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LIFE CYCLE SUSTAINABILITY ASSESSMENT

Abiotic resource depletion in LCA—background and update of the anthropogenic stock extended abiotic depletion potential (AADP) model

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Abstract

Purpose The depletion of abiotic resources needs to be discussed in the light of available geologic stocks. For the evaluation of long-term resource availability under consideration of the resources' functional relevance, the abiotic resource stock that is ultimately available for human purposes needs to be identified. This paper discusses the determination of geologic resources stocks and outlines an approach for the estimation of the resource stocks ultimately available for human use in the long-term. Based on these numbers, existing characterization factors for the assessment of resource depletion by means of the anthropogenic stock extended abiotic depletion potential (AADP) model can be updated.

Methods For the assessment of long-term resource availability, the share of abiotic resources ultimately available for human extraction needs to be inferred from the quantity of the elements available in the earth's crust. Based on existing data on crustal concentrations and assumptions regarding the maximal extractable amount of resource, three different approaches for the determination of *ultimately extractable reserves* are proposed. The different resource numbers are compared, and their effects on the resulting characterization factors derived from the abiotic depletion potential (ADP) and the AADP models are analyzed.

Results and discussion A best estimate for the determination of *ultimately extractable reserves* is proposed. Based on this new resource number, AADP characterization factors for 35 materials are calculated. The use of *ultimately extractable reserves* leads to an improved applicability of the AADP model and increases the overall significance of the results.

Conclusions Resource security is a premise for sustainable development. The use of resources needs to be evaluated in the context of their decreasing availability for future generations. Thus, resource choices should also be based on an analysis of available resource stocks. The proposed AADP characterization factors based on *ultimately extractable reserves* will enable a more realistic evaluation of long-term resource availability for human purposes.

Keywords Abiotic depletion potential · AADP · LCA · Long-term resource availability · Resource scarcity

1 Introduction

The evaluation of abiotic resource availability is currently a topic of growing interest. The global demand for metals has increased exponentially and humankind has consumed more minerals during the past century than in all earlier centuries together (Graedel and Erdmann 2012; Krausmann et al. 2009; Tilton 2003). In Fig. 1, an overview of the cumulated world production of different metals is provided. Around 80 % the cumulative mine production of platinum group metals (PGM) or rare earth elements (REE) has occurred over the last 30 years (Hagelüken and Meskers 2010; USGS 2014a).

In the context of the ever increasing demand, the necessity of a sustainable use and preserving of abiotic resources for current and future generations is widely accepted. Even though mineral production could apparently be expanded in the last decades to meet increasing demand, resource scarcity can no longer be seen as a remote threat as trends show that the era of cheap and plentiful resources is over (European Commission 2011b; Steinberger et al. 2010). Access to abiotic

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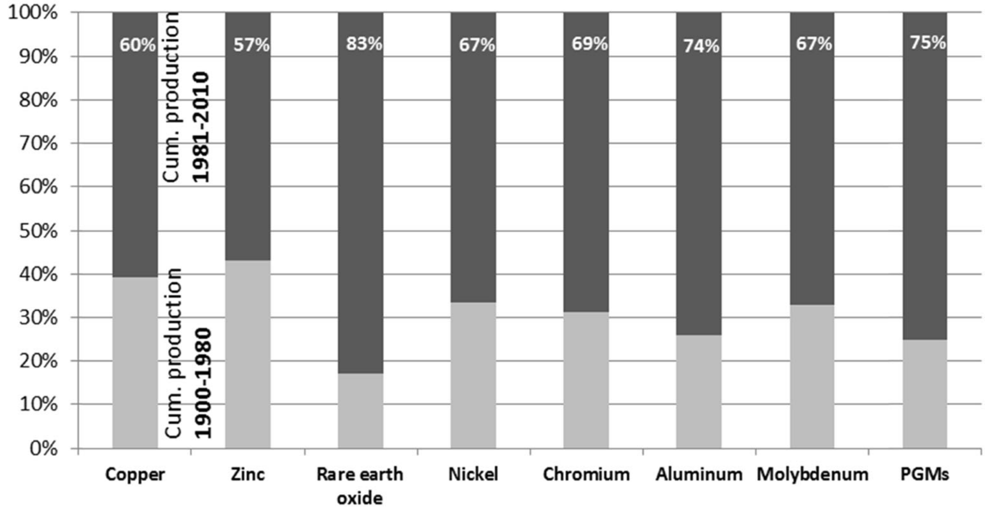

Fig. 1 Cumulated world production of metals (based on data published by the U.S. Geological Survey, USGS 2014a) (see also Schneider 2014)

resources and sufficient supply well into the future are integrant in the debate on sustainable development. The use and management of resources need to be laid out for securing supply and to prevent scarcity of resources for human needs. However, the evaluation of resource availability is complex and numerous and inconsistent definitions of the problem as such exist.

For evaluating potential resource scarcity, a differentiation between short-term and long-term concerns needs to be made. While the determination of supply risks and the constraint access to resources is of concern in the short term referring to current generations (Erdmann and Behrendt 2010; Graedel et al. 2012; National Research Council 2008; Schneider 2014; Schneider et al. 2013), the decreasing amount of resource stocks needs to be evaluated from a long-term perspective under consideration of potential intergenerational needs. In the long term, economic and social constraints of resources supply or environmental or social impacts of extraction cannot be anticipated. Rather, the depletion of resource stocks as such is of concern. *Depletion* can be defined as the process of exhausting the abundance of resources and occurs due to diminishing volumes or a deteriorating quality of the available stocks (Guinée and Heijungs 1995; Guinée et al. 2002; Lindeijer et al. 2002; Radetzki 2002). Hence, depletion refers to the decrease of the physical amount of a resource that is available for (future) human use. Current extraction and use is depleting ore reserves and will diminish or limit the opportunities for future generations to use this resource (see, e.g., Hagelüken and Meskers 2010; Kleijn 2012; Lindeijer et al. 2002; Petrie 2007; van Oers et al. 2002). Even though resource depletion is often not perceived as an immediate threat, there is consensus in regarding abiotic resources as something that is subject to depletion or decreasing availability and scarcity (Steen 2006).

