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NON-TOXIC IMPACT CATEGORIES ASSOCIATED WITH EMISSIONS TO AIR, WATER, SOIL

Top-down characterization of resource use in LCA: from problem definition of resource use to operational characterization factors for resource inaccessibility of elements in a short-term time perspective

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Abstract

Purpose When resources are extracted and used by society, they are not necessarily lost for future generations. Therefore, recent publications on impact assessment of abiotic resource use in life cycle assessment focus on a decreased accessibility of resources due to dissipation, rather than depletion. In a previous study, dissipation was defined as a function of the global change in accessible stock due to human actions, and the global amount of the accessible stock, assuming a very long-term time perspective (more than 500 years). In this paper, a short-term time perspective (25 years) is adopted.

Methods The same generic characterization model is used, but different choices are outlined to derive characterization factors for a short-term perspective (25 years). To illustrate how the short term might be approached, a preliminary set of characterization factors is developed, based on assumptions and estimates.

Results The problem of resource use is defined as follows: the decrease of accessibility on a global level of primary and/or secondary elements over the short term due to the *net* result of compromising actions (i.e., emissions, dissipation in the technosphere, occupation in use, and exploration for new stocks). Characterization factors are derived based on assumptions, like the following: the accessible stock is based on present estimates of accessible stocks in the environment and the technosphere; estimates of accessible stocks in the technosphere are based on past extractions and generic recycling rates; all flows that are presently not recycled are assumed to be inaccessible. Finally, weighting between elements and the functions they have for the present society is based on the added value of the economic sector that is affected due to the decreased accessibility.

Discussion and conclusion A preliminary set of characterization factors is proposed for 55 elements. They assess the impact of the present use of resources on the decreased accessibility in the short term due to emissions and dissipation in the technosphere. However, calculation of impact category scores is still hampered by a lack of appropriate data for dissipative flows in life cycle inventory databases. The presented calculations are based on several simplifications and proxies. A more detailed distinction of dissipative flows and estimates of stocks in the technosphere may be possible based on (dynamic) SFA modelling of elements in different applications. To derive a more mature set of characterization factors, it is recommended to use the presented model as a basis and further elaborate or replace the proxies.

Keywords Abiotic resources · Elements · Minerals · Metals · Life cycle impact assessment · System model · Characterization model · Characterization factor · Dissipation · Short term

1 Introduction

The impact assessment of the use of abiotic resources in life cycle assessment (LCA) has been heavily debated. Several studies have brought up the diversity of ways

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abiotic resources are dealt with in LCA (Liao et al. 2012; Klinglmair et al. 2014; Rørbech et al. 2014). Recently, harmonization efforts have been undertaken by the UNEP-SETAC Task Force on natural resources (Sonderegger et al. 2017, 2020; Berger et al. 2020) and the SUPRIM project. Such harmonization efforts have shown that the debate on how to assess resource use in life cycle impact assessment (LCIA) mainly originates from different perspectives on the problem of resource use for humans and the environment and the underlying mechanisms that are considered to be relevant to the problem.

To structure the discussion of the problem of resource use and how to assess this for future generations, a multi-level framework was created in the SUPRIM project (Schulze et al. 2020a, b). The framework advocates a so-called top-down approach, in which the characterization model is developed, starting with a clear definition of the problem of resource use, and then builds further on this definition, using a step-by-step approach in which assumptions on a lower level are made consistently with decisions on the previous level. Thus, the framework distinguishes four different levels: (1) an overarching perspective, defining the problem and temporal and geographical scope of the problem; (2) a conceptual level ("Modelling Concept"), in which the relevant parameters and their relations are defined; (3) a practical implementation level that actually derives characterization factors (CF) by implementing data into the characterization equation; the last level, (4) "data collection in line with method" is necessary to align the system boundaries and assumptions that are made in the LCIA model and the LCI model. The SUPRIM framework is also believed to be helpful for the comparison of different impact assessment methods for resource use that are, or will be, developed. It might help to monitor similarities and differences in choices that are made in the different steps of the development of the characterization models and might help to signalize possible inconsistencies.

An example of the use of the framework is given by van Oers et al. (2020), in which the step-by-step procedure is followed to develop a generic characterization model for the use of abiotic resources in a short-term and long-term perspective,[1] distinguishing three different impact categories: (1) environmental dissipation, (2) technosphere dissipation, and (3) occupation in use. Based on additional assumptions and simplifications, considering a long-term time perspective and focused on elements only, an operational set of CFs was then derived for the dissipation of elements from the technosphere to the environment, the environmental dissipation potentials long term (EDP_{LT}). In van Oers et al. (2020), all emissions are considered dissipative, while this is not necessarily the case. On the one hand, emissions of some elements might originate from resources in which the elements already could be considered dissipated. And, on the other hand, considering a very long time scale, some elements might accumulate after emission into accessible stocks again. Therefore, in the work by Owsianiak et al. (2022), it is proposed to make a distinction, in the classification, between dissipative emissions and non-dissipative emissions.

The long-term time perspective was taken because it is in line with the perspective of most of the other impact categories in LCIA, like the infinite time horizon adopted for toxicity-related impact categories—referring to the time horizon adopted over which impacts are integrated for toxicity—or the time horizon of 100 years for climate change. It is also believed that in the long-term time perspective, the accessibility of resources is mainly determined by physical availability[2] of elements in the crust, instead of technical and economic limitations of present and short-term exploration, mining and refining developments, and thus most close to an environmental (and not an economic and/or social) assessment. Note that, even if considered an environmental assessment, the area of protection is the functional use of elements for humans in the technosphere, which is in the economic domain, while the mechanisms that lead to insufficient accessibility are partly but not only in the physical (environmental) domain.

Although the limits to accessible resources for the long-term perspective are mainly determined by physical availability (e.g., the concentration of elements in the earth's crust), the interest of European policy makers to assess resource use in LCA is currently motivated by short-term concerns: how will the present use of resources limit the accessibility of resources for the next generation, say in the next 25 years (Wolf et al. 2022). On this short-term time perspective, the accessibility of abiotic resources is less determined by physical availability and more determined by the present geo-political, technical, and economic conditions, i.e., which exploration, mining, and refining techniques are available and which stocks in the environment and the technosphere are commercially feasible to extract.

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[1] In van Oers et al. (2020), two time perspectives were chosen, the very long term (e.g., somewhere between 100 years and infinite) to allow sufficient time for very long-term effects to be established in line with the general time horizon for other impact categories addressed in LCIA and the short term (25 years) to minimize temporal changes in technology and economy, but remain true to the notion of at least one "future generation".

[2] In this paper, we follow the distinction which is made in the SUPRIM framework between availability and accessibility of resources. In brief, availability is defined as the presence of a resource in environment and/or technosphere. Presence is defined as the (estimated) physical presence of a resource in environment and/or technosphere independent of potential human use. Accessibility, is defined as the ability to make use of a resource (Schulze et al. 2020a).

So, the assessment of abiotic resource use on the short term is more a techno-economic instead of an environmental assessment (Dewulf et al. 2015).

Please note that also in a criticality assessment (Graedel et al. 2012; JRC 2017; Schrijvers et al. 2020) recent geopolitical and economic conditions determine the risk of supply of resources. However, there is a difference between the impact assessment of reduced accessibility of resources in LCA and the supply risk indicators (e.g., the reserve-production ratio) that are used in criticality assessment. In short, the direction of the assessment is opposite. In the LC impact assessment, one tries to assess the impacts of the product system on the environment (in the case of resources, the impact on reduced accessibility due to dissipation of resources). While, in the supply risk indicators, one tries to assess which external factors (mostly geopolitical and economic constrains to the extraction[3] of resources, like monopolization, stability of regions, but also the reserve-production ratio) might hamper the supply of resources to the product system (mostly a national economy, but sometimes also a product system like in LCA) (Cimprich et al. 2019).

Several papers seem to take a short-term time perspective of resource use as a starting point to assess resource use in LCA. Meanwhile, the focus in these papers is on the use of primary and secondary resources from both the earth's crust and urban mines (Charpentier Poncelet et al. 2019, 2021, 2022; Beylot et al. 2020a, b, 2021). Recent papers refer to price or value-based characterization factors to assess resource use in LCIA (Ardente et al. 2022; Greffe et al. 2022; Lai and Beylot 2022; Santillán-Saldivar et al. 2023).

To suit the policy need to assess short-term effects of resource use on accessibility, we elaborate in this paper a short-term characterization model, building on the generic models developed in van Oers et al. (2020) and using the SUPRIM framework (Schulze et al. 2020a, b). CFs for inaccessibility of elements in a short-term time perspective are developed based on physical constraints, like global yearly "losses" and the size of accessible reserves in the environment and technosphere. Finally, the valuation of resources by society is incorporated. For this, we suggest the economic importance indicator as used in criticality studies by the EU (Blengini et al. 2017a, b; JRC 2017).

In Dewulf et al. (2021), it is proposed to distinguish different impact categories for inaccessibility of resources due to compromising actions, i.e., tailing, landfilling, abandoning, hoarding, downcycling, and emitting. Such a breakdown of inaccessible stocks makes sense, because the different inaccessible stocks might have different potential for recovery within different time frames. However, for the illustrative purpose of this paper, we do not yet adopt this high resolution of flows and stocks leading to inaccessibility. Derivation of CFs for these different impact categories in the future will likely require rather detailed SFAs (see, e.g., Charpentier Poncelet et al. (2022)).

In contrast to detailed SFA modelling, this paper aims to demonstrate more simply how the SUPRIM framework can be relied upon to develop a model that takes into account inaccessibility due to human actions in the short term and can be practically implemented based even on more limited data. In Section 3.1, we will explain that to be able to develop CFs, we chose to lump all flows that go into inaccessible stocks. So, in this paper, the term "dissipative flows"[4] refers to a broad group of flows that might lead to reduced accessibility of resources, like emissions to the environment and flows in the technosphere to (temporarily) inaccessible stocks like tailings, landfill sites, and hibernating abandoned products.

The main aim of the present paper is to outline the different steps that need to be taken in the SUPRIM framework to derive characterization factors for dissipation in the short term. Thereby, the same line of reasoning is taken as for the long-term characterization model (van Oers et al. 2020). Although the present paper presents a simplified model, in the discussion, some attention is given to how this work can be further developed; when in due time, assumptions can be adjusted or replaced by more accurate data when they become available. The work of Charpentier Poncelet (2019, 2021, 2022) is a promising source for this and is recommended for further development of the dissipation model for the short-term time perspective (for more details see Section 4).

The paper will focus on the development of the characterization model and practically applicable characterization factors for LCIA only. It will not go into the LCI modelling that is necessary to classify resource use that might lead to inaccessible stocks. A requirement for the use of these CFs is that dissipative flows are already identified, classified, and

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[3] Please note that in the criticality assessment, the supply risk indicators (reserve-production ratio, Herfindahl–Hirschman-index (HHI) etcetera) refer to flows of extraction of resources and their geographic location. While in the suggested LCIA for resource use the indicators refer to flows that are dissipative (emissions, dump on landfill etcetera).

[4] In Dewulf et al. (2021), a more strict definition of dissipation is given, namely additions of resources to stocks with low concentrations and/or dispersed over large areas, like emissions to the environment and downcycling of resources in the technosphere. Other authors, like Ardente, Beylot, and Charpentier Poncelet, use a more general definition, referring to dissipative flows of abiotic resources as flows to sinks or stocks that are not accessible to future users due to different constraints. Because in this paper, flows to inaccessible stocks are lumped; without classifying the level of concentration (confined versus dispersed), we stick to the general definition of dissipation.

quantified in the life cycle inventory (LCI) phase. This has been shown to require significant effort (Zampori and Sala 2017; Beylot et al. 2020a, b, 2021; Owsianiak et al. 2022).

The reasoning behind the characterization model and the calculation of the CFs follows the framework that is developed in the SUPRIM project (Schulze et al. 2020a, b) and builds further on the generic model that is described in (van Oers et al. 2020). Section 2 gives the definition of the problem of resource use that is used and discusses the model concept, i.e., which flows and stocks in the technosphere and environment are used to assess the defined problem of reduced accessibility. In Section 3, the general conceptual model is elaborated into a mathematical equation for calculating CFs, based on assumptions considering the short-term time perspective. In order to be able to demonstrate calculation of operational CFs, proxies are suggested for the flows that are considered dissipative and the size of the stocks, in the environment and the technosphere, that are considered accessible. Next, in Section 3, weighting factors are suggested that give an indication of the value that different elements have for the economy, so the loss of accessibility between different elements can be weighted and aggregated into one score for all elements. Finally, Section 3 describes how the CFs are used in combination with LCI data to calculate the impact score for reduced accessibility of resources for the short-term time perspective. In Section 4, we discuss our approach and findings, draw conclusions, and define recommendations for further research in Section 5.

2 Perspective on resources and modelling concept

The EDP_{LT} is a set of CFs for the use of resources using a long-term time perspective (van Oers et al. 2020). The aim of this paper is to develop an analogous set of CFs for the short-term time perspective, adopting a time horizon of 25 years. This means that the same perspective on resources and the modelling concept is used for the EDP_{LT}, but assumptions and basic data choices are driven by a short-term view.

