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Oers, L.F.C.M. van; Guinee, J.B.; Heijungs, R.; Schulze, R.K.; Alvarenga, R.A.F.; Dewulf, J.; ... ; Torres, J.M.E.

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NON-TOXIC IMPACT CATEGORIES ASSOCIATED WITH EMMISIONS TO AIR, WATER, SOILORIGINAL PAPER

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

Lauran van Oers[1] · **Jeroen B. Guinée**[1] · **Reinout Heijungs**[1,2] · **Rita Schulze**[1] · **Rodrigo A. F. Alvarenga**[3] · **Jo Dewulf**[3] · **Johannes Drielsma**[4] · **David Sanjuan-Delmás**[3] · **Tobias C. Kampmann**[5] · **Glenn Bark**[5] · **Ainara Garcia Uriarte**[6] · **Pierre Menger**[6] · **Mats Lindblom**[7] · **Lucas Alcon**[8] · **Manuel Sevilla Ramos**[8] · **Juan Manuel Escobar Torres**[8]

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Abstract

Purpose The methods for assessing the impact of using abiotic resources in life cycle assessment (LCA) have always been heavily debated. One of the main reasons for this is the lack of a common understanding of the problem related to resource use. This article reports the results of an effort to reach such common understanding between different stakeholder groups and the LCA community. For this, a top-down approach was applied.

Methods To guide the process, a four-level top-down framework was used to (1) demarcate the problem that needs to be assessed, (2) translate this into a modeling concept, (3) derive mathematical equations and fill these with data necessary to calculate the characterization factors, and (4) align the system boundaries and assumptions that are made in the life cycle impact assessment (LCIA) model and the life cycle inventory (LCI) model.

Results We started from the following *definition of the problem* of using resources: the decrease of accessibility on a global level of primary and/or secondary elements over the very long term or short term due to the *net* result of compromising actions. The *system model* distinguishes accessible and inaccessible stocks in both the environment and the technosphere. Human actions can compromise the accessible stock through environmental dissipation, technosphere hibernation, and occupation in use or through exploration. As a *basis for impact assessment*, we propose two parameters: the global change in accessible stock as a net result of the compromising actions and the global amount of the accessible stock. We propose three impact categories for the use of elements: environmental dissipation, technosphere hibernation, and occupation in use, with associated characterization equations for two different time horizons. Finally, preliminary characterization factors are derived and applied in a simple illustrative case study for environmental dissipation.

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✉ Lauran van Oers
oers@cml.leidenuniv.nl

1 Institute of Environmental Sciences (CML), Leiden University, Einsteinweg 2, Leiden 2333 CC, The Netherlands

2 Department of Econometrics and OR, Vrije Universiteit, De Boelelaan 1105, 1081 HV Amsterdam, The Netherlands

3 Faculty of Bioscience Engineering, Department of Green Chemistry and Technology, Sustainable Systems Engineering Group (STEN), Ghent University, Coupure Links 653, Blok B – 5th floor, Ghent, Belgium

4 European Association of Mining Industries, Metal Ores and Industrial Minerals (Euromines), Avenue de Tervueren, 168, box 15, 1150 Brussels, Belgium

5 Department of Civil, Environmental and Natural Resources Engineering, Luleå University of Technology, SE-971 87 Lulea, Sweden

6 Tecnalia Research & Innovation, C/Geldo, Edificio 700 (Parque Tecnológico de Bizkaia), 48160 Derio, Bizkaia, Spain

7 Boliden Mineral AB, Kontorsvägen 1, SE-936 81 Boliden, Sweden

8 Cobre las Cruces, S.A., Carretera SE-3410 – Km. 4,100, 418 60 Sevilla, Gerena, Spain

Conclusions Due to data constraints, at this moment, only characterization factors for "dissipation to the environment" over a very-long-term time horizon could be elaborated. The case study shows that the calculation of impact scores might be hampered by insufficient LCI data. Most presently available LCI databases are far from complete in registering the flows necessary to assess the impacts on the accessibility of elements. While applying the framework, various choices are made that could plausibly be made differently. We invite our peers to also use this top-down framework when challenging our choices and elaborate that into a consistent set of choices and assumptions when developing LCIA methods.

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

1 Introduction

Since the early development of life cycle assessment (LCA), the use of abiotic resources as one of the impact categories for the life cycle impact assessment has been heavily debated. Natural (or primary) resources are defined as an area of protection by the SETAC WIA (Society of Environmental Toxicology and Chemistry Working Group on Life Cycle Impact Assessment) (Udo de Haes et al. 1999) and are part of the life cycle impact midpoint-damage framework developed by the UNEP (United Nations Environment Program)/SETAC life cycle initiative (Jolliet et al. 2004). Existing methods have been criticized by the scientific community itself and by (mining) industry representatives, while new methods keep being added to the already existing ones.

There are several reasons for the arisen situation: (1) it is debatable whether or not the effects of the use of resources should be taken into account in a life cycle impact assessment, since it mostly refers to an economic instead of an environmental problem; (2) the use of abiotic resources is a problem crossing the economy–environment system boundary, since potential accessible stocks of resources depend on future technologies for extracting them (Guinée and Heijungs 1995); (3) there are different ways to define the problem of resource use, and all can be justified from different perspectives (Giurco et al. 2014; Dewulf et al. 2015; Drielsma et al. 2016, b; Oers and Guinée 2016; Ali et al. 2017; Sonderegger et al. 2017; Schulze and Guinée 2018; Schulze et al. 2020a); and (4) there are different ways of quantifying the problem arising from the use of resources and none of them can be empirically verified, since they all depend on the assumed availability of, and demand for, resources in the future and on future technologies. So, as a consequence, there is no "scientifically" correct method (Guinée and Heijungs 1995), though some modeling assumptions can be more supported by available evidence than others. Recently, harmonization efforts have been undertaken by the UNEP-SETAC Task Force on natural resources (Sonderegger et al. 2017, 2020; Berger et al. 2020). This work has shown that the debate on how to assess abiotic resource use in life cycle impact assessment (LCIA) has partly been a result of modelers simply adopting different views on what the problem of resource use and the related impact mechanism actually are.

The lack of common understanding of the problem related to resource use was the starting point of the SUPRIM project[1]. The aim of SUPRIM was to obtain an understanding of different stakeholders' views and concerns regarding the use of resources and to use derived insights for the development of one or several LCIA methods properly and consistently reflecting these concerns (Schulze et al. 2020b).

For this purpose, a multilevel framework was created to guide the process and to structure discussions (Fig. 1). In Schulze et al. (2020b), this framework is presented and a consensus process is described addressing the first steps of the first level of the framework—"perspective on resources"—structuring the different views on sustainability and resources and finding, where possible, common ground between stakeholder groups (Gorman and Dzombak 2018; Alvarenga et al. 2019). A central outcome of the consensus process was a clear definition of the so-called role of resources (step 1.1 in Fig. 1). In Schulze et al. (2020b), this role was further demarcated by a goal and scope definition (step 1.2 in Fig. 1)

The objective of this article is to further apply the top-down framework suggested by Schulze et al. (2020b). We describe the possible choices and assumptions for each next level and step of the framework to eventually propose three impact categories and develop a new characterization method for one of the proposed impact categories. We start from a more detailed elaboration of step 3 in level 1 (see Fig. 1). Below, we will first briefly introduce the top-down framework and concisely summarize the results for the first two steps of level 1 as reported by Schulze et al. (2020b). In the Section 3, we then present and discuss the third step of level 1, "problem definition," and then two steps ("system model" and "basis of impact assessment") of the second level—"modeling concepts" that are consistent with the "role of the resources" as defined in Schulze et al. (2020b). Next, we elaborate all steps of the third level of the framework, "practical implementation," and we describe the fourth level, i.e., the required life cycle inventory—'LCI data." Finally, we discuss our approach and findings, draw conclusions, and define recommendations for further research.

[1] http://suprim.eitrawmaterials.eu/about-project

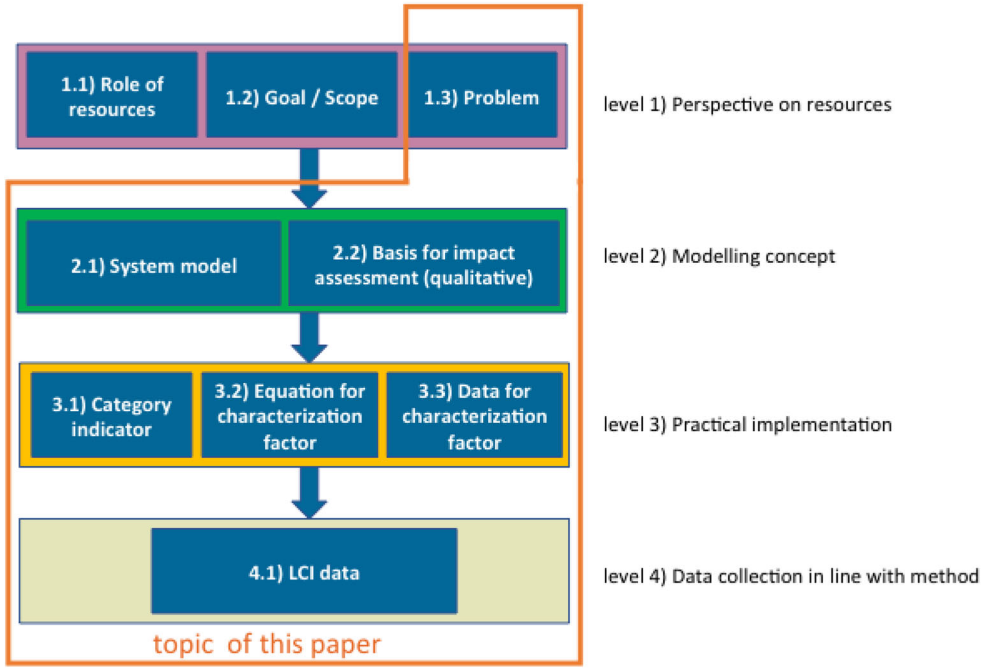

Fig. 1 Framework for the development of LCIA methods (Schulze et al. 2020b). The results in this article refer to levels 1 and 2

2 Top-down approach—the framework

To ensure a transparent and consistent development of impact assessment methods for resource use, a framework was set up (Fig. 1). Progression through the levels in the framework represents a top-down approach. It consists of (1) an overarching perspective, (2) a conceptual level ("Modeling Concept"), and (3) a practical implementation level. 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. Note that the perspective level of the framework covers the whole discussion on the Area of Protection "natural resources" (see Berger et al. 2020). Also note that each level of the framework consists of several steps. For further details on this framework, we refer to Schulze et al. (2020b).

