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Journal Article

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Publication date:

2020-04

Permanent link:

<https://doi.org/10.3929/ethz-b-000397312>

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Originally published in:

The International Journal of Life Cycle Assessment 25(4), <https://doi.org/10.1007/s11367-020-01736-6>

1 *This is a post-peer-review, pre-copyedit version of an article published in The International Journal of*
2 *Life Cycle Assessment. The final authenticated version is available online at:*
3 <https://doi.org/10.1007/s11367-020-01736-6>

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5 Mineral resources in Life Cycle Impact Assessment –

6 Part I: A critical review of existing methods

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40

41 **Abstract**

42 *Purpose*

43 The safeguard subject of the Area of Protection “Natural Resources”, particularly regarding mineral
44 resources, has long been debated. Consequently, a variety of Life Cycle Impact Assessment methods
45 based on different concepts are available. The Life Cycle Initiative, hosted by UN Environment,
46 established an expert task force on “Mineral Resources” to review existing methods (this article) and
47 provide guidance for application-dependent use of the methods, and recommendations for further
48 methodological development (Berger et al., 2019).

49 *Methods*

50 Starting in 2017, the task force developed a white paper, which served as its main input to a SETAC
51 Pellston Workshop® in June 2018, in which a sub-group of the task force members developed
52 recommendations for assessing impacts of mineral resource use in LCA. This article, based mainly on
53 the white paper and pre-workshop discussions, presents a thorough review of 27 different Life Cycle
54 Impact Assessment methods for mineral resource use in the “Natural Resources” Area of Protection.
55 The methods are categorized according to their basic impact mechanisms, described and compared,
56 and assessed against a comprehensive set of criteria.

57 *Results and discussion*

58 Four method categories have been identified and their underlying concepts are described based on
59 existing literature: Depletion methods, Future Efforts methods, Thermodynamic Accounting methods,
60 and Supply Risk methods. While we consider Depletion and Future Efforts methods more “traditional”
61 Life Cycle Impact Assessment methods, Thermodynamic Accounting and Supply Risk methods are

62 rather providing complementary information. Within each method category, differences between
63 methods are discussed in detail, which allows for further sub-categorization and better understanding
64 of what the methods actually assess.

65 *Conclusions*

66 We provide a thorough review of existing Life Cycle Impact Assessment methods addressing impacts
67 of mineral resource use, covering a broad overview of basic impact mechanisms to a detailed
68 discussion of method-specific modeling. This supports a better understanding of what the methods
69 actually assess, and highlights their strengths and limitations. Building on these insights, Berger et al.
70 (2019) provide recommendations for application-dependent use of the methods, along with
71 recommendations for further methodological development.

72

73 Keywords: Life Cycle Assessment, Life Cycle Impact Assessment, method review, mineral resources,
74 raw materials, resource depletion, Life Cycle Initiative, Task Force Mineral Resources

75

76 1 Introduction

77 Mineral resources – defined here as chemical elements (e.g. copper), minerals (e.g. gypsum), and
78 aggregates (e.g. sand) as embedded in a natural or anthropogenic stock – are of great relevance for
79 industry and society. Environmental impacts associated with mineral resource extraction are assessed
80 in relatively well-established Life Cycle Impact Assessment (LCIA) categories, e.g., climate change or
81 acidification (see e.g. Nuss and Eckelman 2014). However, how to assess other impacts of mineral
82 resource use as such – e.g. whether in terms of the availability of these resources for future generations
83 or in terms of shorter-term risks of supply-chain disruptions – has been a subject of persistent debate
84 (see e.g. Dewulf et al. 2015; Drielsma et al. 2016b) and a variety of LCIA methods based on different
85 concepts are available (see e.g. Sonderegger et al. 2017). It is still discussed what the safeguard subject
86 of the Area of Protection (AoP) “Natural Resources” should be (Sonderegger et al. 2017; Berger et al.
87 2019). It is even questioned whether an impact assessment of mineral resource use – that by definition
88 comprises environmental and economic aspects – is in the scope of an environmental LCA at all
89 (Drielsma et al. 2016b). It might be due to the ambiguity on what actually should be protected with
90 regard to mineral resources in LCA that various impact pathways are currently modeled, assessing
91 different consequences of mineral resource use, e.g. the depletion of reserves, increased efforts for
92 future extraction, or short-term supply risks. Furthermore, often inadequate methods are applied in
93 LCA practice, providing the “right” answer to the “wrong” question: e.g. methods assessing the long-
94 term depletion of mineral resources in the Earth’s crust are mistakenly used by LCA practitioners who
95 are actually interested in the short-term economic risks of raw material supply disruptions (Fraunhofer
96 2018).

97 To address these challenges, the Life Cycle Initiative, hosted by UN Environment, established an
98 expert task force on “Mineral Resources” within its broader project on “Global Guidance for LCIA
99 Indicators”. The output of the task force is presented in this review of existing methods, which also
100 served as basis for a recommendations paper (Berger et al. 2019). This review paper describes the task
101 force and its working process, gives an overview of reviewed methods and their impact mechanisms,
102 categorizes and describes the methods in detail, assesses them based on an assessment scheme, and
103 finally discusses their strengths and limitations. The aim is to describe and compare methods with
104 regard to their methodological approaches in order to better understand what the methods actually
105 assess.

106 2 The task force

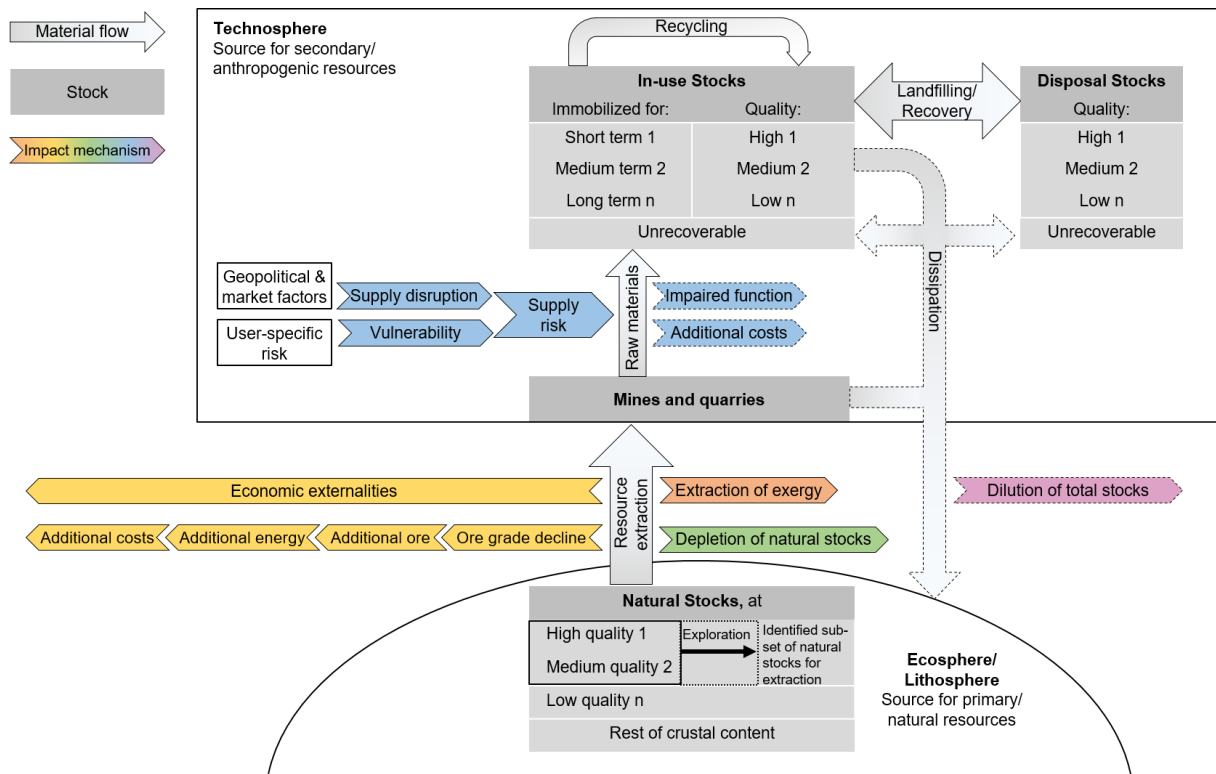
107 The task force comprised 62 members from academia, the metals and mining industry, other
108 industries, geological departments, consulting, and Life Cycle Inventory (LCI) database providers,
109 representing 14 countries around the globe. 23 members (17 from academia, amongst them many

