Short and long-term mineral resource scarcity impacts for a car manufacturer: The case of electric traction motors

Journal of Cleaner Production 361 (2022) 132140

Contents lists available at ScienceDirect

Journal of Cleaner Production

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

Short and long-term mineral resource scarcity impacts for a car manufacturer: The case of electric traction motors

Hampus André [a,b,*], Maria Ljunggren [a]

[a] Division of Environmental Systems Analysis, Chalmers University of Technology, Vera Sandbergs Allé 8, 412 96, Gothenburg, Sweden

[b] Department of Sustainable Development, Environmental Science and Engineering (SEED), KTH Royal Institute of Technology, Teknikringen 10B, 100 44 Stockholm, Sweden

ARTICLE INFO

Handling Editor: Mingzhou Jin

Keywords:
Resource scarcity
Mineral resource depletion
Mineral resource criticality
Electric vehicle
Permanent magnet electric traction motor
Rare earth elements

ABSTRACT

The importance of metals for modern society and future trends puts pressure on companies to handle issues concerning potential mineral resource scarcity (i.e. deficiency in quantity compared with demand). Companies see the need to handle such potential scarcity both in the short-term (is the availability constrained for our current products?) and the long-term (is our current use affecting the availability for future generations?). This study aims to examine the use of complementary methods for short and long-term scarcity in a company context, through a case study on permanent magnet electric traction motors, to provide both empirical and methodological insights. To mitigate long-term scarcity impacts, the results point to copper, neodymium and to some extent dysprosium as priority. These metals contribute to a large share of such impacts both due to themselves and their companion metals. In the short-term, neodymium and dysprosium, which are often regarded as critical (i.e. high supply disruption probability and high vulnerability to supply disruption), were found to be substitutable in the electric motor, reducing their criticality. Instead, the electric motor was most vulnerable to a potential supply disruption of iron and silicon because of no or low substitutability in electrical steel. Methodologically, these perhaps unexpected results, demonstrate that criticality requires a more context-specific assessment than often applied, especially regarding substitutability. By using complementary methods, decision-making about potential mineral resource scarcity impacts in company contexts could become more comprehensive and distinctly address both short and long-term scarcity impacts.

1. Introduction

In recent years, there has been growing attention to different types of impacts related to the sustainability of mineral resource use. Mineral resources can be scarce, meaning deficient in quantity compared with the demand, both in the short and long term.[1] Issues also include social impacts related to e.g. labor conditions and conflict, as well as environmental impacts of extraction and material production (e.g. Young et al., 2014). The diversity of mineral resources used in modern products and their global supply chains pose challenges for product manufacturers wishing to take responsibility for such impacts and minimize risks of supply disruption. Thus, there is a need for methods which could complement each other to address different types of questions related to mineral resource use in a comprehensive way (Dewulf et al., 2015; Mancini et al., 2015; Sonnemann et al., 2015). In terms of mineral resource scarcity, specifically, it has been suggested that life cycle assessment (LCA) could be used to assess depletion impacts from product systems, potentially causing scarcity for future generations, while criticality assessment (CA) and supply disruption probability (SDP) methods e.g. (Bach et al., 2016; Cimprich et al., 2017) could be

* Corresponding author. Division of Environmental Systems Analysis, Chalmers University of Technology, Vera Sandbergs Allé 8, 412 96, Gothenburg, Sweden.
E-mail address: hamand@kth.se (H. André).

[1] The term “scarce” is defined as “deficient in quantity or number compared with the demand” (Merriam-Webster, n.d.). In other words, scarcity is an economic concept denoting a situation where demand exceeds supply.

https://doi.org/10.1016/j.jclepro.2022.132140
Received 20 March 2021; Received in revised form 5 May 2022; Accepted 5 May 2022
Available online 17 May 2022

used to address scarcity issues in the short-term for product systems or companies (Berger et al., 2020; Cimprich et al., 2019; Dewulf et al., 2015).[2]

However, it is not well understood how such methodologies can actually complement each other to compose a comprehensive assessment of mineral resource scarcity as suggested. In fact, the terms depletion and criticality are often confused, both in industry and academia. Berger et al. (2020) report that methods to assess depletion impacts (i.e. potential scarcity in long term for future generations) are mistakenly used by practitioners to assess criticality (i.e. vulnerability to potential scarcity in the short or medium-term for a system under study e.g. company or nation). In addition, Arvidsson et al. (2020) highlight examples where LCIA-methods yield results which are counterintuitive or unreasonable with respect to long-term scarcity. André and Ljunggren (2021) indicate that such methodological confusions and counterintuitive results may be rooted in unintended similarities between life cycle impact assessment (LCIA) methods, CA and SDP methods. In other words, such methods may not be as complementary as they could be.

André and Ljunggren (2021) clarify terminology and methodological features in the context of mineral resource scarcity.[3] Furthermore, they outline how methods and methodologies could be constructed if they are to be individually purposive and mutually complementary. In the long-term, which is often the focus in LCIA-methods, potential scarcity for future generations is most purposively addressed by focusing on depletion of stocks in the ecosphere (i.e. natural systems). In the short-term, potential scarcity for nations, industries and companies, which is the focus of CA and SDP methods, is most purposively addressed by focusing on circumstances within the technosphere (i.e. intentionally man-made systems) e.g. supply concentration and political stability in producing countries (André and Ljunggren, 2021).[4]

The aim of this study is to examine the use of potentially complementary methods in a company-context. More specifically, the study examines what conclusions can be drawn about long and short-term mineral resource scarcity from the perspective of a company. There is an abundance of studies on the criticality of metals, but they are almost exclusively conducted from the perspectives of technologies, sectors, nations and supranational regions (Schrijvers et al., 2020). Company perspectives, on the other hand, are rare in the criticality literature (Gaustad et al., 2018; Lapko et al., 2016; Lloyd et al., 2012a; Lloyd et al., 2012b). Moreover, studies assessing both long and short-term scarcity impacts in close collaboration with a company are, to our knowledge, non-existent. To address these research gaps, a case study was set up in collaboration with a Swedish car manufacturer, Volvo Cars Corporation (VCC). Since rare earth elements have been pointed out as an area of potential concern for the automotive industry and deemed critical in many industry, national and supranational studies (EC, 2014; 2017; Hatayama and Tahara, 2015; Knobloch et al., 2018) the case study addresses electric traction motors using permanent magnets containing rare earth elements (REEs). In addition, it has been stressed that there is a need to study EVs in terms of both short and long term scarcity (Dolganova et al., 2020). A secondary aim of the study is thus to assess long and short-term scarcity impacts associated to this specific component from the perspective of a company – a matter of significant empirical importance in itself.

2. Method

2.1. Study procedure

The study was conducted in collaboration with VCC in a series of workshops (see SI). Most of the collaboration revolved around the criticality assessment, since it required expert inputs from sustainability managers and product designers from VCC.

2.2. Choice of component

A Neodymium(Dysprosium)-Iron–Boron (Nd(Dy)FeB) permanent magnet synchronous machine (PMSM) used in one of the company's battery EVs was chosen for the study. There is a general interest in mitigating different types of sustainability impacts related to electric traction motors due to the expected large-scale diffusion of EVs. In particular, concerns have been raised regarding the potential environmental and social impacts (Widmer et al., 2015) and supply security (EC, 2017) of rare earth elements. For such reasons, the component was of particular interest to VCC since they aim to shift to electric drivetrains while mitigating environmental, social and resource scarcity impacts.

