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LCIA OF IMPACTS ON HUMAN HEALTH AND ECOSYSTEMS

Mineral resources in life cycle impact assessment: part II – recommendations on application-dependent use of existing methods and on future method development needs

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Abstract

Purpose Assessing impacts of abiotic resource use has been a topic of persistent debate among life cycle impact assessment (LCIA) method developers and a source of confusion for life cycle assessment (LCA) practitioners considering the different interpretations of the safeguard subject for mineral resources and the resulting variety of LCIA methods to choose from. Based on the review and assessment of 27 existing LCIA methods, accomplished in the first part of this paper series (Sonderegger et al. 2020), this paper provides recommendations regarding the application-dependent use of existing methods and areas for future method development.

Method Within the "global guidance for LCIA indicators and methods" project of the Life Cycle Initiative hosted by UN Environment, 62 members of the "task force mineral resources" representing different stakeholders discussed the strengths and limitations of existing LCIA methods and developed initial conclusions. These were used by a subgroup of eight members at the Pellston Workshop® held in Valencia, Spain, to derive recommendations on the application-dependent use and future development of impact assessment methods.

Results and discussion First, the safeguard subject for mineral resources within the area of protection (AoP) natural resources was defined. Subsequently, seven key questions regarding the consequences of mineral resource use were formulated, grouped into "inside-out" related questions (i.e., current resource use leading to changes in opportunities for future users to use resources) and "outside-in" related questions (i.e., potential restrictions of resource availability for current resource users). Existing LCIA methods were assigned to these questions, and seven methods ($\mathrm{ADP_{ultimate\ reserves}}$, $\mathrm{SOP_{URR}}$, $\mathrm{LIME2_{endpoint}}$, CEENE, $\mathrm{ADP_{economic\ reserves}}$, ESSENZ, and GeoPolRisk) are recommended for use in current LCA studies at different levels of recommendation. All 27 identified LCIA methods were tested on an LCA case study of an electric vehicle, and yielded divergent results due to their modeling of impact mechanisms that address different questions related to mineral resource use. Besides method-specific recommendations, we recommend that all methods increase the number of minerals covered, regularly update their characterization factors, and consider the inclusion of secondary resources and anthropogenic stocks. Furthermore, the concept of dissipative resource use should be defined and integrated in future method developments.

Conclusion In an international consensus-finding process, the current challenges of assessing impacts of resource use in LCA have been addressed by defining the safeguard subject for mineral resources, formulating key questions related to this safeguard subject, recommending existing LCIA methods in relation to these questions, and highlighting areas for future method development.

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Keywords Life cycle assessment · Life cycle impact assessment · Mineral resources · Raw materials · Resource depletion · Resource dissipation · Life Cycle Initiative · Task force mineral resources

1 Introduction

Given the importance of mineral resources for society and the persistent debate about how mineral resource use should be addressed in life cycle assessment (LCA), a wide variety of impact assessment methods have been developed, each of which assesses different aspects of mineral resource use. Within the "global guidance for life cycle impact assessment (LCIA) indicators and methods" project of the Life Cycle Initiative hosted by UN Environment, a task force has been established to develop recommendations on the LCIA of mineral resource use. This "task force mineral resources" consisted of 62 members representing different countries and stakeholders (academia, the metals and mining industry, other industries, geological departments, consulting, and life cycle inventory (LCI) database providers). While some members followed the process passively, 23 contributed actively on a regular basis, out of which 22 (mainly from academia, among them many method developers) are co-authoring this paper.

As a first step, the task force described, discussed, and assessed 27 existing impact assessment methods. Based on this comprehensive review, which is published in part I of this paper series (Sonderegger et al. 2020), as well as earlier reviews and recommendations (e.g., EC-JRC 2011; Sonderegger et al. 2017), the task force provided initial conclusions regarding the use of existing methods and areas for future method development. In parallel, the task force articulated a precisely defined and agreed upon safeguard subject for mineral resources within the AoP natural resources, which defines what actually should be protected with respect to mineral resources in LCA. At the Pellston Workshop® held in Valencia in June 2018, eight task force members (5 from academia, 2 from consulting, 1 from the oil and gas industry) refined the definition of the safeguard subject and used the task force's initial conclusions to derive recommendations on application-dependent use of existing methods and on future method development needs. This paper presents the final reflections and recommendations of the Pellston Workshop®.

The definition of the safeguard subject for mineral resources is described in section 2. In section 3, a set of impact assessment methods is recommended, addressing seven different questions that stakeholders may have with regard to mineral resource use. These methods are applied on an LCA case study of a European-manufactured electric vehicle in section 4. Section 5 provides recommendations for further improvement of the existing methods and new methodological developments.

2 Defining a safeguard subject for mineral resources in LCA

Although the subject of mineral resource use has been addressed in life cycle impact assessment (LCIA) methods for more than 20 years (Guinée and Heijungs 1995) and more than 20 impact assessment methods have been developed during this time, the safeguard subject within the (AoP) "natural resources" is still debated (EC-JRC 2010; Mancini et al. 2013; Dewulf et al. 2015; Sonnemann et al. 2015; Sonderegger et al. 2017). Previous reflections on the safeguard subject range from (1) the asset (natural resources as such independent of their specific function), (2) the provisioning capacity (the ability of natural resources to provide functions for humans), and (3) global functions (additionally considering non-provisioning functions for humans and functions beyond human needs) to (4) the supply chain (from the provisioning capacity to products and services) and (5) human welfare (including perspectives 2–4) (Dewulf et al. 2015). Such different perspectives of "the problem" with respect to mineral resource use are reflected in the diverse set of impact assessment methods, which model different cause-effect chains (Sonderegger et al. 2020). To address this challenge, the task force used the outcome of a stakeholder survey and workshop conducted within the "Sustainable Management of Primary Raw Materials through a better approach in Life Cycle Sustainability Assessment" (SUPRIM) project (Schulze et al. 2020). The majority of survey respondents indicated that they consider the following:

i) Humans as the most relevant stakeholders for mineral resources, i.e., the focus is on the instrumental value of resources for humans (rather than on the instrumental value for ecosystems or any intrinsic value that might be assigned to mineral resources)
ii) The technosphere as the system of concern, i.e., we are mainly concerned about the availability of mineral resources for use in the technosphere (even though some minerals in the ecosphere also provide an instrumental value for humans, e.g., sand filtering groundwater)
iii) Both primary and secondary supply chains as relevant production systems, i.e., stakeholders are concerned about the availability of mineral resources, regardless of whether they are derived from primary or secondary resources.

After extensive discussions and several iterations within the task force and at the Pellston Workshop®, the safeguard subject was articulated as follows:

Within the area of protection "natural resources", the safeguard subject for "mineral resources" is the potential to make use of the value that mineral resources can hold for humans in the technosphere. The damage is quantified as the reduction or loss of this potential caused by human activity.

This definition reflects the three components of the SUPRIM survey outcome. Further, it clarifies that mineral resources first "hold" a value which humans "make use of" in a second step. Accordingly, mineral resources were defined as follows:

Mineral resources are chemical elements (e.g., copper), minerals (e.g., gypsum), and aggregates (e.g., sand), as embedded in a natural or anthropogenic stock, that can hold value for humans to be made use of in the technosphere.

