Resources Policy xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Resources Policy

journal homepage: www.elsevier.com/locate/resourpol

Applying and advancing the economic resource scarcity potential (ESP) method for rare earth elements

Robert S. Pell[a], Frances Wall[a,b], Xiaoyu Yan[b], Gwendolyn Bailey[c]

[a] Camborne School of Mines, University of Exeter Penryn Campus, Penryn, Cornwall TR10 9FE, United Kingdom
[b] Environment and Sustainability Institute, University of Exeter Penryn Campus, Penryn, Cornwall TR10 9FE, United Kingdom
[c] Department of Materials Engineering, KU Leuven, Leuven, Belgium

ABSTRACT

A number of studies have identified rare earth elements (REE) as critical metals due to their high economic importance combined with a high risk of supply disruption (Du and Graedel, 2011; Nassar et al., 2015; Schneider et al., 2014). The current methods used to calculate resource depletion in life cycle assessments (LCA) neglect socio-economic, regulatory and geopolitical aspects, nor do they include functionalities such as material recycling or reuse that control the supply of raw materials. These are important factors in determining criticality and are the controlling factors on REE availability rather than geological availability. The economic scarcity potential (ESP) method introduced by Schneider et al. (2014) provides a framework to calculate criticality. This paper reviews the ESP method and advances the method based on recent developments in material criticality. ESP criticality scores for 15 REE with the addition of Au, Cu, platinum-group metals (PGM), Fe and Li are measured. The results highlight that Nd and Dy are the most critical REE, owing mainly to the high demand growth forecast for these two elements. A pathway is presented for incorporating these calculated scores into the ReCiPe life cycle impact assessment (LCIA) method of a LCA.

1. Introduction

Life cycle assessment (LCA) is an important tool to quantify the environmental performance of a product or a process such as rare earth element (REE) production. A LCA can detail potential impacts that this process will have on human health, natural environment and natural resources. However there are limitations and problems for assessing abiotic resource depletion during a life cycle impact assessment (LCIA) (Drielsma et al., 2016). Abiotic depletion potential has been used as an indicator, calculating future exhaustion of resources based on current production levels. Advances were made to this approach by Vieira et al. (2016) with the surplus cost potential method, which calculates the increased cost of extracting raw materials due to depleting resources providing a cost per unit of metal extracted in the future. Both methods are useful in understanding the long-term availability of resources but fail to consider a range of factors which control the supply of critical raw materials. In order to correctly assess the criticality of materials, it is necessary to have an indicator that takes into account several impact categories for supply risk and economic importance rather than just resource depletion. Otherwise, the assessment categorizes cerium (which is as abundant in the crust as copper) as highly critical along with dysprosium, praseodymium and the other heavy REE. This paper examines how an alternative method to assess mineral resource inputs can be devised and used for critical metals such as the REE.

Rare earth elements include the lanthanides and the chemically similar elements yttrium (Y) and scandium (Sc). The elements are often divided into two groups, the light rare earths elements (LREE) and heavy rare earth elements (HREE). The LREE include La, Ce, Pr, Nd, and Sm. The HREE include the elements from Eu to Lu in the Periodic Table as well as Y. The REE have strategic importance, with uses in a number of emerging low-carbon technologies. Specific physical properties of individual REE are necessary for efficient electric vehicles, and direct drive wind turbines, such as Nd in NdFeB high strength magnets. The addition of Dy is used to maintain the performance of these magnets at high temperatures. Other REE such as La and Ce are used in catalysts for fluid catalytic cracking of crude oil and production of transportation fuels; and Ce and La are used as emissions catalysts in petrol fueled vehicles. Total industrial demand of REE, excluding Y, is small with an estimated use of 159,500 t in 2016 (USGS, 2016), but REE have a large positive economic contribution to downstream industries. One of the major challenges of REE supply is 'the balance problem'; the misbalance between the economic market demand and the supply of individual REE Du and Graedel (2011). There is often high demand for REE that are minor constituents of a REE ore (such as Pr), while the demand for the major constituents (such as La and Ce) may be much lower.

The security of supply of REE has been a concern for import-dependent industrialized countries with ambitions to advance their low-carbon economy. China currently dominates the production of REE, excluding Y, accounting for 88% of total REE production in 2016 (USGS, 2016). There is a history of supply disruption of REE exports,

E-mail address: rp416@exeter.ac.uk (R.S. Pell).

https://doi.org/10.1016/j.resourpol.2018.10.003
Received 3 August 2018; Received in revised form 8 October 2018; Accepted 8 October 2018

Please cite this article as: Pell, R.S., Resources Policy, https://doi.org/10.1016/j.resourpol.2018.10.003