2.3. Goal and scope

Specifically, the study focuses on a PMSM used in a BEV, model XC40, produced by VCC. The inventory data is based on a scalable life cycle inventory (LCI) model for permanent magnet electric traction motors from cradle to gate (Nordelöf et al., 2017; Nordelöf and Tillman, 2018). In other words, use and post-use phases are outside the system boundary. The functional unit (FU) for the LCA is a complete PMSM (with a specified maximum power of 150 kW and specified maximum torque of 350 Nm) to be used for BEV propulsion, see Table 1.

Mining is a typical example of what LCA terminology refers to as multi-output processes. Impacts of such processes need to be allocated to the respective outputs (further explained in the Supplementary information (SI)). In this study, the cut-off system model of the Ecoinvent database is used (Wernet et al., 2016). The cut-off system model implies that environmental impacts of secondary inputs are allocated to their first use and are thus available to subsequent uses free from impact. This explains why the mass of resources consisting of considerable shares of recycled metal (e.g. copper) can be significantly lower in the LCI compared to the mass in the component as presented in the bill-of-materials (BOM) (see Table 1), as also discussed by Berger et al. (2020). Further, some of the resources used in the PMSM are co-mined alongside other resources, as main-, co- or by-products. In this study, allocation factors for mining processes are based on economic revenue. This reflects that economic interest is what drives mining and hence its environmental impacts (Althaus and Classen, 2004; Ekvall and Tillman, 1997). This implies that allocation factors depend on concentrations and economic revenue of outputs.

CA and SDP methods are generally applied to the resources in actual use, disregarding any resources extracted but lost in extraction and production. Thus, these methods are applied to the BOM generated by

[2] SDP methods are generally called "supply risk methods" in the literature (Berger et al., 2020). In light of points by Glöser et al. (2015), it is however debatable whether they actually assess supply risk, since the term "risk" generally is defined as the product of probability and consequence. Thus, "supply risk" is synonymous to criticality (supply risk = probability of supply disruption * consequence of supply disruption = criticality). SDP methods generally focus on probability of supply disruption and incorporate its consequence to lesser extent. Nevertheless, the term supply risk is used in this manuscript to denote that SDP and CA methods assess issues related to supply risk.

[3] As already described, scarcity can be a concern in several time frames. As clarified by André and Ljunggren (2021) the term criticality most often refers to the vulnerability of a studied system to potential scarcity in short or medium-term perspectives. The term depletion refers to the physical withdrawal of resources from the ecosphere, leaving less resources in the ecosphere for future generations (since resources can be extracted also from within the technosphere, depletion alone does not give the full picture of resource availability for future generations).

[4] For a further elaboration on the complementary nature of, and distinction between, methods focusing on technospheric (often referred to as the opportunity cost approach) and ecospheric aspects (often referred to as the fixed stock approach) of mineral resource scarcity, the reader is referred to André (2020).

Table 1
Mass, subcomponent and potential primary substitutes of resources contained in the PMSM. Notes: underline signifies the potential primary substitutes included in the calculations and, hence, the results. Abbreviations: SmCo=Samarium Cobolt; FeSr=Iron Strontium (ferrite). Boron and silicon lack elementary flows in Ecoinvent.

Resources in component	*Elementary flows [kg] (LCI)*	*Mass in subcomponent [kg] (BOM)*	Present in subcomponent	Potential primary substitutes identified
Aluminium	4.7	16	Housing body	Steel
		5.0	Endbells	Steel
Boron	N/A	0.02	Permanent magnets	SmCo and FeSr magnets
Copper	4.4	6.1	Magnet windings	Aluminium
Dysprosium	0.004	0.1	Permanent magnets	Safety system[a], SmCo and FeSr magnets, Other motor types[a]
Neodymium	0.3	0.74	Permanent magnets	SmCo and FeSr magnets, Other motor types[a]
Iron	65	30	Core laminations	No substitute available
		3.3	Shaft	Titanium Aluminum Brass Ceramics
		1.7	Permanent magnet	Other motor types[a]
Nickel	0.2	0.02	Permanent magnets (coating)	Epoxy
Silicon	N/A	0.6	Core laminations	Nickel and cobalt
Zinc	0.8	0.01	Fasteners and plates (galvanization)	Chromates aluminium-silicon coating
Total		64		
Co-mined resources (i.e. not present in component but visible in LCIA-results)				
Cerium	2.0	N/A		
Gold	0.00028	N/A		
Lead	0.5	N/A		
Molybdenum	0.06	N/A		
Rhodium	0,0000038	N/A		
Silver	0.002	N/A		
Other REEs	0.67	N/A		

[a] Due to data availability, only magnet-level substitutions were considered, excluding motor-level substitutions.

the scalable LCI model of the complete component.

2.4. Choice of LCIA, SDP and CA methods

The choice of complementary methods was based partly on the work conducted by the Life Cycle Initiative's task force on mineral resources, hosted by the UN Environment Programme (LCI-UNEP) (Berger et al., 2020; Sonderegger et al., 2020), and partly on the review of LCIA, SDP and CA methods conducted by André and Ljunggren (2021). Here follow brief descriptions of each method type and the respective methods chosen to represent each method type. For further information on the choice of methods, the reader is referred to the SI.

Depletion LCIA-methods reflect the potential of current product systems to deplete ecospheric stocks and cause potential scarcity in the long-term future. The Crustal Scarcity Indicator (CSI) was chosen since it has been argued to best reflect impacts on potential long term scarcity (André and Ljunggren, 2021; Arvidsson et al., 2020). The main advantage of the CSI over the ADP (recommended by Berger et al. (2020)) lies in the fact that its characterization factors (CFs) are based solely on one ecospheric factor reflecting rarity in the ecosphere, namely average crustal concentrations. It is thus free from temporally variable factors such as extraction rates, reserves and prices which may distort LCA results on long-term depletion impacts (Arvidsson et al., 2020).

Future efforts LCIA-methods include what is reflected by depletion methods, i.e. potential scarcity in the long-term, and add potential consequences of scarcity in terms of substitution to lower grade ores and associated increased costs. The Surplus Ore Potential (SOP) based on ultimately recoverable resources (Vieira, 2018) was chosen as a representation of future efforts methods (as also recommended by Berger et al. (2020)). The SOP reflects that an effect of the depletion and consequent scarcity of high grades ores is substitution to lower grade ores (André and Ljunggren, 2021).

SDP methods reflect the potential of technospheric circumstances to disrupt supply in the short-term and thereby cause scarcity for systems under study, such as companies and products. The ESSENZ method was chosen (as also recommended by Berger et al. (2020)). It covers 11 socioeconomic availability (i.e. technospheric) constraints which could cause supply disruption, namely: concentration of reserves, concentration of production, company concentration, mining capacity, feasibility of exploration projects, occurrence as co-product, trade barriers, political stability, demand growth, primary material use and price fluctuation. It is based on a distance-to-target approach where CFs are based on current situations (last updated 2019 (ESSENZ method)) for each resource in relation to acceptable levels set by expert or stakeholder surveys (Bach et al., 2016).