It should be noted that there are cases in which a mineral (e.g., chalcopyrite – $CuFeS_2$), the contained elements (Cu, Fe, and S – even if Fe ends up in the smelter slag for economic reasons), or both (the mineral and the metals) can be considered as "mineral resources" as all of them can hold a value for humans in the technosphere. The inclusion of both primary and secondary resources is not considered a contradiction to the AoP "natural resources" because all mineral resources – both primary and secondary – originate in nature. The degree to which existing methods are compatible with this definition of the safeguard subject is one aspect considered in the recommendation of methods.

3 Recommendation of methods for current use in LCIA

The first part of this paper series (Sonderegger et al. 2020) identified 27 existing methods to assess impacts of mineral resource use. The wide variety of methods causes confusion among LCA practitioners, and often the "wrong" method is used to answer the "right" question. For instance, methods assessing the long-term depletion of geological resource stocks (e.g., the abiotic depletion potential) are often used by LCA practitioners who are actually interested in the short-term supply risk of raw materials (Fraunhofer 2018). This paper builds on the description and categorization of methods provided in Sonderegger et al. (2020) by providing further guidance on the use of these methods.

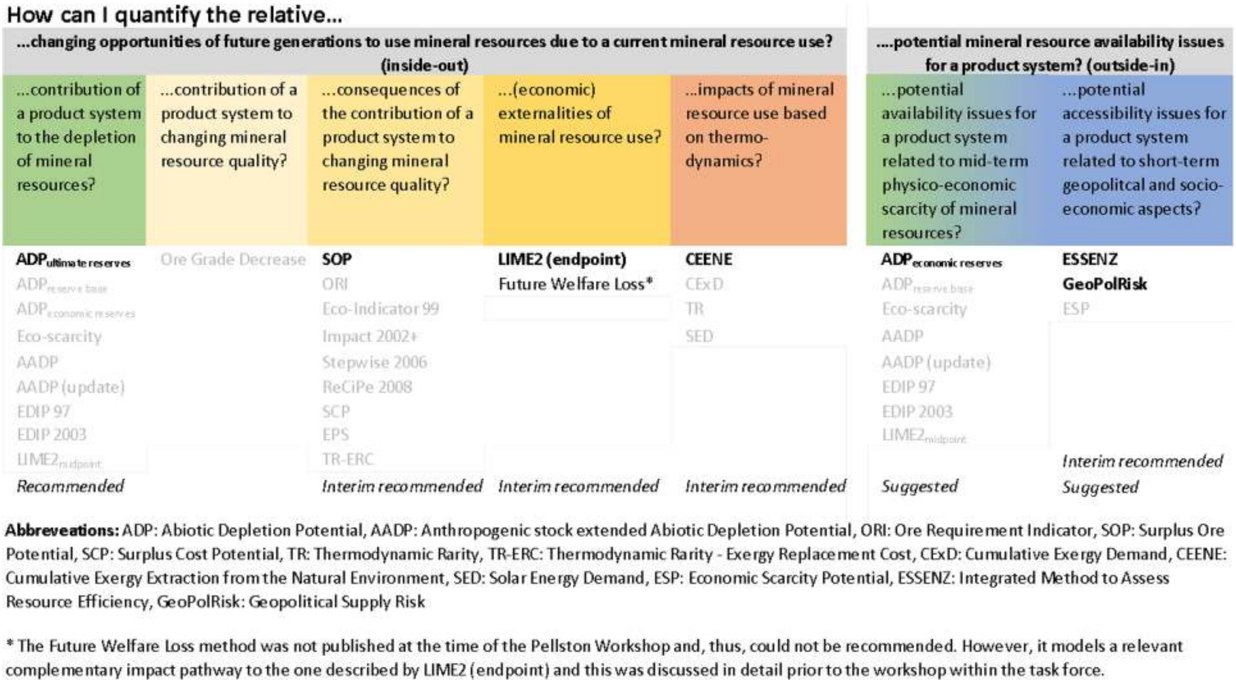
At the Pellston Workshop®, seven questions that stakeholders (policy, industry, consultants, NGOs, etc.) may have with regard to mineral resource use were formulated (Table 1) and grouped into two broad categories.

The first category of questions focuses on how the use of mineral resources in a product system can affect the opportunities of future users to use resources (termed the "inside-out" perspective), whereas the second category focuses on how environmental and socioeconomic conditions can affect the accessibility of mineral resources for a product system (termed the "outside-in" perspective). For the first category, five individual questions are related to physical depletion, resource quality, resource quality change and its consequences, (economic) externalities due to overexploitation of resources, and thermodynamics. For the second category, two questions were identified, concerning the mid- and short-term supply of mineral resources.

Subsequently, the 27 methods were assigned to the question(s) they address, and their capability to answer them was assessed based on (a) the modeling approach, (b) the underlying data used, (c) the coverage of characterization factors (CFs) as analyzed in the method review (Sonderegger et al. 2020), and (d) the degree to which existing methods are compatible with this definition of the safeguard subject. Finally, the most appropriate method(s) for the specific questions were recommended with a level of recommendation ranging from "suggested," "interim recommended," "recommended" to "strongly recommended" (Frischknecht et al. 2016). An interpretation of these recommendation levels and more detailed criteria can be found in the supplementary material. Limitations of recommended methods have been made transparent to justify the level of recommendation and to propose methodological improvements. Also methods published after the Pellston Workshop® in June 2018 (e.g., Bulle et al. 2019; Vogtländer et al. 2019) could not be considered for recommendation but have been included in the discussion if the methodological concepts have been available to the task force (e.g., Huppertz et al. 2019). Since most method developers contributed actively to this task force and partly participated in the Pellston Workshop®, it is unavoidable that methods get recommended whose developers were involved in the recommendation process. Further, recommendations were derived based on transparent criteria and in a consensus finding process which involved all participants of the Pellston Workshop®. The following subsection was written by the members of the Pellston Workshop®, who are co-authoring this paper together with other active members of the task force. To avoid different understandings of the recommendations and rationales, the text below is only slightly modified from the corresponding section in the Pellston Report (chapter 5.4 in (Life Cycle Initiative 2019)).

Table 1 shows the two major categories of questions, the seven individual questions, the methods available to answer them, the recommended methods (bold), and the level of recommendation. In general, we recommend using the inside-out related questions within environmental LCA and the outside-in related questions within broader life cycle-based approaches, such as life cycle sustainability assessment (LCSA). However, it should be noted that this recommendation was strongly

Table 1 Questions related to the impacts of mineral resource use, methods addressing these questions, recommended methods, and level of recommendation. Colors of the questions indicate the link of the question to the four method categories defined in Sonderegger et al. (2020): green, depletion methods; yellow, future efforts methods; orange, thermodynamic accounting methods, and blue, supply risk methods



How can I quantify the relative...