In the same publication by Schulze et al. (2020b), the first two steps of level 1 of the framework were elaborated: "Role of resources" and "Goal and scope." The "role" of resources explains what should be protected and the motivation behind protecting it. The stakeholders participating in the consensus process as described in Schulze et al. (2020b) concluded that the so-called type B perspective best summarized their view on the role of abiotic resources:

Abiotic resources are valued by humans for their functions used (by humans) in the technosphere. Resources may originate from both primary and secondary production.

The "goal and scope" further specify the "role of resources." For example, the goal could focus on ensuring accessibility or ensuring availability of resources in nature and technosphere, where availability concerns the physical presence of a resource and accessibility concerns the ability to make use of a resource. The goal is next defined in the scope, which comprises a time perspective, a geographical perspective, and the types of resources covered by the assessment (e.g., elements and/or configurations, e.g., natural minerals). Also here, we adopt the result from Schulze et al. (2020b), who concluded on four agreed combinations of goal (accessibility or availability), temporal scope of the impact assessment (5, 25 or > 100 years), geographical scope of the impact assessment (country, continent, world), and scope of resources (elements, configurations, or both) (see Table 1).

For further elaboration, two time perspectives were chosen, the very long term (e.g., somewhere between 100 years and

Table 1 Combinations of goal and scope choices within type B perspective

Perspective	Goal: availability/ accessibility	Resource scope: elements, configurations, or both	Geographical scope: country, continent, or global scale	Temporal scope
B1	Accessibility	Elements	Global	VLT
B2	Accessibility	Configurations	Global	VLT
B3	Accessibility	Elements	Global	25 years
B4	Accessibility	Configurations	Global	25 years

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." In Schulze et al. (2020b), the time frames were defined more broadly and with ranges, i.e., long-term 100 years to infinity and short-term 0–25 years. However, when elaborating perspectives into more concrete models, it is necessary to define a more specific time horizon for the short term (i.e., 25 years) and a more abstract, qualitatively described, time horizon for the very long term.

A concrete time horizon for short-term estimates is necessary to allow for some type of modeling based on extrapolation of proven developments in the past. Instead, for the very long term, in the "Impact category indicator and general equation" section, we have defined a qualitatively described future, i.e., assuming some conditions for technological and economic developments necessary to be able to simplify the modeling. Only in this way has it so far been possible to derive an operational set of characterization factors. We don't predict when the envisaged scenario will happen (100 years, 1000 years, or even more), but to pragmatically achieve our purpose of assessing relative differences in impacts of resource use, we assume that it will happen at some point in the far future.

The initial intention was to further elaborate all of these four type B perspectives. However, due to project-related constraints, further discussions and elaborations were limited to elements (perspectives B1 and B3).

3 Results

3.1 Level 1: perspectives on resources and definitions—step 3, problem definition

The final step of level 1 of the framework—the "Problem definition"—was not yet fully elaborated in Schulze et al. (2020b) and is the starting point of our further work here. Definitions of the role, goal, and scope finally led to the following definition of the problem with the *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 very long term (VLT) or short term (ST: 25 years) due to the net result of compromising actions (see below).

Figure 2 shows the result of the first level of the framework on the role of resources, the demarcation of the goal and scope, and the final problem definition. Now what are compromising actions and what do we mean with future impacts on accessibility due to those actions?

3.1.1 Compromising actions

Elements are the basic building blocks of all chemical substances, both synthetic and natural. Elements by definition cannot be transformed except by nuclear fission or decay. As a consequence when elements are extracted from the environmental system, they are introduced into the technosphere system and thus not necessarily lost for future generations (van Oers et al. 2002; Schneider et al. 2011, 2015; Frischknecht 2014; Vadenbo et al. 2014; Oers and Guinée 2016).

Starting from the use of natural and/or secondary resources as a result of the LCI phase and starting point of the impact assessment and the problem identified above, the aim was to assess this use in terms of how it compromises the accessibility of that resource. For this, compromising actions were defined as human-induced actions related to the use of resources resulting in an increase or decrease of accessibility of resources for future generations. The change in accessibility of a resource is quantified as the flow which is the net result of the sum of all compromising actions that increase or decrease the total of the accessible stock. The following compromising actions were distinguished for elements:

a) *Exploration* and feasibility studies continually update the balance between accessible and inaccessible stocks (or funds) within the environment. Exploration activity may, in theory, result in reduced accessible stocks in the environment (if, in times of excess supply capacity and low demand/prices, downward re-evaluation of reserves were to exceed new discoveries) or in increased accessible stocks in the environment (in times of insufficient supply capacity and high demand/prices, upward re-evaluation of reserves and new discoveries both serve to increase the stock). Whereas exploration refers to estimating natural stocks, an analogous activity in urban mining, sometimes referred to as "prospecting for secondary raw materials," explores stocks in the technosphere.
b) *Environmental dissipation* is the quantified flow from an accessible stock that is emitted to the environment within the time horizon considered. Dissipative flows of resources are flows to sinks or stocks that are less concentrated and more spatially spread (dispersion). It is, of course, crucial at which level of concentration and dispersion an element in a stock is considered not accessible anymore and how to determine this level. In this article, elements emitted to the environment are assumed to be ultimately inaccessible, i.e., on the very long time horizon (van Oers et al. 2002; Oers and Guinée 2016; Helbig 2018).

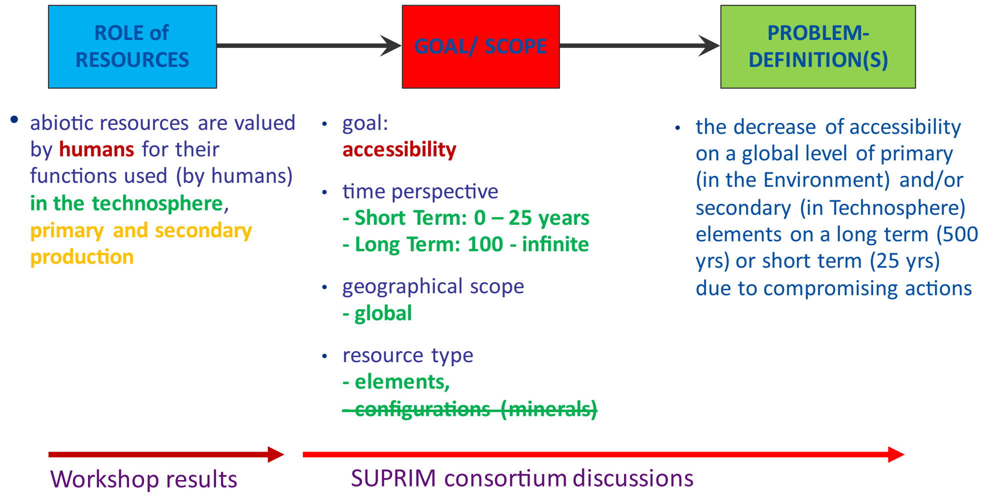

Fig. 2 The common understanding of the role of resources and the problems the use might impose. The result of the first level of the framework "perspective on resources" (adapted from Schulze et al. (2020b))

c} *Technosphere hibernation*: Hibernation and dissipation in the technosphere describe a decreased accessibility of resources due to a hampered recyclability, for any reason (Frischknecht 2014; Vadenbo et al. 2014; Zampori and Sala 2017; Helbig 2018; Charpentier Poncelet et al. 2019). Hibernation is the quantified flow from a resource that ends up in stocks in the technosphere that are not actually used anymore but are also not recovered because of the lack of economic drivers for this *within the time horizon considered* (e.g., unused cables and pipes in the ground, cell phones on attics, remote sunken ships). However, materials in a metal scrap yard are accessible stocks, because apparently there is sufficient economic incentive to collect the scrap for recycling. Dissipation in the technosphere is the quantified flow of a resource that ends up in technosphere stock in such a low concentration or chemically/physically bound (e.g., metals in alloys) in such a way that the resource cannot technically/economically be recovered from that stock for new applications *within the time horizon considered*. Resources dissipated to the technosphere are assumed to be not recoverable and are thus considered inaccessible, *for the time horizon considered*. It is, of course, crucial at which level of concentration you consider an element in a stock not accessible anymore and how to determine this level. The boundary between hibernation and dissipation in the technosphere is arbitrary as it depends on one's definition of "use." In the following sections, both compromising actions will be discussed together as technosphere hibernation. Recyclability is dependent on technical and economic conditions. Since in the future these conditions will develop, what is not recyclable today or in the short term might be recyclable when a very-long-term time horizon is considered.

d} *Occupation in use* is exactly what the role of resources is supposed to be, while it also constitutes the problem that the occupied resource is not accessible for other uses/applications at the same time. For this reason, it can be considered a "compromising action" application/application. If considered a compromising action, it is particularly relevant for the 25-year timeframe and is defined as the temporary decrease of accessible stocks in the short term in the technosphere through the competitive use of resources in materials and products, so the resources cannot be used in other applications in technosphere at the same time.