CA methods include what is reflected by SDP methods, i.e. potential scarcity in the short-term, and add potential consequences of scarcity in terms of substitution to other resources and associated increased costs. As a CA method, the company-level version of the Yale method (Graedel et al., 2012) was chosen. Only a few other company-level CA methods exist (e.g. (Duclos et al., 2010; Griffin et al., 2019). The Yale method was chosen because of its transparent methodology.

2.5. Adaptations to the Yale method

Some adaptations to the company-level version of the Yale methodology were required to make it applicable in this study. The method has a 5–10 year scope and consists of three dimensions: *supply risk*, *vulnerability to supply restriction* and *environmental implications*. Since it is debatable to what extent environmental implications are relevant to criticality (Dewulf et al., 2016; Graedel and Reck, 2016) this dimension was excluded in our adaptation of the methodology (Table 2).[5] Furthermore, since we study criticality on a component-level, some adaptations to the vulnerability dimension were required.

[5] Environmental impacts are however included as a part of substitutability, in the form of *environmental impact ratio* between potentially critical materials and potential substitutes, where they represent potential constraints to substitutability rather than a dimension of criticality.

Table 2
Data sources used for criticality assessment using the Yale method (Graedel et al., 2012). The abbreviations are as follows: DT = depletion time; CMF = companion metal fraction; PPI = policy potential index; HDI = human development index; WGI-PV = worldwide governance indicators - political stability and absence of violence/terrorism; GSC = global supply concentration; SR = supply risk; RI = percentage of revenue impacted; PT = ability to pass through cost increases; CS = importance to corporate strategy; SP = substitute performance; SA = substitute availability; ER = environmental impact ratio; PR = price ratio; AI = ability to innovate; VSR = vulnerability to supply restriction.

Dimension	Supply disruption probability						Vulnerability to supply disruption							
Category	Geological, technological and economic		Social and regulatory		Geopolitical		Importance			Substitutability				Ability to innovate
Criticality factor	DT	CMF	PPI	HDI	WGI-PV	GSC	RI	PT	CS	SP	SA	ER	PR	CI
Data source	USGS (2019)	Graedel et al. (2012); Nassar et al. (2012)	Stedman and Green (2019)	UNDP (2019)	Kaufmann and Kraay (2019)	USGS (2019)	VCC (2020)	VCC (2020)	VCC (2020)	VCC (2020)	Graedel et al. (2012)	Huijbregts et al. (2016)	London Metal Exchange (2020); Nordelöf et al. (2019); USGS (2019)	VCC (2020)

Vulnerability in the Yale method includes Substitutability (see Table 2) based on direct elemental substitution (Graedel et al., 2012). In line with Habib and Wenzel (2016) we address component-level substitutability from the perspective of a product design tree. In addition to element-level substitutions, it also includes magnet (sub-component-level) and electrical motor level (component-level) substitutions. This is motivated by the fact that such higher system-level subsitutions may be the "primary substitute" (Table 1), i.e. the one which will most likely be resorted to in case of a supply disruption (Graedel et al., 2012). Ideally, the *environmental impact ratio* and *price ratio* of substitution (Table 2) would be calculated at the respective substitution levels: e.g. the environmental impacts and costs of producing the same function as the current PMSM using another magnet or motor. Nevertheless, since such alternative designs are the focus of ongoing research and development (VCC, 2020), such data is not yet available. Thus, they were calculated based on the production of the respective amounts of elements in accordance with the Yale method (Graedel et al., 2012) using compositions data reported by Nordelöf et al. (2019) (see SI for equations).

Adaptations of the Yale method were also required regarding the factors related to the subcategory "Importance" (Table 2), namely: *percent of revenue impacted (RI), ability to pass-through cost increases (PT)* and the company's *ability to innovate (CI)*. These factors differentiate the metals' importance based on the products they are used in, and in turn, the importance of those products to the company as a whole. The component level of our assessment implies that in case of a supply disruption of any resource in the component, EVs cannot be produced (disregarding possibilities for substitution since this is reflected by its own factor). Therefore, on a component level, it is not possible to differentiate between resources in terms of the Importance factors: RI, PT and CS. Rather, it is EVs that are e.g. important to corporate strategy and impact revenue if not produced. If EVs cannot be produced, it is obviously impossible to pass through cost increases. With regards to *corporate innovation* however, it is possible to differentiate the company's ability to innovate on a subcomponent level, but such results are omitted from the article due to confidentiality. In other words, the results do not include the company's ability to innovate. Based on these adaptations, two versions of the vulnerability dimension are presented, including:

A) Substitutability. This version yields results which combined with the supply disruption probability dimension[6] reflect the criticality of resources for the PMSM.
B) Substitutability and Importance. This version yields results which combined with the supply disruption probability axis reflect both the criticality of resources for the PMSM and the importance of EVs for the company.

3. Results and analysis

3.1. Long-term scarcity impacts

To a large extent, the same resources are responsible for the contributions to mineral resource depletion impacts according to both LCIA-methods, namely, cerium, copper, dysprosium, molybdenum and neodymium (Fig. 1). Of these resources, copper, dysprosium and neodymium are in the PMSM while the others appear due to co-production. For instance, molybdenum is a by-product of copper production and cerium is co-produced with dysprosium and neodymium. Other resources that do not appear in the PMSM are e.g. gold, lead, silver and rhodium.

Copper contributes most to mineral resource depletion impacts with

[6] In line with the points made by Glöser et al. (2015) accounted for in the first footnote, we refer to the "supply risk" dimension as supply disruption probability dimension.

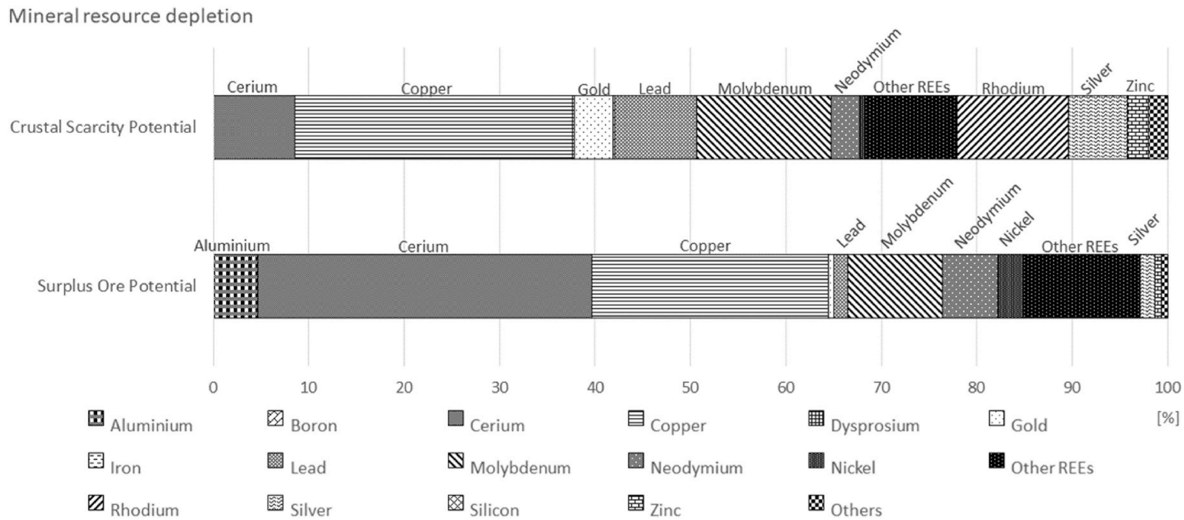

Fig. 1. Relative contribution of mineral resources to mineral resource depletion impacts using LCIA methods Crustal scarcity indicator and Surplus ore potential. Note: cadmium and indium are excluded since their contributions arise due to overestimations in various Ecoinvent processes, and are therefore not linked to the PMSM (Nordelöf et al., 2019). In absolute terms, the PMSM accounts for 151 992 kg Si-equivalents/functional unit (CSI) and 261 kg Cu-equivalents/functional unit (SOP).

