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Introducing a multi-criteria indicator to better evaluate impacts of rare earth materials production and consumption in life cycle assessment

N. Adibi[1,2,*], Z. Lafhaj[2], E.D. Gemechu[3], G. Sonnemann[3], J. Payet[4,5]

(1. PLATFORM [avniR]-cd2e, Rue de Bourgogne - base 11/19, Loos-en-Gohelle, 62750, France; 2.Ecole Centrale de Lille, Villeneuve d'Ascq, 59651, France; 3. University of Bordeaux 1, Talence, 33400, France; 4. Ecole Polytechnique Fédérale de Lausanne, Lausanne, 1015, Switzerland; 5. Cycleco Amberieu, 01500, France)

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Abstract: Life cycle assessment (LCA) is based on the basic principles of sustainable development. LCA method demonstrated its efficiency in providing a systematic environmental assessment approach of a product or a process. The effectiveness and efficiency of these methods lies in the fact that they take into account all life cycle stages of a product, from the extraction of raw materials to end of life treatment (recycling, ...) through an assessment covering different impact categories such as climate change, human health, ecosystems and resources. Existing LCA indicators reflect different issues surrounding resource depletion, creating inconsistency and moreover confusion among LCA practitioners. The evaluation of different life cycle impacts assessment (LCIA) methods done by EC JRC showed that available models did not address the same parameters: short- vs long-term, stock vs backup technology, etc. It also showed that if the correlation between the methods was sufficient for some resources, others such as rare earth elements showed a high level of inconsistency between methods. It was therefore necessary to develop a relevant indicator and harmonized assessment of impacts on resources in LCA. Furthermore, a resource strategy indicator based on the three pillars of sustainable development (economic, environmental and social) would better address wider challenges and making it a more powerful decision making tool. This study aimed to introduce an indicator for evaluating the strategy implications of metal resources for products and to compare different ways of production resulting from extraction of raw materials or recycling, with a special focus on rare earth materials. The indicator would assess the impacts based on a reserve-resource vision [BGS NERC] and the evolution over time and founded over three parameters: technical feasibility, economic viability and political stability (including social and environmental aspects) in representing countries.

Keywords: life cycle assessment (LCA); life cycle impacts assessment (LCIA); resource strategy; rare earth elements

Life cycle assessment (LCA) is based on the basic principles of sustainable development[1,2]. They demonstrate their efficiency in providing a systematic environmental assessment approach of a product or a process. The effectiveness and efficiency of these methods lie in the fact that they take into account all life cycle stages of a product, from the extraction of raw materials to end of life treatment through an assessment covering different impact categories such as climate change, human health, ecosystems and resources. By considering different stages of life cycle of a product and different impact categories, LCA can be used as a decision tool to help the innovation process and avoid the problem of shifting environmental impacts and minimize secondary effects.

In LCA, inputs and outputs as extracted resources and emissions from different stages of life cycle are assessed in terms of impacts called life cycle impact assessment (LCIA). A variety of LCIA methods already exist and at the same time new approaches are emerging due to lack of consistency in providing widely acceptable indicators particularly for impacts associated with resource use. This article, therefore, aimed to analyze the methodological variability of LCIA methods for metals in general and for Rare Earth Elements (REEs) in particular. By doing so it also aimed to discover and suggest new areas of improvement using the case study on REEs.

There is an increasing concern over the environmental impacts of metals. These impacts are either due to toxicity originating from the nature of their chemical composition or due to the use of energy and resources during their life cycle, from mining to final disposal. Impacts associated with the production and consumption of metals are dominated to a greater extent by mining and refining stages as they are very energy intensive processes[3,4]. Raw materials production assessments are then used to model the environmental impacts of different products in which these materials are used. Furthermore one should not forget the indirect impacts of resources and their contribution in reducing global impacts (e.g. REEs and transition to green economy). This paper focused on the LCIA of resource use of REEs.

