%	Average of two compositions reported in Maaitah et al. (2015), recalculated from the corresponding oxides	0.58
Vermiculite	Al 23% Fe 10% Mg 8.7% Si 5.6%	Mineralogy Database (2012)	2.2

*We here assume the flow regards natural garnet extracted for *industrial purposes*, rather than *industrially manufactured* garnet, which would not be an elementary resource flow but rather a technospheric product flow.

APPENDIX D – TYPE D FLOWS

Note that if a flow name ends with “in ground”, it should have the same CSP as the flow with the same name apart from “in ground”.

Material flow extracted	Ore grade applied	Main mineral mined	CSP (kg Si eq/kg)
Chromium ore	23.46%	FeCr ₂ O ₄	490
Copper ore	0.62%	CuFeS ₂	69
Copper ore (1.2%)	As stated	CuFeS ₂	130
Copper ore, 0.14%	As stated	CuFeS ₂	18
Copper ore, 4%	As stated	CuFeS ₂	430
Copper ore, sulfidic	0.62%	CuFeS ₂	69
Copper, Gold, Ore (1.07% Cu, 0.54 g/t Au)	As stated	CuFeS ₂	240
Copper, Gold, Silver, ore (0.51% Cu, 0.6 g/t Au, 1.5 g/t Ag)	As stated	CuFeS ₂	200
Copper, Gold, Silver, ore (1.0% Cu, 0.4 g/t Au, 66 g/t Ag)	As stated	CuFeS ₂	530
Copper, Gold, Silver, ore (1.1% Cu, 0.01 g/t Au, 2.86 g/t Ag)	As stated	CuFeS ₂	140
Copper, Gold, Silver, ore (1.13% Cu, 1.05 g/t Au, 3.72 g/t Ag)	As stated	CuFeS ₂	370
Copper, Gold, Silver, ore (1.16% Cu, 0.002 g/t Au, 1.06 g/t Ag)	As stated	CuFeS ₂	130
Copper, Gold, Silver, ore (1.7% Cu, 0.7 g/t Au, 3.5 g/t Ag)	As stated	CuFeS ₂	360
Copper, Silver, ore (3.3% Cu, 5.5 g/t Ag)	As stated	CuFeS ₂	380
Copper-Molybdenum-Gold-Silver ore (1.13% Cu, 0.02% Mo, 0.01 g/t Au, 2.8 Ag)*	As stated	CuFeS ₂	210
Iron ore	25%	Fe ₂ O ₃	3.2
Lead ore	3.4%	PbS	890
Lead, zinc ore (4.6%, 0.6%)	As stated	PbS	1,200
Manganese ore	33.29%	MnO ₂	120
Manganese ore (R.O.M.)	33.29%	MnO ₂	120
Molybdenum ore	0.13%	MoS ₂	460
Nickel ore	2.25%	Ni _{4.5} Fe _{4.5} S ₈	130
Nickel ore, 1.6%	As stated	Ni _{4.5} Fe _{4.5} S ₈	90
Phosphate ore	12.66% (29% P ₂ O ₅)	P ₂ O ₅	84
Phosphorus ore (29% P ₂ O ₅)	12.66% (29% P ₂ O ₅)	P ₂ O ₅	84
Tin ore	1%	SnO ₂	1,700
Titanium ore	31.6% (as in ilmenite's chemical structure)	FeTiO ₃	23
Tungsten ore	0.63%	CaWO ₄	1,800
Uranium ore, 1.11 GJ per kg	0.13%	UO ₂	290
Vanadium ore	0.34%	V ₂ O ₅	9.6
Zinc ore	10%	ZnS	430
Zinc ore, 12.6%	As stated	ZnS	540
Zinc ore, 8%	As stated	ZnS	340
Zinc ore, sulfide	10%	ZnS	430
Zinc, copper ore (4.07%, 2.59%)	As stated	ZnS	450
Zinc, copper, lead ore (2.11% Zn, 0.51% Cu, 0.86% Pb)	As stated	ZnS	370
Zinc, copper, lead ore (4% Zn, 0.09% Cu, 0.65% Pb)	As stated	ZnS	350
Zinc, copper, lead ore (5.37% Zn, 0.22% Cu, 0.2% Pb)	As stated	ZnS	310
Zinc, copper, lead ore (6.95% Zn, 0.13% Cu, 2.04% Pb)	As stated	ZnS	840

Zinc, lead ore (21.7% Zn, 5.6% Pb)	As stated	ZnS	2,400
Zinc, lead ore (4.21% Zn, 4.96% Pb)	As stated	ZnS	1,500
Zinc, lead ore, (9.7, 14% Zn, 3.1, 6.5% Pb)**	As stated	ZnS	1,800
Zinc, lead, copper ore (12%, 3%, 2%)	As stated	ZnS	1,500
Zinc, Lead, Silver, ore (8,54% Zn, 5,48% Pb, 94 g/t Ag)	As stated	ZnS	2,300

*We assume the unit for the 2.8 value here is g/t.

**We assume the numbers here to be ranges (i.e. 9.7-14% and 3.1-6.5%) and use average values in the calculation.

APPENDIX E – TYPE E FLOWS

Material flow extracted	Reason for categorization
Gemstones	There are many types of gemstones with CSPs varying orders of magnitude, such as quartz (CSP<1 kg Si eq/kg), diamond (CSP=140 kg Si eq/kg) and the beryllium-containing emerald (CSP=7500 kg Si eq/kg)
Metal ore, precious, unspecified, ROM	The CSPs of precious metal (silver, gold, ruthenium, rhodium, palladium, osmium, iridium and platinum) vary by orders of magnitude (from 5,100,000 to 7,600,000,000 kg Si eq/kg) and so could potentially also the CSPs of precious metal ores
Metals n.e.c., extracted for use	The CSPs of metals vary by many orders of magnitude, from 3.4 kg Si eq/kg (aluminium) to 7,600,000,000 kg Si eq/kg (iridium). "N.e.c." stands for "not elsewhere classified"
Metals n.e.c., related unused extractions	The CSPs of metals vary by many orders of magnitude, from 3.4 kg Si eq/kg (aluminium) to 7,600,000,000 kg Si eq/kg (iridium). "N.e.c." stands for "not elsewhere classified"
Open Pit extracted ore	The CSPs of ores vary several orders of magnitude, e.g. between 3.5 kg Si eq/kg for iron ore and 1800 kg Si eq/kg for tungsten ore
Open Pit Mine ore	The CSPs of ores vary several orders of magnitude, e.g. between 3.5 kg Si eq/kg for iron ore and 1800 kg Si eq/kg for tungsten ore
Ore mined	The CSPs of ores vary several orders of magnitude, e.g. between 3.5 kg Si eq/kg for iron ore and 1800 kg Si eq/kg for tungsten ore
Other minerals, extracted for use	The CSPs of minerals vary many orders of magnitude, e.g. between 1.3 kg Si eq/kg for kyanite and 8,100,000 kg Si eq/kg for cinnabar
Raw material, unspecified	The CSP of a raw material could vary many orders of magnitude, e.g. between silica (CSP<1 kg Si eq/kg) and pure iridium (CSP=7,600,000,000 kg Si eq/kg)
Underground extracted ore	The CSPs of ores vary several orders of magnitude, e.g. between 3.5 kg Si eq/kg for iron ore and 1800 kg Si eq/kg for tungsten ore
Underground Mine Ore	The CSPs of ores vary several orders of magnitude, e.g. between 3.5 kg Si eq/kg for iron ore and 1800 kg Si eq/kg for tungsten ore

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