...changing opportunities of future generations to use mineral resources due to a current mineral resource use? (inside-out)					....potential mineral resource availability issues for a product system? (outside-in)	
...contribution of a product system to the depletion of mineral resources?	...contribution of a product system to changing mineral resource quality?	...consequences of the contribution of a product system to changing mineral resource quality?	...(economic) externalities of mineral resource use?	...impacts of mineral resource use based on thermo-dynamics?	...potential availability issues for a product system related to mid-term physico-economic scarcity of mineral resources?	...potential accessibility issues for a product system related to short-term geopolitcal and socio-economic aspects?
$\text{ADP}_{\text{ultimate reserves}}$ $\text{ADP}_{\text{reserve base}}$ $\text{ADP}_{\text{economic reserves}}$ Eco-scarcity AADP AADP (update) EDIP 97 EDIP 2003 $\text{LIME2}_{\text{midpoint}}$	Ore Grade Decrease	**SOP** ORI Eco-Indicator 99 Impact 2002+ Stepwise 2006 ReCiPe 2008 SCP EPS TR-ERC	**LIME2 (endpoint)** Future Welfare Loss*	**CEENE** CExD TR SED	**$\text{ADP}_{\text{economic reserves}}$** $\text{ADP}_{\text{reserve base}}$ Eco-scarcity AADP AADP (update) EDIP 97 EDIP 2003 $\text{LIME2}_{\text{midpoint}}$	**ESSENZ** **GeoPolRisk** ESP
Recommended		*Interim recommended*	*Interim recommended*	*Interim recommended*	*Suggested*	*Interim recommended* *Suggested*

Abbreveations: ADP: Abiotic Depletion Potential, AADP: Anthropogenic stock extended Abiotic Depletion Potential, ORI: Ore Requirement Indicator, SOP: Surplus Ore Potential, SCP: Surplus Cost Potential, TR: Thermodynamic Rarity, TR-ERC: Thermodynamic Rarity - Exergy Replacement Cost, CExD: Cumulative Exergy Demand, CEENE: Cumulative Exergy Extraction from the Natural Environment, SED: Solar Energy Demand, ESP: Economic Scarcity Potential, ESSENZ: Integrated Method to Assess Resource Efficiency, GeoPolRisk: Geopolitical Supply Risk

* The Future Welfare Loss method was not published at the time of the Pellston Workshop and, thus, could not be recommended. However, it models a relevant complementary impact pathway to the one described by LIME2 (endpoint) and this was discussed in detail prior to the workshop within the task force.

debated within the task force and at the Pellston Workshop®. A minority of the task force members and Pellston Workshop® participants argued that outside-in related questions and methods can be considered as part of environmental LCA.

The participants of the Pellston Workshop® did not intend to reach consensus on which of the inside-out related questions is most relevant to LCA. We suggest that the LCA practitioner considers the goal and scope of the LCA study to determine the relevance of the question to the assessment. There is also no recommendation on which of the outside-in related questions is more relevant to broader life cycle-based approaches. Thus, the level of recommendation denotes how well the recommended method can answer the respective question and should not be interpreted as an absolute judgment. To enable a comprehensive analysis of the various impacts of resource use on different aspects of the safeguard subject, a broad set of the recommended LCIA methods can be applied. If the practitioner simply selects the method with the highest recommendation level ($\text{ADP}_{\text{ultimate reserves}}$), he or she should be aware that the result is the answer to a specific question only and cannot be used as a proxy result for other questions (Table 1).

Table 2 provides more information about the geographical resolution, the timeframe of impacts, the users affected, and the number of CFs as related to the recommended methods. The CFs of the recommended methods can be accessed via links to the method developers' websites and publications provided in the supplementary material. As it can be seen, most methods focus on metals, and only SOP_{URR} and CEENE provide a relevant number of CFs for minerals and aggregates. A more comprehensive assessment of the recommended methods, along with the remainder of the 27 methods reviewed, can be found in the Supplementary Material to (Sonderegger et al. 2020).

In the following, the recommended methods are described and a rationale for their recommendation is provided along with a discussion on limitations, which explain the level of recommendation.

3.1 Question: How can I quantify the relative contribution of a product system to the depletion of mineral resources?

Recommended method: $\text{ADP}_{\text{ultimate reserves}}$ (method from Guinée and Heijungs (1995), CFs latest version at CML (2016)

Level of recommendation: recommended

The ADP model relates annual extraction rates to a stock estimate. As shown in Eq. 1, depletion is assessed using the ratio of an extraction rate (E) to a stock estimate (R), and this ratio is multiplied by a factor of 1/R to account for differences in stock size (see Guinée and Heijungs (1995) for a detailed explanation of modeling choices). Furthermore, the ADP is normalized to antimony as a reference substance. Equation 1

Table 2 Description of recommended methods in terms of geographical resolution, timeframe, concerned users, and number of characterization factors available

A	$ADP_{ultimate\ reserves}$	SOP_{URR}	$LIME2_{endpoint}$	CEENE	$ADP_{economic\ reserves}$	ESSENZ	GeoPolRisk
Geographical resolution/ perspective	Global	Global	Global	Global	Global	Global	Country
Timeframe of impacts	More than decades to hundreds of years	More than decades to hundreds of years	More than decades to hundreds of years	Current change	A few decades	Current accessibility	Current accessibility
Users affected	Future users	Current users	Future users	Current users	Next few generations	Current users	Current users
Number of CF for mineral resources (metals and metalloids/non-metal elements/minerals and aggregates)	49 (44/5/0)	75 (45/4/26)	19 (19/0/0)	65 (23/2/40)	42 (39/3/0)	49 (41/4/4)	32 (21/4/7)
Number of CF for energy carriers/other resources (water, land use, biotic resources, intermediates, etc.)	4/0	0/0	4/0	4/12	4/0	4/7	1/13

shows the calculation of the ADP (which serves as the CF for a resource *i* relative to the reference substance antimony (*ref*)). For $ADP_{ultimate\ reserves}$, the stock estimate *R* is the ultimate reserves (also known as the "crustal content").

$$ADP_i = CF_i = \frac{E_i/R_i}{E_{ref}/R_{ref}} * \frac{1/R_i}{1/R_{ref}} = \frac{E_i/R_i^2}{E_{ref}/R_{ref}^2} \qquad (1)$$

According to Guinée and Heijungs (1995), the ultimately *extractable* reserve is the only relevant stock estimate with regard to depletion of natural stocks. However, given that it depends on future technological developments, it can never be known. Therefore, a proxy is needed, and "ultimate reserves" is considered a better proxy than fluctuating stock estimates like "resources" or "economic reserves" as defined by the US Geological Survey (USGS), that provide a midterm perspective (a few decades). Alternatively, a simpler model without extraction rates, such as those used in the EDIP and $LIME2_{midpoint}$ methods, could be used. However, these methods do not provide CFs based on crustal content but economic reserves (although they could be easily calculated). While we recommend using $ADP_{ultimate\ reserves}$ as the baseline method, we, along with the method developers (van Oers et al. 2002), recommend using alternative depletion methods – in addition to $ADP_{ultimate\ reserves}$ – for sensitivity analysis.

Regarding depletion of natural stocks, the ADP model is valid and has also been recommended by other initiatives (EC-JRC 2011). However, the need to use a proxy for the ultimately extractable reserves is a limitation. With regard to depletion of total stocks (i.e., natural stocks in the earth's crust and anthropogenic stocks in the technosphere), further limitations should be acknowledged. The method does not distinguish between the part of the resource extraction that is occupied for current use (but can be available for other uses in the future) and the part that is "dissipated" into a technically and/or economically unrecoverable form (the concept of dissipation is further discussed in section 5.3). By considering the ultimate reserves as a resource stock, anthropogenic stocks are not explicitly taken into account. However, it can also be argued that anthropogenic stocks are implicitly included, as there is no deduction of already extracted resources from ultimate reserves. Further, anthropogenic stocks can be occupied rendering them inaccessible during the life time of the stocks. The AADP and AADP (update) models consider geological and (estimated) anthropogenic stocks explicitly. However, besides uncertainties involved in the determination of anthropogenic stocks, the use of extraction rates in the numerator of the characterization model is considered an inconsistency as extraction shifts mineral resources from geological to anthropogenic stocks. Until the concept of dissipation is operationalized, the $ADP_{ultimate\ reserves}$ method could be interpreted as the best available proxy for depletion of the total resource stock and therefore is a recommended method. An update of the ADP method was published during the processing of this paper (van Oers et al. (2019)) but couldn't be considered by the task force.