* **Corresponding author:** N. Adibi (**E-mail:** n.adibi@cd2e.com; **Tel.:** +33 3 21 13 06 80)

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1 Resource issues in LCA: the case of rare earths

Existing LCA indicators reflect different issues surrounding resource depletion, creating inconsistency and moreover confusion among LCA practitioners. The evaluation of different LCIA methods was performed by EC JRC[5]. It shows that available models do not address the same parameters: short- vs. long- term, stock vs. backup technology, etc[6]. There are more than 5 impact assessment methods assessing resource use and yet Berger and Finkbeiner[7] demonstrated lack of correlation between them.

The methodological issues of metals depletion and scarcity are treated controversially in LCA framework as mentioned by different authors[8,9]. It was also suggested by EC JRC that there is a need for improvements[5]. Generally the environmental impact associated with the use of non-renewable resources such as mineral metals had been addressed by using four main approaches as categorized by Stewart and Weidema[10]. The first approach is based on the summation of mass and energy relative to the mass and energy of the material extracted. The second is based on use-to-stock ratio[1,11–14]. The third is due to consideration of exergy and entropy impacts[15,16]. Finally it is based on the potential future consequence of resources extraction. The later is considered as end-point analysis. It is based on the fact that an increasing demand on metals tempts their extraction at a high concentration, leaving the future generation to require relatively high effort to extract the same amount. This could result in increasing the cost and then the environmental impact of extraction. There are different approaches to measure the future consequence of mineral extraction such as surplus[17,18], marginal cost[19].

In LCA as a decision tool, special attention has been given to the necessity of a sustainable use of natural resources. In order to elaborate the case for metals in an operational level, one needs to define a measurable indicator. Although the necessity of this measurement is widely agreed on, it seems difficult to recommend any of the existing indicators which are used to measure abiotic resource production and consumption. Furthermore, a resource strategy indicator based on the three pillars of sustainable development will better address wider challenges, making it a more powerful decision making tool.

The rest of the paper was structured as follows. The second section explained some important aspects of REEs. The third presented environmental impacts comparison of REEs with Cu. The methodological inconsistency of different LCIA methods was also analyzed and validated based on their characterizations. Then we introduced briefly resource indicators in LCA and showed corresponding impacts related to REEs. Finally, based on the discussion we introduced a new concept to assess the resource issue. Main conclusions were drawn in the last section.

2 Why REEs?

REEs, despite their name, are relatively abundant in the earth's crust. REEs are the seventeen similar metallic elements from lanthanum to lutetium (lanthanides), plus scandium and yttrium.

Due to their applications, REEs are becoming increasingly important in the transition to a green, low-carbon economy (DEMAND). Their consumption in sectors such as transport, energy and high-tech increases both the demand and price of REEs[20]. They are used in permanent magnets, lamp phosphors, rechargeable NiMH batteries, catalysts among other applications[20–22].

REEs are critical materials with strong Supply risk. More than 90% of the global REEs are produced by one country[23]. The European Commission expert working group (2009–2010) report Defining Critical Raw Materials in the EU published in 2010 identifies REEs as the most critical raw materials group with the highest supply risk[24].

In addition direct and indirect Environmental and Social issues are huge concerns for the extraction and processing of REEs, particularly due to presence of uranium and thorium.

The other major issues are the Recycling of REEs and the balance problem[23]. This problem is more significant on the absence of primary deposits. As the demand for different REEs is not the same and REEs occur in different ratios in ores, the extraction of more scarce elements increase more and more. Hence recycling of REEs even for their suppliers is an important issue.

3 LCIA of REEs

Based on available mining data and mineral processing, LCA of REEs is carried out for a number of mines. As an illustration, Fig. 1 shows the environmental impacts of REEs production from cradle-to-gate (from the extraction of raw materials to production of REEs) compared with Cu. We selected copper since its function is partially similar to REEs and reliable data for copper production is readily available. The impact assessment methods used in this case study is based on ILCD recommendations for life cycle impact assessment in the European context[5].

The main data is based on the Chinese Rare Earth Industry Report 2009. Primary production comes from China, Bayun Obo mine Mongolia. Fuel and energy inputs in the system reflect average Chinese conditions and whenever applicable, site specific conditions were applied, to reflect representative situations.

