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Integrated method to assess resource efficiency – ESSENZ

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Abstract

With increasing demand of abiotic resources also the pollution of natural resources like water and soil has risen in the last decades due to global industrial and technological development. Thus, enhancing resource efficiency is a key goal of national and international strategies. For a comprehensive assessment of all related impacts of resource extraction and use all three sustainability dimensions have to be taken into account: economic, environmental and social aspects. Furthermore, to avoid burden shifting life cycle based methods should be applied. As companies need operational tools and approaches, a comprehensive method has been developed to measure resource efficiency of products, processes and services in the context of sustainable development (ESSENZ). Overall 21 categories are established to measure impacts on the environment, physical and socio-economic availability of the used resources as well as their societal acceptance. For the categories socio-economic availability and societal acceptance new approaches are developed and characterization factors are provided for a portfolio of 36 metals and four fossil raw materials. The introduced approach has been tested on several case studies, demonstrating that it enhances the applicability of resource efficiency to assess product systems significantly by providing an overall framework that can be adopted across sectors, using indicators and methods which are applicable and can be integrated into existing life cycle assessment based schemes.

Keywords: Resource efficiency; Life cycle assessment; Resource availability; Supply chain; Resources

1 Introduction

The demand of abiotic resources like metals or fossil fuels has increased significantly in the last decades due to global industrial and technological development. Additionally, the pollution of natural resources like water and soil has risen as well. The use of materials and concurrent environmental pollution will further increase in the future according to several forecasts (Gordon et al., 2006; van den Berg et al., 2016). Thus, enhancing resource efficiency (RE) is a key goal of national and international strategies (Aoki-Suzuki, 2016; Bontoux and Bengtsson, 2016; Giljum and Polzin, 2009; Klinglmair et al., 2014), e.g. Roadmap to a Resource Efficient Europe (European Commission, 2011) or Germanys National Sustainability Strategy (Bundesregierung Deutschland, 2012). As resources are key components of every society to sustain production of goods and services for current and future generations RE is mostly regarded as a macroeconomic concept (Eisenmenger et al., 2016; Giljum and Polzin, 2009; Klinglmair et al., 2014; Schneider et al., 2016). However, often RE is implemented on micro-economic level by optimizing processes or products in a way that less resources are used (Henßler et al., 2016; Klinglmair et al., 2014; Schneider, 2014).

Existing RE schemes refer to the efficient use of resources to generate a specific added value (Fischer-Kowalski et al., 2011; ISO 14044, 2006; Schneider et al., 2016). This can be expressed by the RE ratio (see Eq. (1)).

$$\text{Resource efficiency} = \frac{\text{added value}}{\text{resources}} \quad (1)$$

Added value often refers to economic values (e.g. Gross Domestic Product (Scoreboard, 2013)) but can also include physical values as proposed by ISO 14045 (2012) depending on the overall goal of the evaluation (for more information regarding the added value see supplementary material - section 5.1).

Contrary to life cycle impact assessment practice existing methods determining the denominator resources in resource efficiency assessments so far typically only consider the mass of used metals, minerals and fossil energy carriers (Klinglmair et al., 2014). For an economy-wide perspective mostly material flow indicators like the Domestic Material Input are used (European Commission, 2001). On product level Material Input Per Service Unit (Ritthoff et al., 2002) is applied (e.g. Hinterberger et al. (1997), (Welfens et al., 2016) and von Geibler et al. (2016)). Even though the basic idea of using fewer resources per added value is good, by only measuring the mass of the used resources other relevant aspects associated with the extraction and use of resources (e.g. environmental pollution) are not taken into account. Thus, by applying only mass based indicators and no additional indicators measuring for example environmental impacts little information for a comprehensive RE assessment is provided (Bach et al., 2014; Behrens et al., 2007; Eisenmenger et al., 2016; Schneider et al., 2016; Steen,1999).

The European Commission already expanded their definition of resources in the year 2005, when the protection of environmental compartments was included in the Strategy on the Sustainable Use of Natural Resources (European Commission, 2005). Furthermore, the environmental dimension was included in the resource efficiency scoreboard, which is a scheme to assess the resource efficiency of Europe and its member states (Scoreboard, 2013). The scoreboard also considers a few social impacts (e.g. condition of infrastructure). Furthermore, the academic community agrees that other aspects besides the mass of a used material have to be considered when determining the resource efficiency of products and/or companies (e.g. BIO Intelligence Service (2012), FischerKowalski et al. (2011), Geldermann et al. (2016), Horton et al. (2016), Schneider et al. (2016) and University of the West of England (2012)). Thus, for a comprehensive assessment of all related impacts of resource extraction and use the existing framework for RE has to be expanded to be integrated into existing sustainability frameworks (Horton et al., 2016; Robert et al., 2002; Sonnemann et al., 2015; United Nations, 2016). Therefore, all three sustainability dimensions have to be taken into account: economic, environmental and social dimension (see Fig. 1). As the availability of resources is a precondition for economic development (Eisenmenger et al., 2016; UNEP, 2010), the economic dimension can be expressed through security of resource supply. Restrictions to resource availability can limit the productivity of companies which rely on certain resources to be available anytime to produce goods and services. Thus, they might be forced to discontinue their production if resources they rely on become scarce. This would not only damage the company itself, but also the country/region where the company produces, pays taxes, provides jobs and healthcare to people etc. and therefore ultimately the whole society (BIO Intelligence Service, 2012; Eisenmenger et al., 2016; Gemechu et al., 2016; Rosenau-Tornow et al., 2009; Schneider, 2014). Further, a differentiation between long-term (also called physical availability) and medium-term (also called socio-economic availability) has to be made. Long-term availability refers to the resources in the earth crusts as well as anthropogenic stocks (e.g. electric components consisting of various metals like printed circuit boards in dump sites or buildings). Both have direct influence on

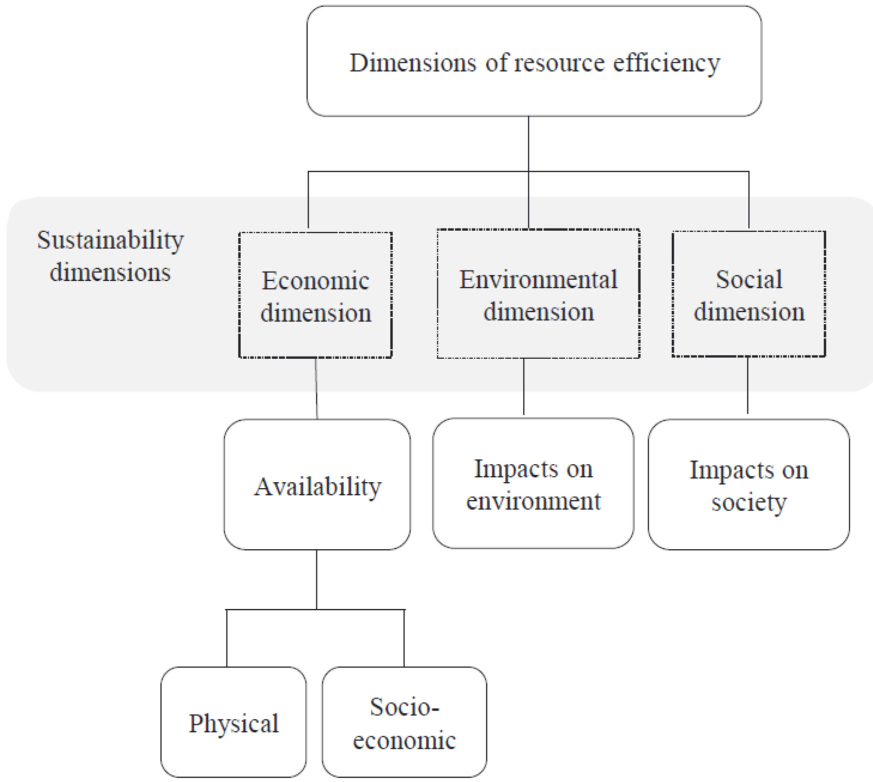

Fig. 1. Considered dimensions for resource efficiency assessment in the context of sustainable development.

