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New resource assessment characterization factors for rare earth elements: applied in NdFeB permanent magnet case study

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Abstract

Purpose Rare earth elements (REEs) are among the most critical raw materials with a high supply risk. Despite their criticality, REEs are not covered by any resource Life Cycle Impact Assessment (LCIA) methods. The main purpose of the current study is to tackle the issue of missing characterization factors (CFs) for REEs in Life Cycle Assessment (LCA).

Methods The development of resource depletion characterization factors for REEs in this study are based on two widely used resource assessment methods, Abiotic Depletion Potential (ADP) and ReCiPe. ADP is based on the use-to-stock ratio, while ReCiPe focuses on the additional cost that society has to pay as a result of extraction. To develop the CFs, a wide range of data is gathered from USGS archives and specific mining reports for 11 large deposits worldwide.

Results and discussion The characterization factors for 15 REEs, following the ADP and ReCiPe, are provided in this article. A comparison of the developed CFs with other resources confirms their compatibility. All REE CFs, except ADP for dysprosium (among the 25% highest CFs), are placed among the highest 50 to 75% available CFs for both methods. The significant difference between the results, whether including REE CFs or not, highlights the possible misinterpretation of LCA results.

Conclusions The results reveal that REEs have a relatively high resource impact; therefore, they should be included in the assessment of resources. In addition, applicability of the provided CFs is checked in a NdFeB permanent magnets case study, and some recommendations are provided for the practice. The proposed CFs can be used for both the further update of methods and readily implementation in main LCA software, such as Simapro and GaBi, to address the resource depletion of REEs.

Keywords Abiotic depletion potential · Characterization factors · LCA · LCIA · Permanent magnet · Rare earth elements · ReCiPe · Resource depletion

1 Introduction

Rare earth elements (REEs) are critical raw materials with high supply risk. The supply risk of REEs is not only related to their low geological availability and the geopolitical instability of supplying countries, but also to their limited substitutability and low recycling potential. Despite the supply risk, REEs are used more and more in products, especially those contributing to the transition to green and low-carbon economies (Alonso et al. 2012; Swart and Dewulf 2013; Binnemans et al. 2013; Dobransky 2015). In Life Cycle Assessment, REE's status is surprising and a source of paradox. While REEs are present in numerous Life Cycle Inventories, especially for electrical and electronic equipment, methods and indicators do not support the reliable quantification of the consequences of their use on the depletion of resources.

1.1 Rare earth elements context

REEs cover 17 similar metallic elements, from lanthanum to lutetium (lanthanides) as well as scandium and yttrium.[1] They

[1] Pm and Sc are not included in this study, because Pm has no stable isotopes, and Sc is rarely available in the global trade of pure metals. Total transport of about 50 kg per year.

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are mainly used in permanent magnets, catalysts, metal alloys, lamp phosphors and rechargeable NiMH batteries. REEs are critical resources with strong supply risk. More than 90% of the global REEs are produced in China (Binnemans et al. 2013; Dobransky 2015). The European Commission Ad-hoc working group (2009–2010) identifies REEs as the most critical raw materials group with the highest supply risk (European Commission 2010). In addition, some direct and indirect environmental and social concerns are raised for the extraction and processing of REEs (Alonso et al. 2012), particularly due to the presence of uranium and thorium (Adibi et al. 2014).

REEs are also affected by the complexity of recycling. Moreover, REEs are used in small quantities and highly dispersed throughout products. They are typically extracted as co-product and are not drivers in the mining production systems (Binnemans and Jones 2015). As the demand for REEs varies, and REEs occur in different ratios in ores, the extraction of less abundant elements increases their scarcity (the balance problem). Hence, the recycling of REEs is an important issue, even for their suppliers.

1.2 Resource assessment in LCA

Life Cycle Assessment (LCA) is based on four steps. The second step, Life Cycle Inventory (LCI), covers the identification and quantification of the consumption of raw materials from earth and emissions of substances in the environment. The third step, Life Cycle Impact Assessment (LCIA) enables the calculation of the total potential impact, by summing up the individual impacts associated with resource consumption and environmental emissions. A variety of LCIA methodologies exist to assess a life cycle inventory (Hauschild and Huijbregts 2015).

To combine and convert the LCI results to impacts, the impact characterization uses science-based conversion factors, called characterization factors (also referred to as equivalency factors). Characterization factors convert multi-scale inputs to a comparable impact indicator.

The following principals may be used to define different groups of CFs for assessing resources in LCA (Klinglmair et al. 2014; Sonnemann et al. 2015; Adibi et al. 2017):

1. Inherent characteristics of resources (e.g. exergy)
2. Reserves and/or annual extraction rates
3. Potential future consequence of resources extraction (e.g. surplus energy, marginal cost)

The first group of methods focus on inherent properties of the materials. These methods cover relatively robust and certain characterization factors. Nevertheless, the resource problem is not limited to the inherent properties of materials.

The second group is based on use-to-stock ratio, e.g. EDIP (Wenzel and Hauschild 1997) and Abiotic Depletion Potential (ADP) published by the Institute CML (Guinée and Heijungs 1995; Van Oers et al. 2002). The environmental relevance is higher than the indicators of the first group. These indicators reflect the problem of scarcity of the resources as production is going on. However, exploratory activities and development of extraction technologies increase reserve availability (USGS 2017). Besides, the elements, extracted from the ecosphere, are transformed, alloyed, dispersed or coming back to the ecosphere directly (they are not vanished after their use), e.g. metallic compartment landfilled, or after a series of changes, e.g. energy resources (Sonnemann et al. 2015; Drielsma et al. 2016a, b).

The third group focuses on environmental impacts of the future extractions: these methods are based on additional energy and cost of extraction for future mining activities, e.g. EcoIndicator 99 (Mark and Renilde 2001), ReCiPe (Goedkoop et al. 2009) and Surplus Cost Potential (Vieira et al. 2016). The main difficulty is the uncertainty of the future prediction. Also, the complexity of parameters and indicators restrain those to a very limited number of characterization factors (CFs). These indicators cover only the resources available in the ecosphere as part of their scope of application.

Although LCA has focused mostly on geophysical availability of the resources, recently, the criticality of resources is introduced and discussed within the framework of LCA. The review of existing critically literature and the importance to integrate criticality in LCA was assessed by (Sonnemann et al. 2015). Later in 2016, the ESSENZ method was proposed, assessing a product's resource efficiency considering the pollution of the environment as well as the physical and socio-economic availability of resources (Henßler et al. 2016). Mancini et al. in 2018 focus on the economic dimension of the resource criticality and propose the integration of this aspect in LCA through the use of characterization factors (CFs) based on the supply risk factors for Europe (Mancini et al. 2018). The concept was applied to several industrial minerals and metals in LCA (Henßler et al. 2016; Mancini et al. 2018). These indicators provide a new supply risk vision to the LCA. Nevertheless, the fact that they are highly correlated with socio-economic aspects makes the prevision in future uncertain and generates high fluctuation in the results due to different interpretations. Finally, the socio-economic parameters are numerous and complex to establish and update.