As can be seen in the figure, for all impact categories except for resource depletion, the ratio of cradle-to-gate

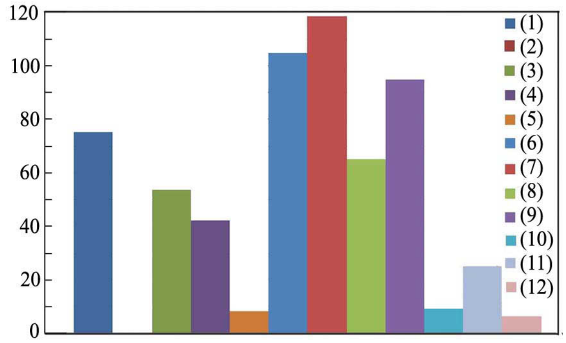

Fig. 1 REEs/Cu 1 kg environmental impacts based on ILCD recommendations for EU context

(1) Acidification (Moles of N or S-Equiv.); (2) CML2002 resource depletion, reserve based (kg Sb-Equiv.); (3) IPCC global warming, incl biogenic carbon (kg CO_2-Equiv.); (4) Particulate matter/respiratory inorganics (kg PM2.5-Equiv.); (5) Ionising radiation (kg U235 Equiv.); (6) Marine eutrophication (kg N-Equiv.); (7) Photochemical oxidant formation (kg NMVOC); (8) Terrestrial eutrophication (Moles of N or S-Equiv.); (9) Freshwater consumption (kg); (10) Ozone depletion air (kg CFC 111-Equiv.); (11) USEtox, Human toxicity, cancer (CTUh); (12) USEtox, Human toxicity, non-canc (CTUh)

impacts of REEs are 10 to 100 times higher than similar impacts from Cu (due to the special environmental problems related to the production of REEs). Fig. 1 illustrates relative effectiveness of environmental impact assessment in LCA. The main issue in this figure is how accurate resource indicators in LCA are?

The CML method for resource depletion as recommended by European commission[24], is based on the use-to-availability ratios of the metals. In this method, annual production of the metal is divided by the square of the ultimate reserves, to measure characterization factors (CFs). Then the value is multiplied by the square of the ultimate reserves of antimony and divided by the annual production of antimony. All CFs are expressed in terms of antimony equivalents. The CML method uses ultimate reserves instead of reserves in order to avoid changes due to new discoveries and changing economic conditions. The ultimate reserve is the total amount of that metal in the earth's hydrosphere, atmosphere and crust. (For REEs the ultimate reserve is approximately equal to the crustal abundance).

The fact that REEs are relatively abundant in the earth's crust[25], and they rarely occur in more concentrated forms validate in Fig. 1 where the ratios of REEs to Cu is smaller. That is the reason why in CML Cu seems more scarce than REEs.

In order to evaluate the effectiveness of resource indicators in LCA for REEs and based on the special characterization of REEs described in Section 2 an assessment of resource depletion was performed using different LCIA methods. The result is presented in Fig. 2. Data used in Fig. 2 for REEs production are the same as the one used in Fig. 1.

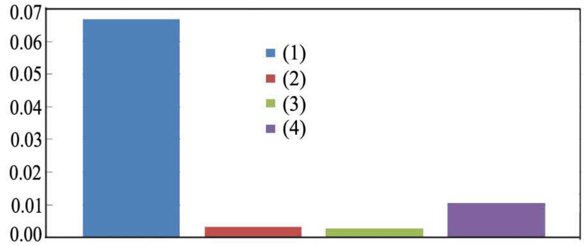

Fig. 2 REEs/Cu for different LCA methods for resource indicators

(1) CML2002 resource depletion, fossil and mineral, reserve based (kg Sb-Equiv.); (2) EI99, IA, resources, minerals (Misurplus energy); (3) 102+V2.1 – mineral extraction – midpoint (MJ surplus); (4) ReCipe endpoint (H) – Metal depletion (S)

The figure shows that in all LCIA methods 1 kg of REEs contribute less than 1 kg of Cu to resource problem. For a wide range of metals such as lead, zinc, silver compared to REEs the resource indicator follows the same trend. As explained the impact obtained from the use of CML method shows a huge variation. This is due to the nature of modeling in which CML approach is working.