Fierce debates have been going on around the questions whether increasing costs and prices, new discoveries and exploitation, technological progress, substitution, or recycling and reuse can in the long run compensate for decreasing ore grades, diminishing resource stocks and lower quality (Bentley 2002; Kesler 2007; Kleijn 2012; Prior et al. 2012; Radetzki 2002; Simon 1980, 1998; Tilton 1996, 2003; Tilton and Lagos 2007). However, price building depends on many factors that have nothing to do with the actual scarcity of resources (e.g., actors may sell well below costs, build stocks, or withhold resources form the market, falsifying and manipulating prices) and are only affected by current resource demand (Frischknecht and Büsser-Knöpfel 2013). Future generations are excluded from price formation. In this sense, the intertemporal equitable distribution of mineral and metal resources is not achieved by means of assessing prices (Frischknecht and Büsser-Knöpfel 2013). Furthermore, cost-reducing effects of new technologies can offset cost increasing effects of depletion which is not in line with sustainable thinking. The exhaustion of individual materials would deprive future generations from using this material, rendering also the argument of substitution of materials as a compensation for depletion of certain resources as such unsustainable. Thus, many authors suggest that market forces are inadequate to successfully manage the problems of resources availability and use and deliver no reliable information about resource scarcity (even in the short term) (see, e.g., Alonso et al. 2007; Kleijn 2012). For evaluating long-term resource availability, the potential depletion of a resource needs to be evaluated by assessing available resources stocks, despite argumentation of prices and substitution.

The availability of resources is a relevant variable in decision making on the product level. Life cycle assessment (LCA) has proven to be a valuable tool for evaluating the use of resources, and different models exist for the assessment of resource availability in LCA. The current paper revisits the assessment of abiotic resource depletion by means of the anthropogenic stock extended abiotic depletion potential (AADP) model. The aim of this paper is to provide relevant background information and to outline an approach for the determination of reliable resource numbers. Furthermore, the calculation of resource depletion by means of the AADP is discussed and characterization factors are updated.

1.1 Resource depletion in LCA

For assessing resource depletion, appropriate indicators need to be selected that display the effects of resource use on the availability of resource stocks. In the past, several approaches for evaluating abiotic resource availability and assessing potential resource depletion have been proposed in the context of LCA. Existing models for the assessment of resource availability in LCA relate to energy and mass of a resource used, exergy or entropy impacts, future consequences of resource extraction (e.g., surplus energy, surplus cost), or diminishing geologic stocks (see i.a. Bösch et al. 2007; BUWAL 1998; Dewulf et al. 2007; European Commission 2010; Finnveden et al. 2009; Finnveden and Östlund 1997; Goedkoop and Spriensma 2000; Goedkoop et al. 2008; Guinée et al. 2002; Hauschild and Wenzel 1998; Klinglmair et al. 2013; Lindeijer et al. 2002; PE International 2013; Steen 2006; Stewart and Weidema 2005; van Oers et al. 2002) (a general overview of the different life cycle impact assessment (LCIA)-models has been provided for example by Klinglmair et al. 2013; Schneider 2014). All indicators have in common that they aim at expressing decreasing availability of resources either based on the physical finiteness of resources or with regard to future consequences of the extraction of a resource (Klinglmair et al. 2013) assuming that extraction today will lead to lower availability or higher costs of resource extraction for future generations. While the assessment of environmental pollution associated with resource extraction and use is common practice, the extent to which current LCIA methods are capable of addressing resource depletion is widely debated, and different perceptions of the underlying concept of depletion exist (see, e.g., Steen 2006, Lindeijer et al. 2002). The abiotic depletion potential (ADP) method (Guinée et al. 2002) is recommended by the ILCD handbook and in the Product Environmental Footprint (PEF) as the best available practice for assessing resource depletion on a midpoint level, while methods focusing on the endpoint level are often considered too immature (see also Dong et al. 2013; European Commission 2011a, 2013; Guinée et al. 2002; Hauschild et al. 2013). The ADP model accounts for the decreasing availability of resource stocks by dividing the extraction rate of a resource by the geologic stock (reserve) squared and normalizing the result to the extraction-reserve ratio of the reference substance antimony (CML 2013) (see Eq. 1).[1] The assessment of natural stocks and extraction rates provides information about the geologic availability of different resources (Guinée and Heijungs 1995; Guinée 1995; Guinée et al. 2002; Heijungs et al. 1997).

$$\mathrm{ADP}_{i,\ \text{geologic stock}} = \frac{\text{extraction rate } i}{\text{geologic stock}^2} \times \frac{\text{geologic stock antimony}^2}{\text{extraction rate antimony}} \qquad (1)$$

While the definition of the extraction rate is straightforward, and reliable estimates exist (see, e.g., IntierraRMG 2013; USGS 2014a), the definition of a reference number for the geologic resource stock is more difficult. Depending on the definition of this number, absolute results will change dramatically. It is difficult to fix convincing boundaries for the determination of resource figures as the stock size depends on the required effort of extraction and the evaluated timeframe (see, e.g., Goedkoop and Spriensma 2000). Mining companies only prove sufficient ore to justify their investments in extraction and processing facilities rather than analyzing what is ultimately available from a geologic perspective (Crowson 2011). In Table 1, an overview of different numbers that aim at defining geologic resource stocks is shown. In the context of assessing long-term resource availability, the possible extent of mineral resources ultimately available to fulfill human needs has to be inferred from the estimated content of each element in the earth's crust (see also Crowson 2011).

1.2 Abiotic depletion—data requirements

The ADP is based on the relationship of extraction rate to available resource stocks in the geosphere. Guinée (1995) provisionally uses the entire geologic reserves, referred to as *ultimate reserves*, as a basis for calculating the ADP. These ultimate reserves are used as an approximation of the ultimately extractable (geologic) amount of resources, assuming that the ratio between the *ultimately extractable* and *ultimate reserves* is equal for all resource types. Based on this assumption, it is not significant whether the *ultimate reserves* or the abundance in only a certain part of the upper crust is analyzed; the relative abundance of elements stays the same and thus also the ranking of their availability. Consequently, the ADP in its current form seems to be sufficient for comparing the

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[1] To use antimony as a reference unit was proposed by Guinée (1995). The use of this reference is standard practice in current assessment of resource depletion, and no adaptation is proposed in this paper. However, other materials could be used as a reference (e.g., for communication purposes on a company level), leading to different absolute results; however, relative comparison will stay the same.