CSI (29%) and second most with SOP (25%). Geologically, copper is quite rare in terms of average crustal concentrations but does occur in deposits at high concentrations (Peiró et al., 2013). The impact with CSI is explained by the former characteristic and the impact with SOP by the latter, namely, that future extraction is expected to require increased amounts of ore as a consequence of the depletion of copper in deposits at high concentrations. Furthermore, the use of copper in the PMSM does not only contribute to depletion impacts of copper, but also of molybdenum, gold, silver, zinc, lead and platinum group metals. Molybdenum is commonly produced as a by-product of copper from sulfide ore, while

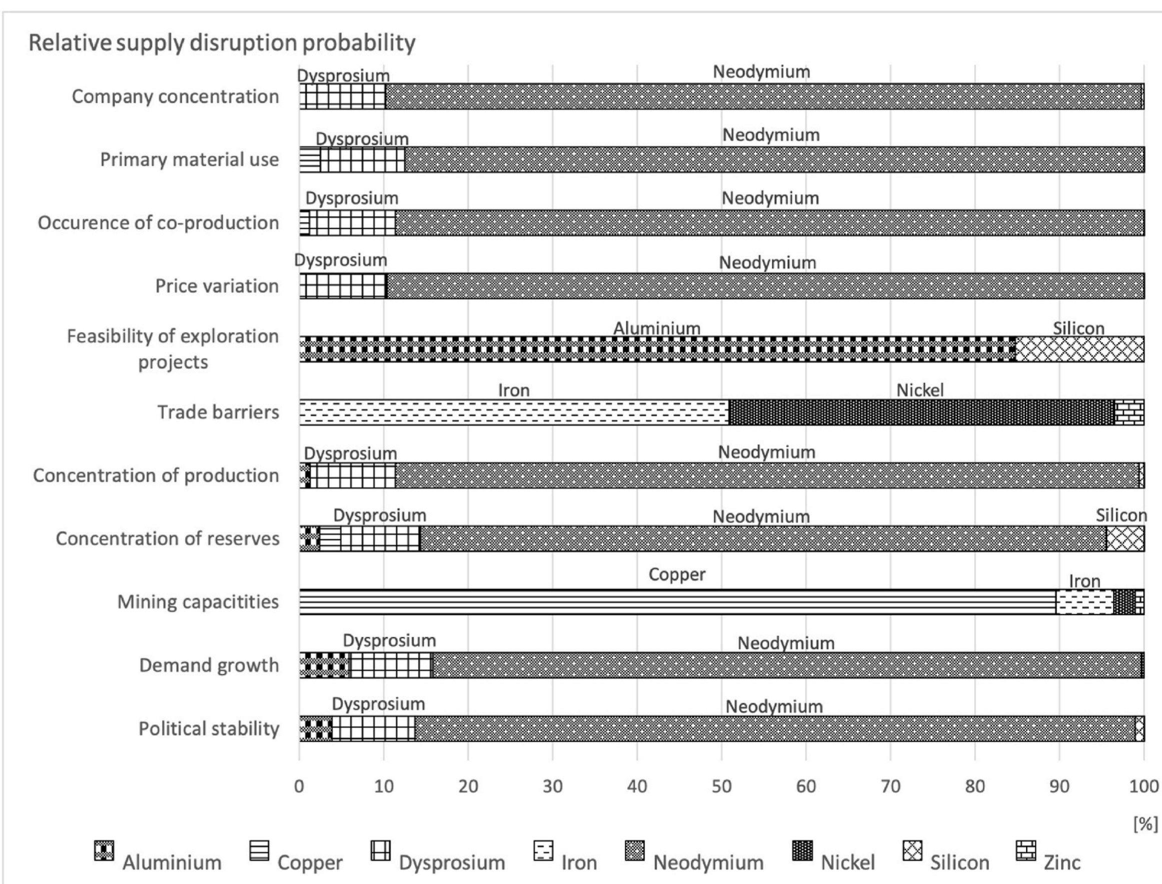

Fig. 2. Relative contribution of mineral resources to supply disruption probability in terms of eleven socioeconomic availability constraints according to the ESSENZ method. Note: Boron has no CF and is therefore not displayed in the results.

gold, rhodium, zinc, lead and silver are co-mined with copper. Although less than a milligram of rhodium is extracted because of the copper needed for the PMSM, the high CSP results in rhodium contributing 11% of the total impact.

Cerium, copper, dysprosium, molybdenum and neodymium account for 64 and 88% of the total contribution with CSI and SOP, respectively. Mostly, this difference relates to REEs, which account for 21 and 53% of the total contribution, respectively. One reason for this difference is that SOPs (surplus ore potentials, i.e. CFs of the SOP method) have a lower distribution compared to CSPs (crustal scarcity potentials, i.e. CFs of the CSI method), likely because SOPs are based on extrapolation from concentrations of cumulatively extracted ores. Since many rare resources occur in deposits at way higher concentrations than their average crustal concentrations (Ayres and Peiró, 2013; Peiró et al., 2013) and these deposits tend to be preferentially extracted, concentrations of cumulatively extracted resources (and consequently SOPs) are reasonably more similar than their average crustal concentrations (CSPs). Another reason for this difference is that REEs are given the same SOPs, whereas each individual REE has a unique CSP. Because REEs account for a large share of total mineral resource depletion impacts of PMSMs, this difference has a large influence on the results. The reason why cerium contributes most of the REEs is because it has a much higher concentration in bastnäsite than other REEs.

3.2. Short-term scarcity impacts

3.2.1. Supply disruption probability method

Supply disruption probability is calculated based on the BOM (see Table 1). Neodymium is clearly the resource with the highest supply disruption probability according to the ESSENZ method (see Fig. 2). It accounts for more than 80% of the total relative supply disruption probability for 8 out of 11 socioeconomic availability constraints. Its high supply disruption probability is due to the production being largely concentrated in terms of companies and nations (USGS, 2019). Reserves are also quite concentrated to a few nations but to a lesser extent than production (USGS, 2019). Neodymium also has high price volatility, growing demand and governance issues in production (low WGI scores) (Golev et al., 2014; Kaufmann and Kraay, 2019; Mancheri et al., 2019). Clearly, in order to reduce supply disruption probability, substitution efforts could be directed towards neodymium. However, all resources present in the component have noticeable relative supply disruption probability according to some constraint(s): *dysprosium*, due to the same constraints as neodymium (having the same CFs) but lower share of the total due to lower content in the component; *aluminium* and *silicon*, feasibility of exploration projects; *iron and nickel*, trade barriers; *copper*, mining capacities.

3.2.2. Criticality assessment method

As for supply disruption probability, criticality is also calculated based on the BOM (see Table 1). Fig. 3 demonstrates the criticality of resources for the company's PMSMs using the adapted version of the Yale method. Neodymium and dysprosium have the highest supply disruption probability, well aligned with the results of the ESSENZ method. But iron is the resource which the company's PMSMs would be most vulnerable to a supply restriction of. The reason is that there are no substitutes to the electrical steel used in core laminations (see Table 1).

