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A framework for evaluating the accessibility of raw materials from end-of-life products and the Earth's crust

Sandra R. Mueller [a,b,*], Patrick A. Wäger [a], David A. Turner [a], Peter J. Shaw [b], Ian D. Williams [b]

[a] Empa, Swiss Federal Laboratories for Materials Science and Technology, Technology and Society Laboratory, Lerchenfeldstrasse 5, CH-9014 St. Gallen, Switzerland
[b] University of Southampton, Faculty of Engineering & the Environment, International Centre for Environmental Science, Highfield, Southampton SO17 1BJ, UK

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ABSTRACT

An increasing number of geochemically scarce metallic raw materials are entering into our lives via new technologies. A reversal of this trend is not foreseeable, leading to concerns regarding the security of their supply. However, the evaluation of raw material supply is currently hampered by inconsistent use of fundamental terminologies and incomplete assessment criteria. In this paper, we aim to establish a consistent framework for evaluating raw material supply from both anthropogenic and geological sources. A method for concept extraction was applied to evaluate systematically the use of fundamental terms in the evaluation of raw material supply. The results have shown that 'availability' is commonly used in raw material supply evaluations, whilst other researchers suggest that raw material supply should be evaluated based on 'accessibility'. It was revealed that 'accessibility' actually comprises two aspects: 'availability' and 'ap proachability'. Raw material 'approachability' has not previously been explicitly addressed at a system level. A novel, consistent framework for evaluating raw material supply was therefore developed. To demonstrate the application of the established framework, we evaluated the raw material supply of four rare earth element case studies. Three case studies are End-of-Life products (the anthroposphere) from Switzerland: (i) phosphors in fluorescent lamps, (i) permanent magnets in the drive motors of electric cars and (iii) fibre optic cable. The fourth case study source is the Earth's crust (the geosphere): Mount Weld deposit in Australia. The framework comprises a comprehensive evaluation of six components relating to raw material mining and processing: their geological knowledge, eligibility, technology, economic, societal and environmental impacts. Our results show that metals are not considered to be fully accessible in any of the case studies due to a lack of necessary technologies and potential societal and environmental impacts. The framework presented here can serve as a starting point for the development of an evaluation framework for raw material accessibility at an early project development stage.

1. Introduction

Due to continuing technological advancement, an increasing number of geochemically scarce metallic raw materials[1] are entering into our daily lives. With a reversal of this trend not foreseeable (Zepf et al., 2014), there are growing concerns for the security of raw material

Abbreviations: Ap., approachability; Av., availability; CO_2 eq., carbon dioxide equivalent; EC, existing conceptualisations; EoL, end-of-life; Er, erbium; Eu, europium; Eu_2O_3, europium oxide; EUR, Euro; HHI, Herfindahl-Hirschman Index; MA, mining the anthroposphere; MG, mining the geosphere; Nd, neodymium; $Nd_2Fe_{14}B$, neodymium–iron–boron; ORDEE, ordinance for the return, take-back, and disposal of electrical and electronic equipment; PPI, Policy Potential Index; ReCiPe, RIVM and Radboud University, CML, and PRé Consultants; REE, rare earth elements; REO, rare earth oxide; REO, rare earth oxides; UBP, environmental impact points; UNEP, United Nations Environment Programme; UNFC, United Nations Framework Classification for Fossil Energy and Mineral Reserves and Resources; USD, United States Dollar; USDOE, U.S. Department of Energy; EEE, electrical and electronic equipment; WEEE, waste electrical and electronic equipment; WGI, world governance indicator.

* Corresponding author at: Technology and Society Lab, Empa, the Swiss Federal Laboratories for Materials Science and Technology, Lerchenfeldstrasse 5, 9014 St. Gallen, Switzerland; International Centre for Environmental Science, Faculty of Engineering & the Environment, University of Southampton, Highfield, Southampton SO17 1BJ, UK (S.R. Mueller).

E-mail addresses: Sandra.Mueller@soton.ac.uk, Sandra.Mueller@empa.ch (S.R. Mueller), Patrick.Waeger@empa.ch (P.A. Wäger), David.Turner@empa.ch (D.A. Turner), P.J.Shaw@soton.ac.uk (P.J. Shaw), idw@soton.ac.uk (I.D. Williams).

[1] Geochemically scarce metallic raw materials' are those metals whose crustal abundance is <0.01 wt.% (Wäger et al., 2012).

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supply. For many raw materials, the supply situation is considered critical due to: (i) their production being concentrated in a few countries (Simoni et al., 2015), (ii) limited options for appropriate substitutes (Graedel et al., 2013), and (iii) very low recycling rates for these materials (UNEP, 2012). To improve the long-term sustainability[2] of critical material supply (Giurco et al., 2014), there is a view that raw material management needs to be rethought (Ongondo et al., 2015). Specifically, raw material management needs to consider the mining of materials from both the geosphere and the anthroposphere. To ensure comparability and consistency, both mining management approaches should be developed and evaluated in parallel. In the cycle of a material, a parallel development and evaluation requires the establishment of linkages between mining the geosphere, anthroposphere and the subsequent processing. In this sense, for both the mining of geosphere and anthroposphere, knowledge of the material (e.g. physical and chemical properties, element concentration, and abundance) and knowledge about potential economic viability is required (Brunner, 2008).