availability: if a resource cannot be extracted from either of these sources, it is not available for industrial processes. As it will be very unlikely that this situation occurs in the next years it is referred to as a long-term availability (Schneider, 2014; Schneider et al., 2016).

Medium-term availability is influenced by socio-economic aspects (e.g. political stability) inhibiting the supply security of resources and leading to a restriction in availability. For example political instabilities of countries due to corruption can disrupt the capacity to effectively implement robust policies including ones related to resource extraction, export, etc. Thus, the availability of a specific resource produced in such a country could be limited. This aspect as well as other socio-economic factors can lead to restrictions of resource availability at different supply chain stages. Availability and criticality of resource supply on macro (country), meso (company) and micro (product) level has been a topic of discussion in various working groups recently (Buchert et al., 2012, 2009; Eggert et al., 2007; European Commission, 2014; Gemechu et al., 2016; Graedel et al., 2012; Klinglmair et al., 2014; RosenauTornow et al., 2009; Schneider et al., 2013; Sonnemann et al., 2015). However, existing approaches are often only applicable for assessing the risk of limited availability on country level (e.g. Eggert et al. (2007), Erdmann et al. (2011), and European Commission (2014)) or are not easily integrated into existing approaches already applied by companies like Life Cycle Assessment (LCA) (e.g. Graedel et al. (2012) and Schneider et al. (2013)).

The LCA method according to ISO 14040 (2006) and ISO 14044 (2006) has been used to assess environmental impacts over the entire life cycle of products for several years (Finkbeiner et al., 2006). Environmental impacts refer to pollution of the environmental compartments land, water and soil. Many industries apply LCA and use existing Life Cycle Impact Assessment (LCIA) methods and indicators to assess the environmental performance of their products (Guinee et al., 2002). To avoid shifting impacts and to capture all potential effects associated with resource use life cycle based approaches should be used as a basis for evaluation. By considering the life cycle of the product system important aspects regarding resource efficiency such as recycling and reuse of resources (Ardente and Mathieux, 2014) in the different supply chain stages are measured as well.

Last, in the context of sustainable development also the social dimension has to be considered in RE assessment to assure that impacts on society (e.g. social inequality, meaning that some people do not have access to products or services they need like food or health care) due to production and use of resources are managed. The guide for Social Life Cycle Assessment (SLCA) published by the UNEP/SETAC Life Cycle Initiative (United Nations Environment Programme, 2009) is applied to assess social impacts over the life cycle of products (Benoît et al., 2010). However, SLCA is less established than LCA (Jørgensen, 2013; Jørgensen et al., 2013) due to limited data inventory and challenges in data collection (Martínez-Blanco et al., 2014). As social conditions highly depend on the geographic location (Benoit-Norris et al., 2012; United Nations Environment Programme, 2009) data has to be collected for every production site individually (Dreyer et al., 2010). Different to environmental data, where emissions can be estimated based on the state-of-the-art of the plant, social conditions can vary depending on the companies involved, the region where the plant is operating etc. Furthermore, applicable and valid impact assessment methods to determine social impacts are missing (Lehmann et al., 2013; Neugebauer et al., 2014). However, some data and indicators exist, which can be used as a starting point (Benoit-Norris et al., 2012; Dreyer et al., 2006; Martínez-Blanco et al., 2014). Currently the most comprehensive database is the Social Hotspot Data Base (SHDB) (Norris et al., 2013), which provides data for several sectors and countries on social conditions and can be used to identify social hotspots of product systems (Benoit-Norris et al., 2012; Martínez-Blanco et al., 2014).

Even though several sectors have guidelines how to measure RE (e.g. Geraghty (2011), Clean Technology Centre (2012), García et al. (2013), Manara and Zabaniotou (2014), Heinemann (2016), Geldermann et al. (2016), and Wiedemann et al. (2016)), general guidance is missing. Existing approaches mostly focus on sector specific aspects but do not take general aspects which are valid for different sectors into account and therefore do not comprehensively evaluate the RE.

To assess RE in the context of sustainable development companies need operational tools and approaches. Thus, a comprehensive method has been developed to measure and assess RE of products in the context of sustainable development (ESSENZ method), which will be explained in more detail in the next sections.

2 ESSENZ method

Following the ESSENZ method (further referred to as ESSENZ) is introduced (Bach et al., 2016). As many companies already use LCA for assessing their environmental impacts, ESSENZ is established to be integrated into LCA (ISO 14040, 2006). All three sustainability dimensions are considered within ESSENZ (see Fig. 2). The environmental impacts are measured by using existing LCIA methods and indicators (see section 2.1). The economic dimension is considered by assessing the physical (long-term) and socioeconomic (medium-term) availability of resources (see section 2.2). Two screening indicators are developed to be applied in ESSENZ to measure social impacts (see section 2.3).