The two versions, A and B, differ only with respect to the resources' values in the vulnerability dimension. Version B reflects that the electric

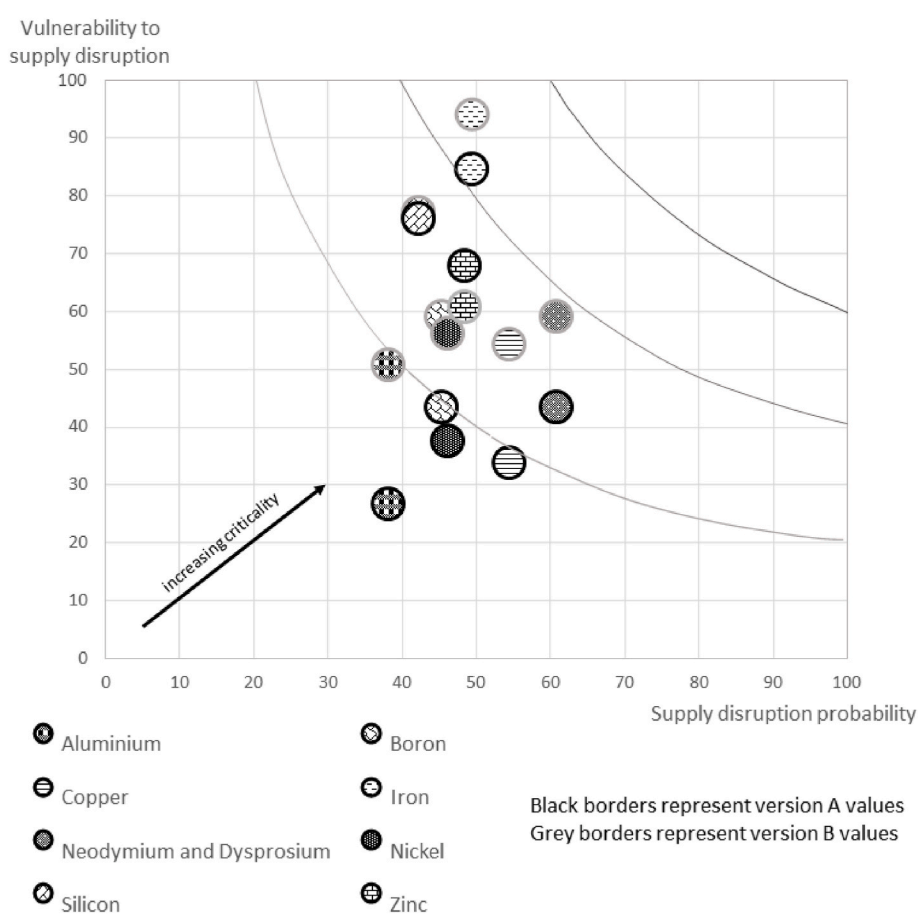

Fig. 3. Criticality assessment of resources in PMSM for VCC. The vulnerability dimension includes A) Substitutability and B) Substitutability and Importance. Criticality lines inspired by Glöser et al. (2015).

Table 3
Criticality assessment scores of resources for VCC's PMSMs. Light blue: 0–9; mid blue:10–20; green: 20–39; light yellow: 40–49: mid yellow: 50–59; mid orange: 60–69; dark orange: 70–79; red 80–89; dark red: 90–100. The abbreviations are as follows: DT = depletion time; CF = companion metal fraction; PPI = policy potential index; HDI = human development index; WGI-PV = worldwide governance indicators - political stability and absence of violence/terrorism; GSC = global supply concentration; SR = supply risk; RI = percentage of revenue impacted; PT = ability to pass through cost increases; CS = importance to corporate strategy; SP = substitute performance; SA = substitute availability; ER = environmental impact ratio; PR = price ratio; AI = ability to innovate; VSR = vulnerability to supply restriction (in versions A and B).

Resource	DT	CF	PPI	HDI	WGI-PV	GSC	**SR**	RI	PT	CS	SP	SA	ER	PR	CI	**VSR A**	**VSR B**
Aluminium	0	0	43	66	51	69	**38**	62	100	63	37	49	8	13	N/A	**27**	**51**
Boron	0	0	37	81	72	82	**45**	63	100	63	38	54	66	16	N/A	**43**	**59**
Copper	87	10	41	61	62	67	**54**	63	100	63	63	38	20	15	N/A	**34**	**54**
Dysprosium	0	100	42	78	56	89	**61**	63	100	63	38	54	66	16	N/A	**43**	**59**
Iron	66	0	34	77	46	72	**49**	63	100	63	91	91	97	97	N/A	**94**	**85**
Neodymium	0	100	42	78	56	89	**61**	63	100	63	38	54	66	16	N/A	**43**	**59**
Nickel	70	0	31	64	45	67	**46**	63	100	63	38	68	5	40	N/A	**38**	**56**
Silicon	70	0	31	64	45	67	**42**	63	100	63	63	46	100	100	N/A	**77**	**76**
Zinc	94	0	30	57	44	66	**48**	63	100	63	63	50	30	100	N/A	**61**	**68**

motor, as a component, is important to the company, which increases the criticality of some resources and decreases the criticality of others compared to version A which only reflects the resources' criticality for the electric motor. Resources such as aluminium are less critical if only considering the resources' criticality for the electric motor (version A). Conversely, resources such as iron are more critical if only considering the resources' criticality for the electric motor (version A).

The results for each criticality factor underlying the criticality scores of Fig. 3, are described here and presented visually in Table 3.

3.2.2.1. Supply disruption probability factors. In terms of *depletion time*, the reserves of copper and zinc are low compared to extraction rates, resulting in high scores. On the contrary, reserves of other resources such as REEs are vast compared to extraction rates (USGS, 2019).

REEs are, on the other hand, always co-produced with other REEs resulting in high scores for *companion metal fraction*. REEs are in turn seldom the primary product of a mine (exceptions exist in the US and Australia) (USGS, 2019). In China, REEs are produced as a by-product of iron (BGS, 2011). Copper is sometimes co-produced while the other resources are generally mined for their own sakes (Graedel et al., 2012; Voncken, 2016).

Policy potential index scores are quite average for all resources, indicating that none of the resources have production concentrated to countries where it is difficult for mining companies to operate due to unpredictable administration or legislation regarding e.g. mining permits.

Human development index (HDI) and *world governance index* (WGI) scores are high for boron. The production of boron is concentrated in countries where HDIs are relatively high (e.g. USA, Chile, Kazakhstan, Russia, Turkey). In particular, more than 50% is produced in Turkey, which, combined with a very low WGI value, results in a high WGI score for boron.[7]

In terms of *global supply concentration*, neodymium and dysprosium as well as boron have the highest scores. In 2018, China produced around 70% of REEs but significant production also occurred in the US (9%) and Australia (12%). Thus, the production of REEs was, in 2018, less concentrated than when China essentially had monopoly (e.g. 2007–2011 more than 95% of global production) (BGS, 2011).