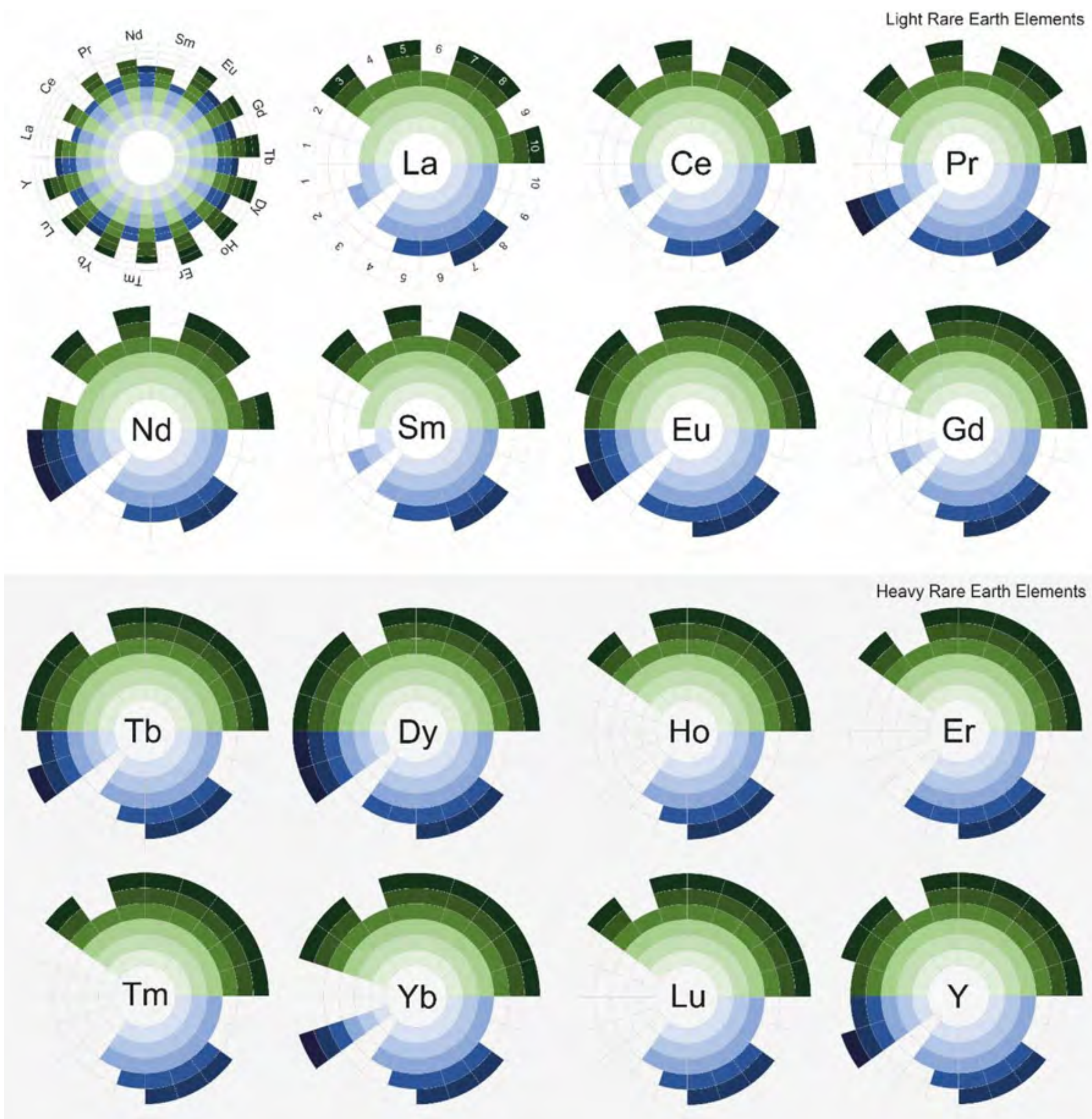

Fig. 1. Criticality assessments for individual REE based on supply risk (green top half of each) and economic importance (blue bottom half) at various scales from national to global in a medium term time scale. White space means that the REE was not included in the criticality study (NRC, 2008; Erdmann and Graedel, 2011; Nassar et al., 2015; BGS, 2015; Moss, 2013; Coulomb, 2015; Glöser et al., 2015) (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

this has fueled increased attention into the future availability of such elements. From 2007–2009 China reduced export quotas of REE by 25% (Binnemans and Jones, 2015). This resulted in significant price increases following the export restrictions which were put in place by China (Mancheri, 2015). Concerns about the future supply of REE and the monopolistic nature of production combined with the growing economic importance of downstream products has led to a number of studies identifying individual REE, or REE as a single group, as critical materials (NRC, 2008; Erdmann and Graedel, 2011; Nassar et al., 2015; BGS, 2015; Moss, 2013; Coulomb et al., 2015; Glöser et al., 2015).

A number of projects exist in various stages of development around the world that if moved into production would diversify the supply of REE. For example mining projects are in the prefeasibility or feasibility stage in Europe, with Sweden's Norra Kärr project; in Africa with Malawi's Songwe Hill, Namibia's Lofdal, and South Africa's Zandkopsdrift; in North America with Canada's Ashram, and Nechalacho, USA's Bear Lodge; Australia's Nolans, Dubbo Zirconia project; South America has projects such as Araxá and Serra Verde, both in Brazil. However, there are a number of barriers making production outside China challenging. China currently possesses excess production capacity within the country, suppressing prices and reducing the chances of projects outside China from accessing funding. There is also a lack of proven processing technologies for the unconventional mineralogy in some of the new prospects and a lack of efficient and clean technology for separating and converting rare earth oxides to metals and alloys (USGS, 2016). These factors mean that a large amount of time and capital are required to bring in new operations online and diversify the supply.

Downstream uses of REE are often considered to have positive environmental impacts when they are used in generating clean energy or replacing conventional combustion engines in cars (Fishman et al., 2018). However, the mining, isolation and recovery of REE has a number of environmental and social impacts throughout the life-cycle (Zaimes et al., 2015, Koltun and Tharumarajah, 2014, Arshi et al., 2018, Du and Graedel, 2011, Haque et al., 2014, Sprecher et al., 2015).

REE production and processing requires a large amount of energy and chemicals, and can produce greenhouse gas emissions, chemical pollutants, hazardous mine waste and wastewater, which can contain radioactive material and can cause extensive land transformation. Chemicals used in the refining process have been involved in REE bioaccumulation and pathological changes in local residents (Li et al., 2013). Contaminants associated with REE production, which include radionuclides and heavy metals, have been identified as having negative impacts on human, plant and livestock health (Rim, 2016).

It is important to understand and manage the environmental and social costs associated with REE production as we progress to a low-carbon economy and renewable energy generation, which is likely to require more metal and mineral raw materials per unit energy produced. When considering the sustainability of the raw materials that are produced for the low-carbon economy, it is important to consider risks to supply disruption, which could include market imbalances or governmental interventions such as export bans.

The aim of this paper is threefold. (i) To show that individual REE have unique supply risks and economic importance and therefore different levels of criticality. (ii) To provide a more appropriate impact category within LCIA for resource scarcity of critical metals (iii) Explain how criticality can be included in LCA frameworks and see what results would look like.

2. Review of REE criticality studies

A variety of methodologies can be used to determine raw material criticality. The approaches may vary but share a common aim to define the supply risk of a raw material and its relative importance to the economy. The criticality calculation methodology typically contains an evaluation of the level of supply risk and the impact of said supply risk in a two-dimensional matrix (NRC, 2008; Erdmann and Graedel, 2011; Graedel et al., 2015). Environmental impacts can be used to create a third axis (Graedel, 2015).

Criticality studies are context dependent and can be carried out on a range of scales and for a range of stakeholders, which can be anything from a single company or technology, to a national or multi-national economy (Graedel et al., 2012). For example, a criticality study from the perspective of a country will be different from that of a company, and short-term risk of raw material criticality may not be the same in the medium or long-term. Criticality studies are connected to the concept of risk theory in a holistic way, including economic, societal or environmental risk (Helbig et al., 2016; Frenzel et al., 2017). A wide variety of factors are often considered in criticality assessments, including geological deposits, geographical concentration of deposit or processing facilities, social issues, regulatory structure, geopolitics, environmental issues, recycling potential, substitutability, and sustainability (Achzet and Helbig, 2013; Erdmann and Graedel, 2011).

Eight studies that include criticality of REE have been reviewed (Fig. 1). Each study had a different context, with various spatial scales, from national to international and looked at different areas of the economy. For example Nassar et al. (2015) looked at the criticality of REE associated with the global economy, whilst Coulomb examined the criticality of REE in the context of the low-carbon economy. Where possible the studies looked at a medium-term time perspective of criticality.

All but one study (BGS, 2015) included two-dimensions typical of criticality studies which could be translated into supply risk and economic importance. Fig. 2 shows the supply risk of the REE on the left hand side of each box and to the right shows economic importance of the REE from these studies. The relative criticality scores are normalized and given a colour scale between 1 (non-critical) to 6 (extremely-critical). The terms used in the study also varied meaning that this approach includes subjective judgement of the criticality scores. The white categories indicate gaps in the criticality study.

2.1. Life cycle impact indicators for abiotic resource depletion

The concept of the Area of Protection was founded in the early 1990s by the Society of Environmental Toxicology and Chemistry (Fava et al., 1993). It is used in the LCA community to identify classes of endpoint category indicators that society deems important to protect, and allows a linkage between damages because of environmental intervention and societal values. The Area of Protection are divided into the protection of: Human Health, the Natural Environment and Natural Resources (Finnveden, 1997; Udo de Haes et al., 1999). Te ILCD handbook defines these natural resources and that challenge as;

> "The concern of natural resources is the removal of resources from the environment (and their use) which results in a decrease in the availability of the total resource stock, as non-renewable (usually abiotic) resources are finite"

This definition and the depletion of abiotic resources is a much disputed category within LCA as it crosses the economy-environment system boundary in combination with the fact that there are different ways to define the depletion problem, and there are different ways of calculating these depletion definitions (Van Oers and Guinée, 2016).

For example Van Oers and Guinée (2016) stated that the environmental impact of LCA should not strive to take into account the different aspects of a criticality assessment due to the varying temporal and spatial nature of each study. However this can be overcome with a clear definition during the goal and scope phase of a LCA and matching the criticality calculation to what is being measured. For example if the environmental performance of a mining project is being measured, it is possible to complete the criticality calculation for the life of the mining project with criticality scores in a global context.