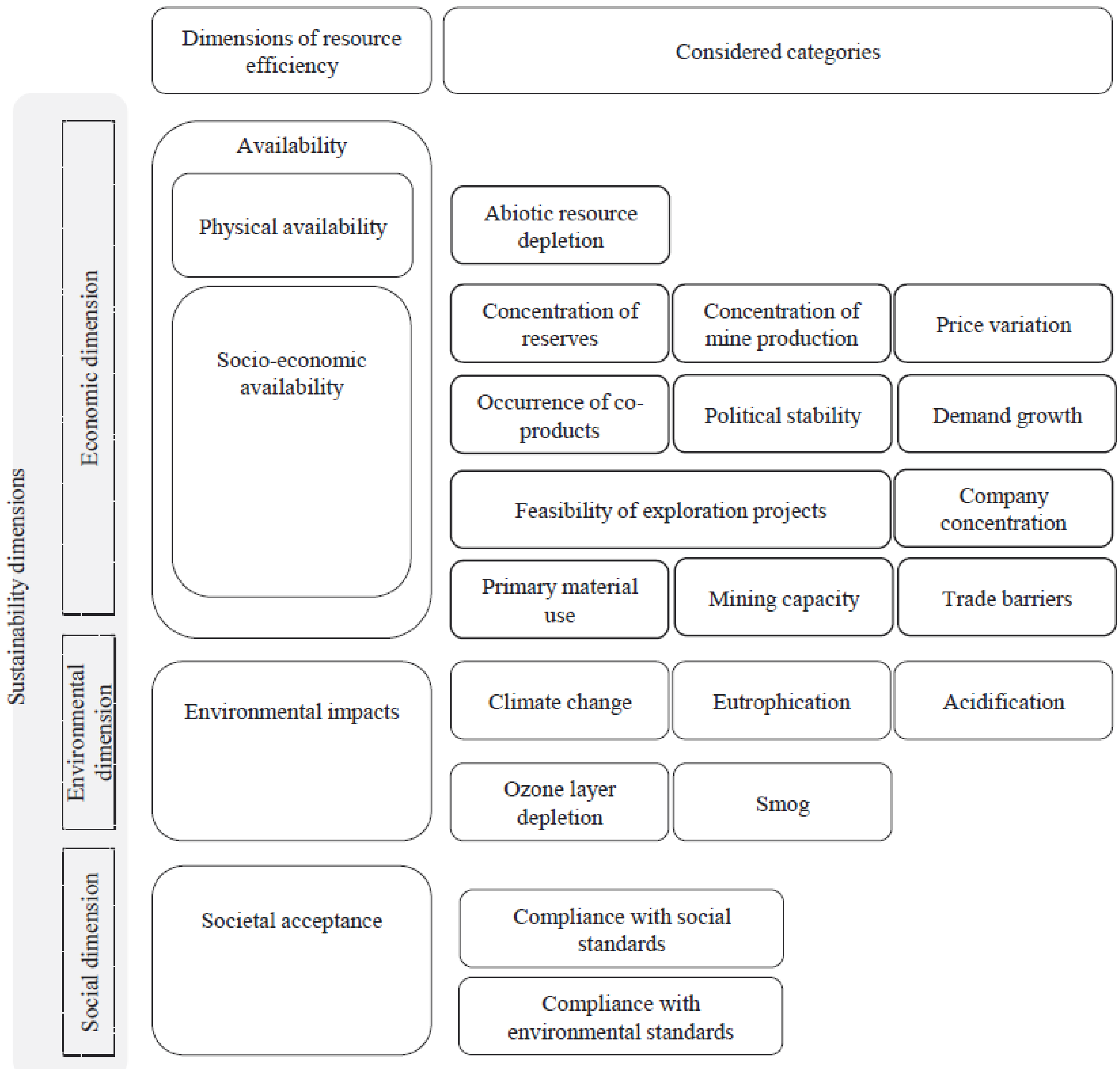

Fig. 2. Overview of considered dimensions and categories in ESSENZ.

The ESSENZ method was developed by Technische Universität Berlin (TUB) in cooperation with the six European companies Daimler, Evonik, Knauer, ThyssenKrupp, German Copper Institute (Deutsches Kupferinstitut) and Siemens during a three year project funded by the German Federal Ministry of Education and Research. In Fig. 3 it is shown how the applied indicators and methods of ESSENZ were determined in the project. First in a bottom-up approach existing methods and indicator for evaluating RE or one of the individual dimensions were identified (e.g. approaches by Graedel et al. (2012) etc. to assess socio-economic availability) including company internal approaches as well as the work done by TUB (e.g. Schneider et al. (2011)). They were analyzed by means of meta criteria and correlation analysis (for more information please see supplementary material - section 1). Based on these results a preselection of indicators was made. In a top-down approach aspects with regard to RE were determined (e.g. compliance with social standards) and their relevancy was discussed within project group meetings. Not all of the identified aspects were seen as relevant enough to be included in the approach, e.g. differences of metals mined in underground or surface mines regarding time frame of extraction and development of mines were determined as minor. For the relevant aspects new indicators or methods were developed (see section 2.1 and 2.2). Data availability had to be checked to guarantee that values can be determined for a variety of materials (thus, to ensure that the overall method is applicable in practice). Then, the newly developed indicators were calculated for as many materials as possible (it became apparent that data availability was a limiting factor). Furthermore, several correlation analyses were carried out to determine if the number of the overall indicators could be reduced. The preselected indicators were tested on several case studies (e.g. Henßler et al. (2016)) to verify the applicability of the indicators and methods as well as to test if the results are reasonable. Based on the results the established indicators were reduced to a set of reliable and applicable indicators (e.g. as toxicity results are not mature enough at this point especially for metals (Joint Research Centre, 2011; Potting et al., 1999; Westh et al., 2015) the category was not included despite its relevance). An iterative approach was chosen to finalize the newly developed indicators and methods: they were applied in several case studies, improved, applied in case studies again, improved again, etc. This way the adequacy of results could be ensured. This led to the final selection of indicators and methods.

The ESSENZ concept is developed with focus on abiotic resources metals and fossil raw materials (this includes but is not limited to fossil energy carriers). Thus, except the environmental dimension, where the chosen indicators are also valid for other abiotic resources (e.g. minerals), the indicators of the dimensions$_0$ availability and societal acceptance are more specific for these materials.

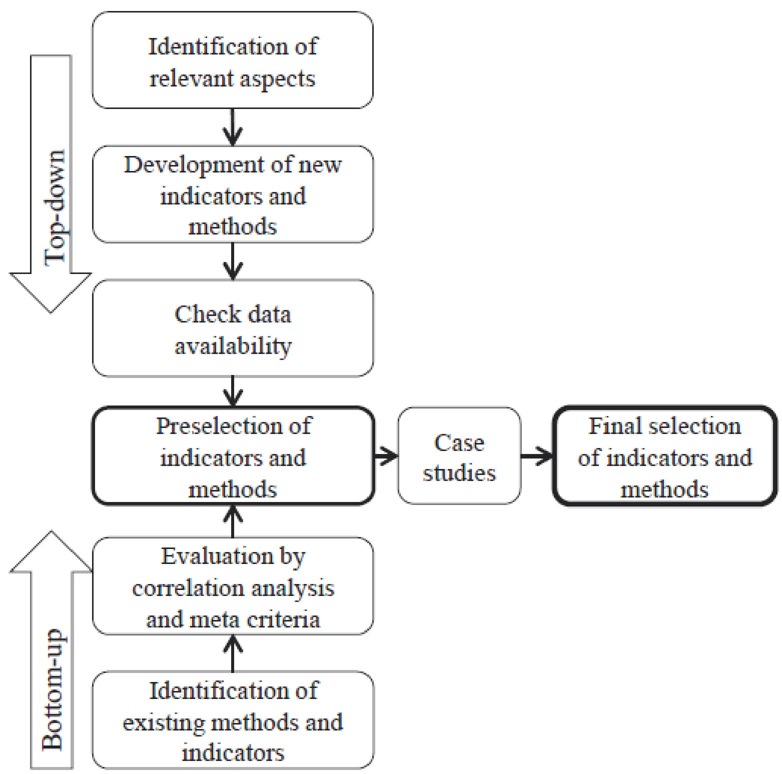

Fig. 3. Combine top-down and bottom-up approach to determine the final indicators and methods used in ESSENZ.