A minority of the Pellston Workshop® participants and task force members disagreed with the level of recommendation of $\mathrm{ADP}_{\text{ultimate reserve}}$. Since the method considers only the extraction and stocks of mineral resources and neglects anthropogenic stocks and dissipation rates, the minority argued that the recommendation level should be "interim recommended" pending future methodological development.

3.1.1 Question: How can I quantify the relative contribution of a product system to changing mineral resource quality?

Recommended method: none

This question refers to modeling approaches that evaluate a change in resource quality without considering any consequences of it. The only suitable method identified – ore grade decline (Vieira et al. 2012) – is operational only for copper and therefore is not recommended. Moreover, methods answering the follow-up question ("How can I quantify the consequences of the contribution of a product system to changing resource quality?") can be interpreted as proxy for the question posed here, depending on modeling choices. For instance, the ore requirement indicator (Swart and Dewulf 2013) and the surplus ore potential (Vieira et al. 2017) methods quantify the amount of surplus ore required to mine the same amount of metal – which can be considered a consequence of a quality change.

3.1.2 Question: How can I quantify the relative consequences of the contribution of a product system to changing mineral resource quality?

Recommended method: $\mathrm{SOP}_{\mathrm{URR}\ (\text{Ultimate Recoverable Resource})}$ (Vieira 2018)

Level of recommendation: interim recommended

The surplus ore potential (SOP) (Vieira et al. 2017) method measures the average additional ore required to produce the resource in the future, based on resource grade-tonnage distributions and the assumption that higher grade ores are preferentially extracted.

A log-logistic relationship between ore grades and cumulative extraction is developed for each resource "x" based upon fitting regression factors (α_x and β_x) to the observed (A_x; kg_x) grade-tonnage distribution of deposits. Prior to this procedure, an economic allocation of ore tonnage is performed to account for potential co-production. An average CF is developed by integrating along the product of resource extraction (RE_x) and the inverse of the grade log-logistic relationship (OM_x, the amount of ore mined per amount of resource x) from cumulative resource extraction (CRE_x) to the maximum resource extraction (MREx) then dividing by total remaining extraction (R_x). Therefore, the CF representing the average surplus ore potential of each resource (SOP_x; kg_{ore} per kg_x) can be expressed as:

$$SOP_x = \frac{\int_{CRE_x,total}^{MRE_x} OM_x(RE_x)\, dRE_x}{R_x} \tag{2}$$

$$OM_x = \frac{1}{G_x} = \frac{1}{exp(\alpha_x)\left(\frac{A_{x,sample}-CRE_{x,sample}}{CRE_{x,sample}}\right)^{\beta_x}} \tag{3}$$

As the total remaining extraction is unknown, it is approximated by demonstrated economic reserves and ultimate recoverable resources (URR, approximated as 0.01% of the resource within 3 km) to provide two sets of characterization factors ($\mathrm{SOP}_{\text{reserves}}$ and $\mathrm{SOP}_{\mathrm{URR}}$). In the recommended version of the method (Vieira 2018), the set of CFs for 18 resources based on the approach described above (Vieira et al. 2017) was extended to 75 resources through the extrapolation of SOP values using a correlation between SOP and resource prices.

Other methods were not recommended for the following reasons: ReCiPe2016 endpoint is based on "surplus cost potential" (SCP) and uses a mid-to-endpoint conversion factor based on copper, which may not be applicable to all resources. The original SCP method (Vieira et al. 2016) and the ore requirement indicator (ORI) method (Swart and Dewulf 2013) were not recommended as they are based on regression data that were determined using mined ore tonnage and mining cost data over a period characterized by very high growth in mineral demand and mineral price increases that significantly distorted short-term mineral markets. Hence, the CFs developed in those methods are highly sensitive to the underlying time period, whereas $\mathrm{SOP}_{\mathrm{URR}}$ is based on grade-tonnage distributions that are considered very robust for each deposit type. ReCiPe2008 (Goedkoop et al. 2013) is based on data for existing mines only and does not include data for undeveloped mineral deposits known to be available. Eco-indicator 99 (Goedkoop and Spriensma 2001), Impact2002+ (Jolliet et al. 2003), Stepwise2006 (Weidema et al. 2008; Weidema 2009), EPS 2000/2015 (Steen 1999, 2016), and thermodynamic rarity methods (Valero and Valero 2014) are not recommended because they do not model an ore grade decline (and its consequences) based on extraction data but only consider an assumed change in ore grades at a future point in time (see section 6.2 in Sonderegger et al. (2019)).

A key limitation of the $\mathrm{SOP}_{\mathrm{URR}}$ method is that it assumes mining from highest to lowest grade and does not explicitly account for competing factors such as technological and economic considerations (Sonderegger et al. 2020). However, the marginal gradient of the grade-tonnage curves should provide a good relative assessment between mineral resources, which is useful for LCA purposes. The extrapolation of observed grade-tonnage data is also an assumption for the long-run future and therefore impossible to prove or falsify. Therefore, the SOP_{URR} method (Vieira 2018) is only "interim recommended." Considering the limitations discussed above, one task force member representing the exploration and mining industry does not support this recommendation and published a split view in parallel to this work (Ericsson et al. 2019) in which the validity of the impact pathway addressed by methods in this category is challenged.

3.1.3 Question: How can I quantify the relative (economic) externalities of mineral resource use?

Recommended method: $LIME2_{endpoint}$ (Itsubo and Inaba 2014)

Level of recommendation: interim recommended

The $LIME2_{endpoint}$ method is based on El Serafy's user cost (El Serafy 1989). The user cost assesses the share of the economic value of extracted resources that needs to be reinvested to maintain the benefit obtained from the extraction of resources (Itsubo and Inaba 2014). The indicator of $LIME2_{endpoint}$ expresses the economic externality of resource use in units of monetary value and is calculated as follows:

$$CF_{LIME2endpoint} = R\left\{1/(1+i)^N\right\}/P \qquad (4)$$

where R is annual profit of the target element; i is the interest rate; N is ratio of economic reserves to production (years to depletion); P is current annual production amount of the target element.

The LIME2 method is recommended given that it incorporates uncertainty data and was the only peer-reviewed method available in this category at the time of the Pellston Workshop®. A few months later, the future welfare loss method was published (Huppertz et al. 2019), which describes a complementary impact pathway to the one modeled in LIME2. While LIME2 assesses the potential externality of lost future income due to a hypothetical lack of investment of earnings from the sale of finite resources, the Future Welfare Loss method assesses the potential externality of lost hypothetical rents due to current overconsumption of the resource.

The main limitations of the recommended LIME2endpoint method are the uncertainty of determining the relevant interest rate, different opinions on the applicability of the El Serafy's method (which estimates pricing failure in the market as a whole society) to a specific mineral, and the limited number of CFs (19 for mineral resources and 4 for energy carriers). The LIME method has three versions (LIME/LIME2/LIME3). LIME2 is the updated version of the original LIME method, with the addition of uncertainty analysis. LIME3, which was not yet published at the time of the Pellston Workshop®, is an extended version of LIME2 with country-specific (LIME and LIME2 provide generic CFs without consideration of country-level differences in production and reserves).

