Abiotic resources: new impact assessment approaches in view of resource efficiency and resource criticality—55th Discussion Forum on Life Cycle Assessment, Zurich, Switzerland, April 11, 2014

Journal Article

Author(s):
Vadenbo, Carl; Rørbech, Jakob; Haupt, Melanie; Frischknecht, Rolf

Publication date:
2014

Permanent link:
https://doi.org/10.3929/ethz-b-000091966

Originally published in:
The International Journal of Life Cycle Assessment 19(10), https://doi.org/10.1007/s11367-014-0784-4

Int J Life Cycle Assess (2014) 19:1686–1692
DOI 10.1007/s11367-014-0784-4

CONFERENCE REPORT

Abiotic resources: new impact assessment approaches in view of resource efficiency and resource criticality—55th Discussion Forum on Life Cycle Assessment, Zurich, Switzerland, April 11, 2014

Carl Vadenbo · Jakob Rørbech · Melanie Haupt · Rolf Frischknecht

Received: 7 July 2014 / Accepted: 14 July 2014 / Published online: 30 July 2014

1 Introduction and overview

Natural abiotic resources (here referring primarily to metals, minerals and fossil resources) have become a growing political concern with increased focus on resource scarcity, natural availability and dependency on foreign supply. For a near-term time horizon, both the USA and the EU have identified so-called critical raw materials including platinum group metals, rare earth elements, etc. (EC 2010; NRC 2008), and resource efficiency has become one key element of the sustainability policy of the EU and Switzerland (EC 2011a; Bundesrat 2012). Within the context of life cycle assessment (LCA), the development of life cycle impact assessment (LCIA) methods has been very diverse without a unifying practice for how to assess the depletion of abiotic resources from the natural environment (Carvalho et al. 2014; EC 2011b; Klinglmair et al. 2013; Mancini et al. 2013). The overarching goal of the 55th Discussion Forum on LCA (DF-55) was to present and discuss recent developments of novel and updated LCIA approaches with respect to the relevance of resources as a separate safeguard subject (or area of protection, AoP) in environmental assessment, the rationale and interpretations of their respective environmental mechanisms related to abiotic resource depletion and the relation to other resource-related concerns such as scarcity and criticality.

Setting the stage for the discussion forum, the first presentation of the day was given by Stefanie Hellweg (ETH Zürich, Switzerland) who gave an overview of the various issues related to the assessment of abiotic resource depletion. The extraction rates and the number of resources put into use are increasing and products are becoming more complex. The resulting heterogeneity of materials and products poses great challenges for recycling and recovery of the resources. In this context, three different methodologies for addressing different issues or questions related to the management of resources were outlined:

- *Material flow analysis (MFA)* is an account of physical flows and stocks (Baccini and Brunner 1991; Brunner and Rechberger 2004) and is thus an apt tool for monitoring and managing resources, for example by identifying the users of the resources; by indicating resource efficiency or recycling potential on industrial, regional, national or global levels; and by quantifying emissions to natural compartments from losses and dissipative uses.
- *Criticality assessment* departs from a corporate, national or global user perspective to assess the risks for a user if the resource were to become unavailable in sufficient amounts in the future. Criticality encompasses supply risks and vulnerability to supply restrictions, and it might also include potential environmental implications (EC 2010; Graedel et al. 2012).
- *LCA* is commonly focused on quantifying and assessing the potential environmental impacts caused by emissions of pollutants and depletion of resources throughout the life cycle of a product. While there is agreement that the environmental impacts from mining and resource use,

---

The presentations from the DF-55 are available for download (www.lcaforum.ch), and the video recordings can be watched online (www.multimedia.ethz.ch/misc/lca/2014).

C. Vadenbo (✉) · M. Haupt
ETH Zurich, Institute of Environmental Engineering,
John-von-Neumann-Weg 9, 8093 Zurich, Switzerland
e-mail: vadenbo@ifu.baug.ethz.ch

J. Rørbech
Department of Environmental Engineering, Technical University of Denmark, Miljoevej, Building 113, 2800 Kgs. Lyngby, Denmark

R. Frischknecht
treeze Ltd., Kanzleistrasse 4, 8610 Uster, Switzerland

such as land use changes and toxic emissions to air, water and soil, etc., damaging ecosystems and human health, should be considered, whether depletion of resources is a purely economic or also an environmental problem is still being debated. Several different approaches exist to assess and express the impacts of resource depletion. It might also be questioned whether it is the removal of abiotic resources from the natural environment or rather the dissipative use of resources (resulting in an 'irreversible' loss) that should be assessed.