One of the major issues, related to the resource assessment, is that the resources availability is influential, and may even halt the development of sustainable products and services. Therefore, assessment of the availability of the resources based on the new indicators, including the anthropogenic stock, exploration, recyclability and geopolitical availability (criticality) may be considered as a way forward (Adibi et al. 2017).

1.3 Availability of resource characterization factors in LCA

Based on available observations, a limited number of characterization factors for resource depletion are available within different methods. As an example, the limited number of available CFs for different types of resurces are provided in Table 1 for the two widely used ADP and ReCiPe methods (Klinglmair et al. 2014; Adibi et al. 2017).

Existing LCA impact assessment methods do not provide CFs for the REEs (Adibi et al. 2014). As the flows are not characterized in the impact assessment methods, no hotspot linked to the REE resource impact may be identified during assessment and interpretation of LCA results.

In the case of ReCiPe, the development of CFs was done for 20 elements. The list of elements does not include REEs (Goedkoop et al. 2009). Nonetheless, we did not find any published work about the CFs of the REEs. Among the LCIA methods (including ReCiPe), the only method providing CFs for REEs was developed by Guinée and Heijungs (ADP 1995 method), in which wrong assumptions were made on the extraction rates of REEs (Van Oers et al. 2002).

The CFs from the ADP method are obtained based on the exraction rates, provided by the USGS reports. As the extraction rates of REEs are not available in the USGS reports (USGS 2017), Guinée and Heijungs (1995) assumed that the extraction rates for all the REEs are equal to the extraction rate of *rhenium* (Van Oers et al. 2002). This assumption resulted in imprecise CFs in the 1995 REEs ADP report (Guinée and Heijungs 1995). If 2014 mine production is compared for REEs and the rhenium (USGS 2017), the REE production is three times higher than the production rate of rhenium. This is the main reason why during the revision of ADP in 2002 (Van Oers et al. 2002), the 1995 CFs were excluded for REEs[2] (Van Oers et al. 2002).

The main purpose of this article is to develop new resource depletion CFs for REEs by applying the two widely used characterization methods, ADP and ReCiPe. Also, their application in a case study comparing the assessment of a product with and without REE CFs is illustrated.

2 Methods

2.1 The Abiotic Depletion Potential method

The Abiotic Depletion Potential (ADP) method is an LCIA method, developed by the Institute of Environmental Sciences (CML) of Leiden University (Guinée and Heijungs 1995; Van Oers et al. 2002). This method developed by CML covers several impact categories, including resource depletion. The ADP method is recommended by International Reference Life Cycle Data System (ILCD) (JRC European commission 2011) and is also used in the Product Environmental Footprint (PEF) method (European Union 2013) to assess the resource depletion potential. In this method, the dimensionless Abiotic Depletion Potential (ADP) (Relation 1) is the annual extraction rate of a given element, divided by the reserve of the same element squared. Antimony is considered to be the reference substance; therefore, the formula is normalized by antimony. So, the CFs of each resource are proportional to antimony. Results are expressed in kg Sb-eq (Antimony Equivalent).

Table 1 Number of natural resources, covered by ADP and ReCiPe

	ADP 2002 (Van Oers et al. 2002)	ReCiPe (Goedkoop et al. 2009)
Abiotic minerals	48	19
Abiotic energy: fossil and nuclear	5	5

$$\mathrm{ADP}_i = \frac{\mathrm{Ext}_i}{\mathrm{Res}_i^2} \times \frac{\mathrm{Res\_Sb}_i^2}{\mathrm{Ext\_Sb}_i} \quad \text{(Relation 1)}$$

where Ext_i and Res_i are respectively the extraction rate and the reserve base of the resource under study in the i^{th} year. $\mathrm{Ext\_Sb}_i$ and $\mathrm{Res\_Sb}_i$ are the same values for the reference, antimony. The larger the reserve, the less valuable the element, so a 10-kilogram extraction of a resource has different depletion impacts on either a large or a small reserve. The estimation of the reserve value can be based on two different assumptions:

- Guinée and Heijungs (1995) used the ultimate reserves, i.e. the resource quantity, which is available in the earth's crust. It is approximated by multiplying the average natural concentration of the resources in the earth's crust by the mass of the crust.
- Van Oers et al. (2002) proposed the economic reserves, reserve base and ultimate reserves. The reserve base includes all the deposits that meet certain minimal chemical and physical requirements to be potentially economically viable.

Both of the described approaches are considered here; each approach has some advantages and disadvantages. The ultimate resource base is a relatively robust reference with low uncertainty, but its environmental relevance seems limited. On the other hand, the economic reserves, which is more uncertain, is more representative of today's available resources. The uncertainty in the economic reserves approach is due to the fact that future exploration activities may lead to an extension of the

[2] Compared to the set of factors, Guinée and Heijungs (1995), some elements are missed in the updated version (2002): actinium, argon, cerium, cesium, dysprosium, erbium, europium, gadolinium, hafnium, holmium, krypton, lanthanum, lutetium, neodymium, neon, polonium, praseodymium, protactinium, radium, radon, rubidium, samarium, scandium, therbium, thorium, thulium, xenon and ytterbium (Van Oers et al. 2002).

available economic reserves. These two extremes (ultimate and economic reserves) can be used as guides to assess the severity of the impacts associated with the use of a resource.

In this article, results are provided for both economic reserves and ultimate resources (ultimate reserves). Based on Drielsma et al. (2016b), fixed stock parameters such as crustal content are most appropriate measures for estimating mineral depletion within the logics of life cycle assessment. The process of converting resources into reserves requires a positive evaluation of many modifying factors, including mining, metallurgical, economic, marketing, legal, environmental, infrastructure, social and governmental considerations (CRIRSCO 2006). Therefore, the obtained ADP CFs from economic reserves must be interpreted with consideration of the previously mentioned parameters.

2.2 ReCiPe methodology

In LCA, the "damage" is sometimes defined as the additional costs that the society has to pay as a result of extraction. This approach is used in the ReCiPe method, where the cost of the resource extraction is calculated with the marginal cost increase of a resource for a certain period of time or a quantity of extracted resource. This could be the annual production of a resource on a global scale, or the apparent consumption of a resource within a specific region (Goedkoop et al. 2009). The characterization factor for extraction in dollars per dollar ($/$) is defined by Relation 2.

$$CF_{\$} = MCI_{\$} \times P_{\$} \times NPV_{\$} \text{ (Relation 2)}$$

$MCI_{\$}$ Marginal cost increase (1/$).
$P_{\$}$: Amount produced per year expressed in value ($/yr).
$NPV_{\$}$: Net present value factor of spending a dollar a year over a time T (yr).