Different approaches can be used to determine the decreasing availability of resources. Different approaches have distinct visions or cultural perspectives for abiotic resource depletion (De Schryver et al., 2018). The cultural perspective theory which has categorised visions on resource depletion as either individualist, hierarchist and egalitarian is explored is incorporated into different LCIA methodologies.

One approach to resource depletion which aims to remove the cultural perspective from the process is through the use of entropy or exergy as a basis for characterization, which considers the efficiency of extraction. A thermodynamic approach which can capture resources is a useful approach as is it has an established scientific basis. Exergy is a measure of available energy, whilst entropy in this context refers to the dispersal of energy within a system.

A common method that has been used and is considered individualist uses resource scarcity for the basis of characterization. This method calculates the long-term depletion of non-renewable resources. The depletion of resources is calculated and considers future resource scarcity as a result of current consumption. The impact from resource use is then calculated as an impact on human welfare due to reduced availability, increased competition, and limited accessibility driven by social and geopolitical factors (Finnveden, 2005; Sonnemann et al., 2015). These approaches have shortcomings. Firstly, calculations of physical resource availability or 'depletion potential' used in LCIA rely on a fixed stock paradigm, as described by Tilton and Skinner 1987. The idea that there is a finite quantity of a resource, often described as a crustal abundance, fails to calculate the reuse or recycling rate of these materials and considers that materials are lost after use. There is also no clear definition for undiscovered resources (Vieira et al., 2016). The alternative method used is the opportunity cost paradigm, which states that if physical quantities reduce, or are more difficult to access, prices will increase and innovations and alternatives to that material will be sought, reducing demand. LCIA practitioners have used both methods which have very different views on natural resources and can significantly alter LCIA results. In the fixed stock method, any use of natural resources results in reduced availability for the future, whereas in the opportunity cost view, natural resources are viewed as flows that

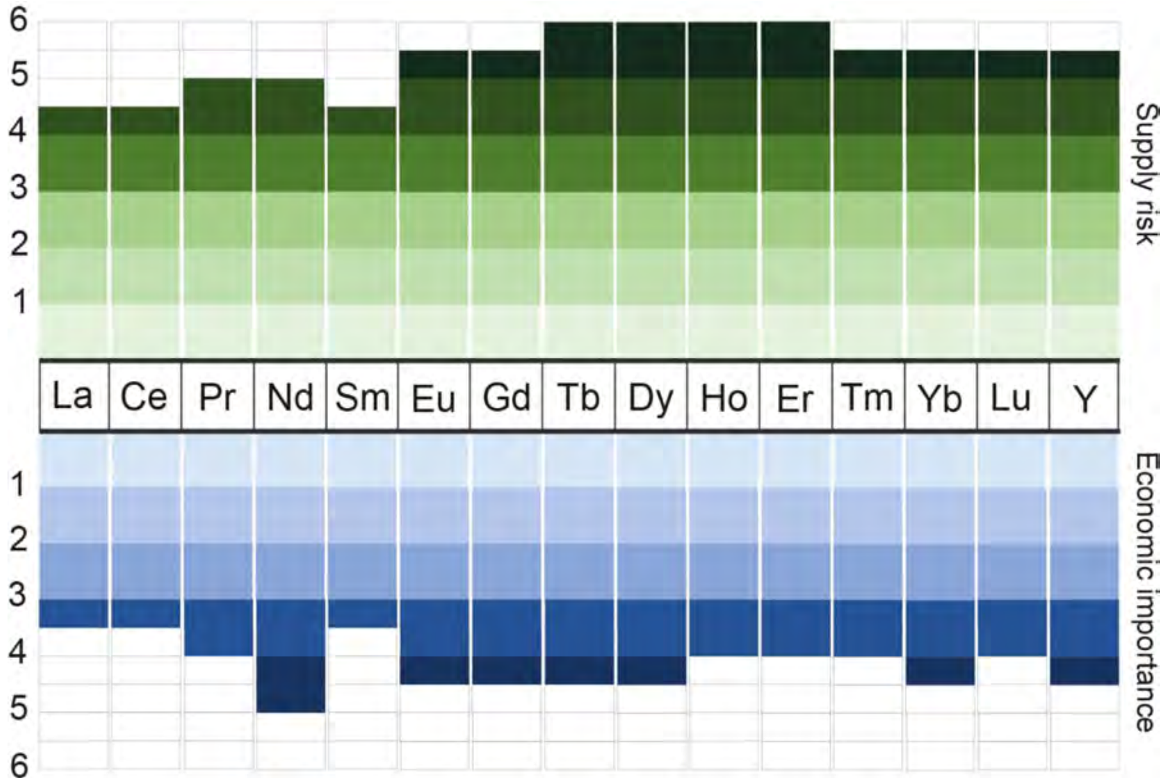

Fig. 2. Normalized average of the combined REE criticality studies from Fig. 1.

need to be managed to meet human demands (Drielsma et al., 2016).

Different methods have different visions and methodologies. Many of these methods that are currently employed to not consider the socio-economic, regulatory and geopolitical aspects or functionalities such as material recycling or reuse.

3. Materials and methods

The abiotic depletion potential method (Van Oers and Guinée, 2016) and the surplus cost potential method (Vieira et al., 2016) are used for comparison in this paper. The latter has been integrated into the ReCiPe methodology (Huijbregts et al., 2016). This method to calculate metal depletion provides scores for 75 mineral resources providing impact scores in relation to 1 kg of Cu. Fig. 3 provides a comparison of five mineral resources and categorizes rare earth elements as a single group.

LCIA is a step in a LCA which translates data such as emissions or resource uses from LCA studies to an easily understandable smaller number of impact scores. The method of calculating these scores is referred to as characterization, and the results will produce an environmental impact per unit of stressor (e.g. per kg of resource). Schneider et al. (2014) identified that economic aspects of resource supply are neglected in current LCA methodologies and attempted to overcome this by introducing the economic resource scarcity potential

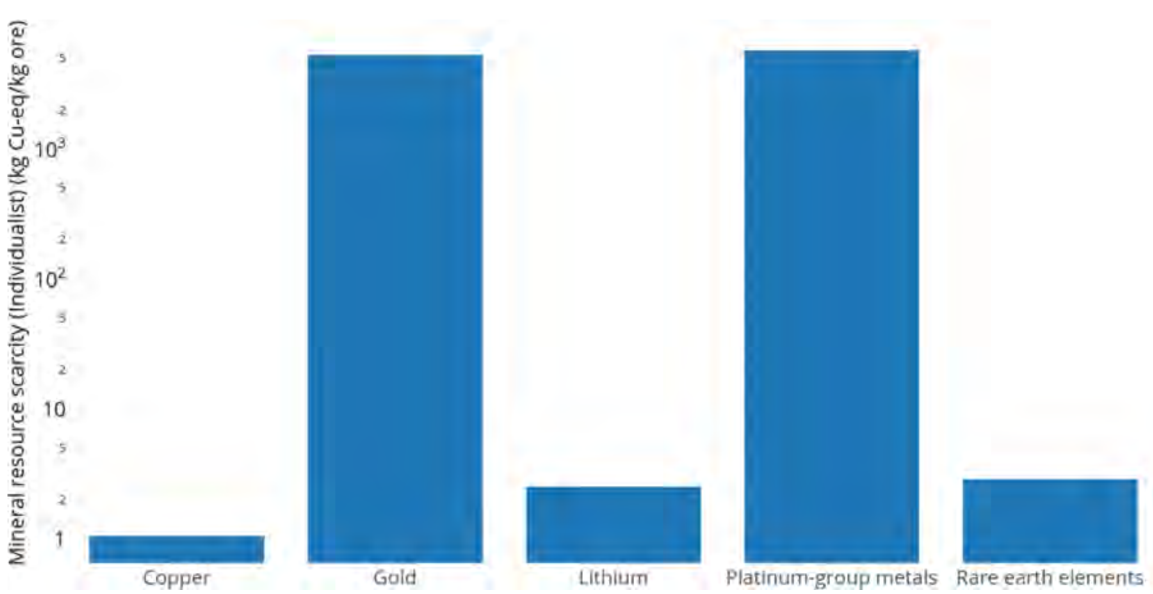

Fig. 3. Mineral resource scarcity results (individualist) using the surplus cost potential approach.