An overview of presentations at the DF-55 and the respective areas addressed is shown in Table 1. The presentation ended with the following key questions related to resource indicators to the participants:

- Is resource extraction and use an economic and/or an environmental issue?
- What is the safeguard subject or AoP related to resources?
- What should be assessed: Resource scarcity? Decline in resource quality?
- Is there an 'ultimate' resource, e.g. energy, exergy, or money?
- Could/should renewable and non-renewable resources be integrated into a unified resource assessment approach?
- How can we include damages of potential resource limitations?
- How can we deal with trade-off between complexity and number of resources assessed?
- Who should bear the burden of resource depletion?

2 Recent method developments

Tommie Ponsioen (PRé Consultants Ltd., the Netherlands) presented the activities on abiotic resource within the LC-IMPACT project.[1] As the ILCD Handbook (EC 2011a) did not provide a recommendation on an endpoint method for mineral and fossil resources, it became the aim to develop a robust endpoint method and, if possible, a related midpoint method. The research started with the cause-effect chain used in the ReCiPe method (Goedkoop et al. 2013), i.e. surplus cost, which is the global future cost increase due to marginal resource use. This approach is based on the assumption that ores with the highest metal concentrations (ore grades) are mined first. To get to the surplus cost of minerals, a relationship between cumulative mineral production and ore grade was derived (Vieira et al. 2012), as decreasing ore grades generally lead to increased mining costs per unit of mineral produced. To convert the ore grade decrease into surplus cost factors, assumptions on future metal demand, recycling scenarios, discount rates and size of reserves were used. Independent of the cultural perspective applied, platinum group metals were assigned the highest characterization factors, followed by gold and silver and then the base metals. Among the drawbacks of the method are that sufficient data are only available for 18 minerals, the difficulty of identifying a related midpoint indicator and that regional differences of scarcity are not taken into account. On the positive side, the obtained characterization factors are comparable to those available for fossil resources (Ponsioen et al. 2013) and water (Pfister et al. 2011). The characterization factors will be available in the LC-IMPACT method upon its release.

Jo Dewulf (Joint Research Centre of the European Commission, Italy/Ghent University, Belgium) started the presentation by stating that many natural resources, particularly those beyond abiotic resources and water, are not covered and comprehensively modelled by current LCIA methods. Another issue is that existing LCIA methods start from an anthropocentric and/or economic perspective, which is not entirely in line with an 'environmental' LCA perspective. A key question is what we would like to protect within the AoP 'natural resources' (Mancini et al. 2013): Is it natural resources in an ecocentric context, e.g. as shaping natural habitats or in biogeochemical cycles, or is it the services they provide, or rather, their role in society? One possible indicator is the cumulative demand for exergy, i.e. the maximum amount of work that could be obtained from a resource over the life cycle of a product. A key challenge of this concept is how to account for land occupation and biomass production and how to compare extraction from the natural environment with production in human-made systems. A possible solution is to assess the human-made system based on the natural potential net primary productivity that would have been produced on the land if not occupied by humans (Alvarenga et al. 2013). J. Dewulf thereafter discussed some challenges of using the change in ore grade to predict the efforts required to extract and produce metals, which proves to be not necessarily linearly related (Swart and Dewulf 2013). Lastly, it was proposed that criticality may be considered for assessing the AoP natural resources from an economic sustainability point of view, where supply risk is quantified as a function of worldwide concentration of production, economic and political stability of producing countries and substitutability and recyclability of the raw material under study.

Laura Schneider (Technische Universität Berlin, Germany) presented the development of a comprehensive method to address the risks associated with resource provision capability from the 'triple bottom line' perspective. Since the lack of access to resources may hamper human well-being and productivity, resources represent a sustainability problem rather than merely an environmental problem. A holistic assessment of resource use must go beyond the analysis of physical

---

[1] Website for LC-IMPACT work package 1 'Resource use impacts': http://www.lc-impact.eu/wp1-resource-use-impacts