The CFs are expressed as surplus cost. These are the costs incurred due to the fact that after the extraction of some part of a resource with the highest grade, future mining would become more expensive. The results are also expressed in relative impact; however, the CFs are normalized by iron (instead of antimony). The values are given in kg Fe-eq (iron equivalent). Two major issues regarding the ReCiPe methodology are:

- The impacts are based on the increase of the cost of resource extraction. However, the consequences of this cost-increase (shift toward unconventional resources and alternatives) are not considered.
- Available resources are supposed to be extracted in an organized programme, i.e. higher concentration ore bodies are extracted first.

2.3 Background data collected in this study

CFs are developed in this chapter for the two mentioned methods, based on the existing data from different available references. The information related to reserve (both total and indicated) and the average grade is extracted from the USGS 2013 and 2014 archive (USGS 2017). Additional information on mining production, mining costs and the availability of different REEs in different commodities are collected from specific mining reports. The development is done for 11 large deposits world-wide (Table 2). The amount of REE differs from one deposit to another, in different geographical situations. Availability of REEs in different commodities is reported in (Table 3).

2.3.1 Prices of rare earth elements and iron in ReCiPe method

The prices of the REEs and iron are the base information to make the calculations in the ReCiPe method. The REEs were subject to significant price fluctuations due to geopolitical issues (related to the Chinese export quotas on REEs in the recent 5 years). The prices from 2013 are more stable (given more stable REEs market and opening of new mines) and better reflect the scarcity of the REEs (Table 4). The recommended REE CFs for ReCiPe in this article are those derived from the 2013 prices. The CFs based on the REE prices in 2013, and the average price within 5 years from 2009 to 2013 in kg Fe-eq, are provided in Annex A (Electronic Supplementary Material). From 2013 to 2016, prices fluctuated due to production and consumption patterns and some geopolitical issues (including Chinese export quotas on REEs). In 2016, excess global supply caused prices for many rare-earth compounds and metals to decline (USGS 2017).

3 Results

3.1 Characterization factors of rare earth elements by ADP

Using the extraction data of different mines and the grade of REEs in different commodities, the extraction rate (mineral production) and the reserves (from indicated and inferred resources) for the REEs are estimated. To compare our results with the ReCiPe method, the results are converted to Fe-eq as a reference, following the approach to calculate the Sb-eq (Table 4).

In addition, the ultimately extractable resources are estimated assuming that 0.001% of the total amount of REEs in the crust to 3-km depth will be available ultimately as co-elements for extraction (Schneider et al. 2015). The ultimately extractable resources are used to obtain ADP CFs for ultimate resources. It is important to highlight that REEs

Table 2 Specifications of giant deposits, used in the case study

		Total reserve: indicated and inferred (Mt)	Average grade of TREO (in percentage)	Total REO reserve base (Mt)	Predicted total REO production (t)	OPEX (S/kg)-mining cost	CAPEX (US-S-M)-mining cost	Total mining cost (CAPEX), over10 years (US-S)	Host rock
Mountain Pass	USA	47	8.90	18.40	18,000	2.7	1420	3.77	Carbonatite
Bayan Obo (Baotou)	China	800	6.00	48.00	55,000	5.6	962*	5.74	Carbonatite
Strange Lake (Lac Brisson)	Canada	492	0.90	278.13	13,650	0.5	2309	0.51	Alkalic igneous
Kvanefjeld	Greenland	437	1.09	10.33	10069**	6.0	810	6.00	Alkalic igneous
Lovozero	Russia	1000	0.01	15.00	12,000	6.4	962*	9.83	Alkalic igneous
Mount Weld	Australia	24	7.71	0.37	11,000	12.1	907	12.16	Carbonatite
Nolans Bore	Australia	25	2.72	0.67	22,000	7.0	1408	7.00	Carbonatite
Zandkopsdrift	South Africa	23	2.32	0.95	20,000**	13.0	1760	13.08	Carbonatite
Bear Lodge	USA	3	3.77	0.56	13,000**	7.0	404	6.55	Carbonatite
Ngualla	Tanzania	175	2.32	0.94	10,069	12.0	367	11.74	Carbonatite
Norra karr	Sweden	42	0.57	0.34	8000	11.0	266	10.93	Alkalic igneous

TREO, total rare earth oxide, e.g. TREO = 25% means that RE in the form of oxides becomes 25% of the original. *OPEX*, operating expenditure, are the current costs to operate a mine. *CAPEX*, capital investment expenditure, referring to the cost of development or supplies and non-consumable parts for the product or system of the mine. Measured resource, the estimated quantity and grade of that part of a deposit of which the size and grade configuration is well-established by observations and samplings on the outcrops, drilled holes, trenches and mine workings. Indicated resource: the estimated quantity and grade of part of a deposit of which the continuity of grade, together with the extent and shape, are well-established, so a reliable grade and tonnage estimation can be figured out. Inferred resource: this part of the resource is determined by limited sampling, but there is sufficient geological information and reasonable understanding of the continuity and distribution of metal bodies to outline that part as a potentially economic merit. **Non-operational mines (in 2013). *Data not available, average value for other deposits is used as proxy

are relatively abundant in the Earth's crust, but discovered minable concentrations of REEs are less common than most other ores. This is the reason why significant differences may be identified between ADP CFs based on economic reserve and ultimate extractable resources.

3.2 Characterization factors of rare earth elements by ReCiPe

The steps below (Goedkoop et al. 2009) are followed to develop the CFs for REEs based on the ReCiPe method:

- *Step 1: Low weighted grade value if the weighted yield value increases.*

Weighted grade value of mine m ($/kg) is calculated following the Relation 3.

$$g_{\mathrm{v,m}} = \sum\left(g_{\mathrm{c,m}}.V_{\mathrm{c}}\right) \text{ (Relation 3)}$$

$g_{\mathrm{c,m}}$ Grade of commodity c at mine m.
V_{c} Market value of commodity c ($/kg).

Weighted yield value of mine m ($) is calculated following the Relation 4.

$$Y_{\mathrm{v,m}} = \sum\left(\mathrm{Y}_{\mathrm{c,m}}.V_{\mathrm{c}}\right) \text{ (Relation 4)}$$

$Y_{\mathrm{c,m}}$ Yield of commodity c at mine m (kg).

We obtained $g_{\mathrm{c,m}}$ and $Y_{\mathrm{c,m}}$ and plotted them in the same graph for each alkali igneous and carbonatite hosts (Fig. 1). A certain amount of extraction ($) will cause a certain change in the weighted grade value ($/kg), determined by the slope M_{d} (kg) and the constant C_{d} ($). For each deposit, we can write the Relation 5.

$$Y_{\mathrm{v.d}} = M_{\mathrm{d}} \times g_{\mathrm{v.d}} + \mathrm{C}_{\mathrm{d}} \text{ (Relation 5)}$$

where $Y_{\mathrm{v,d}}$ is the cumulative weighted yield value, over all mines of deposit d ($), $g_{\mathrm{v,d}}$ is the weighted grade value of deposit d ($/kg), and M_{d} is the slope (kg), while C_{d} is a constant, in $. As per Fig. 1, M_{d} for carbonatite and alkalic igneous is respectively − 57,586 and − 85,865 in kg. The obtained C_{d} for carbonatite and alkalic igneous is respectively 2,000,000 and 4,000,000 in $.