Table 1 Overview of resource numbers for determining geologic stocks

(Economic) Reserves	Measure of the metal content in deposits that are known and profitable to exploit at current prices, state of technology, etc. (Tilton and Lagos 2007; USGS 2014b)
Reserve base	That part of a resource that meets specified minimum physical and chemical criteria related to current mining and production practice (UNEP 2011; USGS 2014b). The reserve base was used as an estimate of the size of those parts of resources that had reasonable potential for becoming economic within planning horizons. However, these estimates were based on expert opinion rather than on actual data. The USGS discontinued reporting of estimates of the reserve base in 2010
Resources	A concentration of identified naturally occurring mineral in or on the earth's crust in such form and amount that economic extraction is currently or potentially feasible (USGS 2014b). However resource estimates are based on current knowledge and are continually revised in the context of technological changes and shifts in prices and costs
Ultimate reserves	The quantity of resources that is ultimately available in the earth's crust. Estimated by multiplying the average natural concentration of the resources in the earth's crust by the mass or volume of these media (Guinée 1995). The definition includes nonconventional and low-grade materials and common rocks
Ultimately extractable reserves	The amount available in the upper earth's crust that is ultimately recoverable. The extractability requires specific characteristics of purity and other physical and chemical properties (van Oers et al. 2002)

In the mining industry, a different terminology is used to determine geologic stocks (see Drielsma 2014). However, in this work, the terminology as used by the U.S. Geological Survey (see USGS 2014a) and Guinée (1995) is adopted

geologic availability of different materials. However, the *ultimate reserves* are an overestimation of the amount of material that can eventually be used by humans (Schneider et al. 2011; van Oers et al. 2002). Even though elemental abundance ratios in the continental crust can be used to establish upper limits, referring to the ultimate reserves leads to wrong conclusions when trying to quantify available stocks since much of this material is unsuitable for mining (UNEP 2011). In 2011, Schneider et al. published a paper reemphasizing the fact that abiotic resources are valued for the function they fulfill for human purposes rather than their availability in nature as such (see, i.a., Lindeijer et al. 2002; van Oers et al. 2002) and pointing out that next to geologic stocks, anthropogenic stocks need to be considered for drawing conclusion with regard to resource depletion (Schneider et al. 2011). For this new parameterization, the AADP model (see Eq. 2), the ultimately extractable part of the geologic reserves needs to be defined to enable a combined evaluation of geologic and anthropogenic resource stocks and to determine the physical availability of resources.

$$\mathrm{AADP}_{i,\ \text{ultimately extractable reserves}} = \frac{\text{extraction rate } i}{(\text{extractable geologic stock } i + \text{anthropogenic stock } i)^2} \times \frac{(\text{extractable geologic stock antimony} + \text{anthropogenic stock antimony})^2}{\text{extraction rate antimony}} \tag{2}$$

In the next section, different resource numbers are revisited and a transparent approach for determining the ultimately extractable amount of resources as common basis for further analysis is proposed. An overview of different estimates for the definition of stocks is presented, and different options for determining ultimately extractable reserves are outlined.

2 How much is actually there?

The question of "how much is there?" is very challenging to answer (see also UNEP 2011). There is a massive abundance of almost every metal. However, so far, reliable estimates of the total amount of minerals that may be available for human use are not in place (Graedel et al. 2014). In the paper published by Schneider et al. (2011), the *resources* as published by the U.S. Geological survey are currently used as the "best quantitative estimate" for determining the ultimately extractable amount of resources from the earth's crust. The possible extent of *resources* is currently inferred from the estimated content of each element in the earth's crust (Crowson 2011). However, those estimates are continually being revised in the light of technical changes, shifts in prices and costs, and new knowledge. As Crowson (2011) pointed out, the land-based *resources* of *copper* were estimated at 1.6 billion tons in 2000 and at more than 3 billion tons in 2011. Even though *resources* can be considered as the most expansive estimate of how much is there (UNEP 2011), they are rarely estimated, available only for a limited number of materials, and associated with high uncertainties. Similarly, *reserves* or *reserve* *base* as defined by the U.S. Geological Survey provides limited information with regard to geologic availability, as these numbers have a strong economic link (USGS 2014b). *Economic reserves* and use (extraction) are co-dependent, as the search for new reserves depends on the probability of exploration and use of resources (Steen 2006). The *economic reserves* and *reserve base* of most resources have increased over the past, while the actual depletion problem (referring to the geologic availability of resources) must necessarily have increased (Guinée 1995). *Reserves* are affected by many factors that can change in a very short time (e.g., available technologies, resource prices). Thus, the assessment of *reserves* or *reserve base* is ephemeral (see, e.g., Kesler 2007) and not a good basis for the assessment of the physical dimension of resource availability.

To make reliable estimates, all resources that could potentially be extracted in the future would need to be assessed. In the following sections, the assessment of the mineral concentrations in the continental crust is revisited and a proceeding for the determination of the *ultimately extractable* reserves is proposed based on existing practices and assumptions (Kesler and Wilkinson 2008, 2009; Rankin 2011; Skinner 1976, 1979; UNEP 2011).

2.1 Composition of the continental crust

It seems fairly easy to estimate the total quantity of an element present in the earth's crust as values for the average crustal abundance are readily available. The structure of the continental crust consists of upper, middle, and lower crustal layers (see, e.g., Christensen and Mooney 1995; Rudnick and Gao 2005). There have been a variety of estimates of crustal composition. The upper continental crust with a typical thickness of 10–25 km (Artemieva 2009) is the most accessible part of our planet (Rudnick and Gao 2004), and estimates of its composition are available for most elements.[2] Detailed numbers are subject to various assumptions in the models of the global distribution of the various rock types within the crust and are based on large-scale sampling programs (surface exposure studies) (Greenwood and Earnshaw 1984; McLennan 2001; Rudnick and Gao 2004). Rudnick and Gao (2004) recommend values based on an evaluation of 11 studies. These values are taken as a basis in the following examination (thus using more up-to-date values than currently used as a basis for the ADP). In Table 2, an overview of these estimates is provided for a selected material portfolio. A more complete list can be retrieved from Rudnick and Gao (2004).