Table 1 Overview of topics addressed at the DF-55 and the related presentations

Management of abiotic resources	Sustainability assessment	
X. Du, EMPA, Switzerland[a]	L. Schneider, TU Berlin, Germany	
J. Drielsma, Euromines, Belgium[a]		
H.-J. Althaus, swisscleantech, Switzerland[a]		
Material flow analysis (MFA)	Criticality assessment	Life cycle impact assessment (LCIA)
D. Laner, TU Wien, Austria[a]	P. Nuss, Yale University, USA	T. Ponsioen, PRé consultants Ltd., the Netherlands
		J. Dewulf, EC-JRC, Italy/Ghent University, Belgium
		R. Frischknecht, treeze Ltd., Switzerland
		J. Rørbech, DTU, Denmark

[a] Short presentations

availability of resources in the natural environment or the impacts associated with their extraction. The evaluation of resource provision needs to be extended to also include limited supply (scarcity) of resources caused by economic, e.g. distributional or political, or social, e.g. abuse of human rights, constraints or risks. By extending existing assessment methods from LCA to also include economic and social dimensions of resource availability into product evaluations, a contribution towards life cycle sustainability assessment is achieved. In this context, resource scarcity can be classified into absolute scarcity due to geological limits and actual scarcity arising from economic, environmental and/or social constraints. The geologic availability is based on the abiotic depletion potential (ADP, Guinée et al. 2002) but is extended to also include anthropogenic stocks (Schneider et al. 2011). For the effective scarcity, each indicator is related to a threshold value at which scarcity is expected in a distance-to-target approach. By including economic and social scarcity, the former sharing several elements with criticality assessment (Schneider et al. 2013) and the latter based on the framework of social LCA, the method enables producers to make sustainable material choices and to successfully manage their products.

Rolf Frischknecht (treeze Ltd., Switzerland) focused in his presentation on the role of borrowing and dissipative resource use in impact assessment of abiotic resources. Material resources on earth cannot be lost (unless converted into energy or lost into space) but might be dispersed. Departing from the premises that resources represent a separate AoP, and have an intrinsic value, the question of 'What is the appropriate resource flow to be assessed in the impact assessment?' was posed. In the assessment of water use, a difference is made between water that is withdrawn and water that is consumed, e.g. embedded into products or evaporated. This concept may also be applied to primary mineral resources by assessing the amount extracted from the natural environment and the amount of resources used in a dissipative way separately. This approach was illustrated with an exemplary case for aluminium comparing single use with recycling. Based on the Swiss political target to increase resource efficiency (Schweizerischer Bundesrat 2012), abiotic resources were introduced in the recently published Ecological Scarcity 2013 method (Frischknecht and Büsser Knöpfel 2013). The characterization step is based on ADP using the most recent production and reserve data (USGS 2011). The resulting eco-factors are applied to dissipative use of resources, which is derived as the difference between the amounts of resources extracted and recycled, i.e. the aggregated amount lost during manufacture, use and end-of-life treatment. An open question is where to draw the boundary between borrowing and dissipative uses, e.g. metals disposed of in landfills. Potential criteria might be (current) recovery costs (comparable to current mining costs) or resource concentrations (comparable to currently mined ore grades).

Jakob Rørbech (Technical University of Denmark, Denmark) presented a quantitative comparison of 11 impact models for the assessment of resource depletion (indicated in Fig. 1) (Rørbech et al. Resource depletion indicators in LCA: quantitative comparison of selected characterization models, in submission). The comparison encompassed indicator characterization factors and characterized impact scores based on impact assessment of the activities covered by the ecoinvent inventory database v3.0 (Ecoinvent Centre 2013). The results of the comparison did not suggest any consistent correlations between methods applying similar assessment models. Instead, the methods could be divided into two groups with relatively high internal correlation of total impact scores, where the first group consists of CML-IA (ultimate reserves), EI99, IMPACT 2002+, ReCiPe, CEENE and CExD and the second group of CML-IA (reserve base), EDIP, EPS and ORI. The conclusions of the study suggest that the selection among available assessment methods for resource depletion might influence the results and consequently the recommendations of LCA studies considerably. Furthermore, the coverage of the methods is an important factor to avoid shifting burdens between resources. The existing classification of resource depletion indicators neither systematically reflects underlying environmental concerns within the methods nor groups according to impact profiles. A revised grouping of methods according to AoP addressed and a classification into mid- and