110 method developers, 4 from consulting, 1 from the metals and mining industry, 1 from oil and gas
111 industry) have been “active” members, participating in calls, working in sub-groups, and finally
112 contributing to the scientific publications. The task force commenced in the beginning of 2017. Based
113 on discussions in regular online meetings, the task force developed a white paper, which served as the
114 main input to a SETAC Pellston Workshop® in June 2018. In this workshop, a sub-group of 8 of the
115 task force members with complementary backgrounds and expertise (5 from academia, 2 from
116 consulting, 1 from oil and gas industry) agreed on recommendations. This review paper is mainly
117 based on the white paper and the pre-workshop discussions whereas the recommendations paper
118 (Berger et al. 2019) mainly presents the workshop discussions and output.

119 3 Material flow and impact mechanisms overview

120 At the time the task force started its work, ~~27 different methodological approaches~~33 methods
121 assessing impacts of mineral resource use were available from literature or provided to the task force
122 internally by method developers. For those methods with methodological differences between an old
123 and an updated version, e.g. Anthropogenic Stock Extended Abiotic Depletion Potential method
124 (AADP) or EDIP, we reviewed both in order to cover all the different approaches. For the other
125 methods, we only considered the most recent version, e.g. LIME. This resulted in a set of 27 different
126 methodological approaches. We first identified their basic impact mechanisms and related these to
127 flows of mineral resources from the lithosphere through the technosphere and finally back into the
128 ecosphere (Figure 1).

129



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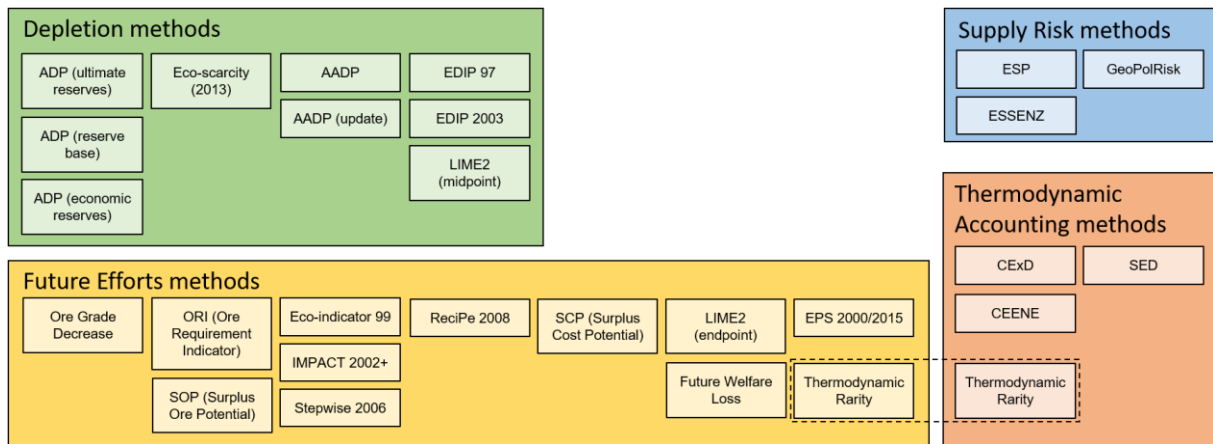
131 Figure 1: Material flow (grey layer) and impact mechanisms overview, presented in color for Depletion methods (green),
 132 Future Effort methods (yellow), Thermodynamic Accounting methods (orange), Supply Risk methods (blue), and the
 133 “Dilution of total stocks” approach (purple). Dashed material flows and impact pathways are proposed or discussed but not
 134 agreed, operational, or published yet.

135 The material flow layer (grey layer in Figure 1) shows that primary/natural mineral resources are
 136 extracted from natural stocks in the lithosphere (a part of the ecosphere) and enter the technosphere via
 137 mining and quarrying, further on just called mining. Mineral resources are immobilized in products
 138 and infrastructure (collectively termed “in-use stocks”) for short to long time scales (e.g. aluminium
 139 can vs. steel bridge) and at different qualities. By means of recycling, mineral resources can be kept
 140 and cycled inside the technosphere for different time scales and at different qualities (up- or down-
 141 cycling). If products are not recycled, mineral resources can be stored at different qualities in disposal
 142 stocks, e.g. landfill stocks, from which they potentially may be recovered. The quality of an abiotic
 143 resource may be a complex composite of different quality aspects. With regard to the efforts needed to
 144 extract a resource from a natural mineral deposit, this might for example include target element grade,
 145 “gangue minerals” or impurity grades, grain size distributions and grain “texture”, ore hardness, size
 146 and heterogeneity of the deposit, or accessibility (e.g. depth, remoteness). Conceptually many of these
 147 aspects may be applicable to extraction from anthropogenic stocks with some tweaking. The
 148 anthropogenic stock in the technosphere (product + disposal stocks) is the source for
 149 secondary/anthropogenic mineral resources. Therefore, it is argued that an actual loss of mineral
 150 resources for human use only occurs through dissipation, i.e. any form of use rendering a mineral

151 resource unrecoverable, whether in the ecosphere or in the technosphere. For further discussion of the
152 dissipation concept, see Berger et al. (2019). Supplementary ~~material~~-Material 1 (section S2) further
153 describes and details mineral resource quality, dissipation, and the ecosphere-technosphere boundaries.