3.1.2 Time approach to assess future impacts

When addressing future impacts of the present use of resources on accessibility of elements, which future do we mean? Which compromising actions that might affect accessibility in the future should be taken into account?

The chosen problem definition is related to the future impacts of the *present* use of resources, in terms of the decrease of accessibility over a time horizon, short term (ST: 25 years) or very long term (VLT).

The present use drives present compromising actions (e.g., emissions), which impact upon accessibility. However, when elements are recycled after the end of life of an application, the successive applications of the present uses would also drive future (or successive) compromising actions (e.g., emissions), which further impact upon accessibility (see Fig. 3).

Thus, given the *integrated impact over a time horizon*, the following approach for assessing impacts over time should be adopted: the characterization model is based on total resources used in a given year (e.g., 2020) with all associated (present and potentially future) compromising actions (environmental dissipation, technosphere hibernation, occupation in use) aggregated over successive applications within the time horizon considered (e.g., 2020–2045 or 2020–2520). Figure 3

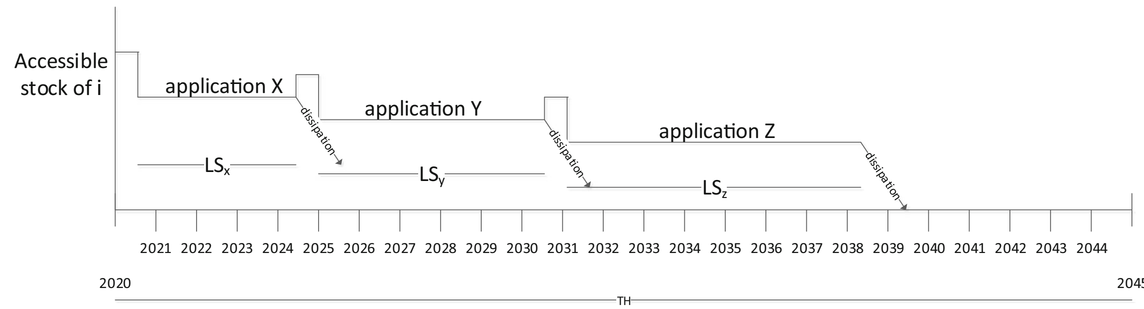

Fig. 3 Subsequent applications of resource *i* over time (LS = life span of the application)

illustrates this time approach. So, the future impacts on accessibility arising from the *present use* are defined as a function of the total of *successive compromising actions*[2] within the time horizon.

Figure 3 shows that a resource first is applied in application X for about 5 years, then discarded and recovered (taking approximately one year), and then applied in another application Y, etc. The difference in the accessibility of the stock at the beginning and end of the application is due to environmental dissipation and technosphere hibernation. We view occupation in use, technosphere hibernation, and environmental dissipation as three independent "states" an element can be in. If an element is emitted, it cannot be hibernated at the same time. An element can first be hibernated and then, at a different point in time, be emitted. However, this would represent a change in "state of inaccessibility of the element over time," for which some kind of dynamic substance flow analysis that avoids double counting would be necessary. As will be discussed later, for now it is proposed to calculate the cumulative compromising action as an integral over time.

3.2 Level 2: modeling concept

3.2.1 System model

The system model defines the relevant flows and stocks to be assessed by the LCIA method and how these flows and stocks of resources are positioned in or between the environment and/or the technosphere. The system model must be aligned with the role of resources and the goal and scope definition (Schulze et al. 2020a).

Figure 4 is a depiction of the general[3] system model that is proposed in this article, describing the stocks in the environment and the technosphere, as well as the physical flows between them, i.e., extraction and emission (in LCA the so-called elementary flows), and the flows within the technosphere, i.e., those which lead to occupation and hibernation.

Stocks of an element can occur in both the environment and the technosphere. *Environmental stocks* of elements are present in the earth, the oceans, and the atmosphere. *Technosphere stocks* can be further distinguished into in-use stocks present in products and hibernating stocks in, for example, abandoned products, landfill sites, or tailings. Only a part of the available stock in both systems will be accessible *within the time horizon considered*, depending on the technological and economic conditions present throughout that time horizon. Extraction of some resources from these technosphere stocks might readily take place (reworking of tailings deposits has regularly taken place over the last 100 years), but some might be too expensive or impractical to extract, since they are, for example, too diluted or difficult to reach *within the time horizon considered*. Reworking of old tailings (waste) might also generate new and chemically different types of waste that are more difficult (i.e., expensive) to treat from an environmental perspective.

Within the environment, the accessible stock can be distinguished into a "known accessible stock" and an "unknown accessible stock." Due to *exploration*, technological innovations, and fluctuations in demand, the "known accessible stock" may increase or decrease from one day to the next.

Within the technosphere, only one part of the available stock may be accessible due to "hibernation" or "occupation in use." So, the inaccessible stock in the technosphere is a combination of occupied stocks (pipes in the ground, in use)

[2] However, practically it might prove to be difficult to estimate future compromising actions due to the present use of resources. For example, compromising actions (e.g., emissions) will depend on the type of secondary (or tertiary, etc.) application of the element (e.g., in electronics or as pesticide?). To define these future potential applications and their associated compromising actions is highly uncertain, particularly for the long term. For this reason, another time approach might be used as a proxy. For example, the characterization model can be based on the compromising actions (environmental dissipation, technosphere hibernation, occupation in use) of one snapshot year, say the present year (so not life cycle based, as proposed in the main text, but of 1 year, e.g., 2020). However, a comprehensive set of global present emissions for such an approach is not readily available.

[3] Depending on the final impact assessment method that is developed, the system model may relate to only part of this general system model. For example, the characterization model for the abiotic depletion potential (ADP) (Guinée and Heijungs 1995; Oers and Guinée 2016) is a function of the extraction of elements from the environment and the size of the available stock of elements in the environment.

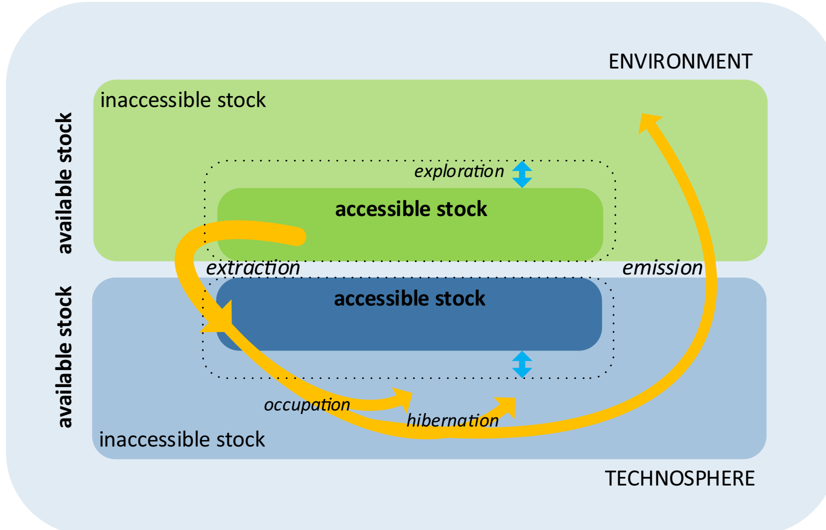

Fig. 4 The general system model for the impact assessment of the use of elements in LCIA

and hibernating stocks (pipes in the ground, abandoned). The remainder is the accessible stock, such as held up within exchanges, industries, and businesses (including stocks at recycling companies).

The flows crossing the boundary between the environment and the technosphere are the so-called *elementary flows* in LCA. A list of quantified elementary flows is the result of a (conventional) LCI analysis and is typically the input for LCIA models.

An *extraction* is an example of such an elementary flow. It represents a physical flow from the environment to the technosphere. Extraction alone decreases the available stock of a specific element in the environment. However, in the case of elements, the resource is not destroyed and thus the elementary flow will contribute to an equal increase of the total stock of the same element in the technosphere. Thus, if not dissipated to the environment, the total sum of environmental and technosphere stocks will not decrease.

An *emission* is defined as a flow from the technosphere to the environment. An emission will lead to a decrease of the accessible stock of the element in the technosphere. An emission is here considered to cause an addition to the dissipated stock in the environment and is therefore also called a dissipative flow to the environment, which is considered (in this system model) to be an irreversible loss. This means that we assume that an emitted element will no longer be accessible for human use over the considered time horizon.