(ESP) model.

Various data that contribute to scarcity of resources are included, expanding the Area of Protection for natural resources to include economic or socially derived scarcity. The factors that are included in ESP include reserves, recycling, and country and company concentration of mining activities, economic stability, demand growth, trade barriers, and companion metal fraction. Drielsma et al. (2016) highlighted that this method assesses short term availability of resources, and is a useful tool in identifying disruptions that may arise in this timeframe. Drielsma et al. (2016) also argued that the Area of Protection for natural resources is altered using this method as the ESP method aims to protect the product system being measured rather than the resources themselves. For example, the protection of the value that a resource has when being used rather than the resource itself.

Current LCIA methods, such as the ReCiPe approach only take into account geological availability and the increased cost of accessing raw materials in the future. The surplus cost potential method fails to take into account resource criticality. Additional methods, such as the ESP approach, would be a useful step to incorporate criticality factors into the life cycle sustainability assessment framework which would better represent impacts on the Area of Protection for Natural Resources (Sonnemann et al., 2015). The ESP method put forward by Schneider (2014) allows for a new characterization factor for resource use impact assessment. Using these characterization factors and a framework to incorporate criticality into the life cycle sustainability assessment context by Sonnemann et al. (2015) allows for integration of the ESP method into the LCA.

3.1. Methodology of ESP calculations

The factors that impact resource availability were suggested by Schneider et al. (2014) and have been highlighted in Table 1. Equal weighting was used for all impact categories initially replicating the method used by Schneider (2014). This was followed by a comparison of results if the economic importance impact category was increased to represent 50% of the total ESP score. Production data were obtained by combining the USGS data with other project scale information. Individual REE data were obtained from individual companies, and when not possible were estimated from literature. All sources of information and origins of data used in the study are included in the Supplementary information.

Table 1
Overview of impact categories, indicators and thresholds used in the ESP calculations (Thresholds are based and on data from Schneider et al. (2014) DOJ and FDT (2010), The World Bank Group (2012), UNDP (2011), Rosenau-Tornow et al. (2009).

Impact category	Category indicators	Threshold
Supply risk		
Reserve availability	Reserve/Annual production	Low < 0.4 < high
Recycling	New material content (%)	Low < 0.5 < high
Mining country concentration reserves	HHI index	Low < 0.15 < high
Production bottleneck (country concentration)	HHI index	Low < 0.15 < high
Production bottleneck (company concentration)	HHI index	Low < 0.15 < high
Governance stability	WGI[1]	Low < 0.25 < high
Socioeconomic stability	HDI[2]	Low < 0.12 < high
Trade barriers mine production	Share of mine production under trade barriers (%)	Low < 0.25 < high
Companion metal fraction	Production as companion metal (%)	Low < 0.2 < high
Trade		
Economic importance		
Average production and cost per kg	$ per kg	Low < 0.1 < high

The data incorporate 10 impact categories and can be aggregated to provide a single ESP value (Eq. (2)). Each category has been described in a glossary in the Supplementary information. This allows for the comparison of the 15 REE studied as well as providing a comparison with Au, Cu, PGM, Fe and Li. Other elements were selected because they offered a range of supply risk and economic importance scores in previous criticality studies. They are used for comparison with the REE and to give a context to how REE perform. The criticality in the context of this paper is within a “global economy” and so not specific to a particular technology or group. This also allows for integration within the ReCiPe LCIA as this is on a global scale. It should be noted that it is possible to adjust the context through weighting the results or changing the thresholds. Thresholds used in this study are shown in Table 1 with justification for their values.

The aggregation of the supply risk and economic importance impact factors is given equal weighting. Individual category indicator results (impact factor x LCI) give an indication for the magnitude of the risk. However, the results only provide a comparison of the resources studied. A greater number of resources used for this method will allow for a more comprehensive estimation of supply risk and provide a better basis for decision making.

As noted by Schneider (2014), to produce a supply risk perspective for the resource availability requires each category indicator to be placed in relation to a target. This method is described in detail by the distance-to-target method by Frischknecht et al. (2008). The resulting impact factors (I) provide a threshold, above which high risk of supply disruption is expected. This was calculated for comparison for the 15 REE together with gold, copper, platinum group metals (PGM), iron ore and lithium (i) and each impact category (j). The ratio of current to critical flows is squared allowing large impact values (above the target value) to be weighted above proportional (Frischknecht and Büsser Knöpfel, 2013; Drielsma et al., 2014). The indicators are scaled from 0 to 1, with order being inverted when necessary to ensure high score corresponds to high risk. All values below the value of “1” are deemed uncritical and have no impacting score.

$$I_{i,j} = Max\left\{\left(\frac{indicator\ value_{i,j}}{threshold_{i,j}}\right)^2; 1\right\} \quad (1)$$

$$ESP_i = \prod_j (I_{i,j}) \quad (2)$$

The resulting economic scarcity potential score for each element which includes the impact categories from both supply risk and economic importance is a dimensionless quantity determined by the ratio of the current indicator value to the determined threshold linked to the LCI.

4. Results

The performance of individual REE compared to Au, Cu, PGM, Fe and Li has been calculated and highlighted in Fig. 4.

4.1. Reserve availability

The 15 REE included in the study had a lower score for reserve availability than Au, Cu, PGM, Fe and Li. These other metals had higher impact scores because of their high level of production relative to REE; being produced in thousands or millions of tonnes per annum compared to REE which have a total production of the 126,000 t in 2016. This, combined with the large reserves of REE, calculated as 120,000,000 (USGS, 2016) t based on their continued availability and typical metallurgical recoveries means the reserve availability of REE is higher than the other metals in the study leading to a low impact score. Of the REE, Y, Gd, Tb, Dy and Ho had the highest impact score whilst Ce and La had the lowest. These results can be explained by the fact that HREE

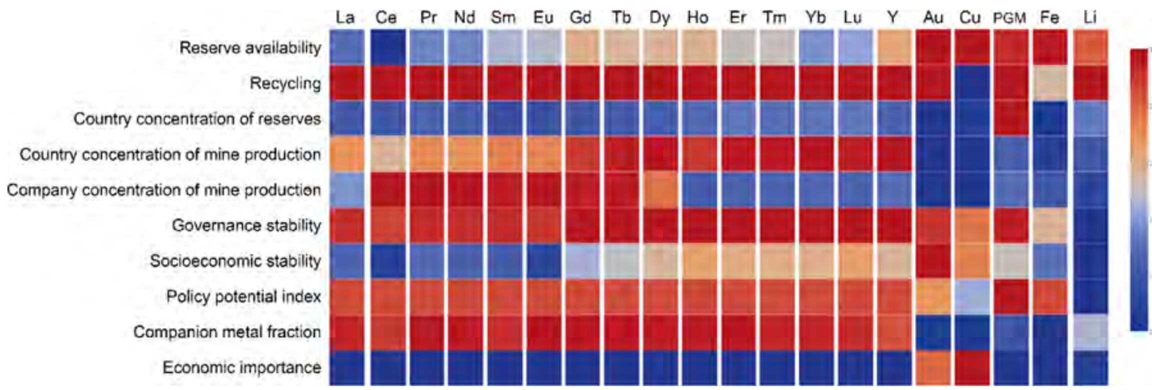

Fig. 4. Individual impact category scores for 10 categories. Data based on (Buijs et al., 2012; NRC, 2016; Graedel et al., 2015; Nassar et al., 2015; Angerer et al., 2009).

are less abundant in the earth's crust and also less abundant in REE deposits, whilst consumption of some of these elements remains relatively high, such as Dy and Tb in permanent magnets. Er, Tm, Yb and Lu are not abundant in deposits but are exploited at very low rates leading to a moderate impact score.