154 On top of the material flow layer, an impact mechanism layer (coloured layer in Figure 1) has been
155 added to show the position of characterization models in the material flow context. Starting from
156 mineral resource extraction, some methods model the depletion of natural stocks (in one case also
157 considering the anthropogenic stock) (in green), others the extraction of exergy (i.e. the exergy
158 difference between the mineral resource as found in nature and a defined reference state in the natural
159 environment) (in orange), and still others an ore grade decline and resulting additional ore
160 requirements, energy, or costs (in yellow). Other methods do not consider physical parameters but
161 directly model economic externalities, i.e. costs or welfare loss for future generations (also yellow).
162 Another category of methods (in blue) model the supply risk of mineral resources/raw materials in the
163 technosphere, taking into account the probability of supply disruption resulting from geopolitical and
164 market factors (e.g., production concentration and political instability of producing countries) as well
165 as the vulnerability of a user to supply disruptions. These methods have conceptualized, but not yet
166 operationalized, the “endpoints” of supply risk as impaired product functions and additional costs of
167 production. The “Dilution of total stocks” approach, as suggested by (van Oers et al. 2002b; van Oers
168 and Guinée 2016), is also still in its conceptual stage of development (in purple). The approach
169 assumes that only dissipation into the ecosphere constitutes an absolute loss, not taking dissipation
170 within the technosphere into account. Therefore, the arrow in Figure 1 starts at the dissipation flow
171 into the ecosphere (as other methods start from primary mineral resource extraction). Furthermore, the
172 approach considers the total stock, i.e. the natural and the anthropogenic stock.

173 Based on the main impact mechanisms illustrated in Figure 1, methods were categorized into four
174 categories: Depletion, Future Efforts, Thermodynamic Accounting, and Supply Risk methods (Figure
175 2). This categorization is in line with those in previous literature (see e.g. Stewart and Weidema 2005;
176 Steen 2006; Rørbech et al. 2014; Swart et al. 2015) adding the “Supply Risk” category. Since the
177 “dilution of total stocks” approach is not yet operational, it is not considered in this categorization but
178 further discussed in Berger et al. (2019). The grouping within a category is explained in the
179 corresponding category subsections (4.1-4.4). A special case is the Thermodynamic Rarity approach,
180 which can be assigned to two categories. On the one hand, it includes typical elements of
181 thermodynamic accounting, i.e. it accounts for exergy extraction assessed as the exergy difference
182 between a mineral resource as found in nature (e.g. copper in the ore) and a defined reference state
183 (see section 4.3). On the other hand, by assessing the cumulative exergy that would be needed to re-
184 concentrate a mineral from crustal concentration to mine concentration, it also considers hypothetical
185 future efforts. The methods are discussed by category in the following section.



187

188 Figure 2: Overview of methods categorization according to underlying impact mechanisms; the Thermodynamic Rarity
 189 approach has elements of two categories.

190 4 Description of methods

191 The discussion of methods is organized into four sub-sections following the four method categories:
 192 Depletion, Future Efforts, Thermodynamic Accounting, and Supply Risk methods. In each section,
 193 methods are shortly presented and some method-category-specific assumptions and challenges are
 194 discussed.

195 4.1 Depletion methods

196 The depletion concept is related to the reduction of a certain stock (or a set of stocks). This concept is
 197 often used as a proxy for the availability of mineral resources: it is assumed that the extraction of
 198 mineral resources from the ecosphere, i.e. the reduction of the natural stock, renders the mineral
 199 resources less available. The characterization models of the ADP (Abiotic Depletion Potential) method
 200 family are based on the ratio between the annual extraction of mineral resources and the square of a
 201 natural stock estimate (Guinée and Heijungs 1995). Members of the ADP method family include the
 202 Swiss Ecological Scarcity Method (Eco-scarcity) (Frischknecht and Büsler Knöpfel 2013), based on
 203 $ADP_{\text{economic reserves}}$, and the AADP method (Schneider et al. 2011, 2015).

204 The variations of the ADP methods can be classified according to the stock estimate used in the
 205 model, i.e., $ADP_{\text{ultimate reserves}}$, $ADP_{\text{reserve base}}$, and $ADP_{\text{economic reserves}}$ (the former is based on crustal content
 206 estimates, the latter two on United States Geological Survey (USGS) estimates (USGS 2010)). The
 207 choice of stock estimate has implications on what is actually assessed by the model and has been
 208 extensively debated (see e.g. Guinée and Heijungs 1995; Hauschild and Wenzel 1998; van Oers et al.
 209 2002a; Drielsma et al. 2016a; Sonderegger et al. 2017; and the discussion section). The Eco-scarcity
 210 method theoretically embeds the $ADP_{\text{economic reserves}}$ model in the method's distance-to-target approach,
 211 i.e. comparing current extraction rates to (politically defined) target rates, but does not modify the

212 model as such. The AADP method considers that mineral resources may still be available after
213 extraction from natural stocks as they are stored in anthropogenic stocks (e.g., electronic
214 devices/waste). The characterization model therefore uses the sum of the natural stock (USGS
215 resources (see [SMTTable S1](#)) in the original version and ultimate reserves in the updated version) and
216 the anthropogenic stock in the denominator. However, the mineral resource extraction rate in the
217 numerator considers only extraction from natural stocks and not from anthropogenic stocks.

218 Other Depletion methods include EDIP 1997 and 2003 (Wenzel et al. 1997; Hauschild and Potting
219 2005) and LIME2_{midpoint} (Itsubo and Inaba 2012). The EDIP and LIME2_{midpoint} methods do not use the
220 annual extraction to stock ratio but only the inverse of natural stock estimates (economic reserves in
221 both cases). They might therefore not be depletion methods in a strict sense, though they are closely
222 related. The argument for this approach is that the integration of current annual production into the
223 indicator may underestimate future risks of mineral supply shortages for minerals that are not yet used
224 in large volumes.

225 4.2 Future Efforts methods

226 Future Efforts methods may be generalized as seeking to assess the consequences of current mineral
227 resource use on societal efforts to extract a unit of mineral resource in the future. Ultimately, use of a
228 specific unit of mineral resource is implying a change in availability to future users of that very unit of
229 mineral resource. This requires future users either to re-use the same unit of the mineral resource (now
230 at a different quality), to use another unit of mineral resource, or to use another technology (Figure
231 S3). It is important to note that use of the future mineral resource or technology can be less impacting
232 and less expensive than the original use, in which case there is no negative impact on future users from
233 current dissipation (Stewart and Weidema 2005).

234 Most existing Future Efforts methods are based on the assumption that ore grades mined in the future
235 will be lower (see Supplementary Material [1](#), section 3.1) and apply various proxy indicators to assess
236 the related assumed increases in costs, e.g., surplus ore to be dealt with, surplus energy use, or surplus
237 costs (see Table S2 for a list of all methods and their underlying modeling). The methods can be
238 grouped into different subcategories according to what they include in their impact pathway.