Table 3 The availability of REEs in different commodities. The unit is in the percentage. Note that for Brockman, production and reserve data are not available. Other commodities like (Fe-Nb_2O_5-Ta_2O_5-ZrO-BeO-U_3O_8-Zn-P_2O_5) are produced in the mentioned mines also, but are not imported in calculations

	LREO %					HREO %									
	Lanthanum	Cerium	Praseodymium	Neodymium	Samarium	Europium	Gadolinium	Terbium	Dysprosium	Holmium	Erbium	Thulium	Ytterbium	Lutetium	Yttrium
Mountain Pass	33.50	49.35	4.20	11.60	0.85	0.11	0.19	–	–	–	–	–	–	–	1.35
Bayan Obo (Baotou)	24.00	50.00	5.65	17.60	1.00	0.20	0.70	0.1	0.10	–	–	–	–	–	0.10
Strange Lake (Lac Brisson)	13.20	30.62	3.33	12.00	1.95	0.14	2.70	0.55	3.64	0.78	2.34	0.33	1.82	0.24	24.80
Brockman	5.80	16.80	0.10	0.40	0.03	–	0.40	0.1	10.4	0.20	7.70	0.10	5.00	0.10	52.40
Kvanefjeld	27.90	37.15	4.57	13.42	2.92	0.20	1.76	0.31	1.36	0.23	0.60	0.07	0.30	0.02	9.89
Lovozero	28.00	57.50	3.80	8.80	0.96	0.13	0.21	0.07	0.09	0.03	0.07	–	0.29	0.05	–
Mount Weld	25.50	46.74	5.32	18.50	2.27	0.44	–	0.07	0.12	–	0.03	–	0.06	–	0.35
Nolans Bore	19.74	47.53	5.82	21.20	2.37	0.40	1.00	0.08	0.33	0.05	0.09	0.01	0.05	0.01	1.32
Zandkopsdrift	25.42	44.17	4.55	15.77	2.31	0.59	1.44	0.17	0.77	0.15	0.15	0.15	0.15	0.15	4.07
Bear Lodge	30.40	45.50	4.70	15.80	1.80	0.40	0.70	0.1	0.20	–	–	0.01	0.5	0.01	1.11
Ngualla	27.10	48.30	4.70	16.30	1.70	0.35	0.78	0.07	0.17	–	–	–	–	–	0.52
Norra karr	8.46	18.04	2.31	9.13	2.89	0.38	3.66	–	5.34	–	3.95	–	4.25	0.67	40.93

- ***Step 2:*** *From the weighted grade value to the marginal cost increase* (Fig. 2)

We plotted, as shown in Fig. 2, the grade-cost relation in both carbonatite and alkalic igneous deposits. The cost to mine a certain amount of ore of deposit d (\$/\$) is obtained following the Relation 6.

$$C_{d.\$} = \frac{1}{g_{v.d}} \text{ (Relation 6)}$$

- ***Step 3:*** *Calculating the Marginal Cost Increase (MCI) on deposit level*

The marginal cost increase $MCI_{d,\$}$ on the deposit level (1/\$) is obtained following the Relation 7.

$$\mathrm{MCI}_{d.\$.} = \frac{\partial C_{d.\$}}{\partial Y_{v.d}} = \frac{\partial C_{d.\$}}{\partial g_{v.d}} \times \frac{\partial g_{v.d}}{\partial Y_{v.d}} = -\frac{x{M_d}^2}{(-0.5c_d)^2} \times \frac{1}{M_d}$$

$$= -4x \times \frac{M_d}{(c_d)^2} \text{ (Relation 7)}$$

Therefore, the CFs at deposit level are obtained based on Relation 8. Units of the characterization factor $CF_{d,\$}$ on this level are \$/\$.

$$\mathrm{CF}_{d.\$.} = \mathrm{MCI}_{d.\$.} \times P_{d.\$.} \times \mathrm{NPV}_T$$

$$= -4x \times \frac{\overline{M}_d}{\left(\overline{c}_d\right)^2} \times P_{d.\$.} \times \mathrm{NPV}_T \text{ (Relation 8)}$$

$P_{c,\$}$ The amount of deposit d, in \$/year.
NPV_T Net present value factor (year).

- ***Step 4:*** *From marginal cost increase on deposit level to cost increase on commodity level*

M_c and C_c at commodity level are obtained from Relations 9 and 10.

$$\overline{M}_c = \frac{\sum_d \left(Y_{c,d} \times M_d\right)}{\sum_d Y_{c,d}} \quad \textit{and} \quad \overline{C}_c$$

$$= \frac{\sum_d \left(Y_{c,d} \times C_d\right)}{\sum_d Y_{c,d}} \text{ (Relations 9 and 10)}$$

M_c and C_c are respectively the slope and constant on deposit level, recalculated to commodity level c.

- ***Step 5:*** *From marginal cost increase per dollar to a characterization factor per dollar*

Table 4 The CFs of REEs, developed based on the ADP method (Fe-eq / Sb-eq)

	Mine extraction / production (ton)	Total economic reserve (ton)	Total ultimately extractable resource (ton)	$\frac{\text{Extraction rate } i}{(\text{reserves } i)^2}$	Depletion Fe-eq. 2013	Depletion Sb-eq. 1999 economic reserve	Depletion Sb-eq. 1999 ultimate resource
Sb 1999	1.38E+05	3.20E+06		1.35E−08		1.00E+00	1.00E+00
Fe 2013	2.95E+09	8.10E+10		4.50E−13	1.00E+00		
La	4.71E+04	1.55E+07	6.44E+10	1.96E−10	4.36E+02	1.45E−02	3.60E−09
Ce	8.79E+04	3.05E+07	1.10E+11	9.44E−11	2.10E+02	7.01E−03	2.31E−09
Pr	9.25E+03	3.14E+06	1.52E+10	9.36E−10	2.08E+03	6.95E−02	1.27E−08
Nd	2.99E+04	9.60E+06	6.85E+10	3.24E−10	7.21E+02	2.40E−02	2.02E−09
Sm	3.22E+03	8.06E+05	1.16E+10	4.95E−09	1.10E+04	3.67E−01	7.53E−09
Eu	5.51E+02	1.29E+05	3.30E+09	3.30E−08	7.33E+04	2.45E+00	1.60E−08
Gd	1.94E+03	4.85E+05	1.02E+10	8.25E−09	1.84E+04	6.12E−01	5.86E−09
Tb	2.47E+02	7.77E+04	1.98E+09	4.10E−08	9.11E+04	3.04E+00	1.99E−08
Dy	1.40E+03	2.34E+05	8.59E+09	2.55E−08	5.68E+04	1.89E+00	6.01E−09
Ho	1.73E+02	3.53E+04	2.15E+09	1.39E−07	3.08E+05	1.03E+01	1.19E−08
Er	7.55E+02	1.09E+05	5.78E+09	6.35E−08	1.41E+05	4.72E+00	7.16E−09
Tm	8.50E+01	1.28E+04	8.59E+08	5.22E−07	1.16E+06	3.87E+01	3.65E−08
Yb	7.65E+02	1.04E+05	5.28E+09	7.04E−08	1.56E+05	5.22E+00	8.68E−09
Lu	1.27E+02	1.46E+04	8.25E+08	5.94E−07	1.32E+06	4.41E+01	5.90E−08
Y	9.29E+03	1.34E+06	5.45E+10	5.21E−09	1.16E+04	3.86E−01	9.91E−10