3.2.2.2. Vulnerability factors. The *percentage of revenue impacted* in case of supply disruption, and consequent inability for VCC to produce an electric motor, is deemed "relatively high" by the company. This is due to the ambition to increase the percent of revenue from EVs in the coming 5–10 years to account for 50% of their sales. Likewise, the electric motor is deemed as "*important" to corporate strategy*.

As already explained, iron stands out in terms of non-substitutability (*substitute performance, substitute availability, environmental impact ratio and price ratio*). Because of the magnetic properties of iron, there are no substitutes for the core laminations made of electrical steel, which accounts for 85% of the iron use in the PMSM. Silicon also has low substitutability in core laminations, since its substitutes aremore expensive and have higher environmental impacts.

There are substitutes for neodymium and dysprosium, both other magnet and motor types. This reduces the vulnerability to a supply disruption of neodymium and dysprosium. The calculations for substitutability are based on an average of samarium-cobalt and ferrite magnets. Samarium-cobalt magnets have a similar availability (based on supply disruption probability) as Nd(Dy)FeB magnets. Ferrite magnets are preferable in terms of availability, environmental impacts and price. However, both alternatives for magnet substitutions would inevitably cause system-level changes which are not accounted for and are difficult to foresee outcomes of, since such designs are not yet finalized. Such designs could, for instance, require larger batteries.

4. Discussion

The complementary methods demonstrate how the PMSM is associated with different types of mineral resource scarcity. Perhaps surprisingly, the least substitutable resources in VCC's PMSM are iron and silicon. This finding contradicts the criticality assessment for passenger cars by Knobloch et al. (2018), which places iron among the least critical resources and neodymium and dysprosium as the most critical. By taking an in-depth perspective on substitutability in EVs, as done by Habib et al. (2016) in wind turbines, this study reinforces their conclusion that there is a lower dependence on neodymium and dysprosium than often claimed (Habib et al., 2016). Application-specific substitutability scores, as suggested by Graedel et al. (2015), are still too generic to capture the conditions for specific technologies or companies. The application-specific scores deem the substitutability of iron in transportation applications as "good" (Graedel et al., 2015) whereas iron in PMSM is "non-substitutable" for VCC (and likely for all companies using this specific component). Such specificities are crucial not to miss when

[7] The Yale method transforms WGI values to WGI scores by substracting them from 100 to reflect a higher supply disruption probability for countries with low WGI value (Graedel et al., 2012).

assessing the criticality of resources in products at both company and country-level. Furthermore, these results support the conclusion by Frenzel et al. (2017) that criticality of traditional industrial metals like iron could be generally underestimated in many criticality assessment studies.

There is room for mitigating long-term scarcity impacts of the PMSM primarily by directing measures towards the use of copper, neodymium and to some extent dysprosium. This would also reduce the impact of their many companion metals which are not present in the motor itself such as cerium and molybdenum. Copper use in windings could be substituted by aluminium. However, direct substitutions from copper to aluminium would likely result in system-level effects since differences in resources' properties affect mass, volume and efficiency which in turn could affect performance or battery requirements. Neodymium and dysprosium used in magnets could be substituted by other magnet or motor types. These substitutions could also lead to similar system-level effects. Potentially, the use of dysprosium could be significantly reduced by means of resource-efficient manufacturing techniques.

The study shows that the least substitutable resources for VCC's PMSMs, iron and silicon, are relatively unlikely to become scarce in either short or long-term. Iron and silicon are among the most abundant mineral resources in the ecosphere. In addition, they seem relatively abundant in the technosphere as implied by the relatively low supply disruption probability according to the Yale and ESSENZ methods. The ESSENZ method does however indicate that iron and silicon each have potential socioeconomic availability constraints which could be important for VCC to investigate and potentially mitigate, namely trade barriers and feasibility of exploration projects, respectively. In addition, even if iron and silicon would be relatively available as raw materials, the study points to a non-substitutable material, namely electrical steel, as potentially critical for the company. Thus, investigating the supply disruption probability for electrical steel would be an important next step for the company. This implies that it could be important to expand CA and SDP methods from only focusing on raw materials to including materials and components.

In addition to the results as such, an important outcome for the company of using these methods was the discussions initiated between different functions within the company about the implications of the mineral resources used in their products. In particular, the process of discussing substitutability as part of the CA stimulated increased learning about the component between different functions of the company. This ties well into findings by Griffin et al. (2019) and Lloyd et al. (2012) suggesting that organizational structure is influential for the potential to assess and mitigate criticality and that cross-functional communication and collaboration are important prerequisites for doing so. In particular, realizing the degree of complexity of substitution was a key learning outcome. Company decision-making could benefit from methods which are adapted to the complexity of substitution.

A drawback of both CA and SDP methods is their quantification of relative, as opposed to absolute, probability of supply disruption. It is extremely challenging (if at all possible) to quantify the probability that a supply disruption will occur within a given time frame. In comparison, it is more feasible to quantify absolute vulnerability since this concerns consequences which depend on the company itself. Thus, as yet, CA and SDP methods do not answer whether e.g. a high dependency on a resource (in this case, electrical steel) warrants mitigative measures. Being able to quantify absolute probability of supply disruption would enable integration of criticality into overall company risk management (Lloyd et al., 2012). Another aspect for method development is relating criticality to mass, in order to reflect the potential of resource-efficiency measures to reduce criticality as discussed by Mancini et al. (2018). For example, reducing the quantity of dysprosium through more resource-efficient manufacturing techniques would not reduce criticality according to the Yale-method.

By revealing the vulnerability with regards to e.g. iron, the substitutability evaluation in CA adds important information compared to SDP methods. Thus, it appears sensible for companies to depart from a vulnerability evaluation using a method that accounts for substitution (e.g. the Yale method), as also suggested by Schrijvers et al. (2020). Thereafter, an SDP method could be used as a screening of supply disruption probability for resources which score high on the vulnerability dimension. Compared to the time and resource-demanding process of performing a full CA, the ESSENZ method is easy to use, with ready-made CFs available online. Using such an approach would also avoid the overlaps in terms of supply disruption factors between the ESSENZ and Yale methods (and between SDP and CA methods in general). In contrast to the vulnerability dimension, the supply disruption probability dimension can be argued to be less context-specific and more readily captured in CFs applicable to any product and user.

At the same time, also the SDP dimension could be more company-specific than what the methodologies of CA methods suggest and finding ways of accounting for such specificities could be an important area of methodological development (Lapko et al., 2016). Nonetheless, it seems inherent to the concept of criticality that supply disruption probability, which largely depends on mechanisms *outside* the power of individual companies, will always be more generic than vulnerability of supply disruption, which largely depends on mechanisms *within* companies.

Another challenge with company-level CA encountered is that a company may not have sufficient information for assessing whether supply disruption also affects their competitors, which has implications for e.g. the ability to pass through cost increases. This could potentially be handled by e.g. assessing a range of scenarios, from very local to global supply disruptions.

Another observation is that discussions on substitutability, undertaken for the purpose of the CA, can be fed in to the LCA study to analyse measures to mitigate resource depletion impacts. This reinforces the benefits of using complementary methods, and more specifically, to use CA rather than only SDP methods alongside LCA. A benefit of using LCA to assess mineral resource scarcity impacts is the life cycle perspective, which reveals impacts from resources that are not in the component. To a company, this points to the potential relevance of sourcing specific resources from specific ores. For instance, VCC could strive to source copper from sulfidic ores to reduce depletion impacts from ecospherically rare resources, e.g. rhodium.