For calculating the amount of resources in the continental crust that will ultimately be extractable, accessible stocks need to be identified. For this purpose, assumptions made by Rankin (2011), Skinner (1976), Erickson (1973), and UNEP (2011) can be used as a basis. The approach as taken up in this paper is outlined in the next section.

Table 2 Abundance of elements in the continental crust based on Rudnick and Gao (2004)—exemplary material portfolio

Element	Concentration [μg/g]
Aluminum	8.10E+04
Antimony	4.00E−01
Cadmium	9.00E−02
Chromium	9.20E+01
Cobalt	1.73E+01
Copper	2.80E+01
Gold	1.50E−03
Iron	3.91E+04
Lead	1.70E+01
Lithium	2.10E+01
Magnesium	1.50E+04
Manganese	7.70E+02
Mercury	5.00E−02
Molybdenum	1.10E+00
Nickel	4.70E+01
Niobium	1.20E+01
Platinum	5.00E−04
Rhenium	1.98E−04
Silver	5.30E−02
Tin	2.10E+00
Titanium	3.80E+03
Vanadium	9.70E+01
Zinc	6.70E+01
Zirconium	1.93E+02

2.2 Ultimately extractable reserves

For assessing resource depletion, especially when considering the functional value of resources rather than only their geologic abundance, the determination of the ultimately extractable global reserves is necessary (Guinée and Heijungs 1995; Schneider et al. 2011; UNEP 2011). Not the entire amount available in the earth's crust is recoverable as the amount of minerals in common rocks is normally too low to be mined. The source of the metals and many of the industrial minerals that humans use today are geochemical anomalies, referring to local enrichments of elements (Rankin 2011). The so-called *mineralogical barrier* separates the smaller amount of minerals at higher concentrations and in easily accessible form (deposits) from the larger amount of a metal at lower concentrations in a more tightly bound form (Skinner 1979). To produce metals from ordinary rocks would imply a "jumping" over the mineralogical barrier and would be associated with significantly higher energy requirements, water use, and pollution and be subject to thermodynamic limits (Gordon et al. 2007; Skinner 1979). The effort of producing metal

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[2] Ocean resources are not addressed further in this work.

concentrates form crustal (common) rock, beyond the mineralogical barrier is one to two orders of magnitude higher than the effort of today's processes (Rankin 2011; Steen and Borg 2002).

To estimate the resource stocks ultimately available for human use in the long-term, the resources in the upper continental crust can be used as a basis. For determining the maximal amount that could be extracted, different estimates have been made. In a recent publication by the UNEP International Panel on Sustainable Resource Management, a way to estimate long-run geological stocks of metals is proposed and numbers for the extractable geologic resources are provided (UNEP 2011). Similarly, Rankin (2011) proposes a way for assessing crustal resources of minerals and estimates of the quantity of elements in mineral deposits. The basis of these works is the assumption that the size of the ore deposit of a particular element is directly proportional to the crustal abundance of the element (Guinée 1995; Rankin 2011; Skinner 1976). For example, Erickson (1973) suggested that the extractable geologic resource approaches 0.01 % of the total amount available in the crust to 1 km depth (see also UNEP 2011). Similarly, Skinner (1976) stated that the mineralogical barrier is reached at 0.1 wt% copper in the crust and further points out that geochemical evidence suggest that copper that occurs in deposits having grades of 0.1 wt% or higher lies between 0.001 and 0.01 % of the total quantity of copper in the crust. Kesler and Wilkinson (2008) estimated that copper and gold deposits present throughout the entire crust contain about 0.08 % of the total crustal copper and gold (see also UNEP 2011). It is not clear whether these assumptions are generally valid. However, following the approach proposed by Rankin (2011), these assumptions are transferred to other minerals.

As of today, the world's deepest mining operation takes place at 3.9 km (TauTona gold mine in South Africa) (see also Rankin 2011). Based on the need for a conservative approach in the context of sustainable development, the assessment of the upper 3 km of the continental crust can be seen as a good estimate for the definition of *ultimately extractable reserves* and is used as a basis for further evaluations in this work. In total, three different approaches are approaches are proposed for quantifying the *ultimately extractable reserves* based on the assumptions outlined above:

- Option 1: assuming that 0.01 % of the total amount in the crust to 3 km depth will ultimately be available (UNEP 2011)
- Option 2: assuming that 0.08 % of the total amount in the crust to 3 km depth will ultimately be available (Kesler and Wilkinson 2008, 2009)
- Option 3: Assuming that 0.01 % of the total amount in the crust to 3 km depth will ultimately be available for carrier metals and 0.001 % for co-elements (based on assumptions made by Skinner 1976, acknowledging the fact that a significant difference between the availability of carrier metals and co-elements is likely to occur)

Figures published by the UNEP (2011) and Rankin (2011) are revisited and verified by means of own calculations. Thus, as a first step, the extractable amount is quantified, based on the mass of the upper continental crust. For that purpose, the amount of resources in 3 km of the upper continental crust is calculated assuming an average density of 2700 kg/m^3 (Artemieva 2009; Rankin 2011). Following Rankin (2011), the volume of rock available can be determined by calculating the according volume of the continental crust. The radius of the earth is about 6371 km and continents occupy about 40 % of the earth's surface (Rollinson 2005; Yanagi 2011). In Eq. 2, the volume (*V*) of the continental crust to a depth of 3 km is calculated.

$$\frac{4}{3}\pi\left(6371^3 – 6368^3\right) \times 0.4 = \mathrm{V}_{\mathrm{continental\ \ crust}} \\ = 6.12 \times 10^8 \mathrm{km}^3 \tag{3}$$

Based on the crustal abundance, the quantity of each element in the continental crust can be readily calculated (Rankin 2011). The overall ranking is the same when considering the concentration in the upper 1 km or for example 3 km, but absolute values change. As the calculations in this work are based on concentrations in the continental crust published by Rudnick and Gao (2004), differences occur compared to previously published figures by UNEP (2011) or Guinée (1995).