Calculating the mid- point characterization factors, by marginal cost increase per dollar is based on Relation 11.

$$CF_{c.kg.mid} = -\frac{\overline{M}_c}{(c_c)^2} \times V_c^2 \times P_{c.kg} \text{ (Relation 11)}$$

Table 5 reveals the results of calculations. The mid-point CFs and Fe equivalent are calculated, using different values of V_c (2013). The results show the importance of taking into consideration the variation of metal price. ReCiPe method end- point characterization factors are provided in Annex C (Electronic Supplementary Material).

3.3 Comparison of CFs, derived from ADP and ReCiPe

The REEs are among those resources with relatively high resource depletion impact (Fig. 3). Therefore, it is important that they be included in the resource impact assessment methods. If we consider the ADP, the highest CF values are allocated to the gold, tellurium and platinum (52, 40.7 and 2.22 Sb eq, respectively) and the lowest values belong to the silicon and aluminium (1.4E−11 and 1.9E−9 Sb eq, respectively). For ReCiPe (before including the REEs), the highest value corresponds to platinum, gold and rhodium (163,000, 69,900 and 20,300 Fe eq, respectively) and the lowest are

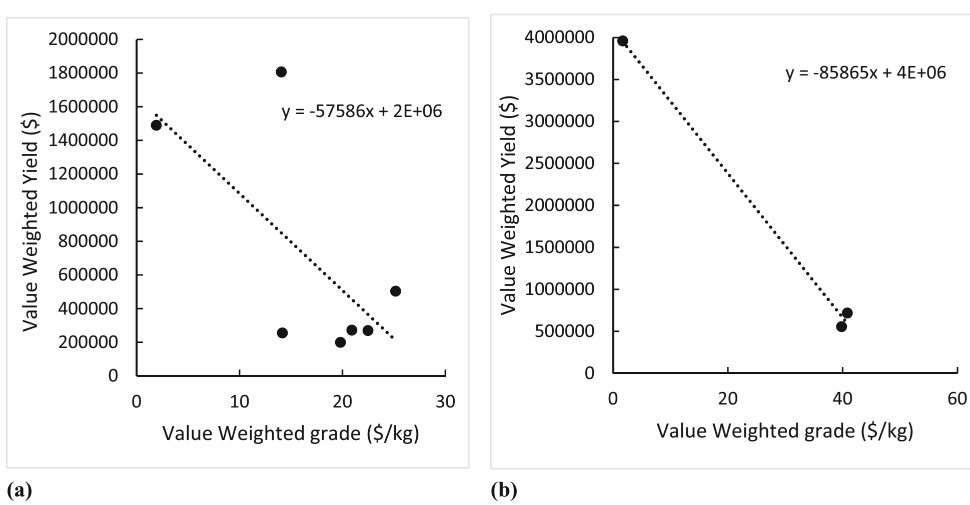

Fig. 1 Cross-plots of weighted yield values and grade for **a** carbonatites and **b** alkali igneous rocks

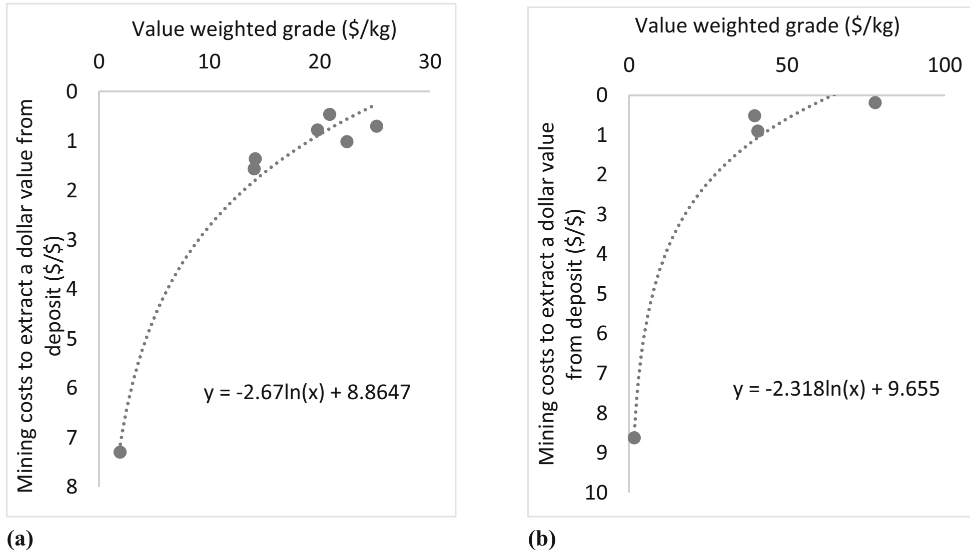

Fig. 2 Grade-cost relation in mines for **a** carbonatites and **b** Alkali igneous

aluminium and iron (0.0901 and 1 Fe eq, respectively). Note that based on the obtained results, the REEs are placed in the middle of the resources for ReCiPe and with high impact in ADP. For instance, neodymium is 2.40E−02 Sb eq for ADP and 2.33E+01 for ReCiPe.

Figure 3 highlights high variation of ADP factors (logarithmic scale), from the lowest to the highest compared to the ReCiPe method. The number of available characterization factors is higher for ADP compared to ReCiPe (35 and 63 substances, respectively). The red line represents the median (50%) for both of the methods. Considering the first tier in the figure, no critical resources are highlighted. Resources like cobalt and copper with high supply risk are placed in the lower middle (for both the methods), confirming the fact that the conceptual framework of the two methods do not reflect the resource challenges, which the society is facing. All REEs, except dysprosium for the ADP method, are placed in the third tier of the figure, highlighting the fact that these resources do not have the highest depletion factors, though using high amount of these elements may generate high resource depletion impacts. Present in the fourth tier is the dysprosium (based on ADP), representing the most critical REE.