4.2. Recycling

More work needs to be carried out to quantify the rate of recycling of different REE because the published data used for the calculations in this study does not represent the quantity of recycled material reentering the system.

4.3. Country concentration of reserves

The country concentration of reserves impact score was high for PGM compared to the other raw material in this study. This is because of the dominance of South Africa in holding the reserves of PGM. In contrast reserves of Au, Cu and Fe appear the most widespread as they have the lowest score in this category. The REE had moderate scores in this area with slightly increasing impact scores of the HREE because of the dominance of China in holding much of the HREE reserves. The country concentration of reserves indicated that although the reserves of rare earths are relatively widespread, there is a high concentration of Sm and Eu in China, whilst Ho, Er, Tm, Yb and Lu in reserves is more geographically widespread.

4.4. Country concentration of production

The impact score for the country concentration of production was high for all REE compared to Au, Cu, PGM, Fe and Li owing to the dominance of REE production from China. The HREE had the highest impact score for this section. Li was highest scoring in this category for the non-REE.

4.5. Company concentration of mine production

The company concentration of mine production impact category displays the dominance of Northern Rare Earth (Group) High-Tech Co., Ltd, China even when put in in the context of other raw materials, with Ce, Pr, Nd, Sm, Eu, Gd, Tb having the highest scores for this section. The lower impact score for the LREE can be explained by production from Lovozerskiy GOK in Russia, Mount Weld in Australia and mineral sands in India, which are all LREE-enriched deposits.

4.6. Governance stability

The impact scores were high for the REE, with highest scores being seen with the HREE that are produced almost exclusively in China. Li had a low impact score in this category is explained by its production in Australia and Chile. PGM and Au had high scores in these categories highlighting that there are risks associated with the stability of governments in regions where these materials are mined.

4.7. Socioeconomic stability

Au was the highest scoring element, followed by Cu and then the Ce, Pr, Nd, Sm, Eu, Gd, Tb. The low socioeconomic stability of the countries producing Au are highlighted as well as the moderate socioeconomic score of China. For REE the lowest impact scores were Ce and Eu. This is owing to the combination of elevated levels of production of these elements from Mt Weld, Australia and Australia's higher performance in government stability and socioeconomic stability.

4.8. Policy potential index

The 15 REE studied had a high score for the policy potential index. However it is PGM that had the highest score in this category, whilst Fe had a similar score to the REE. The policy potential index impact score was the highest for Tb, whilst Ho had the lowest score. Many of the REE received moderate scores in this impact category indicating that there was only a small amount of variation in the impact scores for the REE.

4.9. Companion metal fraction

REE have a high risk associated with the fact that they are commonly exploited as a by-product of each other and of other raw materials (such as iron ore at Bayan Obo, China) among others. The other raw materials used in comparison had low impact scores in this category indicating that they are commonly extracted as the main component at a mine. The companion metal fraction impact scores were relatively similar to each other. Pr had the highest score whilst Y had the lowest.

4.10. Economic importance

In the economic importance category the REE have a low score. This category is dominated by Cu and to a lesser extent Au. These are the two raw materials that have the greatest economic importance during the raw material extraction phase. Of the REE, Nd had a markedly higher economic importance impact score than the other REE. This is owing to the use of Nd in NdFeB magnets, which are predicted to drive demand growth until 2022 (Roskill, 2016). Dy and Pr were calculated as having the next highest economic importance scores. All other REE have low economic importance scores.

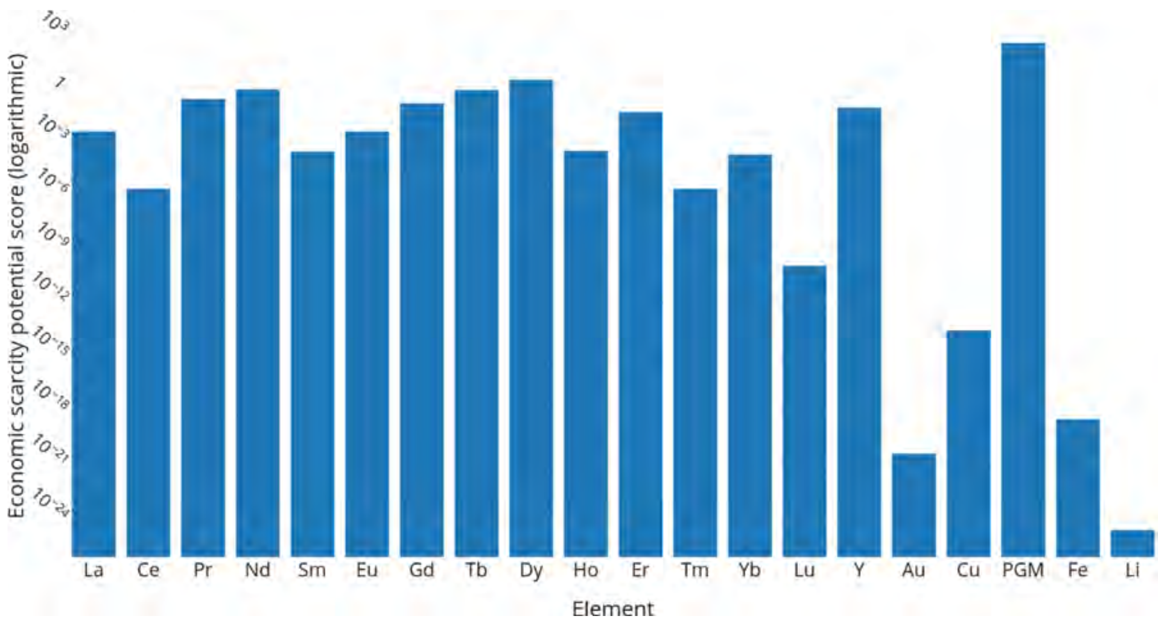

Fig. 5. Individual economic scarcity potential scores for 10 categories, each of which has equal weighting.

4.11. Overall ESP

The final ESP results are presented on a logarithmic scale to better display the relative performance of individual elements. The ESP scores displayed in Fig. 5 show how the REE compared to Au, Cu, PGM, Fe and Li. Giving equal weighting to each category and using the methodology described above resulted in PGM having the highest ESP score and so these elements are considered the most critical in this context. The factors driving the PGM score up are the high policy potential index score, the high governance stability score as well as a high country concentration of reserves. Dy scores second highest for ESP. It is interesting to note that as a greater number of raw materials are included in the study, the relative performance of elements can change, as in this case where Dy has overtaken Nd in terms of relative ESP score. This is because the economic importance was an important factor in driving Nd's ESP score up in the REE comparison, but as more raw materials are added with a greater economic importance, this distinction becomes less important. Nd is the next highest scoring element, followed by Tb, Pr, Gd and Y. Au, Cu, Fe and Li all have lower ESP scores than the REE.