2.1 Availability

As mentioned in section 1 the availability of resources can be divided into physical (long-term) as well as socio-economic (medium-term) availability.

2.1.1 Physical availability

The physical availability is composed of the availability of geological and anthropogenic stocks. To measure the physical availability the Abiotic Depletion Potential (ADP) indicator (baseline approach e based on ultimate reserves) (Guinee et al., 2002, 1993; Oers et al., 2002) can be used. Several options to calculate the ADP indicator are available (e.g. based on economic resources or ultimate reserves) (Guinee et al., 2002). However, as shown by Schneider et al. (2015), Drielsma et al. (2016a, b) for assessing the availability of resources the baseline approach "ultimate reserves in the earth crusts" should be applied. The baseline approach is also the approach, which has been used in LCA case studies for many years (Lehmann et al., 2015; Schneider et al., 2015). The assessment of metals ($ADP_{elemental}$) and fossil raw materials (ADP_{fossil}) is carried out separately.

To account for the availability of anthropogenic stocks the anthropogenic stock extended abiotic depletion potential (AADP) is applied (Schneider et al., 2015, 2011). However, as the name of the indicator already suggests it does not only measure the depletion potential of anthropogenic stocks but also considers abiotic (geologic) ultimately extractable reserves (resource for which economic extraction is currently or potentially feasible (Schneider et al., 2015, 2011; USGS, 2015)). Therefore, by applying AADP and ADP together the geological resources are overrepresented. However, as only few values for AADP are available, it can only be used for product systems, where these few materials occur. To cover a wider range of materials the ADP is applied in addition (for more information see supplementary materials section 2).

2.1.2 Socio-economic availability

Additional to physical also socio-economic aspects can influence the availability of resources significantly and have to be evaluated for a comprehensive RE assessment. Based on this existing work (with focus on Graedel et al. (2012) and Schneider et al. (2013)) eleven potential economic constraints leading to supply shortages along the product's value chain are quantified in ESSENZ (see Table 1). In Fig. 4 the stages of the supply chain considered in ESSENZ and related socio-economic aspects restricting availability are shown. Overall the supply chain is divided into four stages: ore stocks, mining of ores, raw materials and (intermediate) product. In all four stages constrains to availability can occur. Besides the physical availability, the concentration of resources is the most important restriction influencing the availability of ore stocks. In the extraction stage concentration of production, company concentration, mining capacity, feasibility of exploration projects, occurrence as co-product and political stability of ore extracting countries can impact the availability. Trade barriers, price fluctuations, demand growth and primary material use can affect the availability in the raw material stage. For (intermediate) products various socio-economic constrains occur, which can lead to a

Table 1 Overview of the eleven considered categories reflecting socio-economic availability including a description and related category indicators.

Category	Description	Category indicator
Company concentration	Company concentration for producing and trading companies	Herfindahl-Hirschman-Index (HHI) is calculated by squaring the market share of each company or
Concentration of reserves	Reserve concentration based on reserves in countries	country with regard to the production or reserves (Rhoades, 1993)
Concentration of production	Concentration of mine production based on production in countries	
Mining capacity	Overall mining time of a material considering current production	Reserve-to-annual-production ratio (based on data from (USGS, 2015) and BGS (Brown et al., 2014))
Feasibility of exploration projects	Political and societal factors influencing opening of mines	Policy Potential Index (Cervantes et al., 2013)
Occurrence as co-product	Companion metals within host metal ore bodies	Percentage of production as companion metal (Angerer et al., 2009)
Trade barriers	Materials underlying trade barriers	Enabling Trade Index (Hanouz et al., 2014)
Political stability	Governance stability of raw material producing countries	World Governance Indicators (World Bank Group, 2013)
Demand growth	Increase of demand over the last five years	Percentage of annual growth based on past developments (based on data from BGS (Brown et al., 2014))
Primary material use	Recycled content of a material	Percentage of new material content (Graedel, 2011)
Price fluctuation	Unexpected price fluctuations	Volatility (Federal Institute for Geosciences and Natural Resources, 2014)

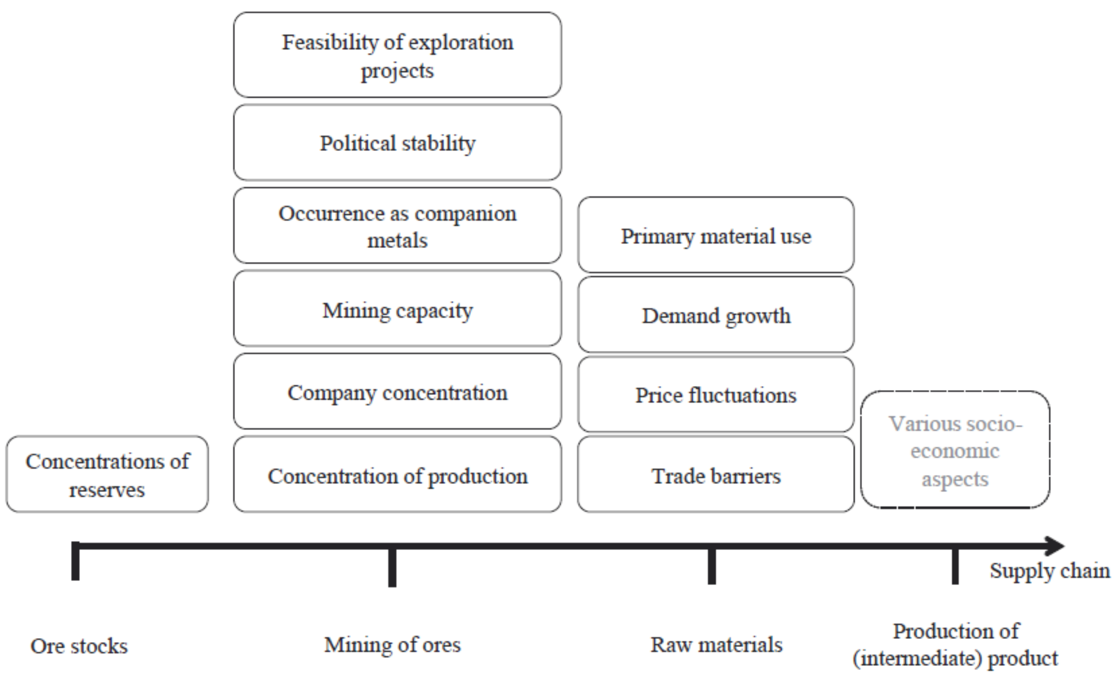

Fig. 4. Supply chain stages and related socio-economic aspects restricting availability of resources for companies.

limited availability for companies. However, as these restrictions are mostly product dependent they have to be determined individually for each (intermediate) product. Thus, characterization factors (CFs) are not provided for the supply chain stage (intermediate) product. As the identified aspects of the other supply chain stages can also influence the availability of (intermediate) products, the approach can be transferred to measure restrictions for (intermediate) products.