239 **Ore grade only methods** – These methods focus on ore grades only without modeling any future
240 efforts (they could therefore also be classified as depletion methods, using ore grades as the indicator).
241 For this review, they are considered to be a proxy for potential future costs. Methods in this
242 subcategory include the Ore Requirement Indicator (ORI) method (Swart and Dewulf 2013), the Ore
243 Grade Decrease method (Vieira et al. 2012), and the Surplus Ore Potential (SOP) method (Vieira et al.
244 2016a; Vieira 2018).

245 **Ore grade – surplus energy methods** – These methods are based on the approach by (Müller-Wenk
246 1998), which uses grade-tonnage relationships based on assumed frequency distribution of
247 concentrations in the earth’s crust (see p. 78 in Goedkoop and Spriensma (2001) for a discussion of
248 assumptions and missing data sources). Surplus energy is calculated for an arbitrary future ore grade
249 (based on five times the cumulative production from 1990 and the grade-tonnage relationship)
250 assuming no efficiency increases. Methods in this subcategory include the Eco-indicator 99 method
251 (Goedkoop and Spriensma 2001), the IMPACT 2002+ method (Jolliet et al. 2003), and the Stepwise
252 2006 method (Weidema et al. 2007).

253 **Ore grade – surplus cost method** – The assessment as implemented in ReCiPe 2008 (Goedkoop et
254 al. 2013), evaluates grades and yields of all mines exploiting a particular deposit type in order to
255 estimate marginal ore grade decline and assumes a constant cost in order to calculate surplus cost.

256 **Cost only method** – The Surplus Cost Potential (SCP) method (Vieira et al. 2016b; Vieira 2018) uses
257 a similar line of thinking to the SOP method but it uses cost-tonnage instead of grade-tonnage
258 relationships. Thus, this method is not related to ore grade decrease. Instead, it is based on the average
259 gradient of cumulative cost-tonnage curves that are fitted to resource size and cost data from existing
260 mines, and extrapolated to known mineral reserves or resources.

261 **Average crustal concentration methods** – These methods, implemented in EPS 2000/2015 (Steen
262 1999, 2016) and Thermodynamic Rarity (Valero and Valero, 2015), assume the mining of the average
263 crustal concentration (of elements or minerals, respectively) and assess the corresponding energy or
264 exergy costs.

265 **Economics-only methods** – These methods can be distinguished from the other Future Efforts
266 methods by not relating their modeling to future ore grades or future costs of mining activities.
267 Instead, they are based on mineral resource prices and economics, directly modeling economic
268 relationships. Although the Future Welfare Loss (Huppertz et al. 2019) and the LIME2_{endpoint} approach
269 (Itsubo and Inaba 2012) both start from prices, they have differences. Since the economics only
270 methods are much less discussed in literature than other methods and internal discussions about their
271 differences were more intense than for other methods~~In order to make these differences clear~~, the two
272 methods are described in more detail below.

273 The Future Welfare Loss approach (De Caemel et al. 2012; Huppertz et al. 2019) takes its starting
274 point in the recognition that a part of the future scarcity value of a resource is already included in the
275 current price of the resource, more specifically as the economic rent. The rent is the net present value
276 (NPV) of the expected future revenue from extracting the resource, and can be estimated as the
277 difference between the price and the extraction cost of the resource. Although a part of the future
278 scarcity value of a resource is thus already included in the resource price, it is not the full future value,

279 since the current rent is calculated with the market discount rate, which is higher than the social
280 discount rate. The current rent is therefore lower than what it would be using the social discount rate.
281 This lower rent also leads to a faster depletion of the resource than what is socially optimal, i.e. when
282 applying the social discount rate. The Future Welfare Loss is the difference between the rent
283 calculated with the social discount rate and the rent calculated with the market discount rate. By using
284 this as the indicator, the Future Welfare Loss approach assesses the potential externality of missed
285 rents due to current overconsumption.

286 The LIME2_{endpoint} method is based on El Serafy's user cost (Itsubo and Inaba 2014). The basic idea
287 behind the user cost concept is to generate a permanent income from earnings from the sale of finite
288 resources (El Serafy 1989). In order to achieve this, a part of the earnings must be set aside as a capital
289 investment to generate this permanent income. This part, also called the user cost, is the difference
290 between earnings without capital investment and the permanent income. By using this as the indicator,
291 the LIME2_{endpoint} method assesses the potential externality of missed future income due to a
292 hypothetical lacking investment of earnings from the sale of finite resources.

293 4.3 Thermodynamic Accounting methods

294 Thermodynamic Accounting methods quantify the cumulative exergy (or energy) used in a product
295 system. The exergy of a system or resource is the maximum amount of useful work that can be
296 obtained from this system or resource when it is brought to (thermodynamic) equilibrium with its
297 environment, implying that an environment or reference state must be defined (Dewulf et al. 2008).
298 For metals and minerals, exergy methods account for either (i) the difference in exergy of these
299 resources compared to the reference state (CEENE and CExD methods), (ii) the exergy replacement
300 cost, defined as the exergy that would be needed to extract a mineral from a theoretical state of the
301 earth's crust, in which all mineral resources are completely dispersed (Thermodynamic Rarity
302 method), or (iii) the solar energy demand for the natural processes that has led to the current ore grades
303 of the extracted primary mineral resources (SED method).

304 The Cumulative Exergy Extraction from the Natural Environment (CEENE) method (Dewulf et al.
305 2007; Alvarenga et al. 2013; Taelman et al. 2014) and the Cumulative Exergy Demand (CExD)
306 method (Bösch et al. 2007) both consider the approach proposed by Szargut et al. (1988), in which the
307 natural environment is the reference state. Thus, they account for the cumulative extraction of exergy
308 embedded in target mineral resources (e.g. copper) as the exergy difference between the mineral
309 resource as found in nature (e.g., copper in the ore) and a defined reference state in the natural
310 environment (as defined by Szargut et al. (1988)). In Szargut's approach, the reference state is
311 represented by a reference compound that is considered to be the most probable product of the
312 interaction of the element with other common compounds in the natural environment and that typically

313 shows high chemical stability (e.g. SiO₂ for Si) (De Meester et al. 2006). Although both methods are
314 based on the same approach, they have differences in operationalization (see discussion section).

315 The Thermodynamic Rarity method (Valero and Valero 2015) incorporates two aspects: exergy costs
316 (EC) and exergy replacement costs (ERC). The first evaluates the exergy cost required to mine and
317 beneficiate a given commodity with prevailing technologies, assuming current average concentrations
318 of mineral deposits and is similar to inventory accounting. The second aspect relates to the fact that
319 having minerals concentrated in ore bodies (and not dispersed throughout the crust) represents a “free
320 bonus” provided by nature, which reduces the otherwise required energy costs of mining. The
321 reduction of this bonus when mines are depleted is quantified as so-called Exergy Replacement Costs
322 (ERC). These are defined as the cumulative exergy that would be needed to re-concentrate a mineral
323 from a completely dispersed state (denoted Thanatia) to the conditions of concentration and
324 composition found in the original mines using prevailing technology. Hence, ERC can be seen as the
325 ultimate future effort that society would need to put into play when all mineral deposits become
326 depleted. In contrast to the Szargut approach, the Thermodynamic Rarity method does not include a
327 reference state in the form of reference compounds, but rather uses the composition and the average
328 concentration of the 294 most abundant minerals found in the earth’s crust from which the
329 concentration exergy is calculated (Valero et al. 2018).