In Table 3, an overview of the *ultimately extractable reserves* is displayed for the exemplary material portfolio of 20 metals, distinguishing between the three different options outlined before. In Fig. 2, these numbers are compared to the *ultimate reserves* as published by Guinée and Heijungs (1995), and the *resources* as published by the U.S. Geological Survey (USGS 2013, 2014a). The extractable reserves identified in options 1 and 2 are in general proportional to the amount of the *ultimate reserves*. However, as mentioned before, different estimates for the crustal abundance of resources are used and thus slight differences occur. *Resources* are independent from the definition of *ultimate reserves* and are based on published data by the USGS (2013, 2014a), underlying different assumptions and estimates.

Future supplies of minerals will come not only from *reserves* and other *identified resources* but also from currently *undiscovered resources*. These undiscovered deposits of minerals are important in assessing the long-term availability of resources. *Resources* as published by the USGS mostly refer to the *identified resources*. As a large amount of resources is still undiscovered, resource figures must be

Table 3 Ultimately extractable resources (options 1–3) and anthropogenic stocks—exemplary material portfolio

	Ultimately extractable resources as defined in Sect. 2.2			Anthropogenic stocks as defined in Sect. 3
	Extractable resources [t], option 1	Extractable resources [t], option 2	Extractable resources [t], option 3	Anthropogenic stocks [t], 20 % dissipation
Aluminum	1.34E+13	1.07E+14	1.34E+13	8.34E+08
Antimony	6.61E+07	5.29E+08	6.61E+06	5.43E+06
Beryllium	3.47E+08	2.78E+09	3.47E+07	1.33E+04
Cadmium	1.49E+07	1.19E+08	1.49E+06	8.57E+05
Chromium	1.52E+10	1.22E+11	1.52E+10	1.52E+08
Cobalt	2.86E+09	2.29E+10	2.86E+08	1.63E+06
Copper	4.63E+09	3.70E+10	4.63E+09	4.47E+08
Iron	6.46E+12	5.17E+13	6.46E+12	4.95E+10
Lead	2.81E+09	2.25E+10	2.81E+09	1.80E+08
Lithium	3.47E+09	2.78E+10	3.47E+09	8.20E+05
Manganese	1.27E+11	1.02E+12	1.27E+10	4.37E+08
Mercury	8.26E+06	6.61E+07	8.26E+05	4.41E+05
Molybdenum	1.82E+08	1.45E+09	1.82E+08	4.87E+06
Nickel	7.76E+09	6.21E+10	7.76E+09	4.06E+07
PGM	2.21E+05	1.77E+06	2.21E+05	1.10E+04
Rhenium	3.27E+04	2.62E+05	3.27E+03	8.05E+02
Thallium	1.49E+08	1.19E+09	1.49E+07	3.36E+02
Titanium	6.28E+11	5.02E+12	6.28E+11	2.39E+08
Vanadium	1.60E+10	1.28E+11	1.60E+09	1.20E+06
Zinc	1.11E+10	8.85E+10	1.11E+10	3.45E+08

Based on data published by Rudnick and Gao (2004), Rankin (2011), Rollinson (2005), and Yanagi (2011). PGM are composed of data for platinum, palladium, and ruthenium. Only materials that have no or limited own production infrastructures are evaluated as companion metals. Based on Reuter et al. 2005, the following materials are evaluated as co-elements: antimony, beryllium, cadmium, cobalt, manganese, mercury, rhenium, thallium, and vanadium. No further differentiation between the companion metals is made. Aluminum is assessed based on the data available at the USGS and assuming that aluminum makes up 25 % of the bauxite mined (based on information provided by the mining industry). $\mathrm{ADP}_{\text{ultimate reserves}}$ values for platinum are used representative for PGM. All values are calculated with current extraction rate numbers (as published by USGS 2013, 2014a)

continuously reassessed in the light of new geologic knowledge or progress in science and technology, etc. (USGS 2014b). The ultimately extractable amount of resources should thus be (significantly) lower than *ultimate reserve*s, but higher than *resources* as published by the USGS. An additional clue for the validity of the calculations and the choice of resource number is a recent and updated publication stating that "known resources contain about 1.8 billion tons of copper […], and undiscovered resources contain an estimated 3.1 billion tons" (Hammarstrom et al. 2013). In Fig. 2, the extractable resources outlined in option 1 and option 3 are in accordance with these (identified and undiscovered) resources of copper.

The numbers for the *ultimately extractable reserves* determined in this paper are based on several assumptions. Thus, some shortcomings with regard to the plausibility of the numbers identified in this work remain (e.g., even though world resources of chromium refer only to the *identified resources*, they are almost as large as the extractable resources identified in option 1 (and 3)). The precise amount of elements available in deposits cannot be known as of today. However, for calculation of the AADP and for making material choices, these estimates provide an important basis, leading to much more realistic results than currently used resource numbers.

3 Results: comparison and update

In a next step, the depletion of different materials is evaluated, comparing currently used characterization factors with factors based on the proposed adaptations.

When calculating the ADP and the AADP, stocks of materials have a comparably higher importance than extraction rates due to the squaring of the denominator (Guinée 1995). Thus, even though the extraction rates used should not be a determining factor (Schneider et al. 2011), changes over time can affect and shift the results (especially when taking into account the exponential growth of resource production). Thus, the extraction rates used in this work for calculating ADP and AADP characterization factors are updated to current data published by the USGS (2013, 2014a). Currently, the USGS is the single best resource for these kinds of data (van Oers et al. 2002). Other databases are available, but often not publicly accessible or covering only a limited number of materials (see for example IntierraRMG 2013). However, data for mine production can differ if other databases are used.