5. Conclusions

The importance of metals for modern society and future trends calls for clear and actionable decision-making support. This study contributes to the development of such support for company contexts. It demonstrates how using complementary methods in a company context can be useful for identifying the resources that may be scarce in either the short-term, for producing a product, or in the long-term, as a result of the product being produced. Contrary to criticality assessments on sector or national levels, which often point to neodymium and dysprosium because of the supposed criticality of these resources for electric motors, this study reveals that VCC's electric motors are most vulnerable to supply disruption of iron and silicon, or more precisely, electrical steel. Neodymium and dysprosium do however contribute considerably to depletion impacts and are the ones with highest supply disruption probability. Substitutions to other magnet or motor types could potentially reduce such impacts but would need to be assessed in terms of their system-level effects. Copper also contributes considerably to depletion impacts, both due to copper itself and its companion metals.

Methodologically, this company case study demonstrates that criticality assessment adds important information in terms of vulnerability to supply disruption compared to SDP methods. Thus, for assessment of short-term scarcity impacts, two recommendations can be made. For a less time-demanding assessment, the vulnerability dimension of a CA could be investigated after which SDP methods can be used to screen potential causes of supply disruption for the least substitutable resources. For a more company-specific assessment, a full CA is recommended. Still, several points for developing CA have been identified, especially for the company context. For the company, one of the most valuable aspects of this study was that it stimulated cross-collaboration and learning between different functions in the company. This illustrates that such assessment methods could not only provide valuable analytical outcomes but also play important roles as a means for the decision-making process at hand.

CRediT authorship contribution statement

Hampus André: Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Visualization. **Maria Ljunggren:** Conceptualization, Methodology, Writing – review & editing, Supervision, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This research was supported by the Mistra REES (Resource Efficient and Effective Solutions) program (No. 2014/16), funded by Mistra (The Swedish Foundation for Strategic Environmental Research) and Chalmers University of Technology via the Area of Advance Production. The authors are very grateful to VCC's participation in the study, specifically Linnea Petersson, Anna Widerberg, Robert Kinisjärvi and Joachim Lindström. The assistance of Anders Nordelöf is also gratefully knowledged.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2022.132140.

References

Althaus, H.-J., Classen, M., 2004. Life cycle inventories of metals and methodological aspects of inventorying material resources in ecoinvent (7 pp). Int. J. Life Cycle Assess. 10 (1), 43–49. https://doi.org/10.1065/lca2004.11.181.5.

André, H., 2020. Assessing Mineral Resource Scarcity in a Circular Economy Context, Chalmers Tekniska Hogskola (Sweden). PhD thesis.

André, H., Ljunggren, M., 2021. Towards comprehensive assessment of mineral resource availability? Complementary roles of life cycle, life cycle sustainability and criticality assessments. Resour. Conserv. Recycl. 167.

Arvidsson, R., Söderman, M.L., Sandén, B.A., Nordelöf, A., André, H., Tillman, A.-M., 2020. A crustal scarcity indicator for long-term global elemental resource assessment in LCA. Int. J. Life Cycle Assess. 1805–1817.

Ayres, R.U., Peiró, L.T., 2013. Material efficiency: rare and critical metals. Phil. Trans. Roy. Soc. Lond.: Math. Phys. Eng. Sci. 371, 1986.

Bach, V., Berger, M., Henßler, M., Kirchner, M., Leiser, S., Mohr, L., Rother, E., Ruhland, K., Schneider, L., Tikana, L., Volkhausen, W., Walachowicz, F., Finkbeiner, M., 2016. Integrated method to assess resource efficiency – ESSENZ. J. Clean. Prod. 137, 118–130. https://doi.org/10.1016/j.jclepro.2016.07.077.

Berger, M., Sonderegger, T., Alvarenga, R., Bach, V., Cimprich, A., Dewulf, J., Frischknecht, R., Guinée, J., Helbig, C., Huppertz, T., Jolliet, O., Motoshita, M., Northey, S., Peña, C.A., Rugani, B., Sahnoune, A., Schrijvers, D., Schulze, R., Sonnemann, G., Valero, A., Weidema, B.P., Young, S.B., 2020. Mineral resources in life cycle impact assessment: part II – recommendations on application-dependent use of existing methods and on future method development needs. Int. J. Life Cycle Assess. 25, 798–813. https://doi.org/10.1007/s11367-020-01737-5.

BGS, 2011. Rare Earth Elements: Mineral Profile. BGS (British Geological Survey), Nottingham, UK.

Cimprich, A., Bach, V., Helbig, C., Thorenz, A., Schrijvers, D., Sonnemann, G., Young, S. B., Sonderegger, T., Berger, M., 2019. Raw material criticality assessment as a complement to environmental life cycle assessment: Examining methods for product-level supply risk assessment. J. Ind. Ecol. 23 (5), 1226–1236. https://doi.org/10.1111/jiec.12865.

Cimprich, A., Karim, K.S., Young, S.B., 2017. Extending the geopolitical supply risk method: material "substitutability" indicators applied to electric vehicles and dental X-ray equipment. Int. J. Life Cycle Assess. 23 (10), 2024–2042. https://doi.org/10.1007/s11367-017-1418-4.

Dewulf, J., Benini, L., Mancini, L., Sala, S., Blengini, G.A., Ardente, F., Recchioni, M., Maes, J., Pant, R., Pennington, D., 2015. Rethinking the area of protection "natural resources" in life cycle assessment. Environ. Sci. Technol. 49 (9), 5310–5317. https://doi.org/10.1021/acs.est.5b00734.

Dewulf, J., Blengini, G.A., Pennington, D., Nuss, P., Nassar, N.T., 2016. Criticality on the international scene: Quo vadis? Resour. Pol. 50, 169–176.

Dolganova, I., Rödl, A., Bach, V., Kaltschmitt, M., Finkbeiner, M., 2020. A review of life cycle assessment studies of electric vehicles with a focus on resource use. Resources 9 (3). https://doi.org/10.3390/resources9030032.

Duclos, S.J., Otto, J.P., Konitzer, D.G., 2010. Design in an era of constrained resources. Mech. Eng. Mag. Sel. Artic. 132 (9), 36–40.

EC, 2014. Report on critical raw materials for the EU - Report of the ad hoc working group on defining critical raw materials. European Commission (EC), Brussels, Belgium.

EC, 2017. Study on the review of the list of critical raw materials. European Commission (EC), Brussels, Belgium.

Ekvall, T., Tillman, A.-M., 1997. Open-loop recycling: criteria for allocation procedures. Int. J. Life Cycle Assess. 2 (3), 155.

Frenzel, M., Kullik, J., Reuter, M.A., Gutzmer, J., 2017. Raw material 'criticality'—sense or nonsense? J. Phys. Appl. Phys. 50 (12).

Gaustad, G., Krystofik, M., Bustamante, M., Badami, K., 2018. Circular economy strategies for mitigating critical material supply issues. Resour. Conserv. Recycl. 135, 24–33. https://doi.org/10.1016/j.resconrec.2017.08.002.

Glöser, S., Tercero Espinoza, L., Gandenberger, C., Faulstich, M., 2015. Resour. Pol. 44, 35–46DOI. https://doi.org/10.1016/j.resourpol.2014.12.003.