In reality, future accessibility of an element will depend on technical and economic developments. Resources in the environment that are not accessible now (or in a short time horizon) might become accessible in the future. So, stocks of elements in both the environment and the technosphere that are considered to be too expensive or impractical to be extracted today or in the near future may still become accessible on a longer time horizon.

3.2.2 Basis for impact assessment

The "basis for impact assessment" refers to the criterion according to which the use of one resource is evaluated against the use of another. This is based on the principle that the use of different resources can contribute differently to the considered impact category. It is primarily a function of the problem definition but must also be in accordance with the role, goal, and scope defined as part of the chosen perspective (Schulze et al. 2020a, b).

The change in accessibility of an element is here defined as the net result of all compromising actions that increase or decrease the accessibility of the total stock, due to the present use of resources. Furthermore, the severity of any individual change in accessibility has been defined as a function of (1) the size of the accessible stock and (2) the change in the accessible stock due to the present use of resources.

The above reasoning can be summarized as follows:

- (In)Accessibility of a resource i is a function of the *global accessible stock* and the *global change in accessible stock due to the present use of resources*.
- The global change in the global accessible stock of a resource i is a function of exploration, occupation in use, environmental dissipation, and technosphere hibernation due to the present use of resources.

The aim is to develop a characterization model with characterization factors (CFs) that best reflects this basis for impact assessment (see Section 3.3). Thereby, the characterization model and related CFs should reflect (1) the global accessible stock and (2) global changes to that stock over the time horizon considered[4] for a given resource, while a product's

[4] This means the integrated compromising actions within the time horizon related to the successive applications of the resource as it is used at present.

inventory analysis in terms of its elementary flows needs to quantify the product's contribution to that. To be able to link the characterization to the inventory analysis, we need to identify the inventory flows (elementary and technosphere flows) that connect to the characterization factors (see Section 3.4).

3.3 Level 3: practical implementation

3.3.1 Impact category indicator and general characterization equation for three different impact categories of resource use

Impact category indicator and general equation The inaccessibility indicator is proposed to be determined by two parameters, i.e., the global change in accessible stock (indicated by C below) and the severity of a decreased global accessible stock (indicated by S). Both are different per resource i. Therefore, the characterization factor (CF) consists of two parts:

$$\boldsymbol{CF_i} = \boldsymbol{f}(\boldsymbol{C_i}, \boldsymbol{S_i}) / \boldsymbol{f}\left(\boldsymbol{C_{ref}}, \boldsymbol{S_{ref}}\right) \quad (1)$$

- C_i: global change in accessible stock, measured as the fraction of the global primary extraction and secondary use of resource i, made inaccessible (so leading to a decrease of the accessible stock)
- S_i: severity of making 1 kg of resource i inaccessible

In the traditional ADP (abiotic depletion potential; (Guinée and Heijungs 1995)), the severity term S_i was implemented using the total accessible stock (R) complemented by the annual production (P) through $S_i = \frac{P_i}{R_i^2}$. The change of accessibility term C_i of Eq. 1 can be considered a "correction" of the original ADP. C_i quantifies the fraction of the total use of a resource i that becomes inaccessible, whereas the original ADP considered the total amount extracted from the environment as eventually inaccessible. Though other definitions of severity could be made here, we have adopted the same S_i as for ADP, for reasons that will become apparent below.

The characterization factor of resource i is expressed in equivalents, i.e., relative to a reference substance. In Eq. 1, *ref* is a reference substance, comparable to CO_2 for global warming. Traditionally, antimony (Sb) is chosen for this, but another choice could also be made (like suggested in Section 3.3.3).

Three different impact categories of resource use To assess the impact of the present use of elements, four different compromising actions were defined: exploration, dissipation environment, hibernation technosphere, and occupation in use. The next framework challenge was to merge these compromising actions into one overall characterization model assessing the impacts of these compromising actions on the future accessibility of resources.

In principle, a characterization model builds upon a cause-effect mechanism linking the use of resources to an impact on the accessibility of resources. Compromising actions with similar mechanisms or starting assumptions can be part of the same model and thus belong to the same impact category, while essentially different actions with different mechanisms or starting assumptions should have their own impact category. In the latter case, the impact categories are essentially different and any aggregation into a single impact score for the use of resources would require additional weighting.

We first argue that exploration is different from environmental dissipation, technosphere hibernation, and occupation in use. Exploration mostly adds to the stock (R) from which humans can extract/use a resource, whereas dissipation, hibernation, and occupation determine the fate of the resource used. In other words, exploration adds to accessibility through the increase of the stock, while the other compromising actions add to some sort of inaccessibility. Thus, in terms of Eq. 1, exploration is not part of the C_i but contributes to S_i (where the R is included). The other compromising actions (occupation in use, hibernation, and environmental dissipation) are part of the parameter that describes the fraction of the used elements that is made inaccessible (C_i).

We next argue that due to the different character of the impacts and mechanisms of the compromising actions, a hierarchy of three different levels of reversibility of the inaccessibility of elements can be distinguished. Consequently, three different impact categories for assessing the impacts of abiotic resource use were distinguished:

1. (Assumed) irreversible inaccessibility of a resource within the time horizon considered: environmental dissipation (see Section 3.1.2)
2. Potentially reversible but temporary inaccessibility of a resource within the time horizon considered: technosphere hibernation (including also dissipation in the technosphere) (see Section 3.1.2)
3. Reversible but temporary inaccessibility of a resource within the time horizon considered: occupation in use (see Section 3.1.2)

Depending on the exact goal and scope of an LCA case study, either environmental dissipation alone, or together with hibernation in technosphere, or together with hibernation in technosphere and occupation in use should be included in LCA studies. We recognize that occupation in use actually corresponds to the desired "role of resources" (Section 3.1.1) and delivers benefits now and for the next generation, but it nevertheless prevents benefits from a second application of the same unit of resource at the same time. Therefore, even for the short term, we argue that it would be more correct not to include occupation in use in the impact assessment at all, since LCA cannot capture such short-term dynamics.

In the case of three impact categories proposed in this article, optional weights could be applied to the different category indicator results to derive one overall indicator score for inaccessibility. When one considers reversible changes less problematic than irreversible changes, a lower weight can be given to the impact category that covers the reversible changes to inaccessibility, i.e., "occupation in use" and, to a less extent, "hibernation in technosphere."

In the Electronic supplementary material (ESM 2), general equations are derived for the three impact categories based on Eq. 1. The generic equations are translated into specific characterization models for all three impact categories and the long and short time horizon.

Note that the way that exploration, environmental dissipation, technosphere hibernation, and occupation in use are handled in the further elaboration of practical methods for type B perspectives depends on the time horizon adopted. For example, for short time horizon, all may be relevant, while for the very-long-term time horizon, only environmental dissipation might be considered relevant, as will be discussed below.

From ESM 1, it becomes clear that particularly for the short time horizon, the elaboration of the characterization model into an operational set of characterization factors is challenging (see discussion in Section 4.3). For practical reasons of data availability, the generic equations provided in ESM 2 will only be elaborated for the environmental dissipation impact category for the very-long-term time horizon.

Elaborating "environmental dissipation" for the very-long-term time horizon Elaborating the general equation for environmental dissipation for the very-long-term time horizon into a practical method is only possible with further simplifications and assumptions. ESM 2 proves that given conditional extra assumptions about stocks and flows, certain compromising actions can be considered negligible for the change in accessibility of elements over the very long term. The following assumptions are made (see also Section 4.2 in the discussion):

- Crustal content is assumed to be a proxy for the accessible stock in the environment and technosphere (see discussion in Section 4.2).
- Therefore, the compromising action "exploration" needs no longer be represented in the equation because its maximum possible contribution is already included in the chosen proxy for the total accessible stock.
- Moreover, hibernation is assumed to be negligible due to the assumption that economic and technical developments will successfully make hibernating stocks accessible on the very long term.
- Finally, we consider that the *present* inaccessibility due to "occupation in use" is not a problem for the accessibility of elements for generations in the very-long-term *future*. Besides this, occupation can be proven to be not relevant if it is assumed that all that is extracted will eventually be emitted (see ESM 2).

For the very-long-term time horizon, this leaves dissipation to the environment as the dominant mechanism for loss of elements from the accessible stocks, present in both the environment and technosphere. Details on the assumptions made are provided in ESM 2. In the next section, the impact category "dissipation to the environment" will be developed into an operational method. Some additional assumptions will make it possible to propose an operational set of characterization factors.

3.3.2 Equation for characterization factor for environmental dissipation for the very-long-term time horizon

Equation 1 provides the generic equation for characterization factors and is assumed to be valid for all three impact categories and both time horizons, very long term and short term. To calculate the characterization factor for environmental dissipation, the $C_{t,\ T,\ i}$ and $S_{t,\ T,\ i}$ are determined for the environmental dissipation potential ($CF_{t,\ T,\ i}$ is $EDP_{t,\ Ti}$). For environmental dissipation, the two components are elaborated, namely, $C_{t,\ T,\ i}$ for the change of inaccessibility due to the compromising action and $S_{t,\ T,\ i}$ for its severity.

Note that Eq. 1 represents a top-down approach regarding the modeling of compromising actions. It models the compromising actions for the change in accessibility of a resource as a fraction of the global use of resources. A bottom-up approach, on the other hand, would rather model the compromising actions on the basis of individual applications (product) in which a resource is applied and then aggregate these resource applications to the global use of that resource. In this article, a top-down approach is assumed to be still challenging but more feasible than a bottom-up approach.