2.1 Level 1: problem definition

For the development of the LCIA method we use the following definition of the problem of *present* use of resources for future generations:

> the decrease of accessibility on a global level of primary (in the environment) and/or secondary (in the technosphere) elements over the short term (ST: 25 years) due to the net result of compromising actions, i.e., exploration, environmental dissipation, technosphere dissipation and occupation in use.

For a more detailed description of the problem of resource use and the compromising actions, we refer to van Oers et al. (2020).

2.2 Level 2: modelling concept

When drafting the modelling concept of the problem of reduced accessibility of the use of elements for future generations, the model is defined as a function of several parameters in a system model. The system model describes the stocks in the environment and technosphere, either accessible or inaccessible, and the dissipative flows between the technosphere and the environment (i.e., emissions) and within the technosphere (e.g., landfilling), see Fig. 1 for flows and stocks of recycling. For details on the system model, see van Oers et al. (2020).

In the context of the present paper, on dissipation of elements in a short-term time perspective in contrast to dissipation on a long-term time perspective, the following observations are highlighted from the system model. An overview of the differences between the long-term and short-term perspective is summarized in Table 3.

For the long-term time perspective, the crustal content is considered the long-term accessible stock, and only emissions are considered dissipative flows. For the short-term time perspective, we again have to ask ourselves the following questions: (1) what is the size of the accessible stock and (2) which flows are considered dissipative, but then for the short-term perspective (i.e., 25 years)?

At present, and in the short term, only part of the total available stock in the environment is accessible. The accessible part of the environmental stock is delimited by the present technological possibilities in exploration, mining, and refining and the present situation in the economic market of demand and supply and thus costs and revenues. If prices of elements will rise due to scarcity, new technologies will be developed, and a larger part of the stock will become accessible because further exploration and mining will become profitable (Yaksic and Tilton 2009; Crowson 2011; Humphreys 2013; Drielsma et al. 2016). However, the system responds slowly, meaning it has a more limited influence on resource accessibility within a period of 25 years.

After extraction of elements from the environment, the elements are not necessarily "lost" for future generations. Stocks in the technosphere might (at least partly) still be available for future mining, so-called urban stocks (Deetman et al. 2020; Marinova et al. 2020; van Oorschot et al. 2022). The stocks in the technosphere can be further distinguished into in-use stocks present in in-use products, and dissipated stocks in, for example, abandoned products, landfill sites, or

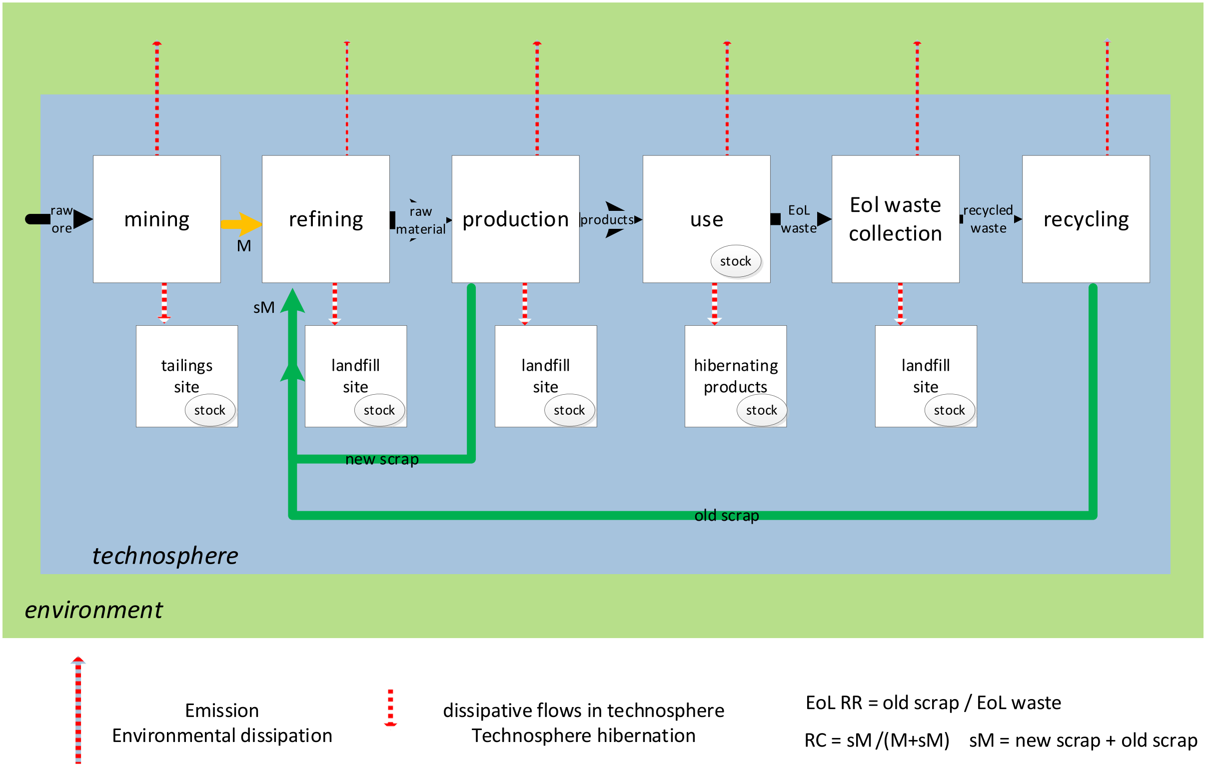

Fig. 1 Stocks and flows and recycling rates in the cradle-to-grave chain of a resource

tailings. Although there are some ongoing research efforts in this area, the technical possibility or economic incentive to recycle elements from dissipated stocks in abandoned products, landfill sites, or tailings is expected to be still limited in the short term. So, these stocks are considered as not accessible and flows of elements to these stocks can be considered dissipative flows, within the short-term time perspective. This is in line with what are considered dissipative flows by Beylot et al. (2021) and Charpentier Poncelet et al. (2021). Next to this, low-quality secondary use of elements in products might also be considered dissipative (Beylot et al. 2020a, 2021; Charpentier Poncelet et al. 2021, 2022). Generally speaking, in the short term, all flows that are not recycled at present can be considered dissipated or added to the stock of in-use products (occupation[5]). The stock in the technosphere that has potential to become accessible in the short term is the stock in in-use products. However, this in-use stock is the maximum estimate of the accessible stock, because after the end of life of products, only part of this in-use stock in these products might be recyclable given the present circumstances.

3 Practical implementation of inaccessibility of elements in the short-term time perspective (level 3)

3.1 Impact category indicator and general equation

In van Oers et al. (2020), three different impact categories were proposed: (1) environmental dissipation, (2) technosphere dissipation, and (3) in-use occupation. The inaccessibility indicators of these categories are proposed to be determined by two parameters, i.e., the global change in accessible stock, either by emissions to the environment, dissipation in the technosphere or accumulation into in-use (occupied) stocks; and the severity of a decreased global accessible stock, depending on the size of the stock. We here refer to the Electronic Supplementary Material (ESM2) of van Oers et al. (2020) for the derivation of general equations for the three impact categories and their CFs, *EDP*, *THP* and *OUP*.

To derive CFs, for the short-term ideally dynamic substance flow analysis (SFA) models are necessary to estimate

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[5] Occupation might hamper accessibility within the short term, t0 + 25 years, because resources are not accessible for other applications at the same time (i.e., in the same period). However, the accumulation of the resource in the in-use products leads to an increase of the reserve in the technosphere, which might become accessible for future applications after end of life. See also Section 3.2.2.

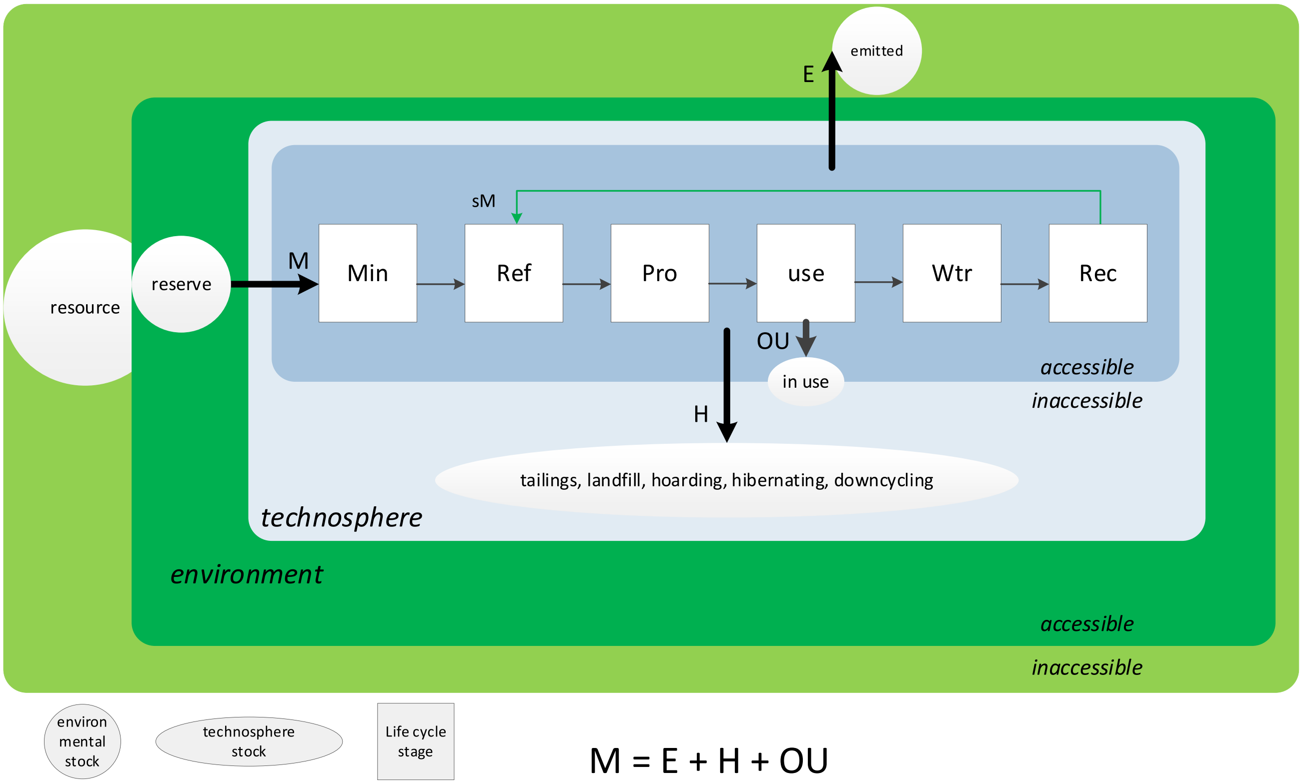

Fig. 2 The balance between the input of primary and secondary resources and the output of emissions, flows going to hibernating stocks in the technosphere and flows accumulating in in-use products (occupation)

(cumulative) flows for elements that are emitted to the environment or go into dissipated or occupied stocks in the technosphere. This implies performing SFAs[6] for all resources and their applications on a global scale. If at all feasible, this is beyond the scope of generic LCIA models. In this paper, we demonstrate a simplified procedure using SFA-like modelling to calculate the global stocks and flows. Now, to generalize and define the inaccessibility model for the short term it is suggested to lump the different possible flows to inaccessible stocks based on the following assumption: *all primary and secondary consumed resources that are NOT recycled*[7] *in the given time frame are assumed to be flows to inaccessible stocks*. So, it is suggested to define a more generic indicator for "flows of resource *i* going into inaccessible stocks" ($I_{2020,i}$) based on the assumption:

$$\begin{aligned} I_{2020,i} &= \left(E_{2020,i} + H_{2020,i} + OU_{2020,i}\right) \\ &\approx \left(M_{2020,i} + sM_{2020,i}\right) \times \left(1 - RR_{2020,i}\right) \end{aligned} \qquad (1)$$

In which $E_{2020,i}$, $H_{2020,i}$, and $OU_{2020,i}$ are flows of resource *i* in the year 2020 that go into inaccessible stocks, either dissipated in the environment, dissipated (aka hibernated) in the technosphere or occupied in in-use stocks, i.e., accumulated into the in-use stock. $M_{2020,i}$ and $sM_{2020,i}$ are, respectively, the global annual production of primary and secondary resource *i* (see Fig. 2). And $RR_{2020,i}$ is the global annual recycling rate in the year 2020 of resource *i*.

In this way, we lump the different types of flows that lead to inaccessibility into one inaccessibility flow. By this, we lose information on the type of flow leading to inaccessibility, but we enable to development of a more generalized model to assess inaccessibility without using detailed SFA models.

3.2 Equation for characterization factor for resource inaccessibility for the short-term time horizon

In this section, the general equation for the impact category "resource inaccessibility" is defined, lumping inaccessibility due to emission, dissipation in the technosphere, and occupation. This equation is elaborated into an operational method to assess inaccessibility due to resource use for the

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[6] For detailed SFAs additional information might be needed such as the use of elements in certain applications, the concentration of elements in applications, the lifetime of applications, the loss (emission and dump etcetera) factors of elements over the different life cycle phases (mining, production, use, waste treatment), the disposal of applications (and the elements contained) to landfill and recycling etc. And to explore possible future scenarios, assumptions must be made on how the regime of these stocks and flows might change over time.