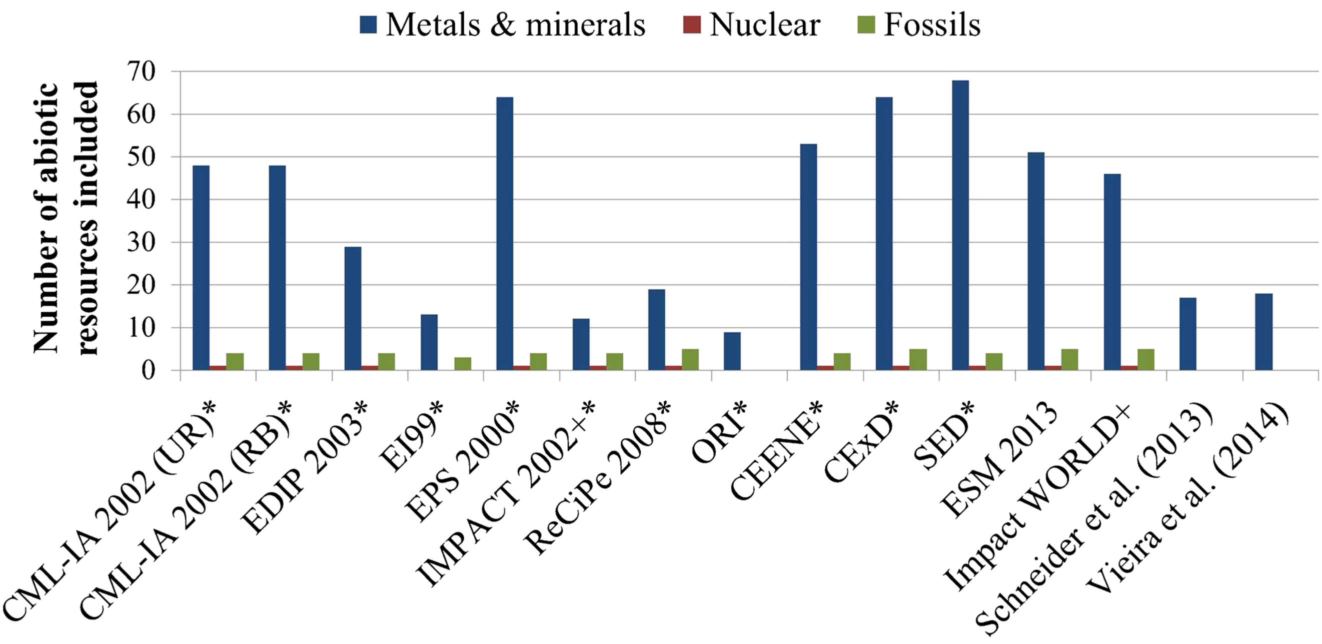

Fig. 1 Summary of resource coverage of LCIA methods for abiotic resource depletion. The figure is based on the information in Table 1 in Rørbech et al. Resource depletion indicators in LCA: quantitative comparison of selected characterization models (in submission) and covers the LCIA methods analysed in the aforementioned study (indicated with an *asterisk*) and additional LCIA methods discussed during DF-55. Legend: *CML-IA 2002* (ultimate reserves, *UR*), *CML-IA 2002* (reserve base, *RB*; ILCD recommended), Environmental Design of Industrial Products (*EDIP*) 2003, Eco-indicator '99 (*EI99*), Environmental Priority Strategy (*EPS*) 2000, *IMPACT 2002+*, *ReCiPe 2008*, Ore Requirement Indicator (*ORI*), Cumulative Exergy Extraction from the Natural Environment (*CEENE*), Cumulative Exergy Demand (*CExD*), Solar Energy Demand (*SED*), Ecological Scarcity Method (*ESM*) 2013 (Frischknecht and Büsser Knöpfel 2013), *Impact WORLD+* (midpoint, beta version, www.impactworldplus.org, assessed on 2014-06-05), Schneider et al. (2013) and Vieira et al. (2014) as presented by T. Ponsioen

endpoint levels based on the indicators suggested by the methods were proposed. This will provide clear information to users about the consequence of their choice of indicator as well as assist method developers in understanding the quantitative performance of existing methods.