Table 2 summarizes the terminology and symbols for the equation of the characterization factor of environmental dissipation. Lowercase symbols m_i, e_i, h_i, o_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 O_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.

In the context of dissipation to the environment, the fraction $C_{t,\ T,\ i}$ in Eq. 1 refers to that part of the present use of resource i that is made inaccessible due to emissions from successive applications within the time horizon

Table 2 Overview of main terms and symbols adopted for describing the equation for the characterization factor of environmental dissipation

Name	Symbol	Unit	Remark
(Number of years of) the time horizon adopted for assessing the potential decrease of resource accessibility	T	Year (yr)	
Time for which the characterization factors are assumed to be representative	t	Year (yr)	
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 resource i emitted by a product system	e_i	kg/FU	Calculated as part of the LCI of an LCA study
Amount of secondary resource i consumed by a product system	sr_i	kg/FU	Not reported by LCA studies yet
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/year	(British Geological Survey 2018; US Geological Survey 2018)
Global amount of resource i emitted by all products in year t	$E_{t,\ i}$	kg/year	
Global amount of secondary resource i consumed by all products in a specific year	$SR_{t,\ i}$	kg/year	
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/year	$=M_i + SR_i$
Cumulative global emissions of resource i over time horizon T (25 years or VLT)	$E_{t,T,i} = \sum_{t=1}^{T} E_{t,i}$	kg	
Characterization factor for resource i	CF_i	kg *ref*/kg *i* (e.g., kg Sb-eq./kg *i*)	
Fraction of the present (t) global primary extraction and secondary use of resource i over time horizon T (25 years or VLT), made inaccessible	$C_{t,\ T,\ i}$	-	
Severity of making 1 kg of resource i inaccessible for time horizon T (25 years or VLT)	$S_{t,\ T,\ i}$	Depending on method (e.g., 1/(year.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	$EDP_{t,\ T,\ i}$	kg-*Cu-eq*/kg *i*	
Category indicator result for time horizon T (25 years or VLT) for "environmental dissipation" for a product system	$ED_{t,\ T}$	kg-Cu-eq.	
Global ultimate stock of resource i in the environment based on the *crustal content*	$R_{ult,\ i}$	kg	(Rudnick and Gao 2014)
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	$R_{tech,\ t,\ i}$	kg	
Total global accessible stock of resource i in the environment and technosphere	$R_{tot,\ t,\ i}$	kg	$R_{env,\ t,\ i} + R_{tech,\ t,\ i}$

FU = functional unit

T considered. In this case $C_{t,\ T,\ i}$ for the impact category, the environmental dissipation is:

$$C_{ED,t,T,i} = \frac{E_{t,T,i}}{P_{t,i}} \tag{2}$$

with $E_{t,\ T,\ i}$ representing the cumulative global emissions of resource i starting at time t within the time horizon adopted due to the present use of resource i and $P_{t,\ i}$ representing the annual global total primary extraction and secondary provision of resource i in year t.

To express the severity of making 1 kg of resource i inaccessible for time horizon T, we propose to use the total accessible stock (R) in the environment and technosphere, complemented by the annual total production (P) of that resource (as presently also defined in the ADP (Guinée and Heijungs 1995) (van Oers et al. 2019))[5]. So, adopting the $\frac{P_i}{R_i^2}$ ratio from the original ADP equation for the $S_{t,\ T,\ i}$, we get:

[5] We have used stocks and production rates as sub-indicators to express the severity of the "loss" of 1 kg of resource. Note that other indicators may equally be possible, like stocks and emission rates; stocks and other flow-in-technosphere rates; concentrations (specific or generic); applications (specific or generic); prices; exergy; etc.

$$S_{t,T,i} = \frac{P_{t,i}}{R^2_{tot,t+T,i}} \quad (3)$$

with $R_{tot,\ t+T,\ i}$ representing the total accessible stock in the environment and technosphere in year $t+T$, which represents the final year of the time horizon adopted. Based on the general equation for characterization factors (Eq. 1), we would get the following general equation for the environmental dissipation potential (EDP) as the characterization factor for the environmental dissipation of resources:

$$EDP_{t,T,i} = \left(\frac{E_{t,T,i}}{P_{t,i}}\right) \times \frac{P_{t,i}}{R^2_{tot,t+T,i}} \Bigg/ \left(\frac{E_{t,T,ref}}{P_{t,ref}}\right) \times \frac{P_{t,ref}}{R^2_{tot,t+T,ref}} = \frac{E_{t,T,i}/R^2_{tot,t+T,i}}{E_{t,T,ref}/R^2_{tot,t+T,ref}} \quad (4)$$

In order to be able to derive an operational set of characterization factors, additional assumptions are necessary. Equation 4 gives the characterization equation for the impact category Environmental Dissipation. Ideally the emission parameter $E_{t,\ T,\ i}$ is based on the cumulative global emission over $T = VLT$ due to the present (t) and successive future applications of the present demand (use) of resource i, e.g., the cumulative emissions from 2020 to VLT of all applications that presently (2020) use resource i.

However, successive emissions over the future time horizon are difficult to estimate. Therefore, we here pose, as a rough assumption, that primary extraction at present (e.g., in the year 2020, so $M_{2020,\ i}$) equals the very-long-term emission to the environment (i.e $E_{2020,\ VLT,\ i}$):

$$E_{2020,VLT,i} \approx M_{2020,i} \quad (5)$$

This assumption is true for the very-long-term time horizon ($T \rightarrow \infty$) but certainly will not be true for the shorter term (see discussion in Section 4.2). So, implicitly we assume that the relative differences between the amounts of various elements for "relative cumulative emissions over the time horizon" and "relative present extractions" will become more and more negligible for the very long term (VLT), starting with 100 years and more (note: it is a consequence of this assumption that any proxy greater than 100 years could be chosen without changing the result of the calculation, e.g., 500 years, 5000 years, 50,000 years, etc.).

Secondly, in the very long term, the total accessible stock $R_{tot,\ t+VLT,\ i}$ can be approximated by the crustal content stock R_{ult}, i:

$$R_{tot,t+VLT,i} \approx R_{ult,i} \quad (6)$$

Referring to the general characterization equation of environmental dissipation (Eq. 4, adopting $T = VLT$, and assuming that emissions in the very long term equal present (e.g., 2020) production, the environmental dissipation potential (EDP) is then constructed as follows:

$$EDP_{2020,VLT,i} = \frac{M_{2020,i}/R^2_{ult,i}}{M_{2020,ref}/R^2_{ult,ref}} \quad (7)$$

Here, $M_{2020,\ i}$ is now the world's annual primary production (kg/yr) in 2020 of resource i, and $R_{ult,\ i}$ (kg) represents continental crustal content of resource i, which is taken to represent the total accessible stock in the environment and technosphere over the very long term.

Equation 7 resembles the old ADP except that we don't apply it to the extraction of i from the environment, but to the total emission of i to the environment (see Section 3.4). In fact, when the reference substance is the same for EDP and ADP, we can write:

$$EDP_{2020,VLT,i}(ref) \approx ADP_{2020,i}(ref) \quad (8)$$

When the reference substances are not the same (see below), they are merely proportional:

$$EDP_{2020,VLT,i}(ref_1) \propto ADP_{2020,i}(ref_2) \quad (9)$$

3.3.3 Data for characterization factor

For the calculation of the environmental dissipation potential (EDP) of the different elements over the very long term, the following input data are needed:

a) $R_{ult,\ i}$, the global stock in the environment and technosphere of resource i, represented by the continental crustal content data of resource i by Rudnick and Gao (2014)
b) $M_{2020,\ i}$, the world's annual primary production of elements for a specific year (here 2020) which can be directly taken from van Oers et al. (2019)

In Oers et al. (2019), accessible stock estimates for the environment are derived from available stocks, consisting of the continental crust, ocean, and atmosphere. For these calculations, the average continental crust concentrations are taken from Rudnick and Gao (Rudnick and Gao 2014).

If the $ADP_{2020,\ i}$ is taken as a second[6] best or currently best and most feasible estimation of the $EDP_{2020,\ VLT,\ i}$, it can be directly taken from van Oers et al. (2019) who updated production data based on the USGS and BGS reports (British

[6] Theoretically the $EDP_{VLT,i}$ should be based on the cumulative global total emission to all compartments (air, water, soil, etc.) of resource i over the very long term due to the present application of the present use of resource i.

Geological Survey 2018; US Geological Survey 2018) for about 80 elements over the period 1970–2015. The $ADP_{i,\ 2020}$ would only be available in the course of 2021 but could be approached for the time being by the $ADP_{2015,\ i}$.

Abiotic depletion potentials (ADPs) are expressed in kg antimony (Sb) equivalents extracted per kg extraction. It is proposed to express environmental dissipation potentials (EDPs) in kg copper (Cu) equivalents emitted per kg emission, for the following reasons:

- Using another reference substance emphasizes that we deal with a different impact category using a different model (depletion versus dissipation) based on a different problem definition.
- A different unit will help to avoid that indicator scores of abiotic depletion and environmental dissipation are mistakenly aggregated.
- Finally, copper is generally perceived as more illustrative to express the problem of decreasing resource accessibility than antimony.

With these choices for the reference substances, the proportionality factor between the two potentials is

$$\frac{EDP_{2020,VLT,i}(Cu)}{ADP_{2020,i}(Sb)} \approx 36.41 \qquad (10)$$

3.4 LCI data

The fourth and final level of the framework (Fig. 1) describes the elementary flows from the inventory ("LCI data") needed as input to run the characterization model.