Raw material supply has previously been evaluated based on the 'availability' of materials (UNEP, 2013b; USDOE, 1996). Evaluation of material availability can be based, for example, on the geological knowledge (UNFC, 2010). Availability can also be evaluated through material criticality assessment, which assesses raw material supply based on two functions: their 'availability' and 'importance of uses' (Graedel et al., 2012). Studies of material availability show a large degree of variability in how availability is defined.

It has been suggested that material availability evaluation is too narrow in its scope and that evaluation of raw material supply should be expanded to consider the 'accessibility' of materials (USDOE, 1996). Cook and Harris (1998), for example, recommend that such an evaluation should consider environmental, legal, social, and political aspects in addition to an evaluation of project feasibility. This would be particularly important for materials that are currently unavailable but approachable. Materials in this category include for instance the large amounts of illegally-exported raw materials from End-of-Life (EoL) products, such as obsolete Waste Electrical and Electronic Equipment (WEEE) from the European Union (Huisman et al., 2015). Rankin (2011) adds that it is important to understand, how access to raw materials will change in the long term. Gruber et al. (2010) considered raw material 'accessibility' in relation to policies about raw materials at the European level and they concluded that indicators and specific targets for raw material conservation remained absent. Accessibility has further been applied to evaluate product recycling, specifically in identifying the relevant product parts for dismantling (Hagelüken, 2014) and in geological mining, where 'accessibility' has been used to describe the physical path to a deposit (Weber, 2015). At a systems level, individual aspects of evaluating raw material accessibility have been implicitly included in the fields of economic geology. For instance, accessibility has been integrated in resource classification frameworks (Cook and Harris, 1998) and ecological and social sustainability studies (MacDonald, 2015).

There is need to advance the management of raw materials at different levels. Firstly, there is a lack of consistency in how the terms 'availability' and 'accessibility' are used in studies of raw material supply and what these terms actually mean. Clarification of fundamental terms used in the evaluation of raw material supply is required before a commonly agreed, rational raw material mining strategy can be developed (Cossu and Williams, 2015; Winterstetter et al., 2015). Secondly, although different efforts have been undertaken to link quantitative evaluation methods across different disciplines, there is a lack of a broadly applicable assessment method for a potential supply of sustainable raw materials (Haines et al., 2014). Thirdly, there is a deficiency in a strategy that evaluates the different operational steps along the collection/mining, processing for continual sourcing of raw material (Roelich et al., 2014). Fourthly, there is need for consistent quantitative evaluations for elements with few available data such as rare earths (Gleich et al., 2013; Weber, 2013). This is particularly important for implementing new waste management regulations, such as the currently revised Swiss 'ordinance for the return, take-back, and disposal of electrical and electronic equipment' (ORDEE). The future ORDEE will require for the first time the recovery of scarce metallic elements from technological equipment wherever possible (FOEN, Federal Office for the Environment Switzerland, 2013).

In this paper we aim to establish a consistent framework for evaluating raw material supply from both anthropogenic and geological sources at an early project development stage. The objectives were to:

(i) systematically investigate the use of fundamental terms in the evaluation of raw material supply;
(ii) develop a novel, consistent framework for evaluating the supply of raw materials; and
(iii) demonstrate the utility of the developed framework by evaluating the raw material supply in four rare earth element (REE) case studies.

2. Method

2.1. Extraction of conceptual framework

Concept extraction was used to elucidate the meaning and use of accessibility and related terms. This process comprised four main stages: pre-processing, text analysis, establishment, and concept extraction (Fig. 1), based on the work of Weinhofer (2010).

2.1.1. Pre-processing

The scope of this research was determined and the opportunistic corpora[3] were established (Fig. 1). For the former, a standard definition of 'accessibility' was created by critically reflecting the definitions and synsets from the Cambridge (Cambridge Dictionaries Online, 2014), Oxford (Oxford Dictionary, 2014), WordNet[4] (WordNet, 2014), and Britannica (Britannica Academic Dictionary, 2014) Dictionaries. Three opportunistic corpora were developed: 'existing conceptualisations' (EC), 'mining the anthroposphere' (MA), and 'mining the geosphere' (MG). The EC corpus was created for the purpose of analysing the use of 'accessibility' and its conceptualisation. For this, relevant literature sources were identified through a key word search for 'concept of accessibility' and 'concept of availability' in *Google Scholar*, *Scopus*, and *Google*. Thereafter, the MA and MG were built with the aim of investigating the use of 'accessibility' and its related terms. Both these corpora were developed based on the bibliography of Simoni (2012) as suggested by Cronin et al. (2008). This literature selection was expanded with a

[2] 'Sustainability' means in this study "certainly a sustainable society would use non-renewable gifts from the Earth's crust more thoughtfully and efficiently than the present world does. It would price them properly, thereby keeping more of them [accessible to] future generations. But there is no reason not to use them, so long as their use meets the criteria of sustainability already defined, namely that they do not overwhelm a natural sink and that renewable substitutes are developed." (Meadows et al., 2004).

[3] 'Opportunistic corpus' is a selection of texts that are needed for the present purpose (Hausser, 2014). They often represents an incomplete collection of electronic texts (Sekhar, 2008).

[4] 'WordNet' is a large lexical database of English that covers a wide range of words, establishes cross linkages between them and is widely applied in linguistics. Nouns, verbs, adjectives and adverbs are grouped into sets of cognitive synonyms (synsets), each expressing a distinct concept (WordNet, 2014).

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