3 Criticality and short presentations

Philip Nuss (Yale University, USA) introduced the Yale metals criticality methodology (Graedel et al. 2012) and discussed a selection of its indicators, such as depletion time, companion metal fraction and global supply concentration. With regard to depletion time, he emphasized that for some metals anthropogenic stocks might represent a significant source and should be included in resource assessment, cf. Schneider et al. (2011). Similar to the three AoP generally considered in LCIA (i.e. human health, ecosystems and natural resources), the Yale methodology assesses criticality by investigating a metal's (a) supply risk, (b) vulnerability to supply restriction (natural resources) and (c) cradle-to-gate environmental implications (human health and ecosystems damage). By doing so, the criticality approach provides additional insights, in particular with regard to the social, regulatory and geopolitical factors of resource use, as well metal substitution—aspects generally not included in traditional resource indicators in LCIA. An application of the criticality methodology to iron and several of its main alloying elements, i.e. vanadium, chromium, manganese and niobium, for the USA and globally in year 2008 was presented (Nuss et al. 2014). Alloyed steel forms the backbone of any industrial society and is vital for national security and economic well-being. Iron has the lowest supply risk, primarily because of its widespread geological occurrence. In contrast, niobium is mainly produced in only two countries (Canada and Brazil), thus representing a high global supply concentration. Manganese and chromium, both essential in steel making, display the highest vulnerability to supply restriction from the national (USA) perspective, largely because of poor substitutability in some end uses. Furthermore, vanadium displays the highest cradle-to-gate environmental implications (per kg of metal at the factory gate), followed by niobium, chromium, manganese and iron. It is important to recognize that resource criticality is highly dependent on the perspective chosen (i.e. corporate, national or global) and that it is dynamic, as the model parameters change over time. Aspects of the criticality approach may be considered when deriving, characterizing, or weighting factors in LCIA to provide a more holistic picture of resource use in the future.

Xiaoyue Du (EMPA, Switzerland) presented the E-RECMET project which aims to evaluate technological and organizational adaptations for the Swiss waste electrical and electronic equipment (WEEE) recycling system to facilitate the recovery of critical metals. Based on criticality, occurrence in WEEE and recovery potential, indium and neodymium were selected. The focus was placed on improving inventory data and comparing the impacts of primary and secondary production: Neodymium is produced as a co-product together with several other rare earth elements or could be recovered from magnets in hard disc drives. Indium is extracted as a by-product of zinc and lead deposits, whereas secondary indium might be recovered as a co-product alongside other metals from liquid crystal displays. Joint metal production poses great challenges for inventory modelling and LCIA (Stamp et al. 2013). The outcomes of the comparison of primary and secondary production were found to be highly dependent on the allocation method chosen.

David Laner (Vienna University of Technology, Austria) focused on MFA as a tool to support national resource management. The end-of-life collection ratio and the old scrap recovery ratio represent indicators useful to evaluate the resource efficiency of the system. Methodological aspects and results were shown for two national case studies focusing on aluminium (widely used with secondary production in Austria; Buchner et al. In-depth analysis of aluminium flows in Austria as a basis to increase resource efficiency, in submission) and palladium (a critical raw material according to the EU, mainly contained in consumer products, without primary and secondary production in Austria). To account for the large uncertainties involved in the palladium balance, fuzzy sets were applied (Laner et al. Applying fuzzy and probabilistic uncertainty concepts to the material flow analysis of palladium in Austria, in submission). Based on the experiences gained from these and other case studies, it was concluded that country-level balances are an important, but not sufficient, basis to assess national resource efficiency and that dynamic MFA models may advance the investigation of resource stocks and end-of-life product flows on a system level.

Johannes Drielsma (Euromines, Belgium) pointed to several issues related to the assessment of abiotic resource depletion in LCA from the mining industry's perspective: Firstly, the discrepancies in the terminology used by the LCA community and the mining industry (CRIRSCO 2013), respectively, were highlighted.[2] J. Drielsma emphasized the need to address these discrepancies as LCA gains importance in a legal context and for guiding investment decisions. Another issue from the industry perspective is the use of ore grades to assess abiotic resource depletion: Declining ore grades might entail increased environmental burdens (per unit of metal extracted) due to increased specific use of energy and water and increased specific amounts of waste and emissions generated. These impacts are, however, already covered by impact categories other than 'resource depletion'. The decision to mine a particular ore is influenced by many factors, such as present commodity and fuel prices, and does not necessarily follow the 'ore-grade-decrease' theory. In the conclusions, J. Drielsma stressed the need to differentiate between different resource-related concerns and to apply the appropriate tools to address these concerns.