In the characterization step of an LCA, the elementary flows, in this case (e_i), are translated into contributions to impact categories by means of characterization factors. In the context of environmental dissipation (ED), the characterization factor is the environmental dissipation potential (EDP) for element i.

Putting this together, we summarize this as:

$$ED_{2020,VLT} = \sum_i EDP_{2020,VLT,i} \times e_i \qquad (11)$$

Here $EDP_{2020,\ VLT,\ i}$ is the environmental dissipation potential of resource i (-) for a very-long-term time horizon, defined on the basis of the current (2020) data, and e_i is the quantity of element i emitted per functional unit (FU) in an LCA study (kg).

Referring to Eq. 11, instead of $EDP_{t,\ VLT,\ i}$, the $ADP_{t,\ i}$ for a specific year (e.g., 2020) can be used (except for the difference of scale due to the difference in reference substance). The equation to calculate the impact category indicator score then is as follows:

$$ED_{2020,VLT} = 36.41 \times \sum_i ADP_{2020,i} \times e_i \qquad (12)$$

There is an important difference here from the calculation of the impact category indicator score of the impact category abiotic depletion (AD) (Guinée and Heijungs 1995; Guinee 2015; Oers and Guinée 2016). To calculate the impact category indicator score for emission to the environment, the ADP is multiplied by the e_i instead of the m_i. The e_i is the quantity of element i emitted per functional unit in an LCA study (kg), while the m_i is the quantity of element i extracted from the environment per functional unit in an LCA study (kg).

3.5 Illustration of the method for environmental dissipation through a case study from Aitik and Cobre las Cruces

Here we briefly report a case study illustrating the use of the new method for assessing environmental dissipation and identifying possible strengths and weaknesses compared with the traditional abiotic depletion method. More information about this case study and the calculations involved can be found in ESM 3.

The ED method was applied to two European copper production companies: Boliden (Aitik mine, Sweden) and First Quantum Minerals (CLC, Cobre las Cruces mine, Spain). The functional unit considered was 1 kg of copper cathode at gate. The LCA of both systems was done using the software SimaPro 8.4 and the database ecoinvent 3.4. Substance emissions in the resulting LCI table were multiplied with their EDP (see ESM 3 "Case study results and tool to derive characterization factors for substance emissions based on elements using the chemical composition" and the EDP in table sheet "ADP and EDP 2015 elements") and aggregated to the indicator result for ED. For this, the EDPs for elements were first converted to EDPs for substances (e.g. sulfur dioxide, toluene, glyphosate), based on their chemical formula (see ESM 3, table sheet "Calc EDP substance"). Additionally, the recently updated ADPs (cumulative ADP2015, van Oers et al. 2019; see ESM 3, table sheet "cumulative ADP2015 elements") were applied to the element extractions to enable a comparison between the AD and ED indicator results.

The contributions by the use of different elements to the ED and AD indicator results for the two case studies are shown in Fig. 5. While the ED indicator result is expressed in copper equivalents emitted (Cu-eq), the AD indicator results are expressed in antimony equivalent extracted (Sb-eq).

As observed in Fig. 5, the contributions to the ED and AD indicator results are completely different. The ED indicator results originate from different elements, whereas for the AD method, the contribution by copper (Cu) is completely dominant. The characterization models for AD and ED are nearly the same, both being based on stock size (crustal content) and

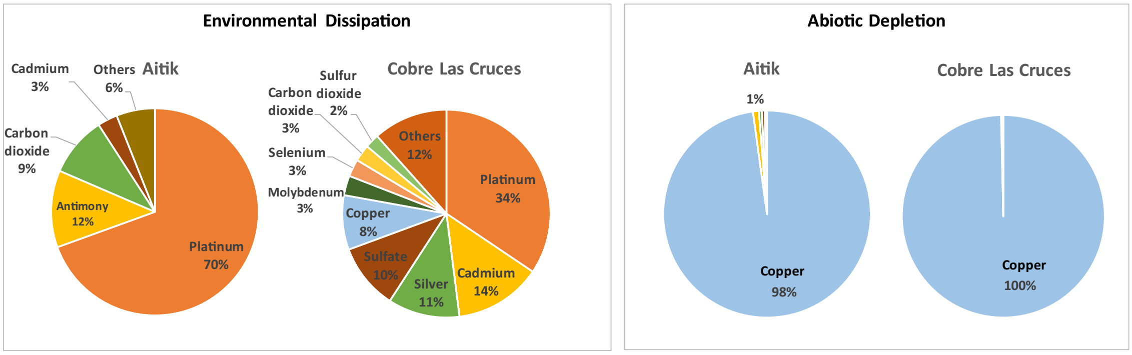

Fig. 5 Breakdown of the impact on environmental dissipation (ED) and abiotic depletion (AD) for copper production by Aitik and CLC

primary production, resp. cumulative (year 1970–2015) or present (year 2015) primary production (they only differ by a factor of approximately 36.41 because they use different reference substances). However, the elementary flow that is assessed is different, namely, extractions for AD and emissions for ED.

Thus, the ED method mainly represents dissipative flows of resources used; dissipative losses of platinum appeared to contribute greatly to the ED indicator results and are related to the manufacture of purchased explosives used at the mines. The AD method, on the other hand, represents primary extraction flows of resources used; copper was the dominant contributor to the indicator result because the production system analyzed is about the primary extraction of copper from the ground. Copper did not represent a major contribution to the ED indicator results, which makes sense since the production system is optimized for keeping the copper within the system and not dissipating it to the environment. Other elements than copper are indicated as being more important in the ED results. Such elements may have a relatively high ADP and a moderate to low emission (like platinum, silver, and cadmium) or a relatively low ADP and a relatively high emission (like carbon in CO_2).

These results are preliminary and due to the limited scope of the case studies presented, two important drawbacks should be mentioned. Firstly, the present LCI databases are far from complete with respect to the emissions of elements, as it is well known that the material balance of unit processes is not always consistent. Consequently, the relative contribution of carbon emissions may now be overestimated. CO_2 emissions have a low EDP in comparison with metal elements, but CO_2 emissions are likely covered by LCA databases to a larger extent. The ESM 4, Section 5, gives some insight into the coverage of elements by ED and AD characterization factors. Secondly, the present case study omits downstream processes, like the use and EoL processes, where most dissipative losses, and thus differences between case studies based on AD or ED, are expected to occur. Therefore, further testing of the methods is recommended, ideally based on more comprehensive LCA studies, i.e., more complete process data sets and more complete process chains (cradle to grave).

Another point of discussion is which impact category might ED replace. In the present AD method, two different impact categories related to resource use are distinguished: abiotic depletion of elements and abiotic depletion of fossil fuels. We suggest that the ED should only be used to replace the impact category "abiotic depletion of elements," maintaining the depletion of fossil fuels as a separate impact category. The current ED method also considers the dissipation of the element carbon through CO_2 emissions, which is mostly related to the combustion of fossil fuels. Thus, are we now double counting resource problems related to the use of fossil fuels? Theoretically speaking, no. Dissipation and depletion are two separate impact categories, indicating different problems. The depletion of fossil fuels represents a type A perspective[7] (Schulze et al. 2020a). It is about the destruction of primary configurations, i.e., fossil fuels, and their reduced availability in the environment, while environmental dissipation represents the type B perspective[8] and focusses on elements and their reduced accessibility. In LCIA there are more examples of elementary flows that contribute to more than one problem, such as emissions of NOx contributing to human toxicity, acidification, and eutrophication.

4 Discussion

4.1 The top-down framework approach

During the process of method development, a framework was used as a guide. The framework has proven to be very useful to get to a common understanding between stakeholders and

[7] Type A perspective: abiotic resources are valued by humans for their functions used (by humans) in the technosphere, taking into account primary production only.

[8] Type B perspective: abiotic resources are valued by humans for their functions used (by humans) in the technosphere, taking into account both primary and secondary production.