Table 5 ReCiPe characterization factors (CFs) of REEs, using 2013 prices

		Mc (average)	Cc (average)	Vc 2013	Vc (avg5 yrs)	Pckg	Vc (2013) Midpoint	Vc (2013) Fe eq
LREO	Lanthanum	− 62,820	2,370,162	3.71	42.65	4.71E+04	7.26E−03	1.76E−01
	Cerium	− 62,831	2,370,921	3.96	43.35	8.79E+04	1.54E−02	3.73E−01
	Praseodymium	− 62,334	2,335,786	94.08	92.80	9.25E+03	9.35E−01	2.26E+01
	Neodymium	− 62,084	2,318,146	52.81	101.48	2.99E+04	9.64E−01	2.33E+01
	Samarium	− 65,492	2,559,166	3.05	51.83	3.22E+03	3.00E−04	7.26E−03
HREO	Europium	− 61,909	2,305,772	759.22	1711.50	5.51E+02	3.70E+00	8.95E+01
	Gadolinium	− 70,081	2,883,695	27.32	75.93	1.94E+03	1.22E−02	2.96E−01
	Terbium	− 70,659	2,924,541	561.16	1536.25	2.47E+02	6.44E−01	1.56E+01
	Dysprosium	− 79,120	3,522,958	288.83	757.25	1.40E+03	7.46E−01	1.81E+01
	Holmium	− 79,318	3,536,939	180.40	2623.33	1.73E+02	3.57E−02	8.64E−01
	Erbium	− 83,907	3,861,547	180.40	165.87	7.55E+02	1.38E−01	3.35E+00
	Thulium	− 74,966	3,229,187	180.40	3986.00	8.50E+01	1.99E−02	4.82E−01
	Ytterbium	− 81,765	3,710,043	180.40	293.80	7.65E+02	1.48E−01	3.58E+00
	Lutetium	− 78,555	3,482,980	180.40	3026.67	1.27E+02	2.68E−02	6.50E−01
	Yttrium	− 80,917	3,650,039	9.90	69.33	9.29E+03	5.54E−03	1.34E−01
	Fe			0.27	0.27	8.50E+11	4.13E−02	1.00E+00

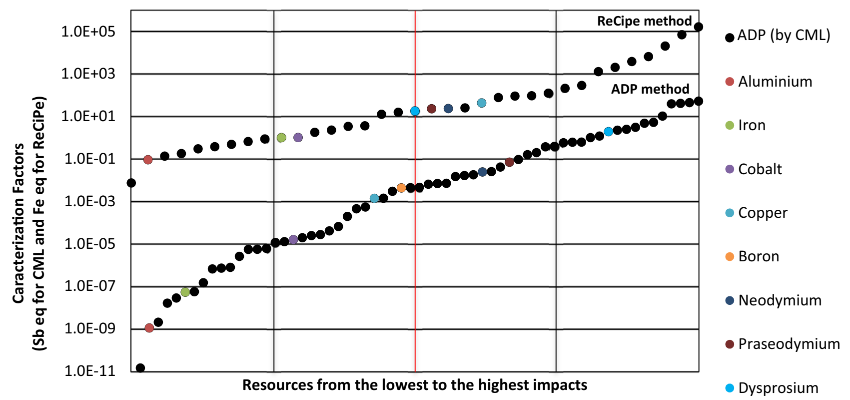

Fig. 3 The CFs, in ADP and ReCiPe methods, using 2013 REEs prices, ranked from the lowest to the highest impacts for each method—figure represents the existing CFs for the 35 substances for ReCiPe and the 63 substances for ADP—including 15 REEs CFs, developed in this study—8 substances are highlighted in the figure—Boron CF is not available in the ReCiPe method

4 Discussion

4.1 Requirements of resource depletion characterization factors

Existing LCIA methods for resource assessment are assessed here from different points of view. The assessment is conducted at different levels: (i) conceptual framework, (ii) basic assumptions, (iii) input parameters and (iv) availability and reliability of CF.

4.1.1 Conceptual framework

A conceptual framework is considered as the first criterion of resource assessment methods and reflects the comprehensiveness of methods to answer the resource problem. The indicator to assess a conceptual framework compares the goal of resource assessment, defined in different methods with the resource related challenges that society is facing.

With regard to a conceptual framework, existing LCIA methods are either based on inherent properties and depletion of materials, or based on the prediction of future extraction efforts (Stewart and Weidema 2005). The challenges that society is facing are not reflected correctly in either the ADP or ReCiPe methods. Both methods consider the accessibility to geological reserves, though the corrected accessibility through recycling and the anthropogenic stock are not part of the models.

The concepts behind different resource depletion characterization methods need to be revised. Given the fact the resource assessment in LCA is based on the geological availability (e.g. ADP and ReCiPe), the current work suggests that there is a need to go beyond the current LCIA method in order to incorporate other important factors (e.g. recycling and anthropogenic stock as the complement of the geological availability) not yet covered by the LCA resource assessment methods.

Ignoring recycling of the metals and minerals in the current models leads to the underestimation of the total available substance. The ratio of recycling to the available End-of-Life stock is similar to the ratio of extraction rate to the resource. Within the context of LCA, further development of the impact assessment methods is necessary to cover the recycling effectively.

In addition, the methods do not provide a conceptual framework to assess all types of resources. Only the extraction rate and the available reserves are considered in ADP method, while regeneration rate (related to the biogenic resources) is neglected. The ReCiPe method does not provide any baseline to assess biotic resources.

Covering all the resource types is necessary for a comprehensive resource assessment by LCIA indicators. This is a major issue in resource assessment by LCA today, as none of the reliable LCIA methodologies (including ADP and ReCiPe) provide full coverage of different resource types.

4.1.2 Basic assumptions

Different assumptions, theory and background exist behind the methods. The assumptions of the LCIA should be coherent within the conceptual framework of method. As an example, the estimation of reserve value in ADP may be assumed to be based on either economic reserves, reserve base or ultimate reserves.

The first assumption in this study is extraction allocation to individual REEs. Allocation of extraction means the ratio at which elements (here REEs) are extracted as a co-product of mining (Table 3). A mass-based allocation is applied based on the values provided in Table 3. The values in Table 3 include some uncertainties, related to geological and exploration reports. The fact that more than 80% of REE resources are covered in this study makes the results much more reliable.

Another major assumption is the choice of prices of REEs, used in ReCiPe method. REEs were subject to significant price fluctuations due to geopolitical issues in the last five-years, related to Chinese export quotas on REEs. Extremely high fluctuations of REE prices affect the CFs. The REEs prices in 2013 are selected, as they are more reliable and more stable, compared to the average prices of the last 5 years.