The economic scarcity potential approach used in this study provides results that greater reflect the reality of resource availability until 2021 when compared to the abiotic depletion potential or surplus cost potential approach, which are more suited to understanding the long-term availability of resources. It considers socio-economic, regulatory and geopolitical aspects or functionalities such as material recycling or reuse in the calculations rather than geological availability. This is an area that is currently missing in the LCA approach but has an impact on low-carbon technology development and proliferation. Nd and Dy are the highest scoring REE using this approach, highlighting the need to broaden the supply chain for these two elements in particular, whilst Ce has a low economic scarcity potential score and is overproduced. New uses of Ce, which is cheap because of the oversupply, would help to even up requirement for REE and help supply of Nd and Dy.

A simplified calculation was used for economic importance, looking only at demand growth, production volume and value of material produced. Improvements could be made to this calculation. A novel empirical approach has been presented by Mayer and Gleich (2015) which looks at risk associated with future price increases of raw materials. The approach which uses a compounding framework to calculate net present values and volatility is a potential avenue to include under these calculations which may provide more realistic economic importance impact scores.

The method used in this study only looks at the impact categories associated with the mining and dissolution phase and fails to consider the larger production chain of final products which can be in a number of forms such as rare earth oxides, misch-metals or separated metals and transport. Future work could look at the different processing stages and see how this would alter the economic scarcity potential scores for different elements. Recent work has examined the role of primary processing (first post-mining stage) in the supply risk of critical metals (Nansai et al., 2017). Understanding the role of different processing stages in raw material availability is an important area of research, especially for REE production which has a long and complex production chain. Future work should cover all elements from the periodic table using the economic scarcity potential approach to calculate scores for the global economy for the short to medium term. Using improved economic importance calculations would make the approach a useful addition to the LCIA results. Annual updates on production would allow the method to be up to date and have practical use.

4.12. Adjusting the weighting of economic importance

Criticality studies are context dependent. The ESP results above use an equal weighting for each impact category. However, it is possible to adjust the level of an impact category or categories to represent a different context. Fig. 6 shows this with the blue bars indicating the results of the ESP scores with equal weighting for the impact factors. The orange bars calculate the ESP score by giving all the supply risk impact categories (reserve availability, recycling, country concentration of reserves, country concentration of mine production, company concentration of mine production, governance stability, socioeconomic stability, trade barriers to mine production, companion metal fraction) equal weighting and giving the economic importance impact category the same weighting as the combined supply risk impact categories.

The results indicate an increased ESP score for Au and Cu, which is the highest scoring element in this context, because of their high economic importance score. A small reduction in the ESP score for PGM, which is the second highest scoring element, and Li which has a small reduction in ESP score. Fe has a large decrease. The REE have a substantial decrease in their ESP score owing to their relatively low economic importance using the simple calculation in this study when compared to the other elements. Nd is highest scoring of the REE,

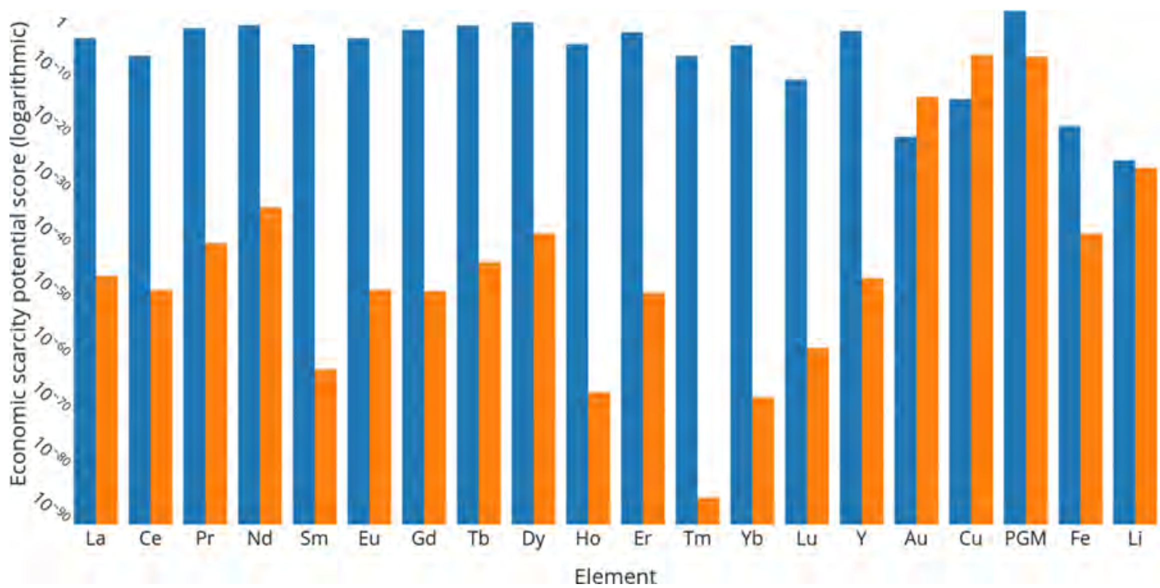

Fig. 6. Economic scarcity potential scores for calculated using 10 categories for each individual element. Blue bars are ESP scores with equal weighting for the impact factors. The orange bars calculate the ESP score by giving all the supply risk impact categories (reserve availability, recycling, country concentration of reserves, country concentration of mine production, company concentration of mine production, governance stability, socioeconomic stability, trade barriers to mine production, companion metal fraction) equal weighting and giving the economic importance impact category the same weighting as the combined supply risk impact categories.

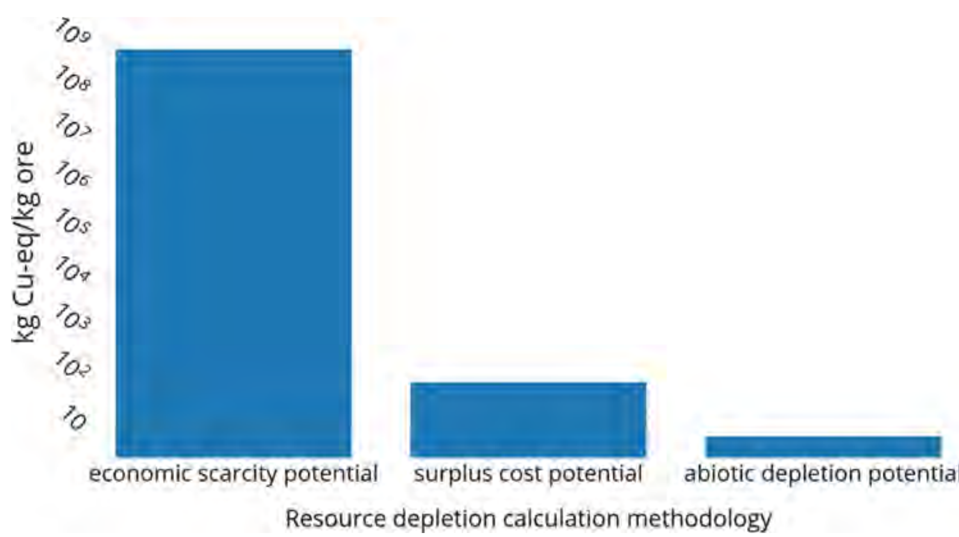

Fig. 7. Comparison of resource depletion calculation methodology on the results for the components of NdFeB magnet.

Table 2
Composition of virgin NdFeB magnet (Jin et al., 2016).

Element	Weight %
Fe	66.88
Nd	18.0
Dy	6.15
Pr	4.6
Cu	0.18

followed by Dy owing to their relative high economic importance compared to other REE.