To display the influence that the choice of resource number exerts on the results, the different characterization models for assessing resource depletion are displayed in Fig. 3, including following results:

- ADP based on *ultimate reserves* as published by van Oers et al. (2002), representing current best practice
- ADP with updated extraction rates, based on mine production data published by USGS (2013) and *ultimate reserve* data published by van Oers et al. (2002)
- ADP based on *resources*(as published by the USGS and as proposed by Schneider et al. 2011)
- ADP based on the three different options for calculating the *extractable resources* as highlighted in the previous section

Furthermore, AADP results are displayed based on *resources* (data published by Schneider et al. 2011 is

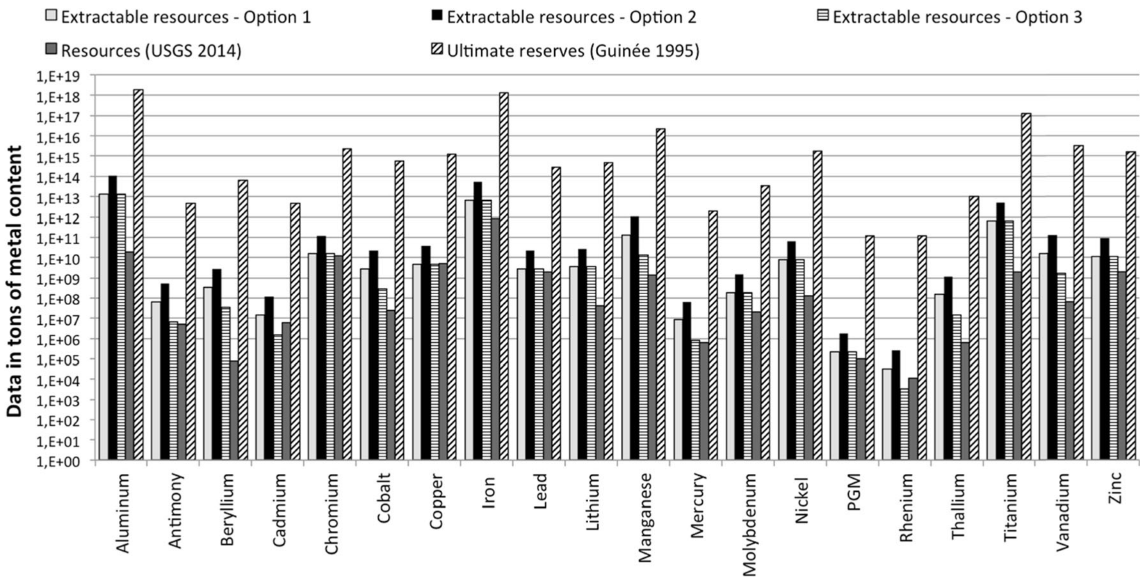

Fig. 2 Overview *ultimately extractable reserves*, *resources* and *ultimate reserves* [t] (logarithmic scale) (USGS 2013, 2014a)

updated and supplemented) and the different options of defining extractable resources, as proposed in this paper. The analysis is conducted for an exemplary material portfolio (additional AADP characterization factors will be provided later in this paper). The determination of the anthropogenic stock is based on the theoretical extractable amount in society and is calculated by means of the accumulated extraction rate since the beginning of records (in approximately 1900[3]) until 2010 based on data from the U.S. Geological Survey and considering a default dissipation rate of 20 % (USGS 2014a; Schneider et al. 2011). The anthropogenic stocks for the exemplary material portfolio are displayed in Table 3 (right column).

In Fig. 3, the sensitivity of the results to the resource numbers chosen is highlighted. Results of the ADP and AADP differ significantly and strongly depend on the resource numbers used. In part one of Fig. 3, an overview of the different results is provided for a material portfolio of 14 metals. Next, to highlight the difference of results, the dominant metals are excluded from the analysis in part two, and the results are again displayed comparing the different characterization models. Similarly, the respective dominating materials are excluded for parts three and four of the figure. For a relative comparison, it does not make a difference whether it is assumed that 0.01 or 0.08 % of the total amount in the crust will ultimately be available. Based on the same estimates for crustal concentrations, these figures will lead to the same relative ADP and are thus displayed combined in Fig. 3. However, for determining the AADP, absolute values are relevant (due to the combination with anthropogenic stocks) and thus a separate evaluation is needed.

The effects of an updated extraction rates on the overall ADP results is assessed in more detail in Fig. 4. Slightly different results are obtained for $\text{ADP}_{\text{ultimate reserves}}$ and $\text{ADP}_{\text{ultimate reserves, new extraction rates}}$. In the exemplary portfolio addressed in this work, the relative relevance of lithium and beryllium changes and lithium is associated with a higher depletion potential than beryllium when using new extraction rates for the calculation of the ADP. Thus, especially in the context of ever increasing extraction rates, frequent updates should be conducted (despite the comparably low impact of the extraction rate on the overall results (Guinée 1995)).

The inclusion of anthropogenic stocks leads to differences in the results. Especially when defining *ultimately extractable reserves* according to option 3 that differentiates between companion and carrier metals, relevant differences occur. Materials with large anthropogenic stocks, such as *antimony* or *cadmium*, are associated with a comparably lower depletion potential (see, e.g., Fig. 3(1) $\text{ADP}_{\text{extractable resources, option 3}}$ and $\text{AADP}_{\text{extractable resources, option 1}}$). Slight differences can be observed for the other options, too. Compared to the $\text{AADP}_{\text{resources}}$, the significance of the anthropogenic stocks for these two options is comparably smaller. This is due to the larger amount of material considered by the use of *ultimately extractable reserves* instead of *resources* and the comparable lower significance of the anthropogenic stock. However, the inclusion of anthropogenic stocks is relevant for a more realistic assessment of resource stocks available for human purposes (see Schneider et al. 2011). Over time, in the context of the ever increasing material use, these differences will become more significant.

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[3] It is assumed that the amount of materials mined before is negligibly low in comparison to the large volumes extracted since 1900 (see also Schneider et al. 2011).