Following the eleven categories are described and the approach for the determination of the CFs is explained. Unless otherwise mentioned United States Geological Survey (USGS e United States Geological Survey, 2015) and British Geological Survey (BGS e Brown et al., 2014) data are used to calculate the indicator results. All indicators are calculated according to the same principle: the higher the determined value, the greater possible supply restrictions. If necessary the indicator values were reversed to follow this principle.

- Concentration: A high concentration of one activity (e.g. mining) refers to the extent to which a relatively small number of companies or countries account for a large share of this activity (e.g. Rosenau-Tornow et al. (2009) and Graedel et al. (2012)). High concentrations increase the risk of limited accessibility of a resource. Within ESSENZ the concentration of reserves, concentration of production and company concentration is quantified by means of the Herfindahl-Hirschmann-Index (HHI) (Rhoades, 1993) as done by Erdmann et al. (2011), Graedel et al. (2012) and Schneider et al. (2013) (see supplementary material - section 3.1 for more details).
- Mining capacity: The category reflects how long a reserve can be extracted considering the current conditions (e.g. amount of recoverable ores with regard to technological and economic feasibility) before all mines are exhausted. Thus, the calculated number reflects the time (in years) until new mines have to be developed[1]; no statement can be made with regard to the physical availability of the resource. As the development of new mines typically takes around 10e15 years restrictions to availability due to supply bottlenecks might occur when the capacity of existing mines lasts for only a few more years and new mines are not under development yet. The capacity of existing mines is determined by the indicator static lifetime (see Eq. (2)). To determine the lifetime of a raw material i its reserves are set in relation to the annual production.

$$\text{Static lifetime}_i = \frac{\text{Reserves}_i}{\text{Annual production}_i} \tag{2}$$

- Feasibility of exploration projects: Laws and regulations, societal conditions (e.g. civil movement) and other framework conditions (e.g. infrastructure) can support as well as restrict development of new mines. When these aspects complicate the development of a new mine the time until the mine is operating can be prolonged for several years or even worse in some cases the mine is not able to be opened at all. Thus, the amount of extracted raw materials decreases, which can lead to restrictions to availability. The feasibility of exploration projects (FEP) is determined by multiplying the raw materials' i share of global production (sgp) per country x with the Policy Potential Index (PPI) (Cervantes et al., 2013) (see Eq. (3)). The PPI assesses the current regulatory situation within a country regrading mining activities (e. g. explorations of new mines) by considering the countries policies e.g. on taxation, environmental regulations, administration of regulations, or infrastructure (Cervantes et al., 2013).

$$FEP_i = \sum (sgp_{x,i} \times PPI_x) \tag{3}$$

- Occurrence as co-product: Main reason to put a mine in operation is typically the existence of one main product that shall be extracted. Additionally, other metals are present and are extracted as well. These are called companion metals (coproducts) as they are mined next to the main metal(s). The guarantee that these co-products are mined is low as feasibility of mining is only evaluated based on the market value of the main metal(s). If the economic importance of the main metal(s) is decreasing and the mining activities are diminished or discontinued, the co-product is not extracted further as well. To determine if a metal occurs as a main or companion product, qualitative values by Angerer et al. (2009) were transformed into quantitative values according to Table 2. Occurrence as coproduct can influence the availability over the whole supply chain. In ESSENZ the category is considered for the step mining of ores (see Fig 4).
  The quantitative values are assigned by dividing one (which is set as the highest value) by three (as numbers for three other criteria have to be assigned). The criteria only mined as main product is set to zero as restrictions to availability are not to be expected in this case.

[1] Development includes the discovery process of the reserves as well as the mining of the discovered ores and returning the land to its natural state after extraction is finished.

Table 2 Qualitative information about occurrence as main and companion metals by Angerer et al. (2009) and transferred quantitative data used in ESSENZ.

Qualitative criteria as reported by Angerer et al. (2009)	Quantitative criteria used in ESSENZ
Only mined as main product	0
Mostly mined as main product	0.33
Mostly mined as companion product	0.67
Only mined as companion product	1

- Trade barriers: Availability of raw materials can be restricted by barriers of trade regarding export (e.g. export duty) of these materials. If an ore producing country limits the export of its produced raw materials to few individual countries the availability to companies in certain countries can be impacted. Trade barriers (TB) are measured according to the same principle as FEP: by multiplying the raw materials' i share of global production (sgp) per country x with the Enabling Trade Index (ETI)[2](Hanouz et al., 2014) (see Eq. (4)).

$$TB_i = \sum \left(sgp_{x,i} \times ETI_x\right) \quad (4)$$

  Trade barriers can occur over the whole supply chain. In ESSENZ restrictions to trade are considered for the step raw materials (see Fig 4).
- Political stability: In unstable countries, where political systems and legal procedures are not reliable, the risk of limited availability of raw materials rises as potential revolutions or riots but also corruption or financial crises may interrupt production. Political stability (PS) of raw material producing countries is determined according to the same principle as for FEP: by multiplying the raw materials' i share of global production (sgp) per country x with the Worldwide Governance Indicators (Kaufmann et al., 2011; World Bank Group, 2013) (see Eq. (5)). Overall six key aspects of governance for over 210 countries are established: voice and accountability, political stability and absence of violence, government effectiveness, regulatory quality, rule of law and control of corruption. As all six world governance indicators reflect parts of an unstable system, in ESSENZ they are all combined as an aggregated evenly weighted index ($WGII_x$).

$$PS_i = \sum \left(sgp_{x,i} \times WGII_x\right) \quad (5)$$

  Politically unstable systems can influence the availability of raw materials or products over the whole supply chain. In ESSENZ only the effect on raw materials is considered.
- Demand growth: Demand describes the need for goods as raw materials. Increasing demand is referred to as demand growth. When the demand growth is higher than the actual production possible restrains to availability can occur. Demand growth (DG) of raw materials is determined by calculating their production increase (or decrease) over the last five years (see Eq. (6)).

$$DG_i = \frac{\sum_1^5 \left(\frac{\text{global production of year nþ1}}{\text{global production of year n}} - 1\right)}{4} \quad (6)$$

- Primary material use: During production primary as well as secondary materials might be used. If more secondary materials are utilized less primary materials have to be produced. As a result the demand for this primary material is reduced and its overall availability increases. To determine the effects of primary material use, the

[2] The ETI e established by the World Economic Forum e ranks countries regarding their policy for trading goods (Hanouz et al., 2014).

recycled content[3] of the raw material is determined based on data published by Graedel (2011). To determine the primary material use (PMU) the recycled content (given in percentage) is subtracted from 100% (see Eq. (7)). Is the recycled contend low, more primary material is used. The bigger the recycled content the less primary material has to be used. Thus, the higher the PMU value the higher are possible restrictions to availability as more primary materials have to be produced.

$$PMU_i = 100\% - \text{recycled content}_i \tag{7}$$

Price fluctuation: Prices of raw materials always fluctuate depending on current market situations. For predictable fluctuations compensation can be expected, as purchasers consider them in their calculations. However, when unexpected fluctuations of raw material prices occur and compensation is not possible, availability of raw materials can be restricted. These fluctuations can be quantified by the volatility indicator applied by Federal Institute for Geosciences and Natural Resources (2014).