Increasing the weighting of economic importance (Fig. 6) highlights the flexibility of criticality studies. For example, giving equal weighting Cu was considered one of the lowest scoring elements in comparison, but when economic importance was increased to 50% of the total ESP score it became the highest scoring element in the study. Criticality studies can be used to compare the relative levels of criticality of raw materials in different scenarios, but these need to be clearly defined. This study used a global spatial scale for the whole economy and used a medium term time scale, but it is possible to adjust the criteria for a number of scenarios. The weighting of the impact categories will be different depending on the context of the study. For example a study of the criticality of raw materials for the low-carbon economy, would give a higher economic importance to the raw materials used in the relevant technologies than has been given in this study. A valuable area of research would be to develop understanding of appropriate weighting for the impact categories under different scenarios. Understanding the importance of different processes of raw material availability would be a useful step in developing a robust method and would be important in its successful integration into the LCA approach.

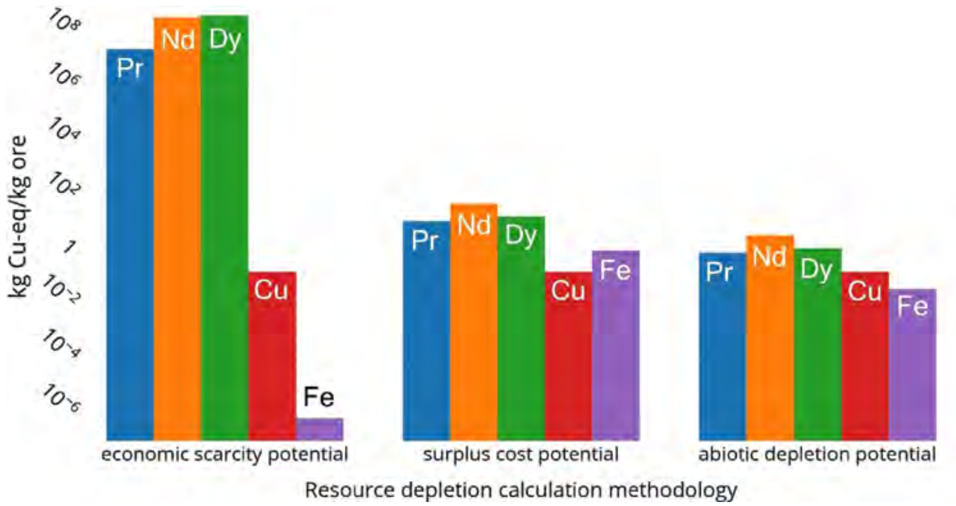

Fig. 8. Elemental contribution to resource depletion calculation scores for economic scarcity potential, surplus cost potential, and abiotic depletion potential for components of NdFeB magnet.

4.13. Integration into LCA

The scores of the individual elements will be calculated against the reference element of copper. Fig. 7 provides a simulation of resource depletion results using three different calculation methodologies (economic scarcity potential, surplus cost potential, abiotic depletion potential) with the example using a 1 kg NdFeB magnet. Simplified inventory data were used (Jin et al., 2016), and is shown in Table 2. A comparison of results is highlighted results using the abiotic depletion potential approach, the surplus cost potential approach and the economic scarcity potential approach.

The results show that there is an increased score (kg Cu-eq/kg ore for the economic scarcity potential calculation method. This is because the REE components, Pr, Nd and Dy have a high economic scarcity potential score as elements. Cu is the reference value for all methods which explains the equal score with each method. Fe has a lower score using the economic scarcity potential approach as it has been calculate to have low criticality. Fig. 8 highlights how the economic scarcity potential approach places greater emphasis on elements that have higher criticality scores and are more susceptible to supply disruption in the short to medium term. This information could prove useful in comparative LCA when examining the environmental performance of a product and process and provides and additional metric for which to compare. Such as scenario could exist when comparing the environmental performance of two mining operations. Results for environmental performance could be included alongside criticality data for a better comparison.

5. Conclusions

The ESP approach is particularly useful when trying to understand the availability of critical metals. This is important as they play a key role as raw materials for the low-carbon economy. This is important as they play a key role as raw materials for the low-carbon economy. This paper aimed to compare the performance of individual REE and put it in context with other raw materials. The results indicate that REE need to be considered as distinct elements with different criticality associated with each of them. For example Dy and Nd had the highest economic scarcity potential scores, whilst Lu and Ce had the lowest of the REE. One of the reasons for Ce having a low score is its overproduction. The excess availability and low criticality means that companies have an opportunity to find new uses for Ce. For example the Critical Materials Institute have developed aluminum-cerium alloys (Sims et al., 2016). The high scores for Nd and Dy are due to the increase in demand of NdFeB magnets in hybrid and electric vehicles until 2026 (Goodenough et al., 2017). Whilst projections for Sm, Tm and Lu suggest that growth and production volume will remain low, keeping the economic importance of these elements low. All REE have higher economic scarcity potential scores than Au, Cu, Fe and Li, whilst PGM had the highest score of all the elements included in the study. The high score for PGM was due to its concentration of reserves and production in South Africa, which has a low score in the governance stability and policy potential index. Although further work needs to be done and more elements need to be included in the method before its integration into LCIA results, this study provides a guideline for the approach.

A major challenge for this approach, as with all raw material studies is the availability of data. An inconsistent amount of data are available for the calculations of the economic scarcity potential impact categories. There is a lack of reliable production data for the REE, and this would also be the case for other raw materials. USGS and BGS are useful sources of data, and they are clear about the uncertainty of some production data. For example the high level of illegal mining in REE in China has been ignored (Rao, 2016).

The development of economic and supply risk indicators that can fit alongside or within LCA should be further explored and methods such as the approach shown here can be considered complimentary to other resource depletion methods currently employed.

Acknowledgements

Research was funded by NERC SoS RARE consortium (NE/M011429/1), www.sosrare.org with University of Exeter co-funding for R. Pell's PhD project. The authors appreciate the funding assistance from the Camborne School of Mines Trust to visit and present this research in USA and gain insight from the Critical Metals team from Yale University and Nedal Nassar and his team at USGS.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.resourpol.2018.10.003.

References

Achzet, B., Helbig, C., 2013. How to evaluate raw material supply risks – an overview. Resour. Policy 38, 435–447.

Angerer G., Erdmann L., Marscheider-Weidemann F., ScharpM, Lüllmann A., Handke V., Marwerde M., 2009a. Rohstoffe für Zukunftstechnologien. ISI-Schriftenreihe Innovationspotenziale. Fraunhofer IRB Verlag, Stuttgart.

Arshi, P.S., Vahidi, E., & Zhao, F., 2018. Behind the Scenes of Clean Energy: The Environmental Footprint of Rare Earth Products, http://doi.org/10.1021/acssuschemeng.7b03484.

BGS World Mineral Statistics, 2015. British Geological Survey, ⟨http://www.bgs.ac.uk/mineralsuk/statistics/risklist.html⟩.

Binnemans, K., Jones, P.T., 2015. Rare earths and the balance problem. J. Sustain. Metall. 1 (1), 29–38.

Buijs, B., Sievers, H., Tercero Espinoza, L.A., 2012. Limits to the critical raw materials approach. In: Proceedings of the ICEe Waste and Resource Management, pp. 201–208.

Coulomb, R., Dietz, S., Godunova, M., Bliggard Nielson, T., 2015. Critical minerals today and in 2030: an analysis of OECD countries, ESRC Centre for Climate Change Economics and Policy, Grantham Research Institute on Climate Change and the Environment.

Drielsma, J., Russell-Vaccari, A., Drnek, T., Brady, T., Weihed, P., Mistry, M., Perez Simbor, L., 2016. Mineral resources in life cycle impact assessment – defining the path forward. Int. J. Life Cycle Assess. 21, 85–105.

Du, X., Graedel, T.E., 2011. Global in-use stocks of the rare earth elements: a first estimate. Environ. Sci. Technol. 4096–4101.