Finally, Hans-Jörg Althaus (swisscleantech, Switzerland) provided an overview of the development of a strategy for more sustainable use of natural resources while maintaining or strengthening the success factors of the Swiss economy. There is a wide range of concepts to address different resource-relevant issues, e.g. related to criticality, dependency or the environment. LCA models should go beyond assigning burdens among the different life cycles (in the case of a recyclable resource). It was therefore recommended to model use and transformation (as loss or gain of quality) of resources separately in the inventory phase and to develop corresponding impact assessment methods similar to the assessment of land use impacts. He emphasized the need to provide unallocated life cycle inventory data to ensure full flexibility in subsequent modelling.

4 Discussions and conclusions

The discussion round was initiated by dividing the audience into three groups to address the following discussion topics:

- Resource indicators: practicality versus scientific rigor
- What are the potential role(s) of thermodynamic concepts for managing resource use?
- Borrowing or dissipating resources—does it matter?

The discussion in the first group confirmed that there is not a clear consensus about the relevant AoP for (abiotic) natural resources, as the related issues are on the borderline between purely environmental and sustainability concerns. The LCA community still has a way to go to define which questions related to the extraction and use of resources the results of LCA studies should be able to answer. Several of the recently developed methods for assessing resources in LCA apply quite advanced cause-effect-chain models but only cover a limited set of resources (Fig. 1). This can be considered a major problem since many potentially important resources may lack adequate representation in the assessment methods, e.g. due to missing or insufficient data. Furthermore, most of the geological models were challenged by having a stronger relationship to market trends, high cost of market entry (start-up costs of mining operations), investment horizons, supply and demand fluctuations, etc., than to actual change in physical availability on a global scale.

---

[2] The terminology of the LCA community is generally based on the US Geological Survey's principles of resource/reserve classification for minerals (USGS 1980). See Weber (2013) for a comprehensive review and comparison of various mineral resource classification systems.

The second group concluded that exergy (efficiency) represents a suitable indicator to support an efficient management of resources in the economy. An advantage of this approach is that it is applicable to different types of resources (e.g. minerals, fossils, biomass/land) and that characterization factors can be derived with almost complete resource coverage. The relative importance of different resource types, however, might be questioned as energetic resources typically dominate the results. In relation to scarcity, thermodynamic indicators might be useful if declining ore grades represent the main concern, as it results in a larger exergy demand per unit of resource extracted. One of the drawbacks is that the impact is calculated as the minimum amount of exergy required to form the resource from a reference state, which has limited practical relevance.

Concerning the differentiation between borrowing and consumptive (dissipative) uses of resources, the third group found that it is sensible to distinguish between the two aspects and to assess the dissipative resource use. This approach entails that the impacts of abiotic resource depletion are shifted to the life cycles in which the resource is deemed to be irrevocably lost. Current economic feasibility (e.g. based on profitability) of resource recovery from post-consumer ‘wastes’ was considered a suitable approach to draw a line between borrowing and dissipative use of resources. The practical implementation of the concept in inventory databases faces several challenges, e.g. the quantification of resource losses along the life cycle of products or the differentiation between functional elements and impurities in waste streams.

Acknowledgments The authors would like to thank the presenters for their contributions. Furthermore, ESU-services Ltd. and Quantis Switzerland are acknowledged for their financial and technical support during the organization of the 55th Discussion Forum on LCA. Carl Vadenbo and Jakob Rørbech are grateful for the funding provided by the Danish Council for Strategic Research (grant no. 11-116775, the IRMAR project).

References

Alvarenga RAF, Dewulf J, Langenhove H, Huijbregts MAJ (2013) Exergy-based accounting for land as a natural resource in life cycle assessment. Int J Life Cycle Assess 18:939–947

Baccini P, Brunner PH (1991) Metabolism of the anthroposphere, 1st edn. Springer, Berlin

Brunner PH, Rechberger H (2004) Practical handbook of material flow analysis. Lewis Publishers, Boca Raton

Bundesrat S (2012) Strategie Nachhaltige Entwicklung 2012–2015. Interdepartementaler Ausschuss Nachhaltige Entwicklung, Bern

Carvalho A, Mimoso AF, Mendes AN, Matos HA (2014) From a literature review to a framework for environmental process impact assessment index. J Clean Prod 64:36–62

Committee for Mineral Reserves International Reporting Standards (CRIRSCO) (2013) International reporting template for the public reporting of exploration results, mineral resources and mineral reserves (November 2013)

Ecoinvent Centre (2013) ecoinvent data v3.0. Swiss Centre for Life Cycle Inventories, Dübendorf, Switzerland