[7] See also Section 3.2.2.

short-term time perspective. To be able to do this, assumptions are made and explained in the following sections.

Table 1 summarizes the terminology and symbols for the equation of the characterization factor of technosphere dissipation. Lowercase symbols m_i, e_i, h_i, ou_i and sr_i refer to product system-related quantities (as a result from an LCA study), while the capital symbols E_i, H_i, and OU_i refer to the global total amounts of the same flows, which are used in one or more characterization models for the three impact categories.

Lumping of the general equations for the three impact categories, environmental dissipation, technosphere dissipation, and in-use occupation (van Oers et al. 2020), the following general equation for the resource inaccessibility potential ($RIP_{t_0,T,i}$) as the characterization factor for inaccessibility of resources is derived:

$$RIP_{t_0,T,i} = \left(\frac{I_{t_0,T,i}}{P_{t_0,i}}\right) \times \frac{P_{t_0,i}}{R^2_{tot,t_0+T,i}} \Bigg/ \left(\frac{I_{t_0,T,ref}}{P_{t_0,ref}}\right) \times \frac{P_{t_0,ref}}{R^2_{tot,t_0+T,ref}} = \frac{I_{t_0,T,i} \Big/ R^2_{tot,t_0+T,i}}{I_{t_0,T,ref} \Big/ R^2_{tot,t_0+T,ref}} \tag{2}$$

Referring to the general characterization equation of resource inaccessibility (Eq. 2), adopting $t_0 = 2020$, $T = 25$ years, and the short-term time approach, we would get:

$$RIP_{2020,25,i} = \frac{I_{2020,25,i} \Big/ \left(R_{tot,2045,i}\right)^2}{I_{2020,25,ref} \Big/ \left(R_{tot,2045,ref}\right)^2} \tag{3}$$

The parameter $I_{2020,25,i}$ is the cumulative global amount (kg) of resource i that goes into inaccessible stocks in the environment and technosphere over 25 years, e.g., the cumulative dissipating flows from 2020 to 2045 from present applications that presently (2020) use resource i. $R_{tot,2045,i}$ represents the total global accessible stock in nature and technosphere as projected for the year 2045 (25 years from the present year, which was assumed to be 2020).[8] The 25-year foresight of the natural reserve part should be 25-accomplished by including exploration data for 25 years; the 25-year foresight of the technosphere stock could be based on an exploration of past years of annual economic reserves data. The $RIP_{2020,25,i}$ is expressed relative to a reference resource *ref*, e.g., copper (Cu) or any other element.

Now, we adopt Eq. 1, the assumption that flows to inaccessible stocks ($I_{2020,25,i}$) are approximated by all primary and secondary consumed resources $\left(M_{2020,25,i} + sM_{2020,25,i}\right)$ that are NOT recycled in the given 25 years $\left(1 - RR_{2020,25,i}\right)$. This implementation of Eq. 1 into Eq. 3 leads to the following equation:

$$RIP_{2020,25,i} = \frac{\left(M_{2020,25,i} + sM_{2020,25,i}\right) \times \left(1 - RR_{2020,25,i}\right) \Big/ \left(R_{tot,2045,i}\right)^2}{\left(M_{2020,25,ref} + sM_{2020,25,ref}\right) \times \left(1 - RR_{2020,25,ref}\right) \Big/ \left(R_{tot,2045,ref}\right)^2} \tag{4}$$

3.2.1 Simplification of the equation for resource inaccessibility for the short-term time horizon

Ideally, the characterization factors should be based on estimates of flows and stocks over a period $t+T$ (e.g., 2020 to 2045) for example using dynamic SFA (Helbig 2018; Charpentier Poncelet et al. 2019, 2021; Helbig et al. 2020). Although drafting dynamic SFAs for 25 years is already much more feasible than drafting them for 500 years (EDP_{LT}), it's still an elaborate task to do this for all the different elements and their applications into the most important products, and it still would depend on debatable assumptions about the near future.

For this reason, in this paper, resource inaccessibility for the short-term time horizon is elaborated in a relatively practical method adopting some additional simplifications and assumptions:

- As a proxy for the quantification of cumulative flows and development of stocks over the next 25 years, the present flows, stocks, and recycling rates at year t (e.g., 2020) are adopted.
- The accessible stocks are the sum of the accessible stocks in the environment and the technosphere
- (Economic) reserves as defined and estimated by USGS (USGS 1980) and other geological surveys are assumed to be a proxy for the presently accessible stock in the environment.
- Additionally, stocks in the technosphere should be estimated. That is, in-use stocks that might come available in the ST. A procedure to do this will be proposed in Section 3.2.4.
- Exploration of new resources for possible exploitation in the short-term future is one of the important compromising actions that actually will lead to an increase of estimates of accessible stocks in the environment. Estimates of the reserves of primary elements in the environ-

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[8] For an explanation of adopting the square of the R, we here refer to the appendix to the original article introducing the ADP (Guinée and Heijungs 1995).

Table 1 Overview of main terms and symbols adopted for describing the equation for the characterization factor of technosphere dissipation

Name	Symbol	Unit	Remark
(Number of years of) the time horizon adopted for assessing the potential decrease of resource accessibility	T	year (yr)	
Specific year for which the parameter (e.g., characterization factor) is assumed to be representative	t	year (yr)	
Specific resource for which the parameter (e.g., characterization factor) is assumed to be representative	i		*ref* refers to the reference resource, in this case copper
Amount of primary resource i consumed by a product system	m_i	kg/FU	Calculated as part of the LCI of an LCA study
Amount of secondary resource i consumed by a product system	sm_i	kg/FU	Not reported by LCA studies yet
Amount of resource i emitted by a product system	e_i	kg/FU	Calculated as part of the LCI of an LCA study
Amount of resource i going into hibernation for a product system	h_i	kg/FU	Calculated as part of the LCI of an LCA study
Amount of resource i going into occupation in in-use stock for a product system	ou_i	kg/FU	Calculated as part of the reference flow in the LCI of an LCA study
Amount of resource i going into inaccessible stock for a product system	ri_i	kg/FU	Calculated as part of the LCI of an LCA study
Global amount of primary resource i consumed by all products in year t, equalling the world annual extraction of resource i as reported by USGS or BGS	$M_{t,i}$	kg/yr	(British Geological Survey 2018; US Geological Survey 2018)
Global amount of secondary resource i consumed by all products in a specific year t	$sM_{t,i}$	kg/yr	
Global amount of primary and secondary resource i consumed (represented by total primary and secondary *production*) by all products in year t	$P_{t,i}$	kg/yr	$= M_i + sM_i$
Global amount of resource i emitted by all products in year t	$E_{t,i}$	kg/yr	
Global amount of resource *i* going into hibernation for all products in year *t*	$H_{t,i}$	kg/yr	
Global amount of resource *i* going into occupation in use stock for all products in year *t*	$OU_{t,i}$	kg/yr	
Global amount of resource *i* going into inaccessible stock for all products in year *t*	$I_{t,i}$	kg/yr	Equation 1
Global annual recycling rate in year *t* of resource *i*	$RR_{t,i}$	-	
The fraction of secondary resource *i* (scrap) in the total resource *i* input (primary and secondary) in year *t*	$RR_{RC,t,i}$	-	Equation 7 (Graedel et al. 2011; Talens Peiró et al. 2018)
The fraction of resource *i* in the end of life (EoL) waste that goes to recycling in year *t*	$RR_{EoL,t,i}$	-	Equation 8 (Graedel et al. 2011; Talens Peiró et al. 2018)
The functional recycling flow of resource *i* in old scrap from the EoL recycling process in year *t*	$OS_{t,i}$	kg/yr	
The EoL waste flow of resource *i* in year *t* after discarding products from the use phase	$W_{EoL,t,i}$	kg/yr	
Cumulative global emissions of resource i over time horizon T (25 years) starting at year *t0*	$E_{t0,T,i} = \sum_{t=t0}^{t=t0+T} E_{t,i}$	kg	
Cumulative global hibernation of resource i over time horizon T (25 years) starting at year *t0*	$H_{t0,T,i} = \sum_{t=t0}^{t=t0+T} H_{t,i}$	kg	
Cumulative global flows going into inaccessible stocks of resource i over time horizon T (25 years) starting at year *t0*	$I_{t0,T,i} = \sum_{t=t0}^{t=t0+T} I_{t,i}$	kg	
Characterization factor for resource *i*,	CF_i	kg *ref*/kg *i* (e.g., kg Sb-eq./kg *i*)	
Fraction of the present (t_0) global primary extraction and secondary use of resource i over time horizon T (25 years), made inaccessible	$C_{t_0,T,i}$	-	

Table 1 (continued)

Name	Symbol	Unit	Remark
Severity of making 1 kg of resource i inaccessible for time horizon T (25 years)	$S_{t_0,T,i}$	depending on method (e.g., 1/(yr.kg *i*))	
Environmental dissipation potential (CF_i for environmental dissipation of resources), based on the cumulative global emission of resource i that goes into hibernation within the time horizon adopted due to the use of resource i on time t_0	$EDP_{t_0,T,i}$	kg *Cu-eq*/kg *i*	
Technosphere hibernation potential (CF_i for technosphere hibernation of resources), based on the cumulative global flows of resource i that goes into hibernation within the time horizon adopted due to the use of resource i on time t_0	$THP_{t_0,T,i}$	kg *Cu-eq*/kg *i*	
Resource Inaccessibility Potential, based on the global flows of resource i that goes into inaccessible stocks within the time horizon adopted due to the use of resource i on time t_0	$RIP_{t_0,T,i}$	kg *Cu-eq*/kg *i*	Equations 5 and 10
Weighted resource inaccessibility potential (CF_i for resource inaccessibility of resources), based on $RIP_{t_0,T,i}$ and the Economic Importance of resource *i*	$wRIP_{t_0,T,i}$	kg *Cu-eq*/kg *i*	Equation 15
Category indicator result for time horizon T (25 years) for 'Environmental dissipation' for a product system	$ED_{t_0,T}$	kg-Cu eq	
Category indicator result for time horizon T (25 years) for 'Technosphere Hibernation' for a product system	$TH_{t_0,T}$	kg-Cu eq	
Weighted category indicator result for time horizon T (ST, e.g., 25 years, or VLT) for 'Resource Inaccessibility' for a product system	$wRI_{t_0,T}$	kg-Cu eq	Equation 16
Global accessible stock (e.g., economic reserve) of resource *i* in the environment as projected for year t	$R_{env,t,i}$	kg	US Geological Survey 2018
Global accessible stock of resource *i* in technosphere as projected for year t	$R_{tech,acces,t,i}$	kg	Equation 13
Global inaccessible stock of resource *i* in technosphere as projected for year t	$R_{tech,inacces,t,i}$	kg	Equation 12
Total global accessible stock of resource *i* in the environment and technosphere	$R_{tot,t,i}$	kg	Equation 6
Economic Importance indicator of resource *i* in year t	$EI_{t,i}$	€	Equation 14 (Blengini et al. 2017a, b; JRC 2017)
Share of end use by manufacturing industry of a resource *i* in a NACE Rev. 2 (2-digit level) sector *S* for resource *i* in year t	$A_{S,t,i}$	-	
Value added by manufacturing industry in the NACE Rev. 2 (2-digit level) sector *S* for resource *i* in year *t*	$Q_{S,t,i}$	€	
The substitution index of a resource *i*	$SI_{EI,i}$	-	

FU functional unit

Technosphere hibernation = technosphere dissipation

ment are updated regularly by USGS. These updates will include adjusted estimates due to exploration as well as mining that has taken place since the last estimation. So, it is recommended to update CFs based on these reserves regularly, for example, every 5 years.

Implementing these simplifications into the characterization equation of resource inaccessibility (Eq. 4), we would get:

$$RIP_{2020,25,i} \approx \frac{\left(M_{2020,i} + sM_{2020,i}\right) \times \left(1 - RR_{2020,i}\right) \Big/ R^2_{tot,2020,i}}{\left(M_{2020,ref} + sM_{2020,ref}\right) \times \left(1 - RR_{2020,ref}\right) \Big/ R^2_{tot,2020,ref}} \quad (5)$$

So, ideally, the dissipative flows that go into inaccessible stocks are based on the cumulative global flows over $T = 25$years due to the present (t) and successive future applications of the present demand (use) of resource i, e.g., the cumulative dissipation from 2020 to 2045 of all applications that presently (2020) use resource i. However, for the sake of deriving characterization factors, it is sufficient to have estimates of relative differences of dissipative flows between elements, instead of absolute figures. So, to simplify the calculations, instead of cumulative dissipative flows over a period of 25 years we take the snapshot of one year (e.g., 2020) as a proxy. So, we thereby assume that the relative differences between the amounts of various elements for "relative cumulative flows (e.g., dissipation in the technosphere) over the time horizon of 25 years" and "relative present recycling flows" will be negligible for the short term. While this may be a reasonable assumption for established commodities such as base-metals serving mature markets, we know that relative rates of use can and do change quite rapidly amongst newer specialty metals serving emerging markets (van Oers et al. 2019). The use of a proxy introduces uncertainty. However, trying to make predictions for the (short term) future probably will be equally disputable. This paper tries to explore the possibilities of a simple model, instead of trying to model using detailed (dynamic) SFA modelling. Next to that, the relatively simple proposed method can be performed regularly to incorporate updates to the chosen proxies.