330 The Solar Energy Demand (SED) method (Rugani et al. 2011) is based on the emergy concept,
331 whereby emergy is the amount of energy that was required across direct and indirect transformations
332 to make a product or service (Odum 1996). The SED method estimates this total direct and indirect
333 environmental work for minerals and metals, measured in equivalent solar energy units. For metals,
334 this includes consideration of the global sedimentary cycle as well as mine concentrations, whereas
335 minerals are assumed to be co-products of the global sedimentary cycle (Rugani et al. 2011, SI).

336 To summarize, CEENE and CExD consider the same impact mechanism, i.e. the exergy extraction
337 assessed as the difference between a mineral resource as found in nature and a defined reference state
338 in the natural environment. The ERC approach also considers an exergy difference, calculated as the
339 exergy requirement to re-concentrate a mineral resource from a completely dispersed state to mine
340 concentration. The SED method has yet another starting point and differentiates between minerals and
341 metals.

342 4.4 Supply Risk methods

343 Three Supply Risk methods based on the criticality concept have been developed in the context of
344 LCA: The Geopolitical Supply Risk (GeoPolRisk) method (Gemechu et al. 2016; Helbig et al. 2016a;
345 Cimprich et al. 2017b), the Economic Scarcity Potential (ESP) method (Schneider et al. 2014), and the
346 Integrated Method to Assess Resource Efficiency (ESSENZ) (Bach et al. 2016), which is an extension

347 and update of the ESP method. The criticality concept typically includes considerations of potential
348 supply disruption (e.g. due to trade barriers, armed conflicts, economic and technological limitations
349 of exploration and extraction, environmental regulations, and natural disasters) and vulnerability to
350 supply disruption (e.g. assessed by potential (socio-economic) impacts of this supply disruption), and
351 it typically considers 10-year time horizons (defined within the task force as a short time horizon) (see
352 e.g. Achzet and Helbig 2013; Graedel and Reck 2015). In accordance with classical risk theory, we
353 refer to the three methods mentioned above as “Supply Risk methods”, whereby supply risk is
354 conceptualized as a function of supply disruption probability *and* vulnerability (Cimprich et al. 2019).
355 Importantly, our conceptualization of “supply risk” deviates from the common use of this term in the
356 criticality literature, which, as argued by Glöser et al. (2015) and Frenzel et al. (2017), refers to supply
357 disruption probability only.

358 While supply risk assessment concerns potential “outside-in” impacts of supply disruptions *on a given*
359 *product system* (for example, impaired product performance, increased production costs, and/or lost
360 revenue due to production shutdowns), the characterization models of LCA traditionally concern
361 “inside-out” impacts *of a product system* on the environment (for example, climate change,
362 acidification, and particulate matter formation) (Cimprich et al. 2019). Another key difference from
363 “traditional” LCA characterization models is that, as the total supply risk associated with a product
364 system is a function of its entire supply chain, supply risk is evaluated for both elementary flows and
365 intermediate flows; which here are collectively termed “inventory flows” following (Cimprich et al.
366 2019).

367 The ESP method, along with the ESSENZ method that supersedes it, directly build upon criticality
368 concepts and thereby include many factors relevant to supply disruption probability – for ESSENZ
369 these include mining capacity, primary material use, concentration of reserves and production,
370 company concentration, price volatility, demand growth, feasibility of exploration projects, trade
371 barriers, political stability and co-production. The GeoPolRisk method, on the other hand, focuses
372 more narrowly on geopolitical stability. Although the ESSENZ method includes other supply
373 disruption probability factors besides political stability, the impact pathways for the other factors are
374 conceptually similar to those for political stability. We therefore focus on this indicator for the purpose
375 of describing and comparing the GeoPolRisk and ESSENZ methods. Supply disruption *probability*
376 depends on the geopolitical stability of countries from which inventory flows are sourced. To measure
377 political stability all three methods apply a different set of the Worldwide Governance Indicators
378 (WGIs) published by the World Bank (2018). Supply disruption probability is also a function of
379 mediating factors that influence the likelihood and severity of supply disruptions arising from political
380 instability. All three methods use the production concentration, typically measured by the Herfindahl-
381 Hirschman Index (HHI), as a mediating factor. All else being equal, higher production concentration

382 reduces the potential for supply-chain restructuring to mitigate supply disruptions, and therefore
383 increases supply risk. While the GeoPolRisk method weights the WGI values of upstream raw
384 material producing countries by their import shares to downstream product manufacturing countries,
385 the ESP and ESSENZ methods calculate a global average WGI index using country production shares
386 of raw materials. Supply disruption *vulnerability* reflects the impacts of supply disruptions that may
387 occur (Helbig et al. 2016b). Whereas the ESP and ESSENZ methods consider larger amounts of
388 materials used in the considered product system to indicate higher vulnerability, the GeoPolRisk
389 method considers all materials to be of equal importance regardless of the amounts in which they are
390 used. An extension of the GeoPolRisk method by (Cimprich et al. 2017a) also considers
391 substitutability of materials as a mediating factor for vulnerability. A more detailed review of the
392 GeoPolRisk, ESP, and ESSENZ methods can be found in (Cimprich et al. 2019).

393 5 Criteria-based assessment of methods

394 All 27 methods were assessed [by method developers and/or one to three other reviewers from the task](#)
395 [force](#) using a set of 45 mainly descriptive criteria grouped into seven main categories [\(see](#)
396 [Supplementary Material 2\)](#). While the Life Cycle Initiative provided the seven main categories, the
397 mineral resources-specific sub-criteria were developed by the task force through an iterative process to
398 arrive at a comprehensive assessment scheme [\(SM2\)](#). Here, we focus on those criteria that highlighted
399 differences between methods and therefore can be used to guide application-dependent use of the
400 methods, while highlighting areas for further methodological development (see Berger et al. (2019)).

401 **General characteristics** – Since the methods differ in the impacts intended to be assessed, their
402 characterization factors have different units, even within method categories. Furthermore, the methods
403 consider different time horizons (from a few years to hundreds of years). As discussed in previous
404 sections, all “traditional” LCA methods have an inside-out perspective whereas Supply Risk methods
405 have been developed with an outside-in perspective.

406 **Completeness of scope** – All methods have a global scope and no further geographical resolution,
407 except for the GeoPolRisk, which is at the country level. With regard to the categorization into
408 midpoint and endpoint methods, our result is consistent with existing literature (e.g. EC-JRC (2011)).
409 Depletion and Thermodynamic Accounting methods are considered to be midpoint methods. Within
410 Future Efforts methods, “Ore grade only”-methods (see section 4.2) are considered midpoint methods,
411 whereas the others are considered endpoint methods. The exception is the SOP method, which is
412 considered to be a midpoint in ReCiPe 2016 and to be an endpoint in LC-Impact. This illustrates that
413 within the midpoint and endpoint indicators, there is no general agreement yet on what *the* midpoint or
414 *the* endpoint should be and the distinction between the two is not always obvious. Supply Risk
415 methods are considered midpoint methods.