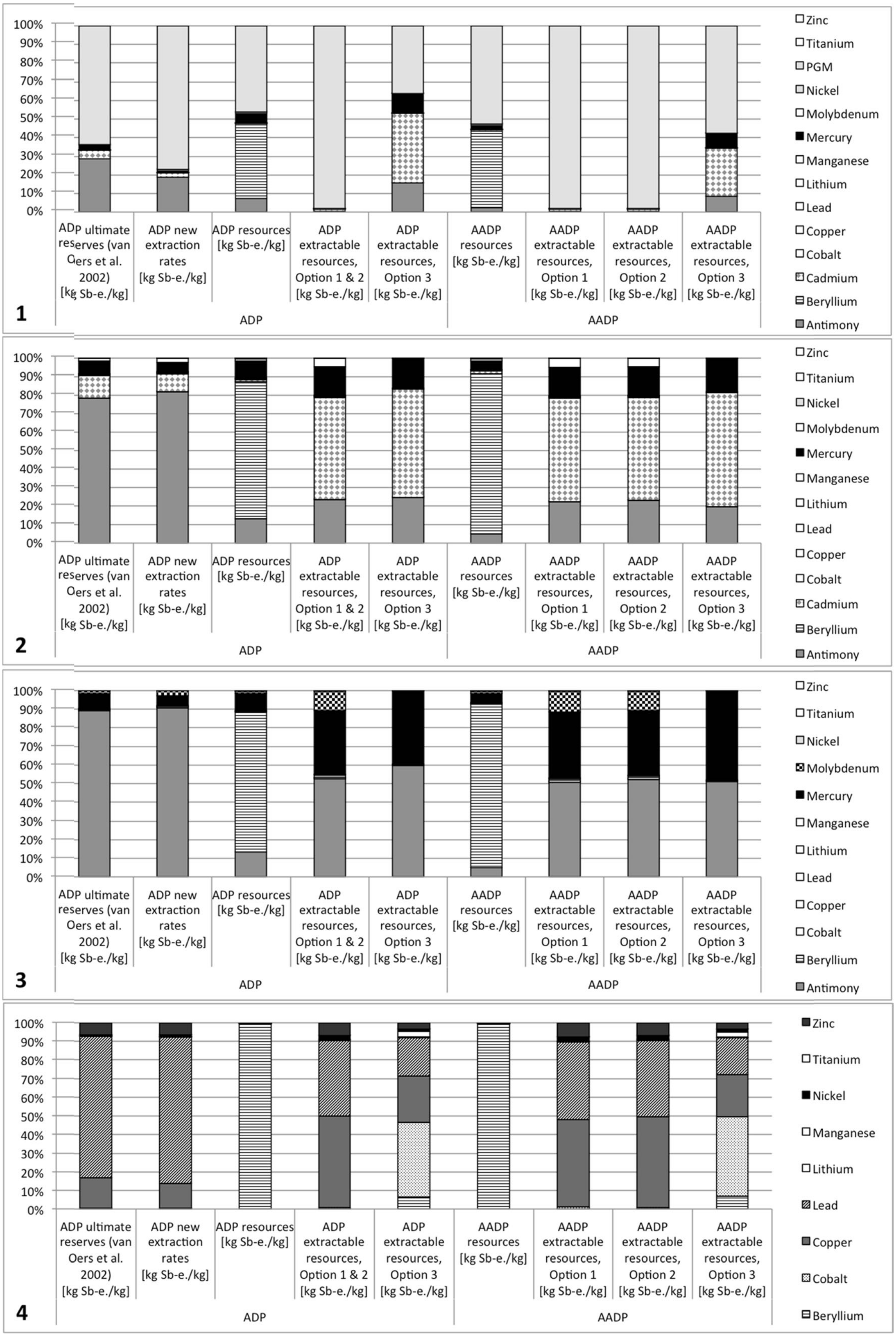

Fig. 3 Overview ADP and AADP for a material portfolio of 14 metals (*1*); excluding *PGM* (*2*); excluding *cadmium* (*3*); and excluding *mercury*, *antimony*, and *molybdenum* (*4*)

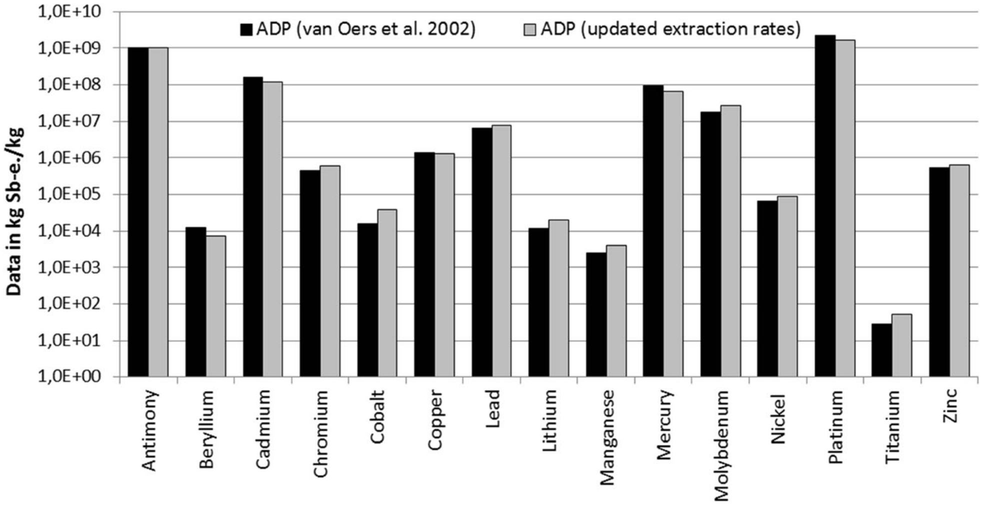

Fig. 4 ADP$_{\text{ultimate reserves}}$—current values and values based on new extraction rates (logarithmic scale)

The aim of the AADP model is to acknowledge the existence of the anthropogenic stocks as a potential source for materials. Thus, based on the results presented in Fig. 3 and the discussion earlier, it is proposed to use data of *ultimately* rather than *resources* published by the U.S. Geological Survey.

The determination of *ultimately extractable reserves* needs to take into account the geological processes that influence companion elements in host formations (UNEP 2011). Many metals are not found individually, but together with major metals (Hagelüken and Meskers 2010). Only the ore with sufficient metal content to be economically removed is mined. Thus, minor metals are often left behind (Hagelüken and Meskers 2010). Consequently, when assessing the availability of resources, it can be assumed that, less companion metals are ultimately extractable than main metals, as the extraction of companion metals is directly dependent on the extraction of the carrier metals (Crowson 2011). For achieving sustainable development and securing long-term availability of resources, conservative assumptions should be made and it is preferable to rather underestimate than overestimate the available resource deposits. Thus, for determining the best estimate for the *ultimately extractable reserves*, the use of resource numbers based on option 3 is proposed in this work.