The total accessible stock $R_{tot,t+25,i}$ will be the sum of the accessible stock in the environment and the accessible stock in the technosphere. After all, as stated in Section 2.2, after extraction of elements from the environment, the elements are not necessarily "lost" for future generations, because the elements can be extracted from urban stocks (reserves in the technosphere) when products are discarded at the end of their life. Ideally, one would use the estimate of the stock in the year $t_0 + 25$ years. However, predictions of accessible stocks, even in the near future, are difficult to make. Therefore, we here pose, as a rough assumption, *that estimates of present accessible stocks in the environment and technosphere will be a good indicator for total accessible stocks in the short-term future*. So, like for the flows, we assume that the relative size of stocks between elements over the short term will remain approximately the same. Again, with the notion that this might be a reasonable assumption for base-metals, but probably less valid for specialty metals for which exploration might grow rapidly.

For the short-term accessible environmental stocks, the (economic) reserves as identified by geological surveys, like USGS, can be used (US Geological Survey 2022). In the USGS terminology a "reserve" is defined as follows: That portion of an identified resource from which a usable mineral or energy commodity can be economically and legally extracted at the time of determination. So, the estimates of reserves by geological surveys like USGS refer to the expected extractable amount of resources on the short term given the technological and economic conditions (by definition of the term "reserve"). The Electronic Supplementary Material (ESM1), tab sheet "environmental reserves USGS(ST)" contains an overview of estimated stocks in the environment for the year 2020, mainly based on USGS. However, estimates of *accessible stocks in the technosphere* are not readily available. In this paper a procedure will be proposed to make a rough estimate of the size of these technosphere stocks and how much of this stock is accessible (given the present technical and economic conditions).

So, the total short-term accessible stock ($R_{tot,t_0+25,i}$) is the sum of the short-term accessible stock in the environment ($R_{env,t_0+25,i}$) and the technosphere ($R_{tech,access,t_0+25,i}$). As a proxy for the size of the stock at $t_0 + 25$, the present size of the stock in environment ($R_{env,2020,i}$) and technosphere ($R_{tech,access,2020,i}$) is used:

$$\begin{aligned} R_{tot,t_0+25,i} &= R_{env,t_0+25,i} + R_{tech,access,t_0+25,i} \\ &\approx R_{env,2020,i} + R_{tech,access,2020,i} \end{aligned} \tag{6}$$

Again, this simplification is probably incorrect for some mineral resources; in particular those metals necessary for the energy transition (e.g., case of Li, with large increase in extraction during the past recent years). So, the proposed method is sensitive to fast-changing mineral markets. However, in the specific case of lithium, large increases are expected in all places along the value-chain: from economic reserves, through production, in-use stocks, and recycling flows. So, it could be argued that the relative size of dissipative flows will not change that much as all flows will increase more-or-less proportionately. The value of a more detailed modelling needs to be balanced against the fact that there is no absolute stable relation between the elements or classes of elements to be identified. All of the on-to-one relations depend on changes in technology and societal demand. Such a detailed analysis could be out of date as soon as it is completed.

3.2.2 A closer look at the recycling rate (RR) and dissipation in the technosphere

Figure 1 is a depiction of the system model showing different types of dissipative flows to the environment (emissions) and in the technosphere (e.g., tailings, landfill). Next to this, different stocks are located in the environment and the technosphere. The figure is loosely based on the figure published by UNEP on recycling indicators and how they are derived (Graedel et al. 2011).

The notion that $(1 - RR)$ can be used as a proxy for the dissipation is already mentioned in other publications (Vadenbo et al. 2014; Frischknecht 2016; Sala 2020). However, looking at Fig. 1, you can see that this is only partly true.

There are different indicators to express recycling, amongst others you have the recycled content (RC) and the end of life recycling rate (EoL RR) (Graedel et al. 2011; Talens Peiró et al. 2018).

The RC is described as the fraction of secondary resource (scrap) in the total resource input (primary and secondary). In Fig. 1, the $RR_{RC,t,i}$ is described by the following flows and equation (based on Graedel et al. 2011; Talens Peiró et al. 2018):

$$RR_{RC,t,i} = {sM_{t,i}} \Big/ \left(M_{t,i} + sM_{t,i}\right) \tag{7}$$

In which $M_{t,i}$ is the global primary input and $sM_{t,i}$ is the global secondary input from old and new scrap into refining or fabrication of resource i in year t.

The other recycling indicator "EoL RR" is described by the following equation (based on Graedel et al. 2011; Talens Peiró et al. 2018):

$$RR_{EoL,t,i} = {OS_{t,i}} \Big/ {W_{EoL,t,i}} \tag{8}$$

In which $OS_{t,i}$ is the functional[9] recycling flow of resource i in old scrap from the recycling process and $W_{EoL,t,i}$ is the EoL waste flow of resource i after discarding products from the use phase to the waste management (final waste treatment and recycling).

Assuming the recycling rate (RR) is defined as RC, the recycled flows are old scrap and new scrap (green lines in Fig. 1). The remaining flows, $(1 - RR)$, of the input, $(M + sM)$, are the dissipative flows (dotted lines in Fig. 1) to the environment and technosphere (like inaccessible stocks in tailings, hibernating products and landfill, and recycling into non-functional applications in Fig. 1), and the flow of the resource to the in-use-stock, i.e., accumulation of the in-use stock (see box "use" in Fig. 1).

Now, on the other hand, assume the recycling rate (RR) is defined as EoL RR. This recycling rate is defined as a fraction of waste going to the life cycle stage "recycling" and the recycled flow is old scrap from EoL waste only. Following the input, $(M + sM)$, at the start of the life cycle stages of the resource, at this position in the chain already several dissipative flows have occurred, like accumulation into tailings, abandoned hibernating products, and in-use stocks (occupation). Thus, when the EoL RR is applied to the input[10] flow, $(M + sM)$, in Eq. 5, the dissipation is largely underestimated, because dissipative flows, to tailings, hibernating products, and the flow of the resource to the in-use stock, i.e., accumulation of the in-use stock (occupation), are all neglected.

So, the assumption for the short term to approach flows of resources that go into the inaccessible stocks by the calculation $(M + sM) \times (1 - RR)$, is only sensible when the recycling rate is defined as recycled content. With the notion that $\left(1 - RR_{RC}\right)$ considers all three flows corresponding to actions compromising accessibility for the short term, i.e., emissions, dissipation, and occupation in the technosphere. The estimated recyclable part of the stock in the technosphere is considered the accessible stock.

The Electronic Supplementary Material (ESM1), tab sheet "Recycling Rates (ST)" contains an overview of recycling rates according to UNEP (Graedel et al. 2011) and EU Critical Raw Material factsheets (Eynard et al. 2020; Latunussa et al. 2020).

3.2.3 Simplification of numerator, primary extraction as proxy for flows to inaccessible stocks

So, in this paper, RR is defined as RC and thus Eq. 7 can be implemented in Eq. 5. In that case, the numerator of Eq. 5 is given as follows:

$$\left(M_{2020,i} + sM_{2020,i}\right) \times \left(1 - {sM_{2020,i}} \Big/ \left(M_{2020,i} + sM_{2020,i}\right)\right) = M_{2020,i} \tag{9}$$

This basically means that the yearly primary extraction is the flow that is necessary to refresh the flow of elements that is dissipated in the technosphere (tailing, landfilling, hibernating, hoarding, downcycling) and environment (emissions), and the flow that is accumulated in the in-use stock in case of increasing stocks. An assumption that is also commonly made in MFA- and SFA-studies (Dewulf et al. 2021). The Electronic Supplementary Material (ESM1), tab sheet "prod USGS + kg elem. in ores" contains an overview of estimated extractions from the environment for the year 2020, mainly based on USGS.

In this case the equation of the resource inaccessibility potential ($RIP_{2020,25,i}$) can be defined as follows:

$$RIP_{2020,25,i} \approx \frac{{M_{2020,i}} \Big/ \left(R_{env,2020,i} + R_{tech,access,2020,i}\right)^2}{{M_{2020,ref}} \Big/ \left(R_{env,2020,ref} + R_{tech,access,2020,ref}\right)^2} \tag{10}$$

In which $M_{2020,i}$ is the primary extraction of a resource i in the year 2020, and $R_{env,2020,i}$ and $R_{tech,access,2020,i}$ are the accessible reserves of a resource i in the year *2020* in the environment and the technosphere.

3.2.4 Simplification of denominator, estimating stocks in the technosphere

For the short-term perspective, the stock in the environment can be approximated by the *(economic) reserve* estimates that are made by USGS (US Geological Survey 2022). However, to estimate the size of the stocks in the technosphere

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[9] EoL RR only refers to functional recycling. In contrast, non-functional recycling is the amount of resource that is collected but not functionally applied ("lost"). It thus becomes an impurity or "tramp element" in the dominant resource with which it is collected (e.g., copper in alloy steel).

[10] Instead of the waste flow for which the EoL RR actually is defined.

and determine which part of this stock is accessible is more challenging. There are several studies that have made a start to estimate stocks in the technosphere, aka urban mine (Graedel 2010). However, these estimates do not cover a global scale. Furthermore, these estimates are only made for a limited number of elements from the periodic system.

In this study, we propose a procedure to approximate the size of the accessible stock in the technosphere based on accumulation of past global productions. The stock of a resource in the technosphere at year *t* is the result of the accumulation of resources from globally consumed resources over a period $t - T$ in the past. The accumulated resources over the past should be distinguished into:

1. Accumulation into *in-use stock* (occupation, partly accessible at the same time at $t_0 + T$)
2. Accumulation in *dissipated stock (e.g., tailings, landfill, and hibernated products)* (not accessible at $t_0 + T$)

The following rough approach to estimate the size of the stock in the technosphere (urban stock) is proposed.

Assume that in year *t* the size of the stock in the technosphere $R_{tech,t,i}$ is approximated by the sum of global primary production $M_{t,i}$ over the past 50 years:

$$R_{tech,t,i} = M_{t,i} + M_{t-1,i} + M_{t-2,i} \cdots + M_{t-50,i} \tag{11}$$

The Electronic Supplementary Material (ESM1), column I in tab sheet “urban and total reserves (ST)” gives an overview of estimated stock in the technosphere based on the cumulative primary extractions from the environment over the years 1970–2019, mainly based on USGS.

Next, we assume that the part of a resource that is not recycled accumulates into inaccessible stocks (in tailings, in EoL discarded products on land fill sites, hibernating in abandoned but not yet discarded products or emitted to the environment or occupied in in-use products in the short-term time frame). Finally, we assume, as a very rough estimate of the recycling over the past period, that the present recycling rate is applicable to the total accumulation of a resource. Of course, this constant recent recycling rate will lead to an overestimation of the recycled part and thus will lead to an underestimation of the dissipated stock. Adopting these assumptions, the next equation gives the inaccessible stock in the technosphere:

$$R_{tech,inacces,t,i} = R_{tech,t,i} \times \left(1 - RR_{t,i}\right) \tag{12}$$

and the following equation then provides the estimate of the in-use-stock that potentially is partly accessible for future generations:

$$R_{tech,access,t,i} = R_{tech,t,i} \times \left(RR_{t,i}\right) \tag{13}$$

The Electronic Supplementary Material (ESM1), tab sheet “urban and total reserves (ST)” gives the calculated stocks in the technosphere, distinguished into dissipated stock (column P) and maximum accessible stock (column Q) by applying these two equations.

Please note that this estimation of the potential accessible stock is an overestimation because of the following:

1. The recycling rates over the past are overestimated due to applying current levels of recycling rates and thus the size of the $R_{tech,access,t0,i}$ is overestimated.
2. After end of life, only part of the discarded products will be available for recycling given the present technical and economic conditions. So, the estimate should be considered as a maximum accessible stock in the technosphere, given the assumed past accumulation.

3.2.5 Appreciation of functions (weighting between resources) for short term time perspective

In the previous sections, it is explained how CFs for the short-term time perspective can be derived for elements. The factors are based on the defined characterization model in which the factors are depending on the size of the accessible stock and the change in the size of accessible stock. Now these CFs express the severeness of the reduction of the accessible stock. If accessible stocks are relatively large and/or the yearly change in accessible stock, is relatively low, the CF is relatively small. However, the CFs still do not express how bad it is that we run out of a particular accessible stock. In other words, how much do we value the different resources and the function(s) they have for society.

In van Oers et al. (2020), it is assumed that, for the very long-term time perspective, different resources and their functions are valued equally. The reason is that for the very long term, it is very difficult or impossible to foresee which function (applications of) resources will have for society, which substitution options will be available, and how the functions will be appreciated by the society. For this reason, for the very long-term time perspective, equal weights are put on the functions different resources have for society.

However, for the short term, given the present technical and economic situation in the present society and economy, it might be possible to say something more about the differences in appreciation of functions delivered by resources, while still holding on to the assumption that the present situation is a good indicator for the short-term future.