4.1.3 Input parameters

The input parameters for different methods are assessed based on different criteria, including stability, geographical representativeness, time representativeness, completeness, uncertainty and variability. In most cases, the difficulty to collect all required inputs results in gaps and missing CFs.

Regarding the geographical representativeness, the data used in the present study was obtained from mining reports, corresponding to specified geographical zones. Time representativeness is very high as the data is gathered for 2013. An issue is the comparability of the new CFs to non-updated ADP base line CFs (since 2000). Nevertheless, even data with a high time representativeness from mining reports present only a snapshot, while future exploration activities may lead to more reserves that are available.

In the case of ADP, the extraction rates from one side and the economic reserves (or reserve base or ultimate reserves) from the other side are required. For most metal resources, the data could be obtained from USGS databases. For resources where data is insufficient, like REEs, it is necessary to collect data from other sources or to consider some assumptions. For REEs, the main difficulty is the extraction rate. Finally, covering more than 80% of worldwide resources guarantees completeness of the results.

The availability of most active mines enables us to have a reliable dataset. Nevertheless, the extraction is either predicted or derived from mining reports, which are sometimes uncertain; there are high fluctuations due to supply restrictions in the recent years. In addition, closing and reopening several REE mines have amplified extraction fluctuations.

For ReCiPe, the complexity is higher as more data and data sources are needed, including the cost of mining and REE Prices (Tables 2 and 3). It is very difficult, and in some cases impossible, to have reliable data for mining costs. As an example, CAPEX for Bayan Obo (Baotou) in China is not available in mining reports. Regarding REE prices used in ReCiPe, extremely high fluctuations within the past years affect reliability of prices. This is also the reason why a sensitivity analysis is done here, considering REEs prices in 2013, compared to the average price within 5 years (2009–2013) and is provided in Annex A (Electronic Supplementary Material).

4.1.4 Availability and reliability of the CFs

Covering all the resources is necessary for a comprehensive resource assessment by the LCIA indicators. This is a major concern in resource assessment, as none of the reliable LCIA methodologies today provide a full coverage of various resource types. Parameters related to reliability of CF are accuracy, preciseness, being updatable, uncertainty of results and coherency with nomenclature. The relevant resources available in different methods reflect the availability of CFs.

The main parameter influencing the existence of CFs is the effort required to develop new CF. This is well reflected when comparing ADP and ReCiPe. ReCiPe requires a set of data that is more exhaustive; therefore, the available CFs are around three times lower than ADP method.

Completeness, variability and uncertainty of inputs play significant roles on preciseness of the CFs. In the case of holmium, erbium, thulium and ytterbium, the lack of deposits and very low extraction rates result in highly unreliable values. Regarding the prices, “Vc” is not available for these four elements, and the average of other REEs is considered instead. That is why the authors exercise caution when using CFs for holmium, erbium, thulium and ytterbium.

5 Case study on NdFeB permanent magnets

In this part, the obtained results of the REEs characterization factors are tested in a real case for NdFeB permanent magnets with high REE contents. The aim of the case study is first to determine the feasibility of the newly developed factors. It also aims to assess and compare the resource impact results of a product when REE CFs are either included or not. Supplementary information on NdFeB (32%/66%/1%) cradle to gate detailed inventory, system boundaries and allocation rules are provided as supporting information in Annex B (Electronic Supplementary Material) of this article.

5.1 NdFeB permanent magnet

Physical properties of REEs make them ideal for permanent-magnet alloys. Their high spin-orbit coupling, results in magnetocrystalline anisotropy, which leads to high values of coercivity (Zakotnik et al. 2016). NdFeB magnets contain magnetically hard phase based on (Nd,Pr,Dy)–Fe–B and other trace elements. REE contents of magnets vary from 27 to 32 wt.%, Fe ranging from 50 67 to 73 wt.%, B at 1 wt.% (Sugimoto 2011), and other minor additions of transition metals. The magnet assessed in this case study is composed of 32% Nd, 66% Fe, 1% B, 0.29% Dy, 0.04% Al, 0.01% Cu, 0.08% Co and 0.57% Pr. The inventory used for LCA modelling of permanent magnets is derived from its energy consumption (Zakotnik et al. 2016) and completed by specific industry data from China.

5.2 NdFeB permanent magnet inventory

The assessment is conducted for production of 1 kg of NdFeB permanent magnets from cradle to gate. The losses (27%) for

Table 6 Inventory of resource inputs for 1 kg of the permanent magnet cradle to gate/impact of resource based in ADP and ReCiPe methods

Substances	Total mass	Unit	ReCiPe (Fe eq)	ReCiPe includingREs CFs (Fe eq)	ADP (Sb eq)	ADP including REs CFs (Sb eq)
Iron	1.25E+00	kg	1.25E+00	1.25E+00	6.54E-08	6.54E−08
Neodymium	4.09E−01	kg		9.54E+00		9.83E−03
Copper, 0.99% in sulfide, Cu 0.36% and Mo 8.2E−3% in crude ore	1.11E−02	kg	4.72E−01	4.72E−01	1.51E−05	1.51E−05
Nickel, 1.98% in silicates, 1.04% in crude ore	1.93E−02	kg	2.41E−01	2.41E−01	1.26E−06	1.26E−06
Chromium	8.11E−03	kg	2.02E−01	2.02E−01	3.59E−06	3.59E−06
Praseodymium	7.29E−03	kg		1.65E−01		5.07E−04
Manganese	9.81E−04	kg	7.51E−02	7.51E−02	2.49E−09	2.49E−09
Cu 0.38%, Au 9.7E−4%, Ag 9.7E−4%, Zn 0.63%, Pb 0.014%, in ore	2.38E−03	kg	1.02E−01	1.02E−01	3.26E−06	3.26E−06
Cadmium	1.02E−04	kg			1.59E−05	1.59E−05
Lead	1.69E−03	kg	3.00E−03	3.00E−03	1.07E−05	1.07E−05
Dysprosium	3.76E−03	kg		6.80E−02		7.11E−03
Other			4.65E−01	4.65E−01	7.04E−05	7.04E−05

all processes from the mining to the final production are included in the assessment. Particles are emitted during the production process and are considered in the inventory. The inventory is cradle to gate; the downstream processes (e.g. End of Life) are not part of the assessment. Detailed inventory is provided in Annex B (Electronic Supplementary Material).

Table 6 provides life cycle inventory of raw materials input for which a CF is available in ADP and ReCiPe methods to which the flows of the REEs are added. Table 6 also provides the characterized results, both including and discluding the REEs, calculated based on the ADP and ReCiPe CFs developed in this study.

As shown in Fig. 4, significant differences are highlighted when the REE CFs are included. The difference is less substantial in ReCiPe based method (ReCiPe with REE CFs is almost five times higher) due to relatively high CF for iron, compared to the ADP method. For the ADP-based method, the impacts are almost 1000 times higher including REE CFs.