Golev, A., Scott, M., Erskine, P.D., Ali, S.H., Ballantyne, G.R., 2014. Rare earths supply chains: current status, constraints and opportunities. Resour. Pol. 41, 52–59.

Graedel, T.E., Barr, R., Chandler, C., Chase, T., Choi, J., Christoffersen, L., Friedlander, E., Henly, C., Jun, C., Nassar, N.T., Schechner, D., Warren, S., Yang, M.-y., Zhu, C., 2012. Methodology of metal criticality determination. Environ. Sci. Technol. 46 (2), 1063–1070.

Graedel, T.E., Harper, E., Nassar, N.T., Reck, B.K., 2015. On the materials basis of modern society. Proc. Natl. Acad. Sci. Unit. States Am. 112 (20), 6295–6300.

Graedel, T.E., Reck, B.K., 2016. Six years of criticality assessments: what have we learned so far? J. Ind. Ecol. 20 (4), 692–699.

Griffin, G., Gaustad, G., Badami, K., 2019. A framework for firm-level critical material supply management and mitigation. Resour. Pol. 60, 262–276.

Habib, K., Hamelin, L., Wenzel, H., 2016. A dynamic perspective of the geopolitical supply risk of metals. J. Clean. Prod. 133, 850–858.

Habib, K., Wenzel, H., 2016. Reviewing resource criticality assessment from a dynamic and technology specific perspective – using the case of direct-drive wind turbines. J. Clean. Prod. 112, 3852–3863.

Hatayama, H., Tahara, K., 2015. Criticality assessment of metals for Japan's resource strategy. Mater. Trans. 56 (2), 229–235. https://doi.org/10.2320/matertrans.M2014380.

Huijbregts, M., Steinmann, Z., Elshout, P., Stam, G., Verones, F., Vieira, 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.

Kaufmann, D., Kraay, A., 2019. Worldwide Governance Indicators. http://info.worldbank.org/governance/wgi/. (Accessed 5 November 2019).

Knobloch, V., Zimmermann, T., Gößling-Reisemann, S., 2018. From criticality to vulnerability of resource supply: the case of the automobile industry. Resour. Conserv. Recycl. 138, 272–282.

Lapko, Y., Trucco, P., Nuur, C., 2016. The business perspective on materials criticality: evidence from manufacturers. Resour. Pol. 50, 93–107.

Lloyd, S., Clifton, A., Lee, J., Elghali, L., France, C., 2012. A framework for environmental risk management. Aeronaut. J. 116 (1183), 941–961, 1968.

London Metal Exchange, 2020. London Metal Exchange. https://www.lme.com/. (Accessed 6 November 2019).

Mancheri, N.A., Sprecher, B., Bailey, G., Ge, J., Tukker, A., 2019. Effect of Chinese policies on rare earth supply chain resilience. Resour. Conserv. Recycl. 142, 101–112.

Mancini, L., Benini, L., Sala, S., 2018. Characterization of raw materials based on supply risk indicators for Europe. Int. J. Life Cycle Assess. 23 (3), 726–738.

Mancini, L., Sala, S., Recchioni, M., Benini, L., Goralczyk, M., Pennington, D., 2015. Potential of life cycle assessment for supporting the management of critical raw materials. Int. J. Life Cycle Assess. 20 (1), 100–116. https://doi.org/10.1007/s11367-014-0808-0.

Nassar, N.T., Barr, R., Browning, M., Diao, Z., Friedlander, E., Harper, E.M., Henly, C., Kavlak, G., Kwatra, S., Jun, C., Warren, S., Yang, M.Y., Graedel, T.E., 2012. Criticality of the geological copper family. Environ. Sci. Technol. 46 (2), 1071–1078. https://doi.org/10.1021/es203535w.

Nordelöf, A., Grunditz, E., Lundmark, S., Tillman, A.-M., Alatalo, M., Thiringer, T., 2019. Life cycle assessment of permanent magnet electric traction motors. Transport. Res. Transport Environ. 67, 263–274.

Nordelöf, A., Grunditz, E., Tillman, A.-M., Thiringer, T., Alatalo, M., 2017. A scalable life cycle inventory of an electrical automotive traction machine—Part I: design and composition. Int. J. Life Cycle Assess. 23 (1), 55–69. https://doi.org/10.1007/s11367-017-1308-9.

Nordelöf, A., Tillman, A.-M., 2018. A scalable life cycle inventory of an electrical automotive traction machine—Part II: manufacturing processes. Int. J. Life Cycle Assess. 23 (2), 295–313. https://doi.org/10.1007/s11367-017-1309-8.

Peiró, L.T., Méndez, G.V., Ayres, R.U., 2013. Material flow analysis of scarce metals: sources, functions, end-uses and aspects for future supply. Environ. Sci. Technol. 47 (6), 2939–2947.
Schrijvers, D., Hool, A., Blengini, G.A., Chen, W.-Q., Dewulf, J., Eggert, R., van Ellen, L., Gauss, R., Goddin, J., Habib, K., Hagelüken, C., Hirohata, A., Hofmann-Amtenbrink, M., Kosmol, J., Le Gleuher, M., Grohol, M., Ku, A., Lee, M.-H., Liu, G., Nansai, K., Nuss, P., Peck, D., Reller, A., Sonnemann, G., Tercero, L., Thorenz, A., Wäger, P.A., 2020. A review of methods and data to determine raw material criticality. Resour. Conserv. Recycl. 155.
Sonderegger, T., Berger, M., Alvarenga, R., Bach, V., Cimprich, A., Dewulf, J., Frischknecht, R., Guinée, J., Helbig, C., Huppertz, T., Jolliet, O., Motoshita, M., Northey, S., Rugani, B., Schrijvers, D., Schulze, R., Sonnemann, G., Valero, A., Weidema, B.P., Young, S.B., 2020. Mineral resources in life cycle impact assessment—part I: a critical review of existing methods. Int. J. Life Cycle Assess. 25, 784–797. https://doi.org/10.1007/s11367-020-01736-6.
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. https://doi.org/10.1016/j.jclepro.2015.01.082.
Stedman, A., Green, K.P., 2019. Fraser Institute Annual Survey of Mining Companies. Fraser Institute.
UNDP, 2019. Human Development Report 2019: Beyond income, beyond averages, beyond today: Inequalities in human development in the 21st century New York. USA United Nations Development Programme.
USGS, 2019. Mineral Commodity Summaries 2019. U.S. Geological Survey., Reston, Virginia, p. 200.
VCC, 2020. Workshop - Criticality Assessment for Volvo Cars Corporation, A Workshop for Assessing Criticality of Metals for Production of Permanent Magnet Electric Motor. Participants Included VCC Employees Working with Design of Electric Motors and Sustainability as Well as Researchers from. Chalmers University of Technology.
Vieira, M., 2018. Fossil and mineral resource scarcity in Life Cycle Assessment. PhD thesis. Radboud University, Nijmegen, the Netherlands.
Voncken, J., 2016. The Rare Earth Elements - an Introduction. Springer, Delft, Netherlands.
Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., Weidema, B., 2016. The ecoinvent database version 3 (part I): overview and methodology. Int. J. Life Cycle Assess. 21 (9), 1218–1230 [online].
Widmer, J.D., Martin, R., Kimiabeigi, M., 2015. Electric vehicle traction motors without rare earth magnets. Sustain. Mater. Technol. 3, 7–13. https://doi.org/10.1016/j.susmat.2015.02.001.