Several approaches are possible to derive weighting factors that express the appreciation of resources and their function:

1. Equal weights: approach used for the *EDP* for LT, all resources/functions are equally important/valued);
2. Prices of resources: approach of the EU Joint Research Centre (JRC) for dissipation in which prices are believed to be an indicator for how functions of resources are appreciated by society.
3. Relative yearly global extraction (and thus consumption) at present: in which the amount of present consumption is believed to be an indicator for appreciation of the resource and its function by society.
4. Economic importance indicator of the EU: The added value of the sectors that are affected, in case a resource is not available for the sectors in the manufacturing industry, as used in the EU criticality assessment.

Although, option 1, equal weighting between resources may be the best valuation for the very long term, this certainly does not reflect the present situation of the importance of resources for society. In option 2, the JRC proposal on how to characterize the use of resources, the price of a resource is proposed as an indicator for the valuation of a resource. In fact, price is used for the total characterization (Sala 2020; Ardente et al. 2022). Of course, part of the market price of a resource is determined by how much the resource is appreciated by society. However, there are more parameters that determine the market price of a resource, like scarcity and production (energy) costs. In this paper, the accessibility or scarcity is already addressed by the presented characterization model using present estimates of stocks and dissipative flows. So, for the valuation of the function of resources, it is better to use an additional independent parameter. Although the present amount of consumption of resources (option 3) indicates something about the importance of resources for society, it is believed that option 4, the share of the (global) consumption of resources by different sectors in the technosphere together with the economic value that the sector adds to the total GDP, is a more subtle indicator for the economic importance of a resource for the present economy. So, in this paper, the economic importance indicator as used in criticality studies for Europe (Blengini et al. 2017b; JRC 2017; Eynard et al. 2020; Latunussa et al. 2020) is proposed as an indicator for the valuation of functions of resources for the present economic system. The concept of economic importance for the valuation of functions that resources have in society is also introduced in a recently developed method for impact assessment, the economic value dissipation potential (EVDP) (Santillán-Saldivar et al. 2023).

The importance of a resource to the economy of the European Union is assessed by the indicator "Economic Importance (EI)." EI is evaluated by taking into account the share of economic sectors by which the resource is consumed at EU level and their gross value added (GVA) (Blengini et al. 2017a, b; JRC 2017).

The indicator is calculated for each resource using the equation below:

$$EI_{t,i} = \sum\nolimits_S \left(A_{S,t,i} \times Q_{S,t,i}\right) \times SI_{EI,i} \tag{14}$$

In which $EI_{t,i}$ is economic importance of a resource i in year t; $A_{S,t,i}$ is the share of end use by manufacturing industry in year t (e.g., 2020) of a resource i in a NACE Rev. 2 (2-digit level) sector S; $Q_{S,t,i}$ is the NACE Rev. 2 (2-digit level) sector's value added in year t; $SI_{EI,i}$ is the substitution index (SI) of a resource i (to be used in economic importance). S denotes sector (Blengini et al. 2017a, b; JRC 2017).

The scope of the indicator is the average over the past 5 years and the indicator refers to the manufacturing industry in the European Union. The higher the value added of the affected sectors, the higher the damage.

The Electronic Supplementary Material (ESM1), tab sheet "Economic Importance Indicator" gives the economic importance of different elements as derived for the critical raw materials studies (Blengini et al. 2017a, b; JRC 2017; Eynard et al. 2020; Latunussa et al. 2020).

Ideally, $EI_{t,i}$ should be determined on a global level. However, to the knowledge of the authors, no information is readily available on the share of applications of resources in sectors on a world level and on the resulting affected GVA.

So, in this paper, it is assumed that the sector structure of the EU is comparable to the overall world economy. Obviously, this is not the case. The aim of this paper is to outline a possible procedure to derive weighting factors for valuation of functions across resources. To derive $EI_{t,i}$ factors on a world level is, however, beyond the scope of this paper.

Now for each element i, the resource inaccessibility potential for short term ($RIP_{2020,25,i}$) and the economic importance indicator ($EI_{t,i}$) can be combined into a weighted resource inaccessibility potential using the following equation (ST is defined as 25 years):

$$wRIP_{2020,ST,i} = RIP_{2020,ST,i} \times EI_i \tag{15}$$

So, the $wRIP_{2020,ST,i}$ is a factor that expresses the severeness of a resource becoming inaccessible due to the present use and the valuation of the function of the resource for society, in particular the manufacturing industry.

3.3 Data for characterization factor

For the calculation of the resource inaccessibility potential for the short term ($\mathrm{RIP_{ST}}$) the following input data are needed:

(a) $M_{2020,i}$, the world annual primary production of elements for a specific year (here 2020) which is the numerator of the characterization equation. Data on annual global extractions are reported by USGS (US Geological Survey 2022). It should be stated that the production values of elements as reported by USGS is the amount of elements that are put on the market. So, these values exclude the amount of elements that are dissipated to tailings. This means that this practical implementation of the USGS data for the calculation of the characterization factors leads to an inconsistency with the theoretical model.

(b) $R_{env,2020,i}$, the (economic) reserve estimates for a specific year (here 2020) as reported by USGS. These estimates represent the accessible stock in natural reserve base, which can be extracted given the technical and economic conditions at the time of determination. Data on annual global extractions are reported by USGS (US Geological Survey 2022). The estimates of the stocks are regularly updated.

(c) The cumulative world annual primary production of elements M_i, over the past 50 years or more for the calculation of stocks in the technosphere. Historical data on world extractions of primary elements are reported by USGS (US Geological Survey 2018).

(d) The recycling rate in terms of recycled content (RC) to estimate which part of the stock in the technosphere, as determined at c), should be considered accessible. Global and EU recycling rates are reported by UNEP (Graedel et al. 2011) and EU Critical Raw Material factsheets (Eynard et al. 2020; Latunussa et al. 2020).

(e) $EI_{t,i}$, the economic importance indicator of the resource i for of the EU (Blengini et al. 2017b; JRC 2017; Eynard et al. 2020; Latunussa et al. 2020), which is used to weight the reduced accessibility between different resources, based on the value they represent for the present economic sectors in the EU.

The Electronic Supplementary Material (ESM1) contains the basic data and their sources for all the parameters that are mentioned above. Please note that for primary extraction data refer to 2019, instead of 2020.

3.4 Resulting characterization factors for Resource Inaccessibility in the short-term perspective

Based on Eqs. 10 and 15, using the basic data on $M_{2019,i}$, $R_{env,2020,i}$, and $R_{techaccess,2020,i}$ and $EI_{t,i}$, CFs are derived for resource inaccessibility in the short term perspective. Two different sets of RIPs are calculated, using different assumptions on the size of the accessible stock:

1. Based on the total accessible stock in technosphere and environment. (ESM1, tab sheet 'RIP 2019 (ST) Rtotal'),
2. Based on the accessible stock in the environment only. (ESM1, tab sheet 'RIP 2019 (ST) Renv only'.

The estimate of the accessible stock in the technosphere is based on many assumptions, like historic extraction data and present recycling rates. As data on historic recycling rates is lacking, the present rates are also applied to the past. Thus, the procedure proposed in this paper will lead to an optimistic estimate of the accessible stock in the technosphere and should therefore be interpreted as the maximum accessible stock. For an alternative set of RIPs, it is assumed that all stocks in the technosphere are considered inaccessible for the short-term perspective. So, in this case, RIPs are based on primary stocks in the environment only. This assumption violates the initial problem definition but can be used as a temporary proxy for the minimum accessible total stock until a better one is developed.

Table 2 shows the top 10 and bottom 10 *wRIP* s, based on the total accessible reserves in environment and technosphere. The top 10 contains some of the platina group metals (PGMs), like rhodium, palladium, iridium, platinum, and ruthenium. The bottom 10 contain some of the bulk metals, like iron, aluminum, chromium, manganese, copper, and nutrients, like phosphorus and potassium.

In Fig. 3 the two sets of *wRIP* s, are plotted for all the 55 elements. The scatter plot shows that there is a large correlation between the two sets of *wRIP* s, i.e., based on total accessible reserves in the environment and technosphere versus based on reserves in the environment only. Given the procedure used in this paper, this means that for the ranking of elements within the resource inaccessibility score it does not matter which set of CFs is used.

However, note that this does not mean that the reserves in the technosphere are negligible. Comparison of the reserves in the environment and technosphere shows that for 25 elements the reserves in the environment are a factor 10, or (much) more, higher than reserves in the technosphere. However, for about 10 elements the reserves in the technosphere seem to be about half, or more, the size of the reserve in the environment and thus should be considered substantial.

So, it also does not imply that for the development of relative characterization factors between elements within the impact category, the knowledge on reserves in the technosphere is not important. After all, it might be that the procedure which is used in this paper to estimate the reserves in the technosphere is not appropriate to estimate differences in the development of the technosphere stock between elements which might lead to more diverging CFs. For example, the size of the technosphere stock is correlated to the size of the yearly extraction. Thus, the effect of a relatively large stock in technosphere might be compensated by the effect of a high extraction rate, thus leading to a more or less unaffected *wRIP*.

Table 2 The top and bottom 10 resource inaccessibility potentials based on total accessible reserves in environment and technosphere

	M_{2019}	**R_{env}**	**$R_{tech\ accessible\ maximum}$**	**Weighting factor EI_{2020}**	**RIP**	**Weighted RIP**
Name	*kg*	*kg*	*kg*	-	*kg Cu equivalents*	*kg Cu equivalents*
Top 10						
Rhenium	5.32E+04	2.40E+06	2.45E+05	0.37	3.77E+02	1.41E+02
Rhodium	2.17E+04	2.91E+06	3.73E+05	1.40	9.96E+01	1.39E+02
Palladium	2.14E+05	7.20E+06	3.31E+06	1.32	9.58E+01	1.26E+02
Iridium	6.10E+03	1.38E+06	4.46E+04	0.79	1.49E+02	1.18E+02
Indium	9.68E+05	1.50E+07	6.01E+06	0.61	1.09E+02	6.66E+01
Platinum	1.87E+05	1.30E+07	5.98E+05	1.11	5.01E+01	5.57E+01
Germanium	1.31E+05	8.60E+06	1.93E+06	0.65	5.85E+01	3.81E+01
Ruthenium	2.77E+04	5.21E+06	7.62E+05	0.77	3.85E+01	2.98E+01
Thulium	9.66E+04	1.28E+07	1.65E+04	0.81	2.91E+01	2.36E+01
Beryllium	2.51E+05	2.10E+07	1.96E+06	0.79	2.36E+01	1.85E+01
Bottom 10						
Copper	2.04E+10	8.70E+11	1.76E+11	1.00	9.24E-04	9.24E-04
Titanium	5.78E+09	4.44E+11	9.84E+10	0.88	9.73E-04	8.55E-04
Strontium	9.57E+07	6.80E+10	0.00E+00	0.66	1.02E-03	6.77E-04
Manganese	2.06E+10	1.30E+12	1.94E+11	1.26	4.57E-04	5.78E-04
Boron	1.87E+09	3.91E+11	0.00E+00	0.66	6.08E-04	4.01E-04
Potassium	3.43E+10	4.81E+12	0.00E+00	1.02	7.33E-05	7.47E-05
Chromium	1.38E+10	3.70E+12	4.94E+10	1.38	4.86E-05	6.70E-05
Aluminum	6.32E+10	7.50E+12	4.72E+11	1.02	4.92E-05	5.02E-05
Phosphorus	3.07E+10	9.61E+12	0.00E+00	1.00	1.65E-05	1.65E-05
Iron	1.52E+12	8.40E+13	1.55E+13	1.28	7.59E-06	9.74E-06

3.5 LCI data

The fourth and final level of the SUPRIM framework (Schulze et al. 2020a, b) describes the elementary flows from the inventory ("LCI data") needed as input to calculate the impact score for the impact category resource inaccessibility of an LCA case study.

In conventional LCA the elementary flows are the flows that cross the system boundary between the environment and the technosphere. Now, the impact category technosphere dissipation and also occupation in use, use mass flows of resources within the technosphere. These mass flows do not represent elementary flows in the inventory table but technosphere flows, like resources dissipated in tailings and end of life discarded products that end up on landfill. These data need to be extracted from the process-to-process matrix ("A matrix") and are not readily available in a conventional LCA. There are several papers that address issues related to the LCI of resource use and the classification of technosphere to technosphere flows as dissipative or not (Beylot et al. 2020a, b, 2021; Greffe et al. 2022).

In this paper, it is assumed that there is a sound procedure to classify and quantify dissipative flows in the LCI. In the next step, in the characterization step of an LCA, the flows that go to inaccessible stocks ri_i, are translated into contributions to impact categories by means of characterization factors.

This results in $wRI_{2020,ST}$, the weighted category indicator results for time horizon T (ST, e.g. 25 years) for "Resource Inaccessibility" for a product system, are summarized as follows:

$$wRI_{2020,ST} = \sum_i wRIP_{2020,ST,i} \times ri_i \tag{16}$$

Here $wRIP_{2020,ST,i}$ is the weighted resource inaccessibility potential of resource i for a short-term time horizon (e.g., 25 years), defined on the basis of the current (2020) data and using EI for weighting between elements, and ri_i is the quantity of element i going into inaccessible stock per functional unit (FU) in an LCA study. This flow going into inaccessible stock per functional unit (FU) can either be an emission e_i or an addition to the dissipated (aka hibernating) stock in technosphere h_i.