3.1.4 Question: How can I quantify the relative impacts of mineral resource use based on thermodynamics?

Recommended method: CEENE (Dewulf et al. 2007)

Level of recommendation: interim recommended

The exergy of a resource is the maximum amount of useful work that can be obtained from it when it is brought to equilibrium with the environment (reference state). As mineral resources differ from the reference state with respect to their chemical composition and their concentration, in principle they can produce work. Although most mineral resources are not extracted from nature with the aim to directly produce work, they still contain exergy. For example, the copper in a copper deposit is much more concentrated and occurs in another chemical form (e.g., $CuFeS_2$) than the copper dissolved in seawater (the reference state for copper). This distinction with respect to commonness makes a resource to be valuable in exergy terms.

The cumulative exergy extraction from the natural environment (CEENE) method (Dewulf et al. 2007) aggregates the exergy embedded in extracted resources (e.g., copper), measured as the exergy difference between a resource as found in nature and the defined reference state in the natural environment. Using the definition of Szargut et al. (1988), the reference state is represented by a reference compound that is considered to be the most probable product of the interaction of the element with other common compounds in the natural environment and that typically shows high chemical stability (e.g., SiO2 for Si) (De Meester et al. 2006). For metals, CEENE calculates the exergy value of the mineral species (e.g., $CuFeS_2$) containing the target metal, making it independent of the ore grade.

The Pellston Workshop® participants recommend the CEENE method over other thermodynamic accounting methods because it was originally operationalized to LCA by proposing a more accurate exergy accounting method than the one used in the Cumulative Exergy Demand (CExD) method. For instance, in CExD the exergy values of metals are calculated from the whole metal ore that enters the technosphere, whereas CEENE only regards the metal-containing minerals of the ore (with the argument that the tailings from the beneficiation are often not chemically altered when deposited). While thermodynamic rarity (TR) offers an alternative reference state (Thanatia) and as opposed to the other approaches considers ore grade in the evaluation of resources, it is not mature enough when compared to Szargut et al.'s (1988) approach (used in CEENE).

Another method with a thermodynamics-based approach is the solar energy demand (SED), which is based on the energy approach (with a few differences in the calculation approach) (Rugani et al. 2011). It considers the equivalent solar energy that nature requires to provide a resource, which includes more energy than what can be used out of this resource. Therefore, the method is less relevant than CEENE with regard to the safeguard subject of mineral resources.

As the focus of this work is on mineral resources, and the overall (inside-out) concern is "changing opportunities of future users to use resources," the CEENE method is "interim recommended." A higher level of recommendation is not given because, although the CEENE method allows quantifying the value of a resource in exergy terms, the approach, as currently applied to mineral resources, does not fully reflect their societal value as it leaves aside non-thermodynamic aspects.

3.1.5 Question: How can I quantify the relative potential availability issues for a product system related to physico-economic scarcity of mineral resources?

Recommended method: $\text{ADP}_{\text{economic reserves}}$

Level of recommendation: suggested

The model for calculation of $\text{ADP}_{\text{economic reserves}}$ is the same as in Eq. 1**,** but economic reserves are used as the stock estimate R. The (economic) reserves are the part of known resources that is determined to be economically extractable at a given point in time. The extraction-to-stock ratio used in the model can be interpreted as a scarcity measure, and accordingly the CFs of $\text{ADP}_{\text{economic reserves}}$ provide a measure of the pressure on the availability of primary mineral resources.

Given that the extraction rates are considered important for this midterm perspective (a few decades), a model excluding extraction rates – as used in the EDIP and $\text{LIME2}_{\text{midpoint}}$ methods – is not recommended here.

The exclusion of anthropogenic stocks is considered a major limitation because these stocks can strongly influence the "resource availability for a product system" (Schneider et al. 2011). Unlike the $\text{ADP}_{\text{ultimate reserves}}$ method, anthropogenic stocks are not implicitly included in the natural stock estimate of the $\text{ADP}_{\text{economic reserves}}$ method. Previous attempts to include anthropogenic stocks in the characterization model (e.g., the AADP method, (Schneider et al. 2015)) still face the challenge of considering how much of this stock would become available within the time horizon considered by the CFs.

Furthermore, the use of the economic reserves estimate is problematic because historically it has actually grown in absolute terms, and the extraction-to-economic-reserve ratios have been relatively stable, indicating no increase in resource scarcity. Furthermore, economic reserve estimates are highly uncertain for by-products. Finally, the method has not been explicitly developed to address outside-in questions, and consequently the results need to be interpreted carefully. For these reasons, the $\text{ADP}_{\text{economic reserves}}$ method is only "suggested."

3.1.6 Question: How can I quantify the relative potential accessibility issues for a product system related to short-term geopolitical and socioeconomic aspects?

Recommended methods: ESSENZ (Bach et al. 2016) and GeoPolRisk (Gemechu et al. 2015; Helbig et al. 2016; Cimprich et al. 2017)

Levels of recommendation: interim recommended and suggested, respectively

The ESSENZ method (Bach et al. 2016), which enhanced the preceding ESP method (Schneider et al. 2014), quantifies eleven geopolitical and socioeconomic accessibility constraints (country concentration of reserves and mine production, price variation, co-production, political stability, demand growth, feasibility of exploration projects, company concentration, primary material use, mining capacity, and trade barriers). Indicators for these categories are determined and divided by a target value above which accessibility constraints are assumed to occur. This distance-to-target (DtT) ratio is normalized by the global production of the respective resource to reflect the assumption that the accessibility constraints described above can be more severe for resources produced in relatively small amounts. Finally, the normalized DtT factors are scaled (to a range between 0 and 1.73×10^{13} in each category) to balance the influence of the LCI and the CFs on the LCIA result and to ensure a similar range of CFs among the supply risk categories.

The GeoPolRisk method weights the political stability of upstream raw material producing countries by their import shares to downstream product manufacturing countries (Gemechu et al. 2015; Helbig et al. 2016; Cimprich et al. 2017). It incorporates the country concentration of production as a mediating factor in supply disruption probability arising from political instability of trade partner countries. The logic is that highly concentrated production of raw materials limits the ability of importing countries to restructure trade flows in the event of a disturbance (such as political unrest) that may lead to supply disruption. Domestic production is assumed to be "risk-free" from a geopolitical perspective. The method also incorporates a "product-level importance" factor that effectively "cancels out" the magnitude of inventory flows. The term "inventory flows" is used to encompass both elementary and intermediate flows – as the total supply risk associated with a product system is a function of its entire supply chain (for further explanation see (Cimprich et al. 2019)).

Comparing the two methods, the GeoPolRisk method allows the consideration of the specific import structure of a particular country, while ESSENZ takes a global perspective. Further, ESSENZ considers a broader set of potential geopolitical and socioeconomic constraints and provides more CFs for mineral resources. Considering the respective strengths of the two approaches, the ESSENZ method is interim recommended to assess the supply risk of multinational companies having locations all over the world. The GeoPolRisk method is suggested to assess country-specific supply risks arising from political instability of trade partners from which mineral resources are imported. Both methods are usually applied outside an LCA software because the elementary flows reported in LCI datasets do not necessarily reflect the intermediate flows or the material composition of products.

The ESSENZ and GeoPolRisk methods rely on the key assumption that supply risk is a function of supply disruption probability and vulnerability. They share the limitation of focusing on the supply risk of primary resources only and either do not consider the country-specific import situation (as in the ESSENZ method) or are limited concerning the accessibility constraints considered (as in the GeoPolRisk method).