The LCA results presented above are only representing the use to availability ratio or future consequences, which are based on the geological availability in long-term horizon. However, it is also of significant importance to consider multi-criteria indicators in order to address issue for example criticality of minerals. This is highly relevant for metals such as REEs. Recent studies consider a wide range of parameters that define both the short-, medium- and long-term implication of resource criticality[6,26,27].

The recent work from Graedel et al. provides a methodological approach to assessing criticality of metals[28], which is also applied for the case of copper by Nassar et al.[29]. The method assesses the criticality of metal from three broad dimensions: supply risk, vulnerability to supply restriction and environmental implication. The supply risk dimension is not only focused on the availability of the resources but also includes other factors that may directly or indirectly affect the geological availability of resources. This includes social and regulatory, geopolitical, technological and economic indicators. The social and regulatory factors reflect the potential risk in which the society or the policy could impose on the resource extraction. The technological and economic factors refer to how the extraction is possible using the existing technology and whether it is economically feasible, respectively. The geopolitical factors deal with the potential risk associated with any political instability or political action. The case of REEs in which their production and supply are dominated by a few countries with partial stability could be a good example. The other dimension of metal criticality is vulnerability to supply restriction which refers to the importance of a given metal to a company or nation. It measures how the functionality of a company or a nation could potentially be affected by the supply disruption of a metal of

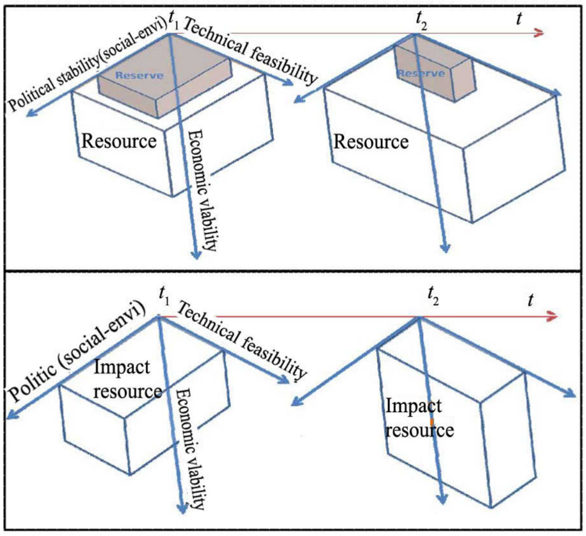

Fig. 3 New indicator founded over three parameters: technical feasibility, economic viability and political stability

interest. Here the substitutability of the metal is the most important factor among others. The third dimension addresses the environmental impacts associated with the life cycle of the metal. Extraction and entire process of metal productions are well known for their high energy intensiveness and also high associated environmental impacts[3,4]. Beside their high energy demand on the extraction and production they also contribute to human toxicity. Therefore, it is important to include their environmental implication while assessing criticality. Generally the method proposed by Graedel et al.[28,30] could be seen as a mile stone for the development of criticality assessment. It could be used to further develop an operational LCIA method for resource which looks not only at the geological availability but also at other criteria. This issue is not yet addressed in the current LCA frameworks.

4 Conclusions

Concern over resource depletion and scarcity is going to be continuous as the demand on resources increase to keep a high product performance coupled with the advances in technologies. These have recently drawn the attention of individuals, researchers, decision-makers at different organizational levels to the issue of criticality assessment. Different methodological approaches under the LCA framework were used to address the impact of resource extraction. However, they did lack consistency. Moreover, they all focused mainly on the geological availability of resources and not on the other critical factors. The case of REEs discussed in this paper could be a good example as it clearly showed the limitation of existing LCIA methods in addressing the issue of criticality. Looking only at the LCIA results we could say that REEs are not scarce. But this doesn't mean they are available for use. REEs are not really rare, but they are widely distributed in the earth's crust. However, their production and supply is concentrated in very few countries. Therefore, assessment which considers only resource availability could not address the potential future consequences properly. The results in LCIA would have been different if multi-criteria indicators have been considered.

This suggest that there is a need to go beyond the current LCIA method in order to incorporate other important factors that have significant importance in addressing the issue of resource criticality. In this regard the method by Graedel et al. could be used as a starting point to develop an operational LCIA method for metal criticality analysis. The work on this topic is in progress.

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