For determining the CFs for the dimension socio-economic availability the developed 4-step approach is explained as follows:

Step 1) Determination of indicator values of the eleven categories as introduced in section 2.1 for the individual raw materials. In ESSENZ a portfolio of 36 metals and four fossil raw materials is considered as data for these materials is available.

Step 2a) Targets for all eleven categories c are determined (see supplementary material esection 3.2). These targets were established based on expert judgment and a stakeholder survey (not published). However, these targets are default values, which can be adapted by practitioners and stakeholders according to their preferences.

Step 2b) The indicator values are then set in relation to the target (see Eq. (8)) to determine the Distance-to-Target (DtT) value based on the ecological scarcity approach (Frischknecht et al., 2009; Müller-Wenk et al., 1990).

$$DtT - value_{i,c} = \left(\frac{indicator\ value_{i,c}}{target_c}\right)^2 \tag{8}$$

Is the DtT value lower than 1, no constraints on availability are expected and the DtT value is set to zero. When the DtT value is 1 or greater than 1 a possible limitation to availability occurs. The larger the number the higher the probability of possible limitations. The chosen target values have a significant influence on the overall result as they determine whether a material is assigned a possible restriction to availability or not. When the targets are set too low materials with no risk would be classified as risky and an overestimation of the limitations in the product system occurs. Whereas possible limitations cannot be identified when the target is set too high, which could lead to an underestimation of the overall restrictions. As setting the target values is a scientifically informed value choice, but not a scientific result as such, sensitivity analyses are recommended to address the associated uncertainties.

Step 3) Normalization of the DtT values is carried out (see Eq. (9)) to determine the normalized DtT (nDtT) value.

$$nDtT\ value_{i,c} = \frac{DtT\ value_{i,c}}{normalization\ value_i} \tag{9}$$

Contrary to the ecological scarcity approach, where the normalization factor is equivalent to the critical flow (e.g. amount of greenhouse gas emissions released during a year) in the considered area (e.g. Switzerland) (Frischknecht et al., 2009; Müller-Wenk et al., 1990), in ESSENZ the critical flows are based on global production data. As ESSENZ is

[3] The recycled content refers to the annual amount of material scrap consumed divided by the amount of material produced (Schneider et al., 2013).

applicable for products with global supply chains (which is the case for almost all industrial products (Berger et al., 2015, 2012)) a global normalization factor was chosen. The normalization values were determined based on USGS (2015) and BGS (Brown et al., 2014) data. By normalizing with global production data the overall amount of the resource currently produced is taken into consideration. For raw materials with small amounts of production, e.g. gallium, the above mentioned effects (quantified in the eleven categories) can be even worse for their availability than for raw materials, where the overall annually produced amount is high.

Step 4) By dividing the DtT values by global production the CFs are expressed in small numbers. Common production systems however use large amounts of materials (e.g. to produce a car (Henßler et al., 2016)). Thus, if the nDtT values are multiplied with the raw material flows, predominantly the amount of the raw material but not the potential raw material specific risk of restriction to availability determines the result. Therefore, for ESSENZ to be able to assess different product systems also ones with large amounts of materials, the nDtT values are scaled up to 1.7 × 1013 (this number was chosen as it presents the highest global production value of the raw material portfolio considered). According to Eq. (10) the final CFs are calculated.

$$CFs_i = \begin{cases} nDtT\ value_{c,i,max} \gg 1.7 \times 10^{13} \\ other\ values\ of\ category\ are\ calculated \gg \dfrac{1.7 \times 10^{13}}{nDtT\ value_{c,i,max}} \times nDtT\ value_{c,i} \end{cases} \quad (10)$$

The highest value of each category (nDtT $value_{c,i,max}$) is set to 1.7 × 1013. The CFs of the other raw materials are calculated by applying the rule of three[4] (Swetz et al., 2001).

The calculated CFs can be found in the supplementary materials - section 6.1. They range from zero to 1.7 × 1013: A value of zero means that the material has no potential restriction to available in this category (e.g. for aluminum no potential limitations to availability occur due to demand growth). The higher the value of the CF the higher are the potential possible restriction to availability. For example, for the category trade barriers the CF of aluminum is lower as the CF of antimony. Thus, the possible restrictions to availability due to trade barriers are lower for 1 kg aluminum as for 1 kg antimony (all CFs refer to 1 kg material). However, with regard to assessing these materials within a product system also their amount has to be taken into account. In the example presented here possible limitations to availability will be higher for aluminum than for antimony when the amount of the used aluminum is much higher than the amount of antimony.

As the developed approach is in line with existing LCIA methods for determining environmental impacts it can be applied as well as interpreted accordingly. To demonstrate the relation between existing LCIA methods and the developed approach the scheme of ISO 14040 for impact categories is applied for an established method as well as for a category of the developed approach (see supplementary material - section 3.3).

2.2 Societal acceptance

To assess RE in the context of sustainable development social aspects have to be considered. As assessing social impacts is challenging (Lehmann et al., 2013; Neugebauer et al., 2014) the screening indicator compliance with social standards was developed for ESSENZ based on the approach by Schneider (2014). This approach considers on the one hand (some of the) social impacts related to the product system (Missimer et al., 2016) and adds on the other hand additional motivation for a company to apply the indicator as consumers are more and more interested in compliance with social standards by companies (e. g Tsurukawa and Manhart (2011), Kannan (2014), The Guardian (2015) and Osburg et al. (2016)). Thus, societal acceptance can be an additional limitation for companies with regard to purchasing

[4] The rule of three (also referred to as the Golden Rule) is a method, which supports solving basic linear equations with four terms where three of the terms are known (Swetz et al., 2001).

materials. In the worst case a certain material cannot be used by a company because of its low societal acceptance, even though it is available from a physical and socio-economic perspective.

The developed indicator is based on SHDB data and provides information for the supply stage extraction. Impacts in other stages are not covered. To quantify the compliance with social standards the aspects child labor (CL), high conflict zones (CZ) and forced labor (FL) are considered. The indicator were chosen according to Schneider (2014) based on relevance for the mining and minerals sector, high public interest and low societal acceptance. The SHDB (Norris et al., 2013) provides a social hotspot index (Benoit-Norris et al., 2012; Norris et al., 2013) for the mining sector (to assess metals) as well as oil, coal and gas sector (to assess fossil raw materials) on country level for these three aspects (Pelletier et al., 2016). The category indicator result for a material i quantifying the compliance with social standards (SC e social compliance) is determined by multiplying the three social hotspot index (ranging from 0 to 10) with the global production shares (sgp) of different countries x and summing them up (see Eq. (11)). To be methodological consistent with the approach of the socio-economic availability the result is squared. Therefore, it will be spread so that small values become smaller and big values become bigger. Thus, differences between low and high impacts are more significant.

$$SC_i = \sum [sgp_x \times (CL_x + CZ_x + FL_x)]^2 \qquad (11)$$

Finally, according to the same principle as in Eq. (10) the results are scaled to a range of 0e100.