Erdmann, L., Graedel, T.E., 2011. Criticality of non-fuel minerals: a review of major approaches and analyses. Environ. Sci. Technol. 45 (18), 7620–7630.

Fava, J.A., Consoh, F., Demson, R., Dickson, K., Mohin, T., Vigon, B., 1993. A Conceptual Framework for Life Cycle Impact Assessment. Society for Environmental Toxicology and Chemistry, Pensacola.

Finnveden, G., 1997. Valuation methods within LCA – where are the values? Int. J. Life Cycle Assess. 2, 163–169.

Finnveden, G., 2005. The resource debate needs to continue. Int. J. Life Cycle Assess. 10 (5), 372.

Fishman, T., Myers, R., Rios, O., Graedel, T.E., 2018. Implications of Emerging Vehicle Technologies on Rare Earth Supply and Demand in the United States. Resources 7.

Frenzel, J., Kullik, J., Reuter, M.A., Gutzmer, J., 2017. Raw material 'criticality' – sense or nonsense? J. Phys. D: Appl. Phys. 50, 123002.

Frischknecht, R., Büsser Knöpfel, S., 2013. Swiss Eco-Factors 2013 According to the Ecological Scarcity Method. Methodological Fundamentals and Their Application in Switzerland. Federal Office for the Environment, Bern, pp. 254 Environmental studies no. 1330.

Glöser, S., Tercero Espinoza, L., Grandenberger, C., Faulstich, M., 2015. Raw material criticality in the context of classical risk assessment. Resour. Policy 44, 35–46.

Goodenough, K.M., Wall, F., Merriman, D., 2017. The rare earth elements: demand, Global resources, and challenges for resourcing future generations. Nat. Resour. Res. 1–16. https://doi.org/10.1007/s11053-017-9336-5.

Graedel, T.E., Harper, E.M., Nassar, N.T., Nuss, P., Reck, B., K., 2015. Criticality of the metals and metalloids. PNAS 112 (14), 4257–4262. https://doi.org/10.1073/pnas.1500415112.

Graedel, T.E., Barr, R., Chandler, C., Chase, T., Choi, T., Christofferson, L., Friedlander, E., Henly, C., Jun, C., Nassar, N.T., Schechner, D., Warrne, S., Yang, M., Zhu, C., 2012. Methodology of metal criticality determination. Environ. Sci. Technol. 46, 1063–1070.

Haque, N., Hughes, A., Lim, S., Vernon, C., 2014. Rare Earth Elements: Overview of Mining, Mineralogy, Uses, Sustainability and Environmental Impact. Resources 3 (4), 614–635.

Helbig, C., Wietschel, L., Thorenz, A., Tuma, A., 2016. How to evaluate raw material vulnerability—an overview. Resour. Policy 48, 13–24.

Huijbregts, M.A.J., Steinmann, Z.J.N., Elshout, P.M.F., Stam, G., Verones, F., Vieira, M.D.M., Hollander, A., Zijp, M., van Zelm, R., 2016. ReCiPe 2016: A harmonized life cycle impact assessment method at midpoint and endpoint level Report I: Characterization, RIVM Report 2016–0104,

Jin, H., Afiuny, P., McIntyre, T., Yih, Y., Sutherland, J.W., 2016. Comparative life cycle assessment of NdFeB magnets: virging production versus magnet-to-magnet recycling. In: Proceedings of the 23rd CIRP Conference on Life Cycle Engineering, 48, pp. 45–50.

Koltun, P., Tharumarajah, A., 2014. Life Cycle Impact of Rare Earth Elements. ISRN Metallurgy 1–10. https://doi.org/10.1155/2014/907536.

Li, X., Chen, Z., Chen, Z., Zhang, Y., 2013. A human health risk assessment of rare earth elements in soil and vegetables from a mining area in Fujian Province, Southeast China. Chemosphere 93 (6), 1240–1246.

Mancheri, N., 2015. World trade in rare earths, Chinese export restrictions, and implications. Resour. Policy 46, 262–271.

Mayer, H., Gleich, B., 2015. Measuring criticality of raw materials: an empirical pproach assessing the supply risk dimension of commodity criticality. Nat. Resour. 6, 56–78.

Moss, R.L., 2013. Critical Metals in the Path Towards the Decarbonisation of the EU Energy Sector. Publications Office of the EU, Luxembourg.

Nansai, K., Nakajima, K., Suh, S., Kagawa, S., Kondo, Y., Takayanagi, W., 2017. The role of primary processing in the supply risk of critical metals. Econ. Syst. Res. 1–22.

Nassar, N.T., Du, X., Graedel, T.E., 2015. Criticality of the rare earth elements. J. Ind. Ecol. 19 (6). https://doi.org/10.1111/jiec.12237.

National Research Council, 2008. Minerals, Critical Minerals, and the U.S. Economy. National Academies Press, Washington, DC.

Rao, Z., 2016. Consolidating policies on Chinese rare earth resources. Min. Econ. 29 (1), 23–28.

Rim, K.T., 2016. Effects of rare earth elements on the environment and human health: a literature review. Toxicol. Environ. Health Sci. 8 (3), 189–200.

Roskill, 2016. Rare Earths: Global Industry, Markets and Outlook, 16th ed. Roskill, London, UK.

Schneider, L., Berger, M., Schüler-hainsch, E., Knöfel, S., Ruhland, K., Mosig, J., Finkbeiner, M., 2014. The economic resource scarcity potential (ESP) for evaluating resource use based on life cycle assessment. Int. J. Life Cycle Assess. 601–610. https://doi.org/10.1007/s11367-013-0666-1.

Sonnemann, G., Gemechu, E.D., Adibi, N., De Bruille, V., Bulle, C., 2015. From a critical review to a conceptual framework for integrating the criticality of resources into life cycle sustainability assessment. J. Clean. Prod. 94, 20–34.

Sprecher, B., Daigo, I., Murakami, S., Kleijn, R., Vos, M., & Kramer, G.J., 2015. Framework for Resilience in Material Supply Chains, With a Case Study from the 2010 Rare Earth Crisis, http://doi.org/10.1021/acs.est.5b00206.

Tilton, J.E., Skinner, B.J., 1987. The meaning of resources. In: Skinner, B.J., McLaren, D.J. (Eds.), Resources and World Development. Wiley, New York, pp. 13–27.

Udo de Haes, H.A., Jolliet, O., Finnveden, G., Hauschild, M., Krewitt, W., Müller- Wenk, R., 1999. Best available practice regarding impact categories and category indicators in life cycle impact assessment. Int. J. Life Cycle Assess. 4, 167–174.

USGS Mineral commodity summaries. U.S. Geological Survey, Department of the Interior, Reston, **2016** ⟨https://minerals.usgs.gov/minerals/pubs/commodity/rare_earths/⟩.

Van Oers, L., Guinée, J., 2016. The abiotic depletion potential: background, updates, and future. Resources 5 (1), 16. https://doi.org/10.3390/resources5010016.

Vieira, M.D.M., Ponsioen, T.C., Goedkoop, M., Huijbregts, M.A.J., 2016. Surplus cost potential as a life cycle impact indicator for metal extraction. Resources 5, 1–12.

Zaimes, G.G., Hubler, B.J., Wang, S., Khanna, V., 2015. Environmental Life Cycle Perspective on Rare Earth Oxide Production. ACS Sustain. Chem. Eng. 3, 237–244. https://doi.org/10.1021/sc500573b.

Further reading

NSTC, 2016. Assessment of Critical Minerals: Screening Methodology and Initial Application; Subcommittee on Critical and Strategic Mineral Supply Chains of the Committee on Environment, Natural Resources, and Sustainability of the National Science and Technology Council; Executive Office of the President, National Science and Technology Council (NSTC).