4 Case study

In order to illustrate the application of different methods, all 27 identified methods were tested on a case study of a European-manufactured electric vehicle (EV). The functional unit is defined as 1 km traveled. The life cycle inventory developed by Stolz et al. (2016), which comprises the extraction of 34 primary mineral resource elements, 37 primary mineral resource aggregates, and 4 energy carriers, has been used for this purpose.

Before presenting and discussing results, it should be noted that the development of a life cycle inventory is controversial with regard to mineral resources. The definition of elementary flows and the allocation of metals in multi-metal ores (e.g., copper-gold ore) can be accomplished in two different ways: either the metal content of the ores (e.g. Cu and Au) is considered the relevant elementary flows and allocated to the produced metals (e.g., copper and gold) based on physical mass balances and the remaining inputs and outputs (e.g.,, gangue and emissions) based on economic or other relationships (Fig. 1a), or the entire ore (e.g., containing Cu, Au, and gangue) is regarded as the elementary flow and allocated to the products using economic relationships (Fig. 1b).

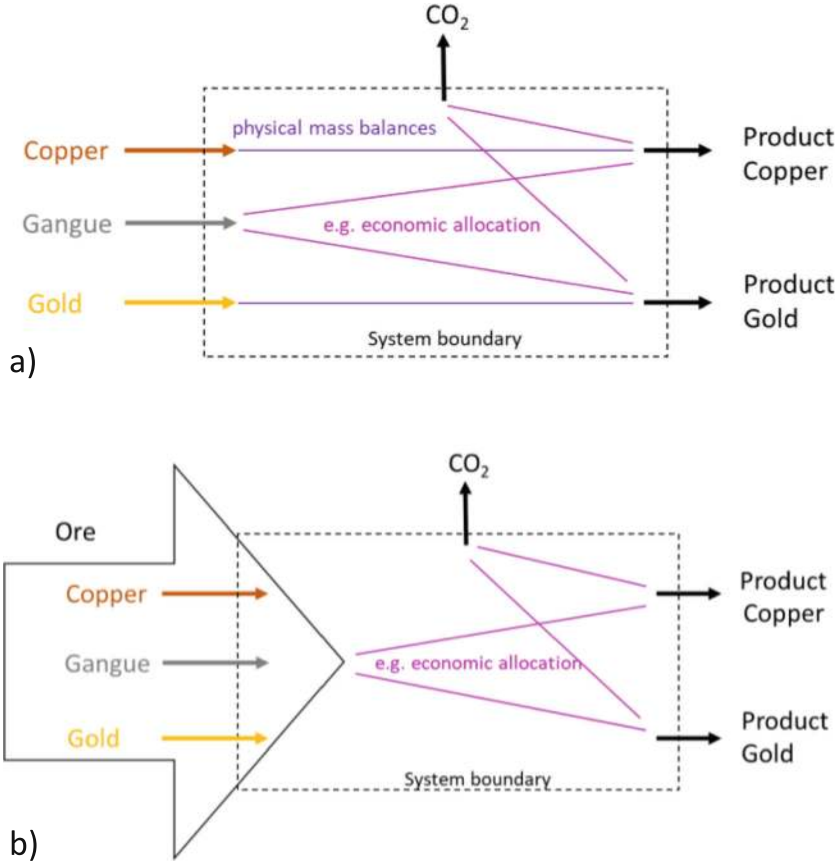


Fig. 1 Addressing the issue of co-production by allocating (**a**) the metal inputs based on physical mass balances to the products and other flows based on different, e.g., economic, allocation parameters, or (**b**) the ore (instead of its components) in the same way as other elementary flows to the products, e.g., via economic allocation

While the task force members could not agree to a recommendation for one approach over the other, it should be noted that the choice of the allocation procedure can strongly influence the resulting LCI: In the first case, the LCI reflects the material composition of the product based on physical mass balances. In the second case, the LCI reflects the environmental interferences related to producing one metal, which often leads to the co-extraction of other metals. So the LCI can contain metals which are not physically present in the product.

Considering the relevance of multi-metal ore allocation for the LCI and the fact that it is handled differently in leading LCI databases, the two allocation approaches are further described in the supplementary material. In this case study, the first option (allocation according to physical mass balances and economic relationship) has been used to derive the LCI.

Figure 2 shows the LCIA contribution analysis for all the minerals included in the LCI of the EV life cycle determined by means of the seven recommended methods. Resources contributing more than 10% each to at least one impact category are presented individually, while the remaining resources are summarized in the category "other resources." As the number of CFs differs between LCIA methods, and as the methods partly cover different elementary flows, care should be taken when interpreting the LCIA results to not confuse a null value with a missing CF. We refrained from reducing the LCI to the number of resources for which all methods provide CFs. While this would ease the interpretation, it would reduce the number of resources drastically and would not reflect the "real" result which LCA practitioner obtain when selecting one of the methods in an LCA software.

Before discussing the case study results in detail, it can be seen that the findings are highly method dependent and hardly any similarities regarding the contribution of resource uses to the total results can be observed. While this might appear confusing at first, such an outcome is logical because different methods describe different cause-effect chains (Sonderegger et al. 2020) and address different questions related to resource use (Table 1). So it is clear that, e.g., a method assessing the long-term depletion of geological stocks does not come to the same results as a method analyzing short-term supply risks.

Despite being used in a relatively small amount in the LCI, gold dominates the result for ADP$_{\text{ultimate reserves}}$ due to its relatively low abundance in the earth's crust. In contrast, the result of ADP$_{\text{economic reserves}}$ is dominated by tantalum as the current economic reserves are under relatively high pressure due to current extraction rates. Even though the reserve and extraction data for tantalum can be considered uncertain, this indicates a potential mid-term technology-driven, physico-economic availability constraint. The different results from the two versions of the ADP method reveal the strong influence of the respective stock estimates (ultimate reserves vs. economic reserves) used in the characterization model (Eq. 1).