Next to social standards also compliance with environmental standards is gaining in importance for consumers (Balanay and Halog, 2016; Evgeny et al., 2016; Kirchner, 2012). Contrary to global impacts like climate change consumers expect that local impacts like eutrophication and eco toxicity are prevented by using proper technology. Thus, for ESSENZ a screening indicator for compliance with environmental standards is established.

To quantify the compliance of a metal or fossil raw material with regard to environmental standards (EC e environmental compliance) the Environmental Performance Index (EPI) (Yale Center for Environmental Law and Policy, 2014) is applied. The EPI consists of overall 16 sub indicators to measure the performance of countries with regard to their environmental protection efforts. For determining the environmental compliance of countries the sub indicators Critical Habitat Protection (CHP), Marine Protected Areas (MPA) and Terrestrial Protected Areas (TPA) are chosen. The assumption is made that the way a country takes care of their protected areas is similar to their overall compliance with environmental standards during extraction of raw materials. The global production shares of different countries (sgp_x) are multiplied with the EPI indicators, squared and summed up (see Eq. (12)).

$$EC_i = \sum [sgp_x \times (CHP_x + MPA_x + TPA_x)]^2 \qquad (12)$$

Then, the result is scaled to 0e100 according to the same principle as in Eq. (10) to have the same dimension as the category indicator assessing social compliance.

The calculated CFs can be found in the supplementary materials - section 6.2. They range from 0.07 to 100 for social compliance and from 0.18 to 100 for environmental compliance. The higher the value of the CF the higher is the potential of being not compliant with social or environmental standards. For example, the potential of antimony producing countries not be compliant with social standards is higher as for beryllium producing countries. On the other hand, these antimony producing countries are more likely to comply with environmental standards as beryllium producing countries.

2.3 Environmental impacts

As the environmental impacts are evaluated over the entire life cycle consequently the whole life cycle has to be modelled. For several impact categories e.g. climate change, eutrophication, etc. LCIA models and methods are available, which have been applied in LCA case studies for many years. Thus, no new indicators and methods were developed, but rather existing methods were chosen to be integrated into ESSENZ. Based on recent publications determining the maturity of LCIA models and methods (e. g Bach and Finkbeiner (2016), Joint Research Centre (2010) and Lehmann et al. (2015)) the CML-IA method (Guinee et al., 2002) for the categories climate change, eutrophication, acidification, ozone depletion and formation of photochemical oxidants (smog) is chosen to be applied in ESSENZ (for more information see supplementary materials - section 1.2).

3 Case study

Following the results of a hypothetical case study are displayed. This case study is simple on purpose as its main goal is to demonstrate the applicability of the introduced ESSENZ approach. Thus, several simplifications were made with regard to the system boundaries. The goal of this case study is to demonstrate, how the ESSENZ method can be applied and how results can be obtained.

However, the approach was also tested for applications to more complex products like cars (e.g. Henßler et al. (2016)). ESSENZ can be used to compare two (or more) options or to analyze one specific product system. For the case study two cables (a silver and an aluminum cable) with the same function (transmission of electricity) used in sound systems are compared. As the electrical conductivity of the silver cable is higher than for aluminum less material has to be used for the same function. Thus, for one cable of silver 0.24 kg silver and for one cable of aluminum 0.44 kg aluminum are used. The plastic coating and other components are not considered for simplicity. Furthermore, utilized fossil fuels in the upstream processes are only considered for the environmental impacts but not in the assessment of availability. The results for the considered dimensions and categories are shown in Fig. 5 (results for the environmental dimension are shown in the supplementary information - section 4). On the top left the result for the physical availability is demonstrated (only $ADP_{elemental}$ is displayed as no fossil raw materials were considered in the example and the AADP value of silver is missing) showing that silver has a much higher risk of restricted (geological) availability than aluminum, meaning that less extractable silver stocks exist in comparison to aluminum. On the top right the (first) result for the socio-economic availability is shown: here the overall results of both materials are set to 100%. This way it can be demonstrated which category influences the overall supply risk of each metal the most. The socio-economic availability of aluminum is most likely to be restricted by trade barriers, (low) feasibility of exploration projects and (low) political stability. Silvers supply risk is most probable to be influenced by price fluctuations, trade barriers and (low) political stability. Thus, for both materials trade barriers as well as political stability might lead to low availability. Center left the overall (second) results for the dimension socio-economic availability are shown. Overall the supply risk is much higher for silver than for aluminum. However, when considering the societal acceptance (see center right for compliance with social standards and bottom left for compliance with environmental standards) aluminum performs worse than silver. Thus, the possibility of societal outrage due to noncompliance with standards is higher for aluminum than it is for silver. Last the result of all dimensions (including environmental impacts) is displayed (bottom right) by setting the highest value of each metal in every category to 100% and determining the percentage of the other metal accordingly. It can be seen that silver performs worse in most of the categories with exception of societal acceptance, and the socio-economic categories concentration of reserves and concentration of production. However, as seen in the results of the socio-economic availability both categories do not contribute much to aluminum's overall supply risk. When comparing both options to decide which material should be used in the sound system the choice would most likely fall on aluminum as the geological availability, the socio-economic supply risks as well as the environmental impacts are lower than for silver. Regarding the societal acceptance however the company should have a more detailed analysis from which countries and/or companies their aluminum is coming from and if compliance with standards can be ensured.