Please note that the flow of the element that goes into occupied in-use stocks ou_i, does not contribute to the impact score. The flow of this element is related to the functional unit. It is the functional use of the element in the product system that

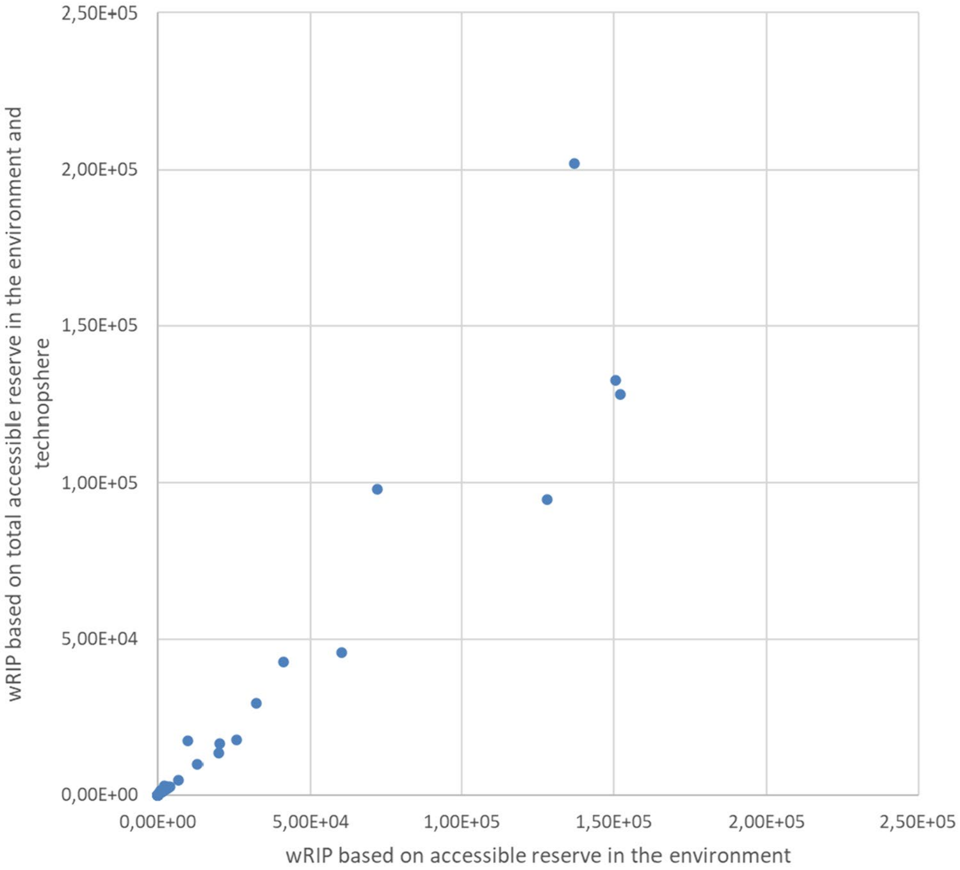

Fig. 3 Scatter plot of wRIP based on total reserve in the environment and technosphere versus wRIP based on reserve in the environment only

is studied. In the short term, this flow leads to inaccessibility for other applications, at the same time (competition for elements). However, the flow also adds to the increase of the accessible stock in the technosphere and might become available for future applications after end of life.

3.6 Normalization, proposal of a new procedure to derive reference totals for normalization

Normalization is an optional step in the life cycle impact assessment. It is a necessary step in case impact category scores are weighted and aggregated using weighting factors based on panel weighting (Huppes et al. 2012). In ESM 2 a procedure is outlined on how to estimate normalization totals for the impact category weighted resource inaccessibility short term ($wRI_{2020,ST}$).

4 Discussion

4.1 LCIA model, consistency

In van Oers et al. (2020), general characterization models for the impacts of resource use are defined for environmental dissipation, technosphere dissipation, and in-use occupation for the short-term and the long term characterization. Now, in this paper, the same basic characterization model and prerequisites are used. However, the variables with which the function (Eq. 10, based on the general equation of the characterization model for resource dissipation, Eq. 3) is populated, i.e., accessible stocks in environment and technosphere and change in accessible stocks, are chosen specifically for the short-term time perspective. Furthermore, the reasoning and assumptions made for the short-term perspective, to populate the variables are explicitly described using the step-by-step SUPRIM framework in which diverging choices between the long-term and short-term perspective are indicated.

In order to derive operational CFs, some simplifications are made in the choice of parameters. All parameters, i.e., stocks and flows, are based on the present situation instead of the cumulative situation over the period $t_0 + T$ (e.g., 2020 to 2045). The present situation (e.g., year 2020) is thus assumed to be an acceptable proxy for the relative differences between elements for stocks and flows over the short term. In future research, these simplifications could be redeemed by more detailed modelling of stocks and flows over time using dynamic substance flow models, taking into account different applications of the resources in products as far as feasible.

The work by Charpentier Poncelet et al. (2022) seems to be a promising source for a more detailed elaboration of the characterization model (see recommendations).

Regarding the *total global accessible stock of elements in the environment for short term* the estimates for (economic) reserves as made by geological surveys, like USGS, are appropriate. In the presented simplified characterization model the estimated reserve at present ($t = 2020$) is used. A possible option to model the size of these stocks on $t_0 + T$, e.g., 2045, is to extrapolate current estimates of the environmental stocks at $t = 2020$ by linear extrapolation over the past. However, due to dynamics in demand and supply, it is very difficult to estimate the size of presumed accessible stocks in the environment, even for the short term (e.g., rare earth elements necessary for the energy transition, where a boom in the demand has lead to an accelerated exploration for reserves). That is why, the present sizes of the stocks are used here as a proxy. For the purpose of relative characterization factors, the relative stocks of elements are of importance—not the absolute quantification of accessible stocks at $t_0 + T$, e.g., 2045. Therefore, for a relative assessment of the contribution of the use of different resources to the considered impact category, the present estimate of (economic) reserves is suggested as an acceptable proxy, even though there still might be differences in exploration, even on the short term.

Regarding the *total global accessible stocks of elements in the technosphere for the short term* it is assumed that the available stock in the technosphere is the result of the cumulative extractions of elements from the environment in the past. The cumulative extraction of elements in the past constitutes the stocks in the technosphere. These stocks can be divided into inaccessible stocks and accessible stocks. Inaccessible stocks are considered to be elements in tailings, landfill, abandoned but not yet discarded EoL products (hibernating products), and non-functional or low-quality recycled resources. The remaining elements are occupied in the in-use stock. After end of life, but within the short-term, part of these occupied elements might become accessible for future generations. This part, i.e., being newly accessible, will depend on the Recycling Rate at $t_0 + T$ ($1 < T < 25$ years). The estimated in-use stock is the most optimistic estimate of accessible stock at time $t_0 + T$, e.g., 2045. The proposed procedure to estimate the accessible stock can be argued as a rough approach. A more sophisticated approach to estimate size of the stock could include dynamic stock modelling, considering a growth of recycling rates over the past period (e.g., 50 years) from nearly nothing to the present rate, and ideally distinguishing between different applications of the resource in different products. Different applications might have distinct characteristics, like lifetimes, concentrations of elements, Recycling rates, which might change over time. In this paper, the procedure to estimate stocks in the technosphere serves as an illustration of how the stocks might be estimated using generic assumptions and data. Further detailing is possible, but for the moment, for the sake of deriving CFs, this rough approach to estimate stocks in the technosphere is believed to be a reasonable first approach.

Regarding the flows going into dissipation in the technosphere, ideally one wants to assess *the total cumulative global dissipation due to the present demand over a given short-term time horizon.* However, cumulative flows going into technosphere dissipation over a particular time horizon are difficult to estimate. Therefore, for the sake of deriving CFs that assess relative inaccessibility between elements, it is argued that a snapshot of present flows that go into inaccessible stocks (like present landfill and accumulation into in-use stocks) is an acceptable temporary proxy for cumulative flows from present use over a *short-term* time horizon. In Charpentier Poncelet et al. (2022) cumulative dissipative flows are estimated over the life time of an element. This information looks promising for a more detailed elaboration of the characterization model (see recommendations).

Finally, to be able to develop CFs for the short term for a comprehensive set of elements, all flows that go into inaccessible stocks in the environment and technosphere are lumped. By doing so information is lost. For instance, different inaccessible stocks probably will have different potential for recovery, over different possible time frames. For this reason, in Dewulf et al. (2021) it is proposed to define six different impact categories for inaccessibility. The impact categories refer to different inaccessible stocks due to different compromising actions, i.e., tailing, landfilling, abandoning, hoarding, downcycling, and emitting. However, in this paper, the aim was to demonstrate a more simplified result of the SUPRIM framework, for several reasons:

- Breaking down inaccessibility in different impact categories based on detailed flows and stocks, will require highly detailed SFAs of all elementary resources in order to calculate CFs. A first start is made to compile such SFAs and model flows for a comprehensive set of 61 elements (Charpentier Poncelet et al. 2022). However, including stocks and a regular update of these models based on new developments will be a challenge;
- Next to this, the efforts you have to put into the LCI and the classification will extend accordingly;
- Finally, the definition of criteria to label the different flows (and stocks) might be a challenge and will depend on the chosen time frame.

Nevertheless, the breakdown of flows that lead to inaccessibility as proposed by Dewulf et al. (2021) is acknowledged to be relevant for the assessment of circularity of resources. Theoretically, it reflects in more detail possible differences in inaccessibility due to compromising actions. Such a detailed analysis is appropriate for a more tailored detailed (dynamic) substance flow analysis that also might take into account different applications of the resources in products and their typical lifetimes and recycling possibilities. Developing such CFs for use in LCA, for an encompassing group of elements, that due to rapid technological developments will need regular updates, such a detailed analysis is a challenge. Therefore, in this paper, a more simple model is suggested, and flows that lead to inaccessibility due to compromising actions are lumped.

As already stated in Section 3.3, the practical implementation of primary extraction data based on USGS statistics for the calculation of the characterization factors leads to an inconsistency with the theoretical model, since the values do not include the amount of elements that are dissipated due to the dump in tailings.

4.2 LCI model, consistency

In conventional LCA the elementary flows are the flows that cross the system boundary between the environment and the technosphere. The impact category “Resource Inaccessibility on the Short Term” uses mass flows of resources that go into technosphere dissipation. These mass flows do not represent elementary flows in the inventory table but technosphere flows that need to be classified as “dissipative” and extracted from the process-to-process matrix (“A matrix”).

There are several papers that have the LCI of dissipative flows as a topic (Beylot et al. 2020a, b, 2021). In the LCI, the flows that are considered to be dissipated should be classified and quantified. In general, the flows that are classified as dissipative by Beylot et al. (2020b) are flows of elements that end up in tailings and on landfill sites. These flows are in line with the proposed dissipative flows in the characterization model as defined in this paper. Also, low quality recycling of elements in terms of non-functional recycling is still consistent with the LCI modelling as proposed by Beylot et al. (2020b).

4.3 LCI model, data needs, and availability

Although in this paper CFs are presented for resource inaccessibility of elements over the short term, the calculation of the actual weighted resource inaccessibility score ($wRI_{2020,ST}$) still will be challenging.

For the impact category “Resource Inaccessibility,” the technosphere flows that need to be assessed are dissipative flows of elements which are related to the defined functional unit in the LCA study, like elements in tailings and in products abandoned but not (yet) discarded and EoL products dumped on landfill sites or incinerated. As mentioned above other studies have focused on classification of dissipative flows in the technosphere (Beylot et al. 2020a, b, 2021). However, this classification is not yet implemented in existing LCI databases, like Ecoinvent, that are often used for background processes in LCA studies.

Next, although existing LCI databases already include some of the dissipative flows in technosphere, present LCA software packages are generally not able to provide them as aggregate flows going into dissipation (e.g., landfill). Software should therefore be developed to extract these flows from the process-to-process matrix (“A matrix”) and “classify” these technosphere flows to the proper impact category “Technosphere Dissipation”.

Finally, the unit process data in LCI databases should be critically reviewed. In general, the LCI databases (e.g., ecoinvent) are incomplete when reporting the emissions of a unit process and the flows going to landfill. Next to this, for flows of elements, the data on dumped material and product flows should be translated into flows of chemical elements, using elementary composition data of material and products. In other words, what goes into the process seldom matches with what comes out in terms of element, either as emissions or contained in one of the economic flows that leave the process (waste or products), as also stated by other authors, including Greffe et al. (2022) and Beylot et al. (2021).

4.4 Abiotic depletion, long-term dissipation to environment, and short-term resource inaccessibility

Table 3 shows a comparison of different impact categories for resource use co-developed before by some of the authors of this article, i.e., abiotic resource depletion, environmental dissipation long-term perspective and resource inaccessibility short-term perspective. The indicator results represent three different methods, but also three different impact categories, two different problem definitions, two perspectives, etc. To explain this, we drafted Fig. 4 and Table 3. Figure 4 is a depiction of the system models of the three impact categories. Table 3 shows the differences between the three methods related to the levels and steps of the framework. As partly shown by Schulze et al. (Schulze et al. 2020b), Table 3 clearly indicates the different choices that are made for the role of resources, the problem definitions, the basis for impact assessment, etc. between the three impact categories. Basically, the ADP represents another role of the resource than the $EDP_{2020,LT,i}$ and $wRIP_{2020,ST,i}$ (resp. perspective A and B, see Table 3). The difference between $EDP_{2020,LT,i}$ and $wRIP_{2020,ST,i}$ is the time perspective of the defined problem (resp. very long term and short term. Please note that the *wRIP* can be applied to emissions and dissipative flows in the technosphere and can be aggregated into on overall resource inaccessibility score for the short term.