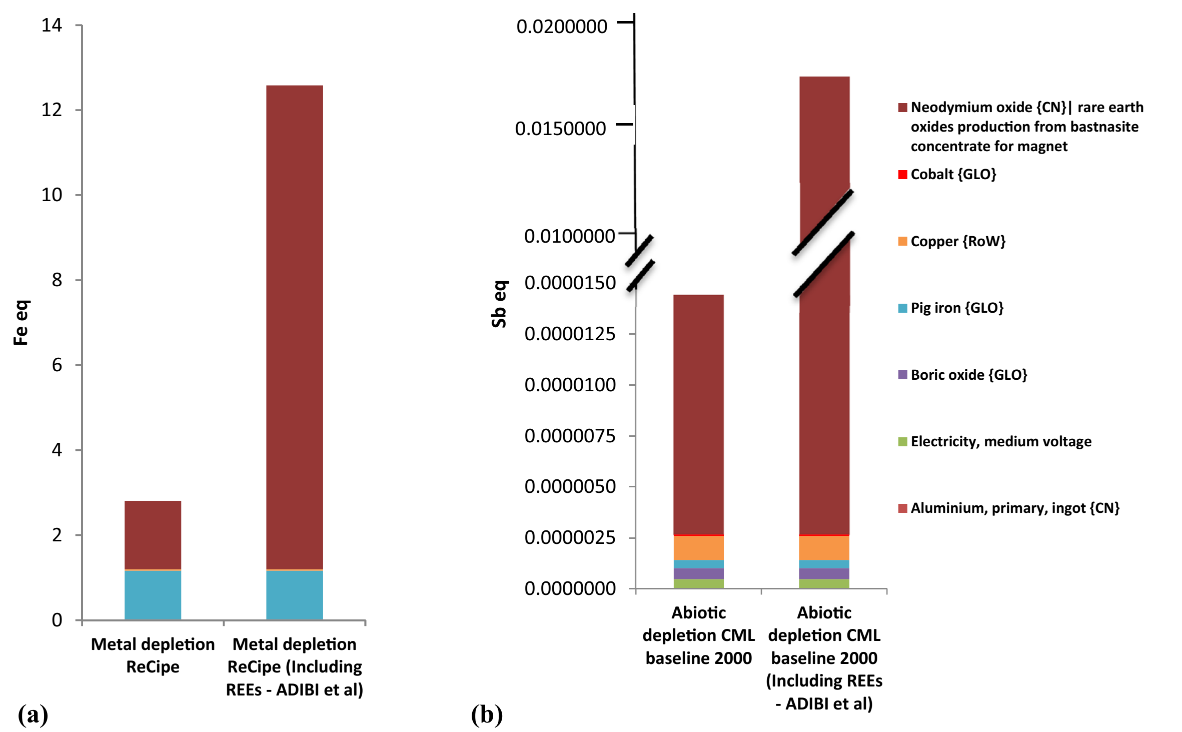

Fig. 4 Resource impact assessment contribution analysis for ReCiPe (**a**) and ADP baseline (**b**) with and without REEs CFs of 1 kg of permanent magnet NdFeB (32%/66%/1%) cradle to gate

In addition, the resource hotspots are shifting from metals like iron, cadmium and copper to REEs like neodymium and dysprosium (Table 6). The results (Fig. 4) show the importance of including the REE characterization factors to help the correct interpretation of the LCA results, especially when a product contains significant content of REEs.

REEs are major elements in the magnets, with 32% of the composition of the studied magnet being neodymium. The mass of the neodymium is 409 g, including the losses during the production phases. Other major inputs include Fe, representing 66% of the magnet composition. In addition, energy consumption is one of the major inputs for the magnet production.

According to the ADP and ReCiPe methods, the REEs have the highest impact, compared to other resources included in the magnets (Fig. 4). In the ADP method, the neodymium is responsible for more than 99% of the impacts. As shown in Fig. 4, the high mass of iron with a relatively high impact in the ReCiPe method (compared to the ADP) represents around 10% of the final impacts, while the neodymium is largely dominant with an impact of more than 80%. Except the pig iron, other inputs do not represent impacts regarding the resource depletion for the ADP and ReCiPe methods. The results (Fig. 4) confirm the importance of including REE CFs in the impact assessment calculations. Finally, it is necessary to highlight the need for checking, and in some cases correcting, the inventory in available generic LCA databases, before using the calculated CFs.

6 Conclusions

REEs are of great importance to be included in the assessment of resource depletion. To examine the applicability of the presented CFs, the NdFeB permanent magnets are used as case study. The assessment of NdFeB permanent magnets showed that the inclusion of CFs of the REEs have a significant effect on the LCA resource impacts of the products.

We expanded the number of characterization factors to 15 rare earth elements in ADP and ReCiPe methods. The proposed CFs can be readily implemented in the main LCA software such as Simapro and GaBi to address the issue of the resource depletion of the REEs.

We illustrated in this work the difficulties and wide range of data needed to develop the missing additional characterization factors. The missing data (or difficulty to find the corresponding data) leads to the fact that several gaps can be identified in the available resource assessment methods. The existing gaps and differences in characterization methods lead to the fact that no method covers all the resources. This problem rises in some strategic resources, including rare earth elements (REEs).

The price plays an important role in CF calculation by the ReCiPe method. Moreover, it affects the ADP factors when economic reserve data is used, as economic reserve is directly influenced by the price. It is shown that there is no correlation between the ADP and ReCiPe methods for the average period of 5 years. However, considering the price in 2013 can improve the correlation significantly; nevertheless, the fluctuation of the prices makes the characterization factors, and consequently the impact assessment results, very unstable. For a REE dominating LCIA results, the authors recommend the verification of price and reserve trends to understand the potential longer-term vulnerability of their results for interpretations.

CFs are a clear step forward; however, further improvements on less common REEs (holmium, erbium, thulium, ytterbium and lutetium) is recommended (i.e. the price, extraction rate and reserve availability).

7 Recommendations

Concerns over the resources rise as the demand increases. Different methodological approaches under the LCA framework have been used so far to address the impact of resource extraction. However, they lack consistency, as available models do not address the same parameters: short vs long term, stock vs backup technology, etc.

Indicators confuse in some cases resource depletion with impacts on resource availability (Drielsma et al. 2016a). Therefore, it is crucial to go beyond the current Life Cycle Impact Assessment (LCIA) methodologies in order to incorporate other important factors (e.g. recycling), not yet covered by the LCA resource assessment indicators and to assess resource availability as a more meaningful and comprehensive concept (Drielsma et al. 2016a).

New indicators are to be proposed based on several aspects of the material circulation during its life cycles such as recyclability, criticality and geopolitical availability of resources. The new approaches enlarge and include to the extent possible different resource assessment related criteria in a comprehensive and coherent framework. The novelty of this work could be a model for developing other methods for calculating resource assessment CFs.

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