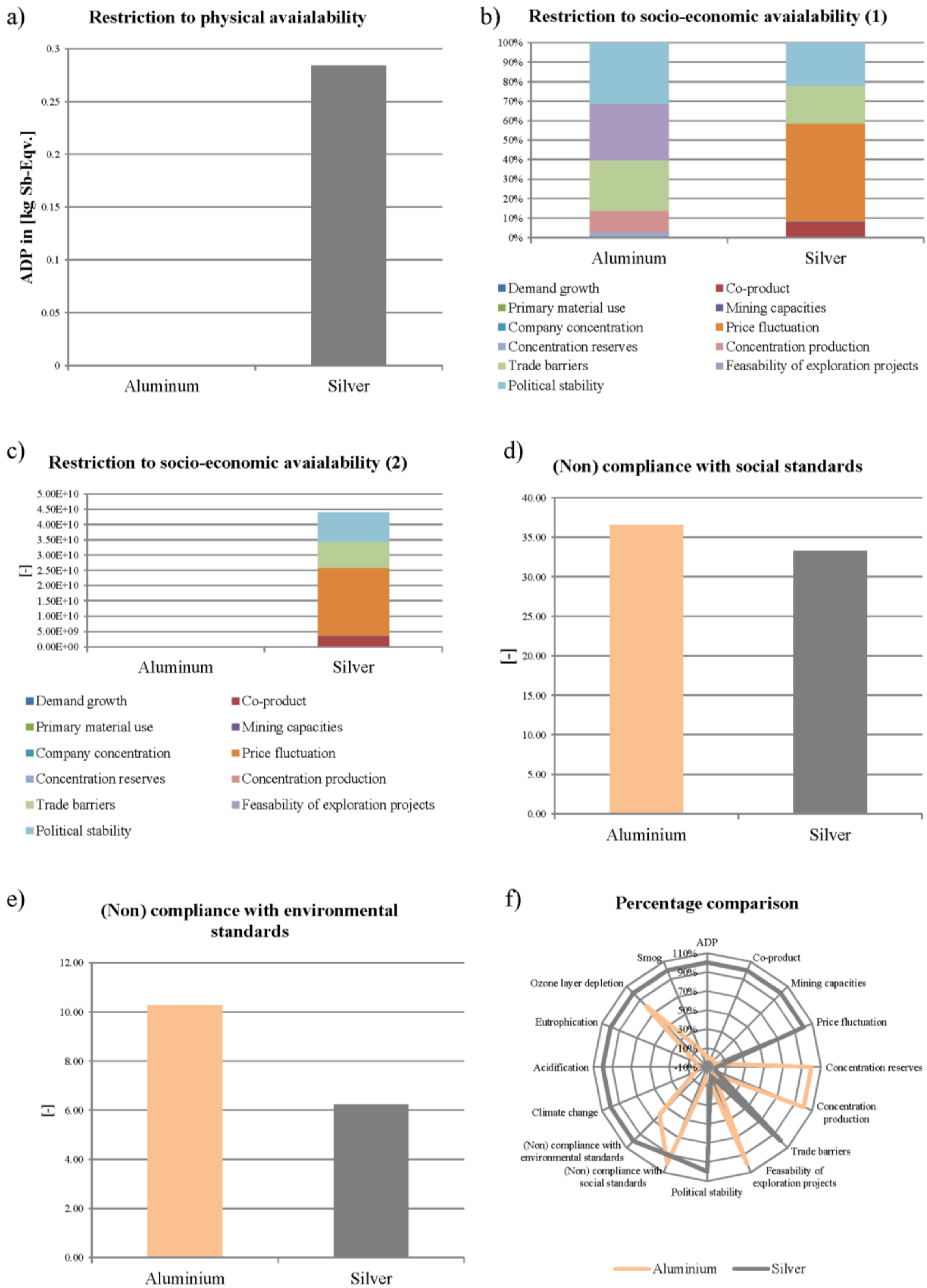

Fig. 5. Results of the case study a) for the dimensions physical (top left) b) for the dimension socio-economic availability in percentage (top right) c) overall result for the dimension socio-economic availability (center left) d) for societal acceptance e (non) compliance with environmental standards (center right) e) for societal acceptance e (non) compliance with social standards (bottom left) f) for all dimensions in percentage (bottom right).

4 Results and discussion

The ESSENZ approach was developed to determine the resource efficiency of product systems. The numerator of the RE formula (see Eq. (1)) is referred to as added value. So far there is no common agreement on how to determine this added value. The main measure for added value in ESSENZ is the benefit of the product system quantified by the functional unit as done in LCA (ISO 14044, 2006). To calculate the RE of product systems Eq. (1) is applied: dividing the added value (functional unit) by the results of the three dimensions (availability, environmental impacts and societal acceptance). Results with a higher number reflect high RE, whereas low numbers reflects low RE. This step is shown in the supplementary material (section 5.1), where also a detailed description about the added value and the determination of the RE is provided.

Company specific monetary values, e.g. investments, or value added to the resources used (Neugebauer et al., 2016), are heterogeneous and also depend on which actor along the supply chain the assessment is focused on (e.g. selling a product for a high price is good for the business case of the seller, but results in high costs for the buyer). These monetary values cannot be determined in a generic way and may even distort the overall RE result (as demonstrated in an example in the supplementary materials - section 5.1). They can only be used as additional factors, but do not replace the RE assessment by ESSENZ, which focusses on the generic socio-economic resource efficiency risks of materials. This information can be used by companies to decide their specific purchasing strategies, which then determine their pecuniary costs and benefits.

The developed approach measures RE in the context of sustainable development. Several dimensions influencing RE are combined to achieve a comprehensive evaluation enabling meaningful decision making processes. CFs are available in literature as well as provided for the dimensions socio-economic availability and societal acceptance for a portfolio of 36 metals and four fossil raw materials (see supplementary materials - section 6). The developed ESSENZ approach has several uncertainties, which have to be considered when interpreting the results. These are described in detail in the supplementary material (section 5.3).

One very prominent challenge is described here as it should be especially considered when interpreting the results. For the assessment of the socio-economic availability ESSENZ currently only considers primary materials. The socio-economic availability of secondary materials is not taken into account. This might not be a significant limitation for natural gas, oil and coal as they are mostly burned and therefore not feed back into the system as a recycled product. Metals on the other hand are often recycled with only low restrictions to quality. Most product systems do not use only primary but often secondary metals as well. A first approach to determine socio-economic availability of secondary materials was established by Finkbeiner and Schneider (2012). However, due to lack of data the socio-economic availability of secondary materials could not be determined. Thus, in ESSENZ limitations to the socioeconomic availability are determined based on the restrictions on primary metals only.

5 Conclusion

The introduced approach enhances the applicability of RE to assess product systems significantly by providing an overall framework that can be adopted across sectors. As already 21 categories are included in the approach ESSENZ serves as a starting point to carry out a comprehensive assessment of RE. However, as every sector has its individual characteristics sector specific aspects should be added.

Furthermore, ESSENZ considers RE in the context of sustainable development by considering existing sustainability goals (United Nations, 2016). For decision making support on a product level and in the context of sustainable development a comprehensive assessment of sustainability is needed (Schneider et al., 2016). ESSENZ contributes to this aim by considering all three sustainability dimensions and providing indicators for quantifying environmental, economic and social implications of material use.

For determining the socio-economic availability a new approach is developed, which complements existing approaches as it can be integrated in existing life cycle assessment based schemes. Thus, companies which already use LCA for determining their environmental impacts can adapt their framework and integrate the assessment of additional aspects more easily. As the developed approach has the same framework condition interpretation of the results is also straightforward. CFs for 36 metals and four fossil raw materials are provided. This enhances the applicability tremendously.

To make the developed approach even more practical a reduction of the current indicator set should be pursued. As 21 indicators are applied the communication of the results can be challenging, especially with regard to stakeholders with less experience in the field of LCA and sustainability. Thus, identifying key indicators which represent the individual dimensions could be one option to reduce the indicator set. So far there is no experience on how to determine such key indicators. Another option could be to aggregate the indicators into a single score. However, numerous challenges accompany aggregation of indicators. These are explained in more detail in the supplementary material (section 5.2).

Even though several case studies were carried out during the development of the approach (e.g. Bach et al. (2015) and Henßler et al. (2016)) further case studies also from other sectors so far not included should be performed to continuing the testing of the developed indicators and related results. Furthermore, as ESSENZ is so far focused on metals and fossil raw materials only, but various product systems also include biotic raw materials (or a comparison on abiotic vs. abiotic based products is performed), the ESSENZ approach should be adapted to be applicable for biotic raw materials as well. Preliminary studies have shown that the ESSENZ framework can be applied to other materials (e.g. biotic materials like wood or organic substances) as well.

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