416 **Coverage of impact mechanisms and resources (Environmental) relevance** – Our classification of
417 methods reflects to some extent the (environmental) impact mechanisms considered ~~in order to assess~~
418 impacts, i.e. Depletion methods consider depletion rates, Thermodynamic Accounting consider exergy
419 extraction from nature, and Supply Risk methods assess supply disruption probability and
420 vulnerability. With Future Efforts methods this is less clear: By assessing (future) additional efforts
421 needed to access mineral resources, they are implicitly also assessing aspects of depletion. Not all
422 impact mechanisms considered are environmental. Those for the GeoPolRisk method for example are
423 primarily socioeconomic and often there is a mixture of environmental and economic mechanisms as
424 for example in the ADP methods. Existing methods have been designed for mineral resources and,
425 except for the Thermodynamic Accounting methods, typically have limited, if any, coverage of other
426 natural resources (e.g. water, land, biotic resources).

427 **Peer review, data sources, and uncertainty**~~Scientific robustness and certainty~~ – Except for
428 ReCiPe 2008, all methods were peer reviewed. Characterization factors based on stock estimates
429 throughout the different methods often rely on data from the USGS, with original publication dates of
430 the data differing widely from the 1990's to almost up to date. Eco-indicator 99 (and hence IMPACT
431 2002+ and Stepwise 2006, which are based on it) are based on non-transparent data sources (see
432 Goedkoop and Spriensma 2001, p.78, for a discussion of assumptions and data sources).

433 **Documentation, transparency, and reproducibility** – All methods are documented – although with
434 varying levels of detail – and the underlying models and the input data needed are accessible in most
435 cases. However, some of the documentation, models, and data are not accessible for free.

436 **Applicability and ease of implementation** – All Depletion and Future Efforts methods are
437 compatible with existing Life Cycle Inventories (LCIs), which provide elementary flows in kg primary
438 resource. Thermodynamic Accounting methods are also compatible except for Thermodynamic Rarity.
439 The Supply Risk methods are based on both elementary and intermediate flows and are therefore not
440 yet fully compatible with “traditional” LCIs. The coverage of elementary flows varies widely from 9
441 to over 70 elementary flows, being 40 on average (for details see [Supplementary Material 2](#)). The lack
442 of characterization factors for rare earth metals has been highlighted for many methods; and mineral
443 aggregates are rarely covered (only Eco-scarcity, SOP/SCP, and Supply Risk methods).

444 6 Discussion of methods

445 Some of the main points of contention, particularly in relation to Depletion and Future Efforts
446 methods, pertain to a broader discussion around resource depletion and scarcity - and whether these
447 are real or perceived issues. Significant research efforts have been undertaken within the broader
448 geoscience, sustainable development, mineral economics and industrial ecology research communities
449 to understand the complexities underpinning their assessment. These studies highlight the fluidity of

450 mineral reserve and resource estimates (Meinert et al. 2016), the complexity and shortcomings of
451 metrics such as ore grades for assessing resource depletion (West 2011; Priester et al. 2019), the
452 general uncertainty over society’s future mineral resource needs and the degree to which mineral
453 exploration will be successful in meeting these (Ali et al. 2017), and the ultimate impact of this on
454 commodity prices and policy requirements (Tilton et al. 2018).

455 The following subsections discuss each of our four method categories (Depletion, Future Efforts,
456 Thermodynamic Accounting, and Supply Risk) in more detail.

457 6.1 Depletion methods

458 The main points for discussion of depletion methods are the choice of stock estimate, the use of
459 extraction to stock ratios or stocks only, and the inclusion of anthropogenic stocks.

460 While the “ultimately extractable reserves” is the relevant stock estimate in terms of depletion of the
461 natural stock, it will never be exactly known because of its dependence on future technological
462 developments (Guinée and Heijungs 1995) and unavoidable geologic uncertainty. Therefore, it can
463 only be approximated and $ADP_{\text{ultimate reserves}}$ is currently considered the best proxy according to the ADP
464 developers (Guinée and Heijungs 1995; van Oers et al. 2002b; van Oers and Guinée 2016). This
465 recommendation is mainly based on the fact that estimates of economic reserves and the reserve base
466 fluctuate over time as they are defined by economic considerations not directly related to the depletion
467 problem, thus resulting in unstable and continuously changing estimates. However, the use of ultimate
468 reserves has been criticized by geologists as inappropriate for the assessment of mineral resource
469 availability because a majority of the material contained in the earth’s crust may always remain
470 unavailable for extraction (Drielsma et al. 2016a). The use of $ADP_{\text{reserve base}}$ and $ADP_{\text{economic reserves}}$ has
471 also been criticized as irrelevant to assess the relative rate of long-term depletion of the natural stock,
472 since both are a function of the level of exploration undertaken, which is based on economic
473 considerations (Drielsma et al. 2016b). They should be interpreted as a snapshot taken at a certain
474 point in time that reflects a subset of the reserves currently available, so they imply a short to mid-term
475 time horizon (up to a few decades). Therefore, they could rather be seen as an indicator for potential
476 mineral resource availability issues related to mid-term (a few decades) physical-economic resource
477 scarcity (see also Berger et al. 2019). Furthermore, as they vary in time, the characterization factors
478 would need to be updated on a regular basis. Since the USGS no longer estimates the reserve base
479 (USGS 2010), this is only possible for $ADP_{\text{economic reserves}}$ (stock estimate and extraction rates) and
480 $ADP_{\text{ultimate reserves}}$ (extraction rates).

481 The inclusion of current annual extraction in the characterization model has advantages and
482 disadvantages. On the one hand, the inclusion of extraction may lead to an underestimation of future
483 risks of supply shortages for minerals that are not used in large volumes, as suggested by the

484 developers of the LIME method. On the other hand, even the authors of the LIME_{2midpoint} method
485 discuss extraction rates as a relevant factor, since they provide an indication for the risk of depletion.
486 The definition of what constitutes the flow that renders mineral resources unavailable is often not
487 explicitly stated in available methods. The extraction of mineral resources from nature to technosphere
488 is usually approximated with production data, which refer to the net production of target metals rather
489 than the overall quantities extracted from nature to technosphere (i.e. flows of material which end up
490 in tailings, waste rock, or as emissions to nature are not accounted for). This is equal to the implicit
491 assumption that the efficiency of concentrate production is similar for all metals and does not
492 influence the relative results of the ADP indicator. This assumption may not hold in all cases,
493 particularly for co- and by-product commodities.