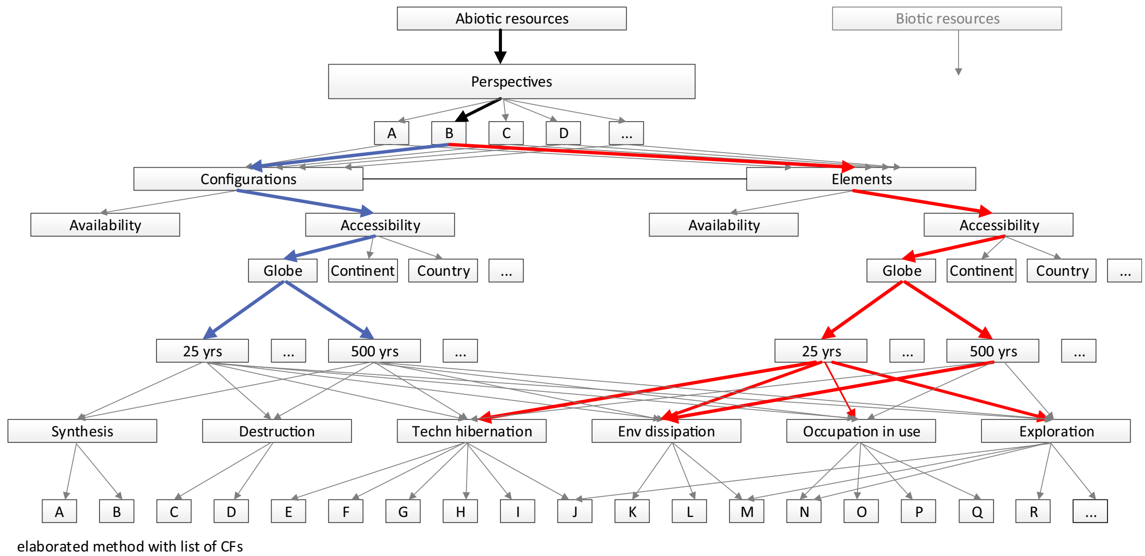

Fig. 6 Decision tree of choices made in the framework along the progress of developing methods

the partners in the project consortium. Particularly in a group process, the step-by-step approach forces participants to formulate results, the assumptions behind the results and the logic of the argumentation clearly, and step by step while building up a consistent argument. Only after sufficient agreement was achieved in a module of the framework was it possible to move to the next module. Of course, the decisions made in a previous step may narrow down the choices of possible assumptions and arguments in succeeding steps. As could have been expected, the development of the described methods, using the framework, was an iterative process. It sometimes became apparent that the definitions used in previous steps were not clear or complete enough and adjustments were necessary. In the end, the choices made on the more operational level of the framework must always be consistent with the assumptions made on the top level and the step-by-step approach proved to be very helpful in ensuring that they are.

Along the pathway of the framework, many different choices and assumptions can be made. The bold and red arrows in Fig. 6 indicate the path taken by the work described in this article. It shows in summary the choices we made to come to our final results, and it also shows the vast amount of alternative choices that could have been made. The chosen role, goal, scope, and problem definition for elements and configurations are the same. However, the second level of the framework (the modeling concept) was not elaborated for configurations (e.g., minerals). To elaborate a practically feasible method for the characterization of configurations, it is necessary to lump the large amount of possible configurations into a manageable number based on some equivalency principle. Identification and elaboration of equivalent configurations based on, for example, composition or property criteria were not considered to be feasible within the SUPRIM project due to the complex geological character of ore deposits and materials in use. So, although in reality mining produces combinations of minerals[9] and resources are most often valued as configurations in the technosphere, the development of an operational impact assessment method is unfortunately only considered feasible on the level of elements for the time being.

Any combination of impact assessment method and its indicators is the result of a sum of choices. So, the route followed in this process of the development of an impact assessment method is only one path out of many possible alternative choices. We think that to achieve consensus within the LCIA community on how to assess impacts on accessibility of resources in LCIA, the described framework is useful. In general, the use of a framework such as this should preferably be used to review and adjust existing impact assessment methods of other impact categories as well.

4.2 LCIA model: consistency

At this moment, an operational method could only be developed for the very-long-term impacts of use of elements on future generations, i.e., the "dissipation to the environment." This method is built on two parameters: (1) the total global accessible stocks in environment and technosphere for the very long term and (2) the total cumulative global emission

[9] It is very rare to find pure metals in the environment or the technosphere. Even if a geologist would label something, for instance, native gold, meaning almost pure gold, "almost" is the key word here. Together with the gold, there might be small amounts of silver and perhaps mercury, copper, bismuth, etc. The same holds for "almost" pure traded commodities, which are almost always used to prepare new configurations for use.

of elements within the time horizon due to the present demand.

Regarding the *total global accessible stock of elements in the environment for the very long term*, the following argumentation was used. Ideally, the stock parameter should be based on the ultimate extractable stock in the environment. However, given the uncertainties on future technological and economic developments, this ultimate extractable stock is unknown and will always remain unknown. For the very long time frame (e.g., 100 years, 500 years, or more), it has therefore been assumed that the ultimately extractable element stock will asymptotically approach some critical portion of the total available resource in the environment. Of course, not all of the available total (the crust) will be extractable, not even on the very long term. Also, the geologically heterogeneous nature of the crust will in the very long time frame still likely require exploration activities to target the parts of the crust that are richer in metals. However, for the purpose of relative characterization factors, the relative stocks of elements are of importance—not the absolute quantification of ultimately accessible stocks. Therefore, for a relative assessment of the contribution of the use of different resources to the considered impact category, the continental crustal content is suggested as an acceptable proxy, even though there still might be differences in the extractability of the available elements, even on the very long term.

Regarding the *total global accessible stocks of elements in the technosphere for the very long 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 minus the cumulative emissions up until now. So, extractions are a shift of elements from the stock in the environment to the stock in the technosphere, except for the emissions flowing back to the environment[10]. Because occupation and hibernation are assumed to be negligible over the very long term, the accessible stock in the technosphere can be considered equal to the available stock in the technosphere. Next, the crustal content is assumed to be a proxy for the total available stock (which equals the accessible stock for the very long term) in both the environment and technosphere, while not correcting for the cumulative emissions up until now (because of missing data for the latter). This implicitly assumes that historic emissions to the environment will not alter the relative availability of elements in the technosphere from now onward. In reality, the use of elements in more dissipative or less dissipative applications may have differed between elements.

Regarding the emissions, ideally one wants to assess *the total cumulative global emissions due to the present demand over a given time horizon* relevant to the existence of mankind (e.g., 60,000 years). However, cumulative emissions over a particular time horizon are very difficult to estimate. Therefore, in Section 3.3.2, it is argued that cumulative emissions from the present use over an *infinite* time horizon (i.e., present extractions) are a useful proxy for cumulative emissions over *the very long term*. Another potential proxy to estimate the relative inaccessibility between elements due to emissions would be a snapshot of current emissions (see Section 3.1.2, Footnote 2).

We acknowledge that using the present extraction as a proxy for cumulative emissions over a very-long-term time horizon is a very rough assumption and, although theoretically true for a time horizon of infinity, this assumption certainly is not validated by experience in real life for shorter, but still long, time horizons, like 500 years. However, for this moment, we believe present extractions are a better proxy for cumulative emissions over a very-long-term time horizon, than a snapshot of present emissions, the more because at this moment no comprehensive data for the second proxy is readily available.

A different choice here, e.g., based on a shorter time horizon of 25 years, might lead to a different relative ranking of elements. As an outlook to the future, the development of two different sets of characterization factors for dissipation to the environment, one based on present emissions and another based on present extractions, might enable sensitivity analyses quantifying the difference that either of these two choices has on the characterization results.

4.3 LCIA model: data needs and availability

As described above, the data needs to derive characterization factors for assessing the accessibility of elements over the very long term may be reduced by restricting the number of impact categories to only one (instead of three) and making additional assumptions for stocks and emissions over the very long term.

It is foreseen that development of characterization factors for the short term would be extremely data intensive. To derive characterization factors for accessibility of elements over the short time, it is necessary to estimate present accessible stocks in the environment and technosphere within the time horizon of, say, 25 years. Global flows of elements that are emitted or go into hibernation or occupation within the time horizon of 25 years would also need to be estimated.

For the estimation of stocks in the environment, the (economic) reserves as reported by USGS (US Geological Survey 2018) can be used. They represent that part of the natural reserve base, which can be economically extracted at the time of determination. The estimates of the stocks are regularly updated and time series might be used to incorporate exploration by extrapolation of recent trends in stocks into the future. Such estimates of present accessible stocks do not

[10] In the proposed case, where crustal content is used as a proxy for the ultimate extractable stock, theoretically emissions will replenish the accessible stock in the environment. Nevertheless, we still define emissions as dissipative flows, using the same argument that the relative instead of the absolute accessibility is of importance.

readily exist for elements in the technosphere. More research would be needed to estimate the present stocks in the technosphere (e.g., based on the cumulative extraction from the past). These present stocks could then be broken down into different levels of accessibility for future generations. These could be based on economic and/or technical criteria ideally specified for different time horizons.

Next to the stocks, the cumulative flows representing successive compromising actions within the time horizon should also be gathered, i.e., data on emissions, hibernation, and occupation.

Depending on the approach to be used—a detailed substance flow accounting (SFA)-like approach or one using generic average factors (see ESM 1)—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 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. Finally, these data would be needed on a global scale and in time series for all resources, applications, and processes.

Such data for a short-term analysis are not all readily available. Estimating such short-term changes to stocks and flows is likely to be time-consuming and elaborates a task as performing globally detailed dynamic SFAs for all resources and their applications. This is far beyond the scope of generic LCIA models. The calculation of global stocks and flows should then be based on simplified procedures using SFA-like modeling. The challenge would be to develop a generic method, to be applied to all elements covered by the method, which is simple but still makes sense and is sufficiently detailed to discriminate between elements. More research is needed to elaborate such a generic method, map its data needs, and check data availability.

4.4 LCI model: consistency

In conventional LCA, the elementary flows are the flows that cross the system boundary between the environment and the technosphere. Only the impact category "environmental dissipation" appears to be consistent with the conventional LCA practice based on elementary flows, using emissions quantified in the LCI phase as input to the LCIA phase. In contrast, the impact category technosphere hibernation uses mass flows of resources that go into technosphere hibernation. These mass flows do not represent elementary flows in the inventory table but technosphere flows that need to be extracted from the process-to-process matrix ("A matrix"). Similarly, the impact category occupation in use does not use conventional elementary flows as flows to be assessed.