5 Conclusions and recommendations

This paper builds on the previous paper by van Oers et al. (2020) on the impact assessment of resource use in LCA in which the SUPRIM framework (Schulze et al. 2020a, b) was used to define general characterization equations for environmental dissipation, technosphere dissipation and in use occupation. In this paper, adopting the same framework, assumptions, and equations were elaborated for a short-term perspective while in the previous paper they were elaborated for a long-term perspective. The assumption and equations elaborated in this paper were based on the following problem definition for the present use of elements: *the decrease of accessibility on a global level of primary (in the environment) and/or secondary (in technosphere) elements over the short term (ST: 25 years) due to explorations, dissipation to the environment, dissipation in the technosphere and occupation in use.*

In van Oers et al. (2020), it was concluded that at that point only CFs for the long-term dissipation of elements to the environment could be derived. The long-term perspective allowed for simplifications in the model which made the development of operational factors possible. When a short-term time perspective was adopted, it was foreseen that there would be numerous obstacles to populate the characterization equation with appropriate data. Basically, it was argued that to derive CFs for accessibility of elements over the short term, it is necessary to estimate presently accessible stocks in the environment and technosphere within the time horizon, and to estimate global flows of elements that are emitted or go into technosphere dissipation or occupation within the time horizon. Theoretically, this could be achieved by using dynamic SFA modelling taking into account the use of elements in certain applications, the concentration of elements in applications, the lifetime of applications, the emission factors of elements over the different life cycle phases (mining, production, use, waste treatment), the disposal of applications (and the elements contained) to landfill and recycling, etc. These data would be needed on a global scale and in time series for all resources, applications, and processes. This implementation of a short-term approach was considered infeasible at that time.

However, recent developments in the field show that first attempts are made to compile global SFA data and models for an encompassing set of elements (Charpentier Poncelet et al. 2022). The SFA models that are used, assume that the regime of stocks and flows to the future remains the same and thus future developments in application of elements and technological changes in efficiency of processes and recycling, are not covered in the models. Particularly for the mid and long-term future (say > 25 years) this will lead to high uncertainties in the modelling. For the short-term modelling of stocks and flows, another option is to regularly update the compilation of the detailed SFA data and derived models. Needless to say that such an exercise will be a challenge.

In this paper, the challenge is taken up to enable such a short-term approach by demonstrating calculation of global stocks and flows based on simplified procedures and by developing a generic method, to be applied to all elements covered by the method. This is practical and simple but still makes sense, and is sufficiently detailed to discriminate between elements. Many simplifications can be justified by the notion that for the calculation of the CFs the relative flows and stocks, and not their absolute values, are of importance. The following simplifications are made for the development of CF:

- Use of present flows to dissipation, instead of cumulative flows over 25 years
- Use of present extraction as a proxy for flows going into dissipation and occupation
- Use of present stocks in the environment and the technosphere, instead of stocks at $t_0 + 25$ years
- Estimation of stocks in the technosphere based on past extractions over a period of 50 years
- Estimation of the fraction, which is accessible, based on a generic[11] recycling rate[12] per element
- The EU economic importance indicator as a proxy for the global valuation of the function of elements.

Using these simplifications, we were able to demonstrate elaboration of an operational set of CFs, $wRIP_{t0,ST,i}$, for the impact category weighted resource inaccessibility over the short term using the SUPRIM framework.

This further illustrates the value of the SUPRIM framework characterization for deriving CFs in a way that remains consistent with the problem definition, system model, and LCI. For the population of the parameters in the equation, estimates are used based on rough simplifications. However, it is believed that this initial set of factors already is useful to compare with other proposed CFs for resource use (Sala 2020; Charpentier Poncelet et al. 2021, 2022; Ardente et al. 2022). In time, the simplifications described above could,

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[11] Generic means that the same RR is assumed over the past period and no difference is made in types of applications.

[12] Assuming that (1-RR) is the fraction that will be dissipated and thus the remainder is the (maximum) potential accessible fraction.

Table 3 Abiotic depletion, long-term environmental dissipation, and short-term technosphere dissipation of elements

Impact category	Abiotic depletion of elements (van Oers et al. 2019)	Environmental dissipation of elements long term (van Oers et al. 2020)	Resource inaccessibility of elements short term (this paper)
Role of the resource	Abiotic resources are valued by humans for their functions used (by humans) in the technosphere, taking into account primary production only The so-called type A perspective in Schulze et al. (2020a)	Abiotic resources are valued by humans for their functions used (by humans) in the technosphere, taking into account both primary and secondary production The so-called type B perspective in Schulze et al. (Schulze et al. 2020a)	
Problem definition	The potential decrease of accessibility on a global level of primary (in the environment) elements on a long term due to the extraction of elements from the environment	The potential decrease of accessibility on a global level of primary (in the environment) and/or secondary (in technosphere) elements on a *very long term* (VLT) due to the emission of elements (environmental dissipation)	The potential decrease of accessibility on a global level of primary (in the environment) and/or secondary (in technosphere) elements on a *short term* (ST) due to emission to the environment and dissipation in the technosphere
Basis of impact assessment	The LT accessible stock in the environment, i.e., crustal content, and the cumulative global extraction of resource i from this stock up until the present year	The LT accessible stock in the environment and technosphere, i.e., crustal content, and the cumulative (= successive) global emissions of resource i within the time horizon adopted due to the present use of resource i	The ST, i.e., present, accessible stock in the environment and technosphere and the present[a] global flows going to inaccessible stocks of resource i within the time horizon adopted due to the present use of resource i
Characterization model equation	$ADP_i = \frac{M_i / R^2_{i,tot,t+T}}{M_{ref} / R^2_{ref,tot,t+T}}$	$EDP_{t_0,T,i} = \frac{E_{t_0,T,i} / R^2_{i,tot,t_0+T}}{E_{t_0,T,ref} / R^2_{ref,tot,t_0+T}}$	$RIP_{t_0,T,i} = \frac{I_{t_0,T,i} / R^2_{i,tot,t_0+T}}{I_{t_0,T,ref} / R^2_{ref,tot,t_0+T}}$
Proxy	$ADP_{i,cum} = \frac{M_{i,cum} / R^2_{i,ult}}{M_{ref,cum} / R^2_{ref,ult}}$	$EDP_{2020,VLT,i} \approx \frac{M_{2020,i} / R^2_{i,ult}}{M_{2020,ref} / R^2_{ref,ult}} \propto ADP_{i,2020}$	$RIP_{2020,ST,i} \approx \frac{M_{2020,i} / \left(R_{env,2020,i} + R_{tech,2020,i}\right)^2}{M_{2020,ref} / \left(R_{env,2020,i} + R_{tech,2020,i}\right)^2}$
Proxy for flows to inaccessible stocks		Cumulative emissions of present use over T = infinite is equal to present primary extraction $E_{2020,\infty,i} \approx M_{2020,i}$	All consumed resources which are not recycled are considered a flow to inaccessible stock, either dissipated or occupied $I_{2020,i} \approx \left(M_{2020,i} + sM_{2020,i}\right) \times \left(1 - RR_{2020,i}\right) \approx M_{2020,i}$
Proxy for accessible reserve		Crustal content is proxy for accessible stock in environment and technosphere for T = infinite	Present reserve estimates of USGS are used as a proxy for reserves in the environment at T = 25 years Accessible reserves in the technosphere are based on cumulative past extractions over 50 years and a recycling rate (RC), assumed constant over this period
Weighting between elements	Equal weighting	Equal weighting	Based on economic importance indicator (EI)
Impact score equation	$AD = \sum_i ADP_{i,cumulative} \times m_i$	$ED_{2020,\mathrm{VLT}} = \sum_i EDP_{2020,i} \times e_i$	$wRI_{2020,\mathrm{ST}} = \sum_i wRIP_{2020,i} \times ri_i$
(Elementary) flow to be assessed	Extraction (m_i)	Emission (e_i)	Flows of resource to inaccessible stock (ri_i); either emission (e_i), hibernation (h_i)

Hibernation = technosphere dissipation

[a] Theoretically it should be the cumulative (= successive) global flows going into dissipation. A snapshot of the present flow is used as a proxy. This is believed to be appropriate, because for the calculation of the characterization factors the relative differences between resources going into dissipation are of importance

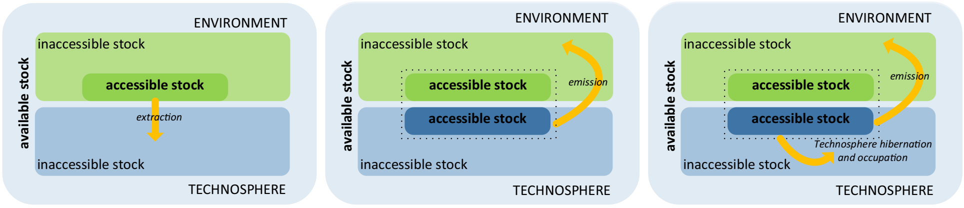

Fig. 4 System model for abiotic depletion and environmental dissipation and resource inaccessibility of elements

System model for abiotic depletion of elements

System model for environmental dissipation of elements

System model for inaccessibility of elements short term

and probably should, be replaced with more sophisticated and detailed modelling.

For this purpose, the work of Charpentier Poncelet et al. (2019, 2021, 2022) might be a promising source for further development of the dissipation model for the short-term time perspective. However, when implementing some of the considerations made by Charpentier Poncelet, there will be (at least) two major differences:

(a) The characterization model of Charpentier Poncelet does not take into account the size of the stock when assessing the severeness of dissipation. In contrast, the characterization model of this paper is a function of the amount of dissipative flows and the size of the accessible stocks (in environment and technosphere) (Eq. 3).

(b) The dynamic SFA model as suggested by Charpentier Poncelet is based on the present situation of the market and the technologies. Therefore, it might be considered valid for the short-term time perspective, say 25 years. However, for estimates of stocks and flows on the long term, the model is for this reason less appropriate.

Additionally, (a) the characterization model of Charpentier Poncelet only focuses on the dissipative flows and does not take into account the size of the accessible stocks. In other words, the reduced accessibility of elements due to dissipative losses is independent of the estimated size of the accessible stocks. That means that the severeness of the dissipation is assumed to be the same between elements that have large respectively small accessible stocks. In contrast, the characterization model we suggest in this paper also does include the size of the estimated accessible stocks (in environment and technosphere), next to the global rate of dissipative flows.

Additionally, (b) in this paper, Eq. 3 is made operational using many simplifications and additional assumptions (see bullets above). However, recent developments in SFA studies of elements on a global level look promising as a starting point to populate the equation with more sophisticated data. Charpentier Poncelet has calculated cumulative losses from present extractions of resources over the lifetime of the resource based on global SFA models of 61 elements. The transfer coefficients used in the model are based on the present market of applications of the elements and the present technology in the different LC stages of the element. Therefore, we believe that the model might be considered appropriate for the short term, say 25 years. However, results will become (far) less valid, for the longer term, when share of applications, lifetime of applications, efficiencies of processes (dissipative flows factors), and recycling percentages of waste will develop over time.

All in all, some of the work by Charpentier Poncelet might be promising to develop more sophisticated CFs, using less simplifications in the presented characterization model. Probably, different ways of combining the work is possible. One option is to use some of the intermediate results of the work by Charpentier Poncelet:

- Assume a 25-year time horizon, because the SFA model is mainly valid for the short term only.
- Use the data of the curves of estimated in-use stocks and losses of metals over time for a yearly cohort of extracted metals, to populate the variables I and R in Eq. 3:

  1. Use cumulative losses until 25 years from the date of extraction for variable I_(2020,25,i)
  2. Use the information of the curves of remaining stock in time for calculations of the stock in the technosphere, based on the historic (past 100 years) extraction of the elements.

Another possible improvement option addresses the weighting of functions elements have for society. Ideally, weighting factors across elements should be based on global economic importance indicators instead of EU economic importance indicators. To do this economic importance indicators that are used in criticality studies for different regions in the world (like EU, the USA, Japan, and such) must be aligned and combined into a global set of values that express the appreciation of the functions of elements for present economies on a global scale.

This paper presents a simplified LCIA method for resource use in LCA for the short-term time perspective. In practice, a complete calculation of indicator results for the $wRI_{2020,ST}$ also needs to classify and quantify the flows which are considered to be dissipative in the LCI., i.e., both in the inventory data of a specific LCA study (e.g., its foreground system) and in the background system, which is often based on LCI databases, such as ecoinvent. Much work can still be done to implement this concept in the available LCI databases of unit processes (Beylot et al. 2020a, b, 2021), and the SUPRIM framework helps ensure that future work addresses defined problems in internally consistent ways.