European Commission (EC) (2010) Critical raw materials for the EU. Report of the Ad-Hoc Working Group on Defining Critical Raw Materials. Brussels, Belgium

European Commission (EC) (2011a) A resource-efficient Europe—flagship initiative under the Europe 2020 strategy. Brussels, Belgium

European Commission (EC) (2011b) International Reference Life Cycle Data System (ILCD) handbook—recommendations for life cycle impact assessment in the European context. doi:10.278/33030

Frischknecht R, Büsser Knöpfel S (2013) Ökofaktoren Schweiz 2013 gemäss der Methode der ökologischen Knappheit - Methodische Grundlagen und Anwendung auf die Schweiz [Swiss Eco-Factors 2013 according to the ecological scarcity method. Methodological fundamentals and their application in Switzerland]. Federal Office for the Environment (FOEN), Bern, Switzerland

Goedkoop MJ, Heijungs R, Huijbregts MAJ, Schryver AD, Struijs J, Zelm RV (2013) ReCiPe 2008—a life cycle impact assessment method which comprises harmonized category indicators at the midpoint and the endpoint level/report I: characterisation. Ministry of Housing. Spatial Planning and Environment (VROM), Den Haag

Graedel TE et al. (2012) Methodology of metal criticality determination. Environ Sci Technol 46:1063–1070

Guinée JB (Ed) (2002) Handbook on life cycle assessment. Operational guide to the ISO standards. I: LCA in perspective. IIa: Guide. IIb: Operational annex. III: Scientific background. Kluwer Academic Publishers, Dordrecht

Klinglmair M, Sala S, Brandão M (2013) Assessing resource depletion in LCA: a review of methods and methodological issues. Int J Life Cycle Assess 19:580–592

Mancini L, De Camillis C, Pennington D (eds) (2013) Security of supply and scarcity of raw materials. Publications Office of the European Union, Luxemburg. doi:10.2788/94926

National Research Council (NRC) (2008) Minerals, critical minerals, and the U.S. economy. Washington DC, USA

Nuss P, Harper EM, Nassar N (2014) Criticality of iron and its principal alloying elements. Environ Sci Technol 48:4171–4177

Pfister S, Saner D, Koehler A (2011) The environmental relevance of freshwater consumption in global power production. Int J Life Cycle Assess 16:580–591

Ponsioen TC, Vieira MDM, Goedkoop MJ (2013) Surplus cost as a life cycle impact indicator for fossil resource scarcity. Int J Life Cycle Assess 19:872–881

Schneider L, Berger M, Finkbeiner M (2011) The anthropogenic stock extended abiotic depletion potential (AADP) as a new parameterisation to model the depletion of abiotic resources. Int J Life Cycle Assess 16:929–936

Schneider L et al (2013) The economic resource scarcity potential (ESP) for evaluating resource use based on life cycle assessment. Int J Life Cycle Assess 19:601–610

Stamp A, Althaus H-J, Pa W (2013) Limitations of applying life cycle assessment to complex co-product systems: the case of an integrated precious metals smelter-refinery. Resour Conserv Recycl 80:85–96

Swart P, Dewulf J (2013) Modeling fossil energy demands of primary nonferrous metal production: the case of copper. Environ Sci Technol 47:13917–13924

U.S. Bureau of Mines, U.S. Geological Survey (1980) Principles of a resource/reserve classification for minerals. Geological Survey Circular 831 (revision of the classification systems published as U.S. Geological Survey Bulletin 1450–a). U.S. Bureau of Mines and U.S. Geological Survey, Arlington

USGS (2011) Mineral commodity summaries 2011. U.S. Geological Survey, U.S. Department of the Interior, Reston, Virginia, USA

Vieira MDM, Goedkoop MJ, Storm P, Huijbregts MAJ (2012) Ore grade decrease as life cycle impact indicator for metal scarcity: the case of copper. Environ Sci Technol 46:12772–12778

Vieira MDM, Ponsioen T, Goedkoop MJ (2014) Ore grade decrease as a basis for modeling impact assessment for mineral scarcity. In: 55th Swiss Discussion Forum on LCA, Zürich, Switzerland, April 11 2014. Available from http://www.lcaforum.ch/

Weber L (2013) Stärken und Schwächen internationaler Vorratsklassifikationssysteme [Strengths and weaknesses of international resource classification systems]. BHM Berg- und Hüttenmänn Monatshefte 158:130–139