4.5 LCI model: data needs and availability

Although in this article characterization factors are proposed for environmental dissipation of elements over the very long term, the calculation of the actual environmental dissipation score (ED) might still be challenging.

For the impact category "environmental dissipation," the elementary flows that need to be assessed are the emissions of the elements related to the defined functional unit in the LCA study. Based on the experiences gained with the case study presented in Section 3.5, three actions might be needed to properly take into account the assessment of the impact category "environmental dissipation":

a. The unit process data in LCI databases should be extended with more emission data in order to be able to assess dissipative losses of more resources (elements) to the environment. In general, the LCI databases (e.g., ecoinvent) are far from complete when reporting the emissions of a unit process. In other words, what goes into the process seldom matches with what comes out, either as emissions or contained in one of the economic flows that leave the process (waste or products) (Charpentier Poncelet et al. 2019).
b. Emissions in LCI databases are mostly not provided as elementary emissions, but rather as substance emissions: emissions of configurations representing a chemical composition of elements. Of course, the LCIA model and LCI model should align in this respect. One way of doing this is by deriving characterization factors for substance emissions based on the characterization factors for elements and using the chemical composition of the substances to derive conversion factors (see ESM 3).
c. Finally, one should ideally distinguish between dissipative and non-dissipative emissions. For simplicity, we have now assumed in the characterization model that all emissions are dissipative, irrespective of the level of concentration of the element before it gets emitted. However, in the LCI, it might be possible to make a distinction between emissions of elements from inflows that were already dissipated (e.g., traces of metals in fossil fuels) and emissions of elements from inflows from a concentrated resource (e.g., metals in ores).

To properly take into account the assessment of the impact category "technosphere hibernation" and "occupation in use," first more specific definitions of these two compromising flows should be developed based on and aligned with the final LCIA model with which flows are going to be assessed. Next, although existing LCI databases already include such flows, the present LCA software packages are generally not able to provide them as aggregate flows going into hibernation (e.g., landfill) or into occupation for the FU considered. Software

Table 3 Abiotic depletion versus environmental dissipation of elements

Impact category	Abiotic depletion of elements (van Oers et al. 2019)	Environmental dissipation of elements (this article)
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. (2020b)	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. (2020b)
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)
Basis of impact assessment	The accessible stock in the environment and the cumulative extraction from this stock up until the present year	The accessible stock in the environment and technosphere and the cumulative (=successive) global emissions of resource *i* within the time horizon adopted due to the present use of resource *i*
Characterization model equation	$ADP_i = \frac{M_i / R^2_{i,tot,t+T}}{M_{ref} / R^2_{ref,tot,t+T}}$	$EDP_{t,T,i} = \frac{E_{t,T,i} / R^2_{i,tot,t+T}}{E_{t,T,ref} / R^2_{ref,tot,t+T}}$
Proxy	$ADP_{i,cum} = \frac{M_{i,cum} / R^2_{i,ult}}{M_{ref,cum} / R^2_{ref,ult}}$	$EDP_{2020,VLT,i} = \frac{M_{2020,i} / R^2_{i,ult}}{M_{2020,ref} / R^2_{ref,ult}} \propto ADP_{i,2020}$
Impact score equation	$AD = \sum_i ADP_{i,cumulative} \times m_i$	$ED_{2020,\mathrm{VLT}} = \sum_i EDP_{2020,i} \times e_i$
Elementary flow to be assessed	Extraction (m_i)	Emission (e_i)

should therefore be developed to extract these flows from the process-to-process matrix (“A matrix”). When doing this, caution must be taken that mechanisms are not accounted for twice, i.e., once in the LCI and then again in the LCIA. To avoid this, a clear distinction should be made between parts of the cause-effect chain belonging to the inventory and those belonging to the impact assessment.

4.6 Abiotic depletion versus dissipation

Both the original ADP impact category based on Guinee and Heijungs (Guinée and Heijungs 1995) and the new EDP make use of up-to-date abiotic depletion potentials (van Oers et al. 2019). The indicator results represent two different methods, but also two different impact categories, problem definitions, perspectives, etc. To explain this, we drafted Fig. 7 and Table 3. Figure 7 is a depiction of the system models of the two impact categories. Table 3 shows the differences between the two methods related to the levels and steps of the framework. As partly also shown by Schulze et al. (2020a), Table 3 clearly indicates the different choices that are made for the role of resources, the problem definitions, basis for impact assessment, etc. between these two impact categories. Basically, the ADP represents another perspective than the EDP (resp. perspective A and B, see Table 3). Still, individual terms

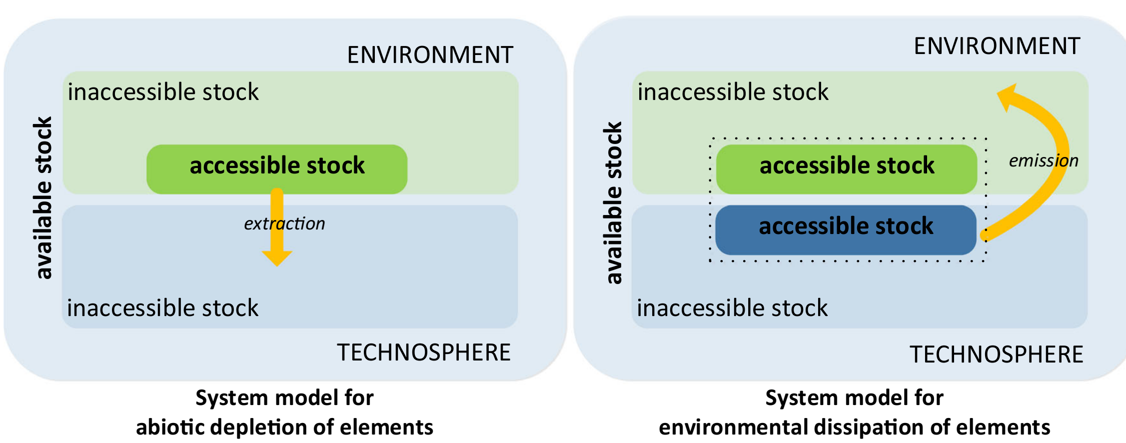

Fig. 7 System model for abiotic depletion and environmental dissipation of elements

of one equation can still be useful as part of another equation as shown by using the abiotic depletion potentials of elements to calculate their EDPs as long as it consistently fits to the choices made for all framework levels and steps.

5 Conclusions and recommendations

For the development of an impact assessment method for resource use in LCIA, a step-by-step top-down approach has been developed. We conclude that the framework has proven to be guiding in defining the problem that needs to be assessed and to elaborate model concepts toward an operational method or methods. It also helps to systematically and consistently elaborate abstract concepts into operational method(s). To conclude, below the most important definitions, choices, and assumptions are summarized, which were necessary to develop an operational set of characterization factors.

Using the top-down framework, the development of an impact assessment method starts with a clear definition of the adopted perspective on resources, consisting of the role, goal, and scope and problem of using resources. We adopted the role, goal, and scope as defined by Schulze et al. (2020b) and added a consistent 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 very long term (VLT) or short term (ST: 25 years) due to compromising actions.* Based on this, we developed the related system model and the basis for impact assessment: the general system *model takes into account both (1) the size of the accessible stocks, in the environment and the technosphere, and (2) the change due to the compromising action, i.e., the flow from accessible stock to non-accessible stock, respectively, emissions, net flow into hibernation, and net flow into occupation in use.*

These concepts for impact assessment were then used as a starting point to practically elaborate operational characterization factors for the assessment of resource use in LCA (levels 3 and 4 of the framework).

A hierarchy of three different levels of reversibility of the inaccessibility of elements was distinguished. This led to the definition of three impact categories, with increasing level of reversibility: (1) environmental dissipation, (2) technosphere hibernation, and (3) occupation in use. We concluded that depending on the problem definition of an LCA case study, either environmental dissipation alone, or together with hibernation in technosphere, or together with hibernation in technosphere and occupation in use should be included in LCA studies.

General equations for characterization models were developed for three different impact categories: environmental dissipation, technosphere hibernation, and occupation in use. We concluded that all three impact categories might be relevant for the short term, but for the very long term only the impact category environmental dissipation needs to be applied.

We were only able to elaborate an operational set of characterization factors (environmental dissipation potentials (EDPs)) for the impact category environmental dissipation over the very long term. The EDPs are based on all cumulative emissions from the present year and thus are assumed to be approximated by ADPs based on present extractions of the most recent year available (van Oers et al. 2019)[11]. However, please note that for environmental dissipation, the elementary flows that are assessed are emissions instead of extractions. In practice, a complete calculation of indicator results for the ED over the very long term appears to be hampered by incomplete process data of these emissions. At the same time, by applying and comparing the new ED method with the AD method for a cradle-to-gate case study on copper production, we have demonstrated that significant and interesting differences are likely to emerge when and if process data gaps are filled. For example, initial indications of dissipative losses were driven by platinum, instead of copper, losses. The indicated platinum emission could be traced to assumptions made in third-party background databases about the manufacture of explosives potentially used at mines.

While applying the framework, developing the characterization method, and operationalizing characterization factors, we had to make various choices and assumptions that could plausibly be made differently. We recommend and invite our peers to also use this top-down framework when challenging our choices, work together with stakeholders and work from a clear problem definition, and elaborate that into a consistent set of choices and assumptions for other steps when developing LCIA methods.

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[11] EDP is proportional to ADP, see Sections 3.3.2 and 3.3.3.

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