494 Recent conceptual developments of the ADP and the AADP method also consider anthropogenic
495 stocks. Accordingly, the extraction from nature to technosphere is not considered to automatically
496 render mineral resources inaccessible. It is rather the type of transformation and the destination of the
497 mineral resource that determine whether it remains (potentially) useable. The depletion of the total
498 stock (natural + anthropogenic) only happens if the mineral resource is emitted or diluted (terms used
499 in van Oers et al. (2002)) or dissipated (term used in Stewart and Weidema (2005)) and remains
500 unrecoverable. While the AADP characterization model includes the sum of the natural and the
501 anthropogenic stocks in the denominator, the numerator only accounts for mineral resource extraction
502 from natural stocks.

503 To summarize, the ADP_{ultimate reserves} may be considered the most suitable existing approach to assess
504 the relative rate of long-term depletion of natural mineral stocks. As suggested by the method
505 developers, ADP methods based on other stock estimates could be used for sensitivity analysis (van
506 Oers et al. 2002b) or they might be used with a different interpretation, as discussed above. In
507 addition, other depletion methods, i.e. EDIP/ LIME_{2midpoint} or AADP, could be used for sensitivity
508 analysis. As described above, none of the existing methods fully reflects the issue of dissipation (for a
509 more detailed discussion of the dissipation concept see Berger et al. (2019)).

510 6.2 Future Efforts methods

511 The main points for discussion of Future Efforts methods are the assumption of declining ore grades
512 and the data upon which the different methods are based. The Economics-only methods, LIME_{2endpoint}
513 and Future Welfare Loss, are discussed separately.

514 The main assumption of many Future Efforts methods is that preferential extraction of *known* higher-
515 grade mineral resources will lead to long-term decline in the average mineral resource grade. This is
516 an assumption for the long-run future and therefore impossible to prove or falsify. At first glance, it
517 appears to be supported by an observed long-term (over the past century) trend of declining mined ore

518 grades for a variety of (but not all) mineral commodities and regions (Crowson 2012; Mudd et al.
519 2013, 2017). However, there is confounding influence of technology, economic, and market
520 conditions: when technology improves or when growth in demand exceeds growth in supply, a decline
521 in mined ore grades would be expected, independent of mineral resource depletion considerations
522 (West 2011; Northey et al. 2017). When supply capacity exceeds demand, mined ore grades have been
523 observed to increase despite continued extraction (e.g., gold between 2014-2017). Furthermore, when
524 demand triggers investments in exploration, deposits are typically found and code based (i.e. JORC,
525 CRIRSCO, NI43-101, etc.) mineral resources or reserves defined with grades profitable under the
526 foreseeable economic situation. Currently, there are no studies that assess in detail how much these
527 competing factors have contributed to historical ore grade changes. Therefore, the methods making use
528 of the declining ore grade concept are effectively using correlations rather than seeking to identify
529 causal factors of grade decline. Furthermore, the Ore Requirement Indicator (ORI) and the Surplus
530 Cost Potential (SCP) methods base their indicators on observed ore grade decline or cost increase
531 during a period with substantial growth in mineral demand as well as in costs and prices. The validity
532 of their assumption of a causal relationship between consumption and ore grade decline or cost
533 increase can therefore be questioned and the underlying data used should ideally be tested over
534 multiple commodity price cycles. The ReCiPe2008 approach (based only on existing mines) and
535 methods using grade-tonnage relationships based on data from existing mines and known deposits
536 (Ore Grade Decrease and Surplus Ore Potential) may be criticized for extrapolating data of known
537 deposits to all potentially accessible deposits, including unknown deposits. As mentioned in section 5,
538 Eco-indicator 99 (and hence IMPACT 2002+ and Stepwise 2006, which are based on it) is based on
539 non-transparent data sources (see Goedkoop and Spriensma 2001, p. 78). Furthermore, these methods
540 assess the surplus energy consequences of extracting natural resources from lower grade deposits at an
541 arbitrarily chosen time horizon, i.e. when extraction reaches 5 times cumulated extraction before 1990.
542 Similarly, EPS 2000/2015 and Thermodynamic Rarity consider extraction from a completely
543 dispersed state of all elements and minerals, respectively. None of these methods model an ore grade
544 decline (and its consequences) based on extraction data but only consider an assumed change in ore
545 grades at a future point in time.

546 Among the ore grade methods, SOP has the most solid data foundation. The cumulative grade-tonnage
547 distributions underpinning the method provide a physical basis for comparing the likely relative (but
548 not absolute) impacts of mineral extraction, based upon current technical and economic supply
549 capabilities. The main weakness of SOP is that it is assuming mining from highest to lowest grade and
550 not explicitly accounting for competing factors such as technology and economic considerations.
551 Besides the discussion on decreasing ore grades, data on future mineral resources and technologies
552 will of course always be inherently uncertain, and the different practical implementations of the future
553 efforts methods will therefore always depend on different forecasts and assumptions.

554 Economics-only methods, i.e. Future Welfare Loss and LIME2_{endpoint}, do not rely on a prediction of
555 future ore grades or efforts and hence avoid the corresponding difficulties and uncertainties. Instead,
556 they model (potential) economic externalities and thereby introduce relative (not absolute)
557 uncertainties of discounting methods, i.e. uncertainties that affect all resources equally and therefore
558 not their relative ranking. The Future Welfare Loss and the LIME2_{endpoint} methods can be seen as
559 complementary, since they address two different economic externalities, namely that caused by the
560 difference between the private and social discount rates (Future Welfare Loss) and that caused by
561 insufficient reinvestment of the economic rent (LIME2_{endpoint}).

562 6.3 Thermodynamic Accounting methods

563 Thermodynamic Accounting methods do not explicitly link used amounts of mineral resources to
564 changes in their availability. Furthermore, the Thermodynamic Rarity method does not yet provide
565 CFs fitting to elementary flows in Life Cycle Inventory databases. However, Thermodynamic
566 Accounting methods may be used in LCA as proxy for (overall) environmental impacts (like
567 Cumulative Energy Demand; Huijbregts et al. 2006, 2010; Steinmann et al. 2017) or for efficiency and
568 renewability assessment as in Dewulf et al. (2005).

569 The CEENE method was developed with the aim of addressing some of the shortcomings of the CExD
570 method, particularly with regard to land use and renewable energies (for a detailed discussion of the
571 differences between the methods see Dewulf et al. (2007)). With regard to mineral resources, CExD
572 calculates the exergy of metals from the whole metal ore that enters the technosphere, whereas
573 CEENE only regards the metal-containing minerals of the ore, with the argument that the tailings from
574 the beneficiation are often not chemically altered when deposited (Dewulf et al. 2007). Furthermore,
575 the CEENE method has been further improved and extended for land use (Alvarenga et al. 2013) and
576 occupation of the marine environment (Taelman et al. 2014).