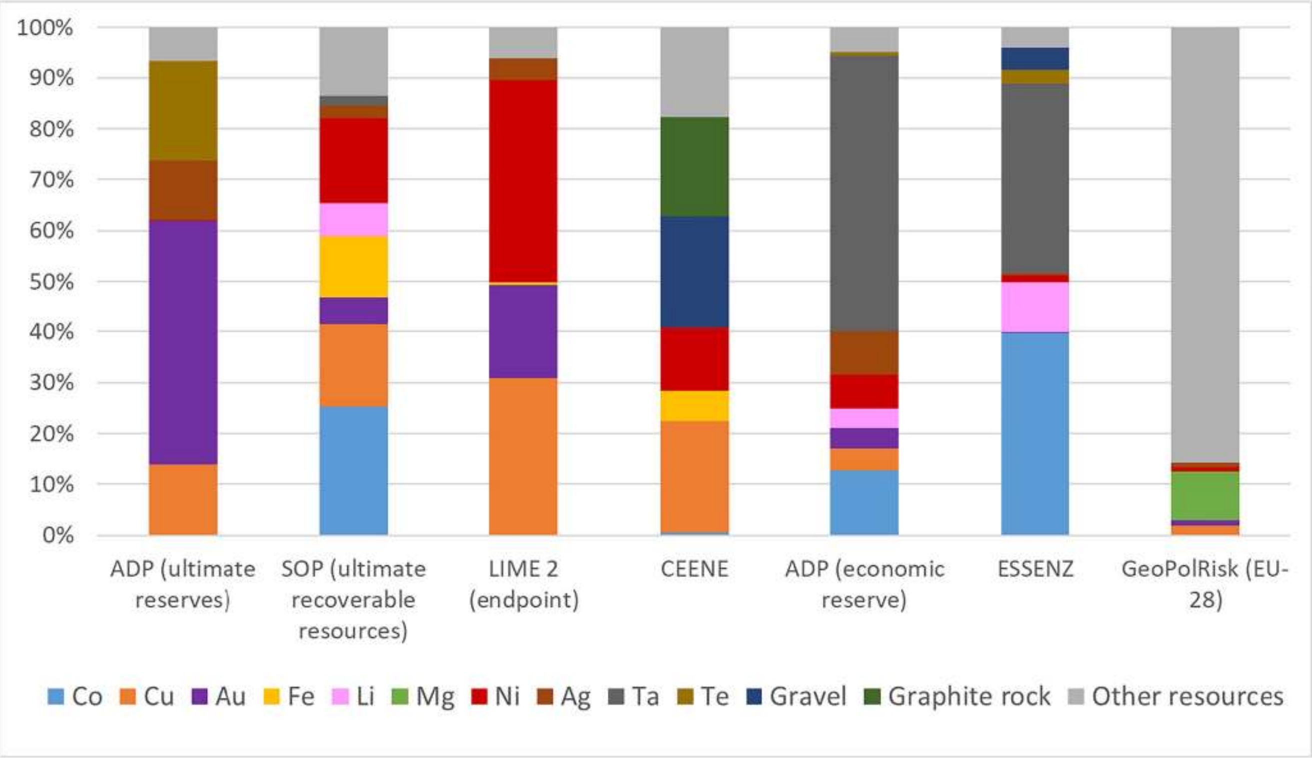


Fig. 2 Contribution analysis for case study of driving 1 km in an European-manufactured electric vehicle using the recommended methods (excluding energy carriers and uranium)

The use of copper makes a significant contribution for the inside-out related methods (13–31%) but makes a smaller contribution for the outside-in methods (0–5%). This result indicates that short-term availability constraints for the use of copper in electric vehicles are relatively small, though this current use may affect the opportunities of future users to use copper. Besides copper, nickel is another large contributor to the LCIA results when using the future efforts methods (SOP and LIME2) or the CEENE method.

Gravel causes a relatively high contribution to the LCIA result obtained by the CEENE method and a noticeable contribution to the result of the ESSENZ method, although the CFs for gravel are relatively small in both methods. The reason for this is the relatively large amount of gravel in the LCI which includes the construction of roads. The other LCIA methods do not provide CFs for gravel.

Cobalt and tantalum are the main contributors to the LCIA results when using the outside-in related methods $\mathrm{ADP}_{\mathrm{economic\ reserves}}$ and ESSENZ – despite the different scopes and timeframes of these methods: mid-term physico-economic availability for $\mathrm{ADP}_{\mathrm{economic\ reserves}}$ and short-term geopolitical and socioeconomic accessibility for ESSENZ. It should be noted that the GeoPolRisk method does not have CFs for these minerals and that the ESSENZ method comprises eleven different supply risk factors that are not intended to be aggregated into an “overall” CF (Bach et al. 2016); aggregation was performed in this case study for illustrative purposes only.

The differences in the LCIA results when using the GeoPolRisk and ESSENZ methods can be explained by the broader range of supply risk aspects considered in the ESSENZ method, the different coverage of inventory flows, the “canceling out” of mineral resource amounts in the GeoPolRisk method, and the spatial resolution of the CFs assessing the supply risk of European imports (GeoPolRisk) or global production (ESSENZ). Further discussion of the case study, results obtained by the supply risk methods is provided in a separate publication by Cimprich et al. (2019).

The impact assessment results for all 27 methods are shown in Figs. S4 and S5 in the supplementary material along with a more detailed comparison and discussion within the four method categories (depletion, future efforts, thermodynamic accounting, and supply risk) presented in Figs. S6–S13.

5 Recommendations for future method development

Based on the review of methods by Sonderegger et al. (2020) and on the findings of the case study presented above, we provide recommendations for future method developments. In the following subsections, we provide general recommendations applicable to all methods along with specific recommendations for each method category (depletion, future efforts, thermodynamic accounting, and supply risk). Finally, we provide recommendations to define the “dissipative resource use” and include it in the development of future characterization models.

5.1 General recommendations

Across all method categories, the CFs need to be updated on a regular basis, the number of CFs should be increased to cover a broader range of inventory flows (especially currently underrepresented minerals and aggregates), and uncertainties should be addressed. Although the safeguard subject for mineral resources defined includes “chemical elements, minerals, and aggregates as embedded in a natural or anthropogenic stock,” the characterization models of existing methods consider only primary resource extraction and natural stocks (except for the AADP method, which also considers anthropogenic stocks). Therefore, secondary resources should be considered in future method developments in all method categories. To facilitate practical application of the methods, method developers should coordinate with software developers to ensure that new methods and updated CFs are incorporated in the latest versions of LCA software.

5.2 Specific recommendations by method category

5.2.1 Depletion methods

It is recommended to consider the full extraction rather than the currently used net production, which neglects flows of material ending up in tailings, waste rock, or as emissions to nature. Considering the relevance of the anthropogenic stock and “dissipative resource use” (see section 5.3) as the actual reason for the depletion of total stocks (natural + anthropogenic), the characterization models of depletion methods could be adopted to reflect the dissipation of total stocks.

5.2.2 Future efforts methods

The future efforts methods based on ore grades have been criticized for their assumption that preferential extraction of known higher-grade resources will lead to long-term decline in the average resource grade (Ericsson et al. 2019). The relative contribution of extraction to declining resource grades in relation to other contributing factors such as mineral prices and technology has not been empirically validated. To validate the relative contribution of extraction to ore grade decline, two approaches for future studies are proposed: (1) to check whether the average cutoff grade required to define newly discovered deposits at a particular contained tonnage is declining over time; and (2) to check whether contained resource tonnages of newly identified deposits are declining when assuming constant resource cutoff grades used in the definition of each resource estimate.

Besides the need to validate the assumptions of existing ore grade-based methods, it should be noted that ore grade is only one measure of resource quality that influences future efforts for resource extraction. This limited focus of existing methods calls for the inclusion of other relevant aspects such as technology-driven, physico-economic accessibility (e.g., depth, morphology, and location), and mineral complexity (e.g., mineralogy, particle size distribution and grain "texture"). Moreover, mining costs and mined ore grades are heavily influenced by short-term trends in market conditions. To ensure that CFs reflect relative rates of declining resource quality, the short-term influences of commodity prices should be controlled for. This is particularly relevant for the ORI and SCP methods, which directly use data from the mining industry for particular time periods. Therefore, baseline ore grade and cost data over multiple commodity price cycles should be used before these or similar methods can be recommended.

The (interim) recommended $\mathrm{SOP}_{\mathrm{URR}}$ method has derived a large share of its CFs from extrapolation of raw material prices. Since extrapolation adds uncertainty, it would be preferable to determine more CFs in an empirical way. Additionally, there is lower confidence in the method's underlying assumption of preferential extraction of higher-grade ores for co-produced minerals, as the extraction of these resources is heavily influenced by the extraction of the primary "host" mineral. Further work to establish the strength of relationships between co-produced resource grades and host-mineral grades may build confidence in the assumptions underlying the SOP and other ore grade decline-based methods.

In an effort to bypass the uncertainties related to physical models discussed above, the $\mathrm{LIME2}_{\mathrm{endpoint}}$ and Future Welfare Loss method use economic relations to assess economic externalities of current resource use. In addition to these methods, there are other methods, from the field of environmental economics, to assess economic externalities with a main focus on the present generation. These different temporal perspectives of economic externalities should be discussed and reflected in future method developments.