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Declarations

Competing interests The authors declare no competing interests.

References

Ardente F, Beylot A, Zampori L (2022) A price-based life cycle impact assessment method to quantify the reduced accessibility to mineral resources value. Int J Life Cycle Assess 28:95–109. https://doi.org/10.1007/s11367-022-02102-4

Berger M, Sonderegger T, Alvarenga R et al (2020) Mineral resources in life cycle impact assessment: part II – recommendations on application-dependent use of existing methods and on future method development needs. Int J Life Cycle Assess 25:798–813. https://doi.org/10.1007/s11367-020-01737-5

Beylot A, Ardente F, Sala S, Zampori L (2020a) Accounting for the dissipation of abiotic resources in LCA: status, key challenges and potential way forward. Resour Conserv Recycl. https://doi.org/10.1016/j.resconrec.2020.104748

Beylot A, Ardente F, Marques A et al (2020b) Abiotic and biotic resources impact categories in LCA: development of new approaches. Publications Office of the European Union, Luxembourg, 2020. https://data.europa.eu/doi/10.2760/232839. ISBN 978-92-76-17227-7

Beylot A, Ardente F, Sala S, Zampori L (2021) Mineral resource dissipation in life cycle inventories. Int J Life Cycle Assess 26:497–510. https://doi.org/10.1007/s11367-021-01875-4

Blengini GA, Nuss P, Dewulf J et al (2017a) EU methodology for critical raw materials assessment: policy needs and proposed solutions for incremental improvements. Resour Policy 53:12–19. https://doi.org/10.1016/j.resourpol.2017.05.008

Blengini G, Blagoeva D, Dewulf J et al (2017b) Assessment of the Methodology for Establishing the EU List of Critical Raw Materials. Publications Office of the European Union, Luxemburg, 2017. https://data.europa.eu/doi/10.2760/73303. ISBN 978-92-79-69612-1

British Geological Survey (2018) World mineral statistics data. http://www.bgs.ac.uk/mineralsuk/statistics/wms.cfc?method=searchWMS. Accessed 15 Nov 2018

CharpentierPoncelet A, Loubet P, Laratte B et al (2019) A necessary step forward for proper non-energetic abiotic resource use consideration in life cycle assessment: the functional dissipation approach using dynamic material flow analysis data. Resour Conserv Recycl 151:104449. https://doi.org/10.1016/j.resconrec.2019.104449

CharpentierPoncelet A, Helbig C, Loubet P et al (2021) Life cycle impact assessment methods for estimating the impacts of dissipative flows of metals. J Ind Ecol 25:1177–1193. https://doi.org/10.1111/jiec.13136

CharpentierPoncelet A, Helbig C, Loubet P et al (2022) Losses and lifetimes of metals in the economy. Nat Sustain 5:717–726. https://doi.org/10.1038/s41893-022-00895-8

Cimprich A, Bach V, Helbig C et al (2019) Raw material criticality assessment as a complement to environmental life cycle assessment: examining methods for product-level supply risk assessment. J Ind Ecol 23:1226–1236. https://doi.org/10.1111/jiec.12865

Crowson PCF (2011) Mineral reserves and future minerals availability. Miner Econ 24:1–6. https://doi.org/10.1007/s13563-011-0002-9

Deetman S, Marinova S, van der Voet E et al (2020) Modelling global material stocks and flows for residential and service sector buildings towards 2050. J Clean Prod 245:118658. https://doi.org/10.1016/j.jclepro.2019.118658

Dewulf J, Benini L, Mancini L et al (2015) Rethinking the area of protection "natural resources" in life cycle assessment. Environ Sci Technol 49:5310–5317. https://doi.org/10.1021/acs.est.5b00734

Dewulf J, Hellweg S, Pfister S et al (2021) Towards sustainable resource management: identification and quantification of human actions that compromise the accessibility of metal resources. Resour Conserv Recycl 167:105403. https://doi.org/10.1016/j.resconrec.2021.105403

Drielsma JA, Russell-Vaccari AJ, Drnek T et al (2016) Mineral resources in life cycle impact assessment—defining the path forward. Int J Life Cycle Assess 21:85–105. https://doi.org/10.1007/s11367-015-0991-7

Eynard U, Georgitzikis K, Wittmer D et al (2020) Study on the EU's list of critical raw materials (2020) non-critical raw materials factsheets (final). Publications Office of the European Union, Luxemburg, 2020. https://data.europa.eu/doi/10.2873/11619. ISBN 978-92-76-21049-8

Frischknecht R (2016) Impact assessment of abiotic resources: the role of borrowing and dissipative resource use. EcoBalance 2016 - Abstract Book. https://doi.org/10.13140/RG.2.2.10182.16962

Graedel TE (2010) Metal stocks in society: scientific synthesis. A Report of the Working Group on the Global Metal Flows to the International Resource Panel. https://wedocs.unep.org/20.500.11822/8438. ISBN 978-92-807-3082-1

Graedel TE, Allwood J, Birat J-P et al (2011) Recycling rates of metals : a status report. A Report of the Working Group on the Global Metal Flows to the International Resource Panel. https://wedocs.unep.org/20.500.11822/8702. ISBN 978-92-807-3161-3

Graedel TE, Barr R, Chandler C et al (2012) Methodology of metal criticality determination. Environ Sci Technol 46:1063–1070. https://doi.org/10.1021/es203534z

Greffe T, Margni M, Bulle C (2022) An instrumental value-based framework for assessing the damages of abiotic resources use in life cycle assessment. Int J Life Cycle Assess 28:1–17. https://doi.org/10.1007/s11367-022-02107-z

Guinée JB, Heijungs R (1995) A proposal for the definition of resource equivalency factors for use in product life-cycle assessment. Abstr Environ Toxicol Chem 14(5):917–925. https://doi.org/10.1002/etc.5620140525

Helbig C (2018) Metalle im Spannungsfeld technoökonomischen Handelns: Eine Bewertung der Versorgungsrisiken und der dissipativen Verluste mit Methoden der Industrial Ecology. Dissertation, University of Augsburg. https://opus.bibliothek.uni-augsburg.de/opus4/frontdoor/deliver/index/docId/47832/file/DissertationHelbig.pdf

Helbig C, Thorenz A, Tuma A (2020) Quantitative assessment of dissipative losses of 18 metals. Resour Conserv Recycl. https://doi.org/10.1016/j.resconrec.2019.104537

Humphreys D (2013) Long-run availability of mineral commodities. Miner Econ 26:1–11. https://doi.org/10.1007/s13563-013-0033-5

Huppes G, van Oers L, Pretato U, Pennington DW (2012) Weighting environmental effects: analytic survey with operational evaluation methods and a meta-method. Int J Life Cycle Assess. https://doi.org/10.1007/s11367-012-0415-x

JRC (2017) Methodology for establishing the EU list of critical raw materials, Guidelines, Publications Office of the European Union, Luxembourg. https://doi.org/10.2873/769526-ET-01-17-370-EN-N. ISBN 978–92–79–68051–9

Klinglmair M, Sala S, Brandão M (2014) Assessing resource depletion in LCA: a review of methods and methodological issues. Int J Life Cycle Assess 19:580–592. https://doi.org/10.1007/s11367-013-0650-9

Lai F, Beylot A (2022) Loss of mineral resource value in LCA: application of the JRC-LCI method to multiple case studies combined with inaccessibility and value-based impact assessment. Int J Life Cycle Assess 28:38–52. https://doi.org/10.1007/s11367-022-02110-4

Latunussa C, Georgitzikis K, Torres de Matos C et al (2020) European commission, study on the EU's list of critical raw materials (2020), factsheets on critical raw materials. Publications Office of the European Union, Luxembourg. https://doi.org/10.2873/631546. ISBN 978-92-76-21053-5

Liao W, Heijungs R, Huppes G (2012) Thermodynamic resource indicators in LCA: a case study on the titania produced in Panzhihua city, southwest China. Int J Life Cycle Assess 17:951–961. https://doi.org/10.1007/s11367-012-0429-4

Marinova S, Deetman S, van der Voet E, Daioglou V (2020) Global construction materials database and stock analysis of residential buildings between 1970–2050. J Clean Prod 247:119146. https://doi.org/10.1016/j.jclepro.2019.119146

Owsianiak M, van Oers L, Drielsma J et al (2022) Identification of dissipative emissions for improved assessment of metal resources in life cycle assessment. J Ind Ecol 26:406–420. https://doi.org/10.1111/jiec.13209

Rørbech JT, Vadenbo C, Hellweg S, Astrup TF (2014) Impact assessment of abiotic resources in LCA: quantitative comparison of selected characterization models. Environ Sci Technol 48:11072–11081. https://doi.org/10.1021/es5023976

Sala S (2020). Abiotic and Biotic Resources Impact Categories in LCA: Development of New Approaches Accounting for Abiotic Resources Dissipation and Biotic Resources. https://doi.org/10.2760/232839

Santillán-Saldivar J, Beylot A, Cor E et al (2023) Economic value dissipation potential (EVDP): an improved method to estimate the potential economic value loss due to resource dissipation in life cycle assessment. Int J Life Cycle Assess 28:1400–1418. https://doi.org/10.1007/s11367-023-02204-7

Schrijvers D, Hool A, Blengini GA et al (2020) A review of methods and data to determine raw material criticality. Resour Conserv Recycl 155:104617. https://doi.org/10.1016/j.resconrec.2019.104617

Schulze R, Guinée J, van Oers L et al (2020a) Abiotic resource use in life cycle impact assessment—Part I- towards a common perspective. Resour Conserv Recycl 154:104596. https://doi.org/10.1016/j.resconrec.2019.104596

Schulze R, Guinée J, van Oers L et al (2020b) Abiotic resource use in life cycle impact assessment—part II – linking perspectives and modelling concepts. Resour Conserv Recycl 155:104595. https://doi.org/10.1016/j.resconrec.2019.104595

Sonderegger T, Dewulf J, Fantke P et al (2017) Towards harmonizing natural resources as an area of protection in life cycle impact assessment. Int J Life Cycle Assess 22:1912–1927. https://doi.org/10.1007/s11367-017-1297-8

Sonderegger T, Berger M, Alvarenga R et al (2020) Mineral resources in life cycle impact assessment—part I: a critical review of existing methods. Int J Life Cycle Assess 25:784–797. https://doi.org/10.1007/s11367-020-01736-6

Talens Peiró L, Nuss P, Andrea G et al (2018) Towards Recycling Indicators based on EU flows and Raw Materials System Analysis data, Publications Office of the European Union, Luxembourg, 2018. https://doi.org/10.2760/092885. ISBN 978-92-79-97247-8

US Geological Survey (1980) Principles of a resource/reserve classification for minerals, Geological Survey circular 831, Principles of the mineral resource classification system of the U.S. Bureau of Mines and U.S. Geological Survey. https://pubs.usgs.gov/circ/1980/0831/report.pdf

US Geological Survey (2018) Historical Statistics for Mineral and Material Commodities in the United States. https://minerals.usgs.gov/minerals/pubs/historical-statistics/. Accessed 15 Nov 2018

US Geological Survey (2022) Mineral commodity summaries 2022: U.S. Geological Survey, 202 p. https://doi.org/10.3133/mcs2022. ISBN 978-1-4113-4434-1

Vadenbo C, Rørbech J, Haupt M, Frischknecht R (2014) Abiotic resources: new impact assessment approaches in view of resource efficiency and resource criticality—55th Discussion Forum on Life Cycle Assessment, Zurich, Switzerland, April 11, 2014. Int J Life Cycle Assess 19:1686–1692. https://doi.org/10.1007/s11367-014-0784-4

van Oers L, Guinée JB, Heijungs R (2019) Abiotic resource depletion potentials (ADPs) for elements revisited—updating ultimate reserve estimates and introducing time series for production data. Int J Life Cycle Assess. https://doi.org/10.1007/s11367-019-01683-x

van Oers L, Guinée JB, Heijungs R et al (2020) Top-down characterization of resource use in LCA: from problem definition of resource use to operational characterization factors for dissipation of elements to the environment. Int J Life Cycle Assess 25:2255–2273. https://doi.org/10.1007/s11367-020-01819-4

van Oorschot J, Sprecher B, Roelofs B et al (2022) Towards a low-carbon and circular economy: Scenarios for metal stocks and flows in the Dutch electricity system. Resour Conserv Recycl 178:106105. https://doi.org/10.1016/j.resconrec.2021.106105

Wolf MA, Kupfer T, Wolf K (2022) Evaluation of element and material resource impact assessment methods, Version 2 of 20 April 2022, maki Consulting & TH Bingen, under the project for the European Commission, DG Environment "Technical support during the transition phase of Environmental Footprint" (Contract ENV.B.1/SER/2017/0004 and Contract amendment 070203/2017/762537/SER/ENV.B.1)

Yaksic A, Tilton JE (2009) Using the cumulative availability curve to assess the threat of mineral depletion: the case of lithium. Resour Policy 34:185–194. https://doi.org/10.1016/j.resourpol.2009.05.002

Zampori L, Sala S (2017) Feasibility study to implement resource dissipation in LCA. EUR28994 EN, Publications Office of the European Union, Luxembourg. https://doi.org/10.2760/869503. JRC109396. ISBN 978-92-79-77238-2

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