577 The Thermodynamic Rarity approach (particularly through the ERC concept) can be seen as assessing
578 the geological and technological availability of mineral resources, assessed as the cumulative exergy
579 that would be needed to re-concentrate a mineral from a completely dispersed state to the conditions of
580 concentration and composition found in the original mines using prevailing technology. Therefore, it
581 is related to the Future Efforts methods (see according sections) and – although it was not purposely
582 developed to be incorporated into the LCA structure – is the closest in addressing the availability of
583 mineral resources for human purposes of the Thermodynamic Accounting approaches. On the other
584 hand, the ERC approach is also different, e.g. with regard to the reference state, which might be
585 considered less mature than the one of Szargut. Furthermore, the underlying hypotheses and
586 assumptions lack on clear cause-and-effect relationships (e.g. Thanatia as the final outcome of
587 humankind, in the very long timeframe, and the need for re-concentration of dispersed metals with

588 current technology). And finally, its role (thermodynamic accounting or future efforts or both?) and its
589 integration into LCA still need to be clarified.

590 In case there is interest to consider the value of resources for beneficiaries other than humans as well,
591 e.g. biota, or to consider the indirect value for humans (provided through the value for others, like
592 natural ecosystem and their biotic elements), the SED might serve this purpose. Like emergy
593 synthesis, SED looks at a system as embedded in the larger natural system that underpins it, and
594 includes all direct and indirect inputs to support it, independently of the actual usefulness of the
595 ecological and technological inputs delivered to the systems under study (Raugei et al. 2014).

596 6.4 Supply Risk methods

597 In comparison to the GeoPolRisk method, the ESP and ESSENZ methods serve different goals and
598 scopes: whereas the latter two aim to provide characterization factors with global applicability – much
599 like “traditional” LCIA mineral resource impact assessment methods – the GeoPolRisk method aims
600 to highlight differences in supply risk between countries based on trading relationships. Accordingly,
601 the ESP method and the ~~more-comprehensive~~ ESSENZ method may be used for calculating global
602 average supply risk characterization factors that can be applied by multinational companies having
603 locations all over the world. The GeoPolRisk method, on the other hand, may be used for country-
604 level supply risk assessment. Since the short-term and outside-in-perspectives of Supply Risk methods
605 are different from those of “traditional” LCIA methods there have been intense discussions without
606 consensus in the task force about whether they should be seen as (i) being clearly outside of LCA, (ii)
607 being complementary (e.g. as part of a broader life cycle sustainability assessment (LCSA) framework
608 (Schneider et al. 2014; Sonnemann et al. 2015)), or (iii) even being another part of LCA (see also
609 Berger et al. (2019)). A more detailed discussion of the three methods can be found in (Cimprich et al.
610 2019).

611 7 Conclusions

612 27 LCIA methods assessing impacts of mineral resource use were thoroughly reviewed. The methods
613 were categorized based on modeled impact mechanisms, and assessed using an extensive set of
614 criteria. The concepts underlying the method categories and the individual methods were described,
615 compared, and discussed. Of the four main method categories (Figure 2), we consider Depletion and
616 Future Efforts methods more “traditional” LCIA methods, whereas Thermodynamic Accounting and
617 Supply Risk methods are rather providing complementary information that might be useful for more
618 encompassing life cycle approaches.

619 Of the Depletion methods, $ADP_{ultimate\ reserves}$ provides the most constant assessment of the relative
620 potential of long-term depletion of natural stocks of mineral resources since crustal content estimates

621 have been quite stable over time. Other variations of the ADP method might be used for sensitivity
622 analysis or with a different interpretation. For example, $ADP_{\text{economic reserves}}$ could be used to assess
623 potential resource availability issues related to mid-term (a few decades) physico-economic resource
624 scarcity. New conceptual developments – further discussed in Berger et al (2019) – strive towards a
625 “dissipation” approach by including the anthropogenic stock and dissipation flows in the modeling.

626 Ore grade-related Future Efforts methods often assume that mining takes place from highest to lowest
627 grade although different ore grades are mined in parallel. Furthermore, they do not explicitly account
628 for competing factors such as technology and economic considerations. Therefore, further studies
629 would be needed to confirm that the assumptions behind the ore grade-related Future Efforts methods
630 are nonetheless valid in the long run. Among these methods, SOP has the most solid data foundation.
631 The ORI and the SCP methods rely on empirical data from a period with substantial growth in mineral
632 demand and prices, which is one reason why their assumption of a causal relationship can be
633 questioned. The underlying data should ideally be tested over multiple commodity price cycles to
634 validate the assumed relationships. Some approaches need more discussion because they consider
635 other aspects or have not been discussed extensively before. One of these approaches is the Exergy
636 Replacement Costs (ERC) as implemented in Thermodynamic Rarity, which provides a different
637 measurement for ore quality than the other ore grade approaches. Another group of methods is the
638 Economics-only methods. They use market prices instead of using physical data on future ore grades,
639 technologies and supply-demand relationships. Thereby, they consider market agents to have
640 privileged access to information on aspects like future applications of the resource, future backstop
641 technologies, recycling potentials, the evolution of reserves and extraction costs, so that all these
642 aspects will be taken into account in the market price (Huppertz et al. 2019). In this way, the
643 uncertainty of the economic information includes the markets' assessment of the uncertainty of the
644 physical information.

645 The Thermodynamic Accounting methods include three different approaches. CEENE and CExD
646 calculate the exergy difference between the mineral resource as found in nature (e.g., copper in the
647 ore) and a reference compound in the natural environment. The CEENE method has been developed to
648 address some shortcomings of the CExD method. The ERC approach includes the aspect of
649 concentrations in mines and considers minerals instead of reference compounds. It is thereby similar
650 to CEENE and CExD (by assessing a difference in exergy) but it also contains elements of Future
651 Efforts methods (by considering mineral resource quality in mines). However, the approach still needs
652 to be integrated into the LCA structure as no characterization factors compatible with LCI databases
653 are available yet. Finally, the SED method estimates the total direct and indirect solar energy
654 requirement to concentrate the mineral resource to its current state.

655 Supply Risk methods have an “outside-in” perspective compared to “traditional” LCIA methods with
656 their “inside-out” perspective, thus complementing environmental LCA with a socio-economic risk
657 perspective (see also Berger et al. (2019)). There was no agreement in the task force whether they are
658 in the scope of LCA or only part of LCSA. In any case, some practitioners might be interested in the
659 short-term and outside-in-perspectives of these methods.

660 Based on the insights from this thorough review and assessment of existing methods, ~~which served as~~
661 ~~an input to the Pellston Workshop@~~, recommendations for application-dependent use of existing
662 methods, along with areas for further methodological development have been developed in a Pellston
663 Workshop@, a report of which ~~are is~~ presented in the second part of this paper series (Berger et al.
664 2019).

665 **Disclaimer**

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

668 **Acknowledgements**

669 We thank the other task force members for their participation in the process and their valuable inputs
670 to discussions. Special thanks goes to Marisa Vieira (PRé Consultants) for providing her expertise as a
671 method developer, to Andrea Thorenz (University of Augsburg) for supporting the supply risk
672 discussions, and to Johannes Drielsma (Euromines) for valuable discussions and comments on the
673 manuscript. This work was supported by the Life Cycle Initiative hosted by UN Environment.

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