5.2.3 Thermodynamic accounting methods

Thermodynamic accounting methods can be used to assess a broad range of resources including fossil energy carriers, land, wind (kinetic) energy, hydropower (potential) energy, and water, among others. However, their meaning in the assessment of mineral resource use is controversial, as thermodynamic indicators, like exergy, only reflect certain physical characteristics and hardly express the societal relevance and value of these resources. To address this shortcoming and to link the exergy (and energy)-based assessment models to the safeguard subject for mineral resources, new exergy reference states or resource availability information should be developed and integrated in characterization models.

Moreover, the system boundaries between nature and the technosphere should be specified (as discussed in the supplementary material of Sonderegger et al. (2020)) in order to clearly define the elementary flows for which exergy values (serving as CFs) should be determined.

5.2.4 Supply risk methods

To enable a comprehensive assessment of supply risks, it is recommended to consider the specific purchase structure and supply chains of companies in addition to the currently available global (ESSENZ) or country-level (GeoPolRisk) assessments. Although recycling can mitigate supply risks, recycled materials can also be subject to accessibility constraints. Furthermore, supply risks can occur along the supply chains and intermediate products (e.g., copper alloys or semifinished copper products) can be affected by accessibility constraints. Therefore, future method development should consider geopolitical and socioeconomic accessibility constraints of secondary raw materials and intermediate products in addition to currently assessed primary raw materials. This recommendation illustrates a challenge for supply risk methods, which often provide CFs for intermediate products (e.g., refined copper) rather than the elementary flows (e.g., mined copper) usually reported in LCI datasets. Further, it is recommended to include additional factors, e.g., raw material stockpiles (or "safety stocks") held by countries or companies to mitigate supply risk and provide an immediate response mechanism in the event of supply disruption (Sprecher et al. 2017). Finally, the characterization models of supply risk methods should be validated and refined using empirical evidence of supply risk factors (e.g., through ex-post analysis of time series data on commodity markets and geopolitical events).

5.3 Outlook on dissipation

A key point of discussion, both in the task force and at the Pellston Workshop®, with regard to further method development was the resource "dissipation" concept. The discussion of mineral resource dissipation starts from the fact that mineral resources are not "lost" for human use when extracted from nature into the technosphere, as long as they can be reused, recycled, or recovered in some way. Resources are only "lost" if converted to an irrecoverable state, which could be called a "dilution" loss (van Oers et al. 2002) or a "dissipative" loss (Stewart and Weidema 2005). To operationalize this concept in LCA, (a) the LCIs need to provide information about dissipative losses in addition to the currently reported resource extraction (where the main challenge occurs with regard to dissipation in the use and end-of-life phases), and (b) LCIA methods should integrate dissipation into characterization models. To date, neither of these conditions has been implemented, but suggestions exist on how to deal with dissipation on both levels:

5.3.1 LCI

Given the lack of inventory data to measure dissipation, Frischknecht and Büsser Knöpfel (2013) and Frischknecht (2014) suggest modeling dissipative use through an inventory correction that credits recycled resources, and by applying existing CFs on the resulting dissipative use of resources. Zampori and Sala (2017) describe different alternatives on how to structure LCIs to measure dissipation and provide simplified case studies to evaluate the features of a dissipation approach.

5.3.2 LCIA

van Oers et al. (2002) and van Oers and Guinée (2016) discuss how the ADP characterization model (Eq. 1) could be adjusted to consider dissipation (or, in their terms, "dilution") of mineral resources. The adjustment would replace the extraction rate (E in Eq. 1) with the dissipation rate, or in their terms the "leakage" rate (i.e., the dissipation from the technosphere to the environment), and the natural stock estimate (R in Eq. 1) with "the total reserve of resources in the environment and the economy" (i.e., the total of the natural and anthropogenic stocks).

To operationalize the dissipation concept in LCA, the following methodological issues still need to be resolved and options to integrate these aspects in LCI databases need to be found:

5.3.3 The dissipation threshold

The threshold between dissipative and non-dissipative mineral resource use is not absolute but depends on technological and economic factors, which can change over time. Furthermore, a definition of resource quality is needed to set the quality threshold beyond which a quality loss constitutes a dissipative loss. Resource quality information, such as concentration, would also need to be provided for resource inputs and outputs in life cycle inventories.

5.3.4 Dissipation within the technosphere

Dissipation to the ecosphere (i.e., the environment) occurs, for example, by dispersion into irrecoverable concentrations in environmental compartments (air, water, and soil), whereas dissipation within the technosphere may include the use of minerals in alloys, which may make a separation of the alloying elements "essentially impossible" (Reck and Graedel 2012), or the unwanted mixing of metals in recycling processes (Reller 2016) or low absolute amounts of resources in landfills making extraction unprofitable regardless of the concentration.. In both cases – dissipation to the ecosphere and dissipation within the technosphere – the dissipation implies that for the use of another unit of the resource, additional resources will need to be extracted either from the environment or from anthropogenic stocks.

5.3.5 Occupation or borrowing use

Another issue with regard to a "loss" within the technosphere is the issue of resource occupation or "borrowing" (van Oers et al. 2002; Frischknecht 2016). As long as resources are in use, they are not available for other users although they are not necessarily dissipated (yet). This constraint to resource availability is not directly addressed by the dissipation concept. Other constraints may similarly be overlooked, e.g., geopolitical accessibility constraints. It is debatable whether resource occupation beyond a maximum lifetime should be assessed as dissipative use, as suggested by Frischknecht (2016).

6 Conclusions

The subject of mineral resource use has been a topic of persistent debate among LCIA method developers and a source of confusion for LCA practitioners given the variety of LCIA methods to choose from. Based on the review of 27 existing LCIA methods assessing the impacts of mineral resource use in LCA, accomplished in the first part of this paper series (Sonderegger et al. 2020), this paper provides recommendations for application-dependent use of existing methods in LCA studies and for future method development. As a starting point, the safeguard subject for mineral resources within the AoP natural resources has been defined. Accordingly, we formulated seven key questions regarding the consequences of mineral resource use (Table 1), which can be grouped into "inside-out" (i.e., current resource use changing the opportunities for future users to use resources) and "outside-in" related questions (i.e., potential resource availability issues for current resource use). Existing LCIA methods were assigned to these questions, and seven methods ($\text{ADP}_{\text{ultimate reserves}}$, SOP_{URR}, $\text{LIME2}_{\text{endpoint}}$, CEENE, $\text{ADP}_{\text{economic reserves}}$, ESSENZ, and GeoPolRisk) are recommended for use in current LCA studies at different levels of recommendation in relation to the questions they address. In general the levels of recommendation are relatively low (1 recommended, 4 interim recommended, 2 suggested) indicating the need for methodological enhancements across method categories. All 27 identified LCIA methods were tested on an LCA case study of a European-manufactured electric vehicle, and yielded divergent results due to their modeling of impact mechanisms that address different questions related to mineral resource use. Besides method-specific recommendations, we recommend that all methods increase the number of abiotic resources covered, regularly update their CFs, and consider the inclusion of secondary resources and anthropogenic stocks. Furthermore, the concept of dissipative resource use should be defined and integrated in future method developments.

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Compliance with ethical standards

Disclaimer The views, interpretations and conclusions presented in this paper are those of the authors and do not necessarily reflect those of their respective organizations.

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