4 The anthropogenic stock extended abiotic depletion potential: additional discussion and update

In this paper, the definition and quantification of the geologic stocks used as a basis for the AADP model were revisited. Limited data availability was so far the main shortcoming with regard to the implementation of the AADP model. Hereby, two main issues were identified previously (Schneider et al. 2011): the limited number of data for determining resource numbers and shortcomings of existing methods for quantifying the anthropogenic stocks. This paper focused on the first shortcoming. The use of the *ultimately extractable reserves* as proposed in this work leads to a significant improvement of the availability of characterization factors. This will enhance the applicability of the AADP model. For calculation of new and more holistic characterization factors, ultimately extractable reserves are defined assuming that 0.01 % of the total amount in the crust to 3 km depth will ultimately be available for carrier metals and 0.001 % for co-elements (see Sect. 2.2). In Table 4, the new AADP characterization factors are displayed. Based on the proceeding outlined earlier, additional characterization factors can be calculated in the future when according data becomes available.

The AADP methodology focuses not on the extraction and use as such but on the reuse and the potential loss of a material for human purposes. The application of materials in a manner that allows for reuse and recycling is not of concern from a depletion perspective. Use that leads to dispersion (e.g., in spray paints) and unfavorable combinations of materials in products, however, will increase losses in the end-of-life phase and recycling (Hagelüken and Meskers 2010; Reuter et al. 2005). As shown in earlier sections in this paper, an extraction from the anthropogenic stock is not included for the calculation of the AADP. Per definition, extraction from the anthropogenic stock as such cannot be determined as the definition of the anthropogenic stock is independent of the actual state of the material in the anthroposphere. Whether the resources are extracted from the geologic or the anthropogenic stock is of no concern for society with regard to the provision of the desired function; rather, the loss of a resources' functionality needs to be considered. When materials are used in a way that renders them recyclable again in the future, the overall resource stock stays the same and no depletion occurs as the extraction of resources decreases the geologic resource stock but increases the anthropogenic stock. The overall resource

Table 4 Characterization factors

Material	AADP
Aluminum	3.00E−10
Antimony	1.00E+00
Beryllium	1.80E−04
Bismuth	8.35E−01
Boron	2.44E−02
Cadmium	3.08E+00
Chromium	9.03E−05
Cobalt	1.04E−03
Copper	5.41E−04
Gallium	3.82E−06
Germanium	1.84E−04
Gold	1.59E+00
Indium	7.48E−01
Iron	2.75E−08
Lead	4.80E−04
Lithium	2.42E−06
Magnesium	8.61E−10
Manganese	7.57E−05
Mercury	9.34E−01
Molybdenum	6.17E−03
Nickel	3.03E−05
Niobium	1.05E−03
PGM	6.93E+00
REE	1.19E−05
Rhenium	2.54E+03
Silver	2.28E−01
Strontium	6.77E−06
Tantalum	2.52E−03
Thallium	3.77E−05
Tin	1.52E−03
Titanium	9.15E−09
Tungsten	5.51E−02
Vanadium	2.40E−05
Zinc	8.60E−05
Zirconium	1.19E−06

stock is only diminished by dissipation and inevitable loss of resources. Thus, the inventory data used for the evaluation of resource availability by means of the AADP should be adapted to account for the loss of a material rather than the primary amount of material used. The amount of material used as such is not of concern, only the part that is not recycled again or used in a way that makes recycling impossible needs to be evaluated. In this case, the question if recycled material is used is not important and instead emphasis needs to be put on the question if the used material can be recycled again and thus stays part of the anthropogenic stock. This does not mean that the benefit of secondary material (e.g., lower environmental impacts) should not be acknowledged. However, accounting for these benefits is outside of the discussion of abiotic resource depletion. How to optimize the implementation of the AADP model needs to be discussed in future works.

The AADP model emphasizes the fact that resources with high anthropogenic stocks that remain in a potentially useable form in the environment can be evaluated as less critical as resource that have low anthropogenic stocks and are mainly used dissipative. Product designers need to enable recycling and preserve the function of resources by evaluating metal combinations and avoid the use of certain elements in highly dispersed states that cannot be recovered (Graedel et al. 2014). This is an important step in the transition towards sustainable resource use, to close material cycles, and to create less pressure on virgin material supplies.

5 Conclusions

This paper revisits the definition of abiotic resource stocks for the assessment of resource depletion, and different resource numbers were discussed. While the *ultimate reserves* as published by Guinée (1995) establish upper limits and can be used for a comparative evaluation, these limits are not applicable when using the AADP model including anthropogenic stocks for the assessment of resource depletion. In this context, the definition of resource stocks ultimately available for human use was revisited and new and transparent estimates of the *ultimately extractable reserves* were provided for several materials. With increasing knowledge, these numbers need to be reassessed and discussed.

Based on the estimates for the *ultimately extractable reserves*, a new set of characterization factors for the AADP model was developed and presented in this paper. These characterization factors enhance and supplement previous publications. In the context of sustainable use of abiotic resources, preservation of resources needs to be in the focus of resource assessments rather than their geologic abundance. However, several shortcomings for assessing anthropogenic stocks in addition to geologic stocks remain. Dissipation of resources is not considered to the necessary extent in this paper. The definition of anthropogenic resource stocks currently neglects the fact that the quality of recovered materials might not be sufficient for certain applications, and downgrading of materials needs to be assessed in the context of defining the functional value stored in anthropogenic resource stocks. Consequently, current characterization factors still show weaknesses. In further works, as a starting point, a differentiation between base and noble metals and the potential effects of corrosion could be made. However, data regarding dissipation of individual materials is hard to obtain, as this strongly depends on product-specific characteristics. Thus, the challenge of a realistic representation of anthropogenic stocks remains. Further research has to be conducted in this area, to provide a better estimate of the amount that is dissipated and to determine the inventory data that needs to be assessed. For future advancements of the method, detailed analysis of material flows or technological applications is needed to define anthropogenic stocks.

Resource security is a premise for sustainable development. The challenge is to secure material supply for the welfare and well-being of current generations without compromising the potential of future generations. Thus, material choices should also be based on an analysis of the materials' availability. However, next to the physical constraints addressed in this paper, the availability of resources can be further limited by environmental, economic, and social aspects, which need to be included in the evaluation of resource availability on a product level. For a comprehensive assessment of resource availability, all dimensions of sustainability need to be considered, and both the effective and absolute availability of mineral resources need to be analyzed.

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