DOI: 10.1111/jiec.13090

RESEARCH AND ANALYSIS

JOURNAL OF INDUSTRIAL ECOLOGY WILEY

Environmental impacts of the future supply of rare earths for magnet applications

Sabine Langkau[1] | Martin Erdmann[2]

[1] Competence Center Sustainability and Infrastructure Systems, Fraunhofer Institute for Systems and Innovation Research ISI, Karlsruhe, Germany

[2] Federal Institute for Geosciences and Natural Resources, BGR, Hannover, Germany

Correspondence
Sabine Langkau, Competence Center Sustainability and Infrastructure Systems, Fraunhofer Institute for Systems and Innovation Research ISI, Breslauer Straße 48, 76139 Karlsruhe, Germany.
Email: sabine.langkau@isi.fraunhofer.de

Funding information Research leading to this publication was funded within the r4-programm of the German Ministry of Education and Research (BMBF, project reference number 033R124C) and within the Fraunhofer Lighthouse Project Criticality of Rare Earths.

Editor Managing Review: Richard Wood

Abstract

The environmental impacts of rare earth mining have recently caused public concern, because demand for the rare earth elements neodymium (Nd), praseodymium (pr), dysprosium (Dy), and terbium (Tb) is expected to increase strongly as a result of their use in magnets for electric cars and other emerging applications. Therefore, we analyzed the future environmental impacts of producing these rare earth metals per kilogram and for global production in the year 2035 to obtain insights into their relevance and draw conclusions about suitable mitigation measures. We introduced a new stepwise approach that combines future scenarios of metal demand, policy measures, mining sites, and environmental conditions with life cycle assessment data sets.

The environmental impacts of 1kg of Nd, Pr, Dy, and Tb will probably decrease by 2035. In contrast, the environmental impacts of the global production of these metals for magnet applications might increase or decrease depending on the development of demand and the environmental conditions of mining and production. Regarding mitigation measures, the attempts included in the Chinese consolidation strategy (improvement of the environmental conditions of mining, prevention of illegal mining) are the most promising to reduce impacts in the categories human toxicity, freshwater ecotoxicity and, in the case of Nd/Pr, also in eutrophication and acidification. For the remaining categories, reducing the increase in demand (e.g., by improving material efficiency) is the most promising measure. Enhancing the environmental performance of foreground processes has larger potential benefits than improving background processes for most impact categories, including human toxicity as the most relevant impact category following normalization. This article met the requirements for a gold-gold JIE data openness badge described at http://jie.click/badges.

KEYWORDS
electric cars, future scenarios, industrial ecology, life cycle sustainability analysis (LCSA), prospective life cycle assessment (LCA), rare earth demand and supply

1 | INTRODUCTION

Electric vehicles are politically supported as green technologies to reduce CO_2 emissions and thereby mitigate the challenge of climate change. However, their successful market diffusion will strongly increase the demand for specialty metals, for example, lithium and cobalt for batteries as well as for rare earths (RE) for the magnets used in electric motors (Marscheider-Weidemann et al., 2016). This raises economic concerns about supply shortages and price fluctuations (Ad-Hoc Working Group on Defining Critical Raw Materials, 2010; Glöser-Chahoud, 2017; Schrijvers et al., 2020; Tercero Espinoza et al., 2020). In addition, much public attention has been drawn to environmental and social problems identified in the supply chains of the respective specialty metals (Amnesty International 2016; Bodenheimer, 2014; Bontron, 2012; Walz, Bodenheimer, & Gandenberger, 2016). While the environmental burden of these specialty metals is not specifically due to their usage in green future technologies, a significant increase in the environmental impacts of the worldwide production of these specialty metals is to be expected from the unusually strong market diffusion of future technologies (Langkau & Tercero Espinoza, 2018; Marscheider-Weidemann et al., 2016). Therefore, there is a need to analyze what the most effective measures could be to mitigate any future increase in environmental impacts. Methods of future research (Gerhold et al. 2015), especially the scenario technique, can help to answer this question by describing and modeling different possible future developments, assessing which are desirable, identifying the key parameters to influence future developments and, deriving policy recommendations. Scenarios on future demand for the RE neodymium (Nd), dysprosium (Dy), praseodymium (Pr), and terbium (Tb) can be found in the literature up to the year 2035 (Marscheider-Weidemann et al., 2016). In contrast, data concerning the environmental impacts of their production is only available for the present or recent past (Lee & Wen, 2017; Marx, Schreiber, Zapp, & Walachowicz, 2018; Schreiber et al., 2016; Zapp, Marx, Schreiber, Friedrich, & Voßenkaul, 2018). Hence, this study aims at constructing scenarios of the future environmental impacts of Nd, Dy, Pr, and Tb per kg and for worldwide production. Based on these scenarios, we derive recommendations for mitigation measures.

To analyze the environmental impacts of future metal production, van der Voet, van Oers, Verboon, and Kuipers (2019) and Kuipers, van Oers, Verboon, and van der Voet (2018) developed a new approach that combines life cycle assessment (LCA) with future scenarios of metal demand. They classified this method as part of the life cycle sustainability assessment (LCSA) framework. This framework is intended to broaden the life cycle approach from the environmental assessment of products or services to more universal questions of sustainability science and thereby derive recommendations for society and policy makers (Guinée & Heijungs, 2011).

Van der Voet et al. (2019) describe their method for assessing the future environmental impacts of metal production in three successive steps: (1) LCA to determine the environmental impacts of producing 1 kg of refined metal, (2) analysis of future changes in these environmental impacts, and (3) multiplying the future environmental impacts of 1 kg metal by the future production worldwide.

In contrast to the mass metals examined in Kuipers et al. (2018) and van der Voet et al. (2019), our study focuses on specialty metals. The overall production quantity of specialty metals is smaller than mass metals by several orders of magnitude, but the complex processes involved in their mining and refining mean the environmental impacts of their global production are still relevant (Nuss & Eckelman, 2014). The global production of these specialty metals is often provided by only a few countries or even mining sites (DERA, n.d.). Therefore, any changes in demand have strong influence on changes in mining sites, which in turn influence the environmental impacts of mining. Consequently, demand changes are relevant for the development of LCA data over time. As a result, it is not possible for us to follow the three steps of (van der Voet et al., 2019), which assume demand development to be irrelevant to the development of the environmental impacts per kilogram of metal. We therefore propose a novel stepwise approach to analyzing the future environmental impacts of specialty metal production per kilogram as well as of global production by combining LCA data on different mining sites with expert knowledge on the potential contribution of these mining sites to global metal supply.

2 | METHODS, ASSUMPTIONS, AND SCENARIOS

Our method can be described as an iterative approach comprising four steps. First, we analyze which parameters influence the future development of the environmental impacts of 1 kg of metal and how these parameters interrelate. Second, we derive assumptions and sub-scenarios for the most influential parameters. Third, we combine these assumptions and sub-scenarios into consistent overall scenarios. Fourth, we calculate the environmental impacts per kilogram and for global production to derive recommendations.

We describe these four steps in more detail in the following sections. The baseline year of this study is 2013. Scenarios refer to the horizon year 2035.

2.1 | Identification of influential factors

Causal loop diagrams (CLD) visualize the interdependencies of parameters in a dynamic system at one point in time. They can be used as a starting point for the dynamic modeling of complex systems, but also more generally to document interdependencies in a complex system or to make mental models transparent (de Vries, 2012). Figure 1 depicts the parameters influencing the future environmental impacts of RE production, and their mutual dependencies. In the following, we summarize the existing knowledge on these parameters, and derive assumptions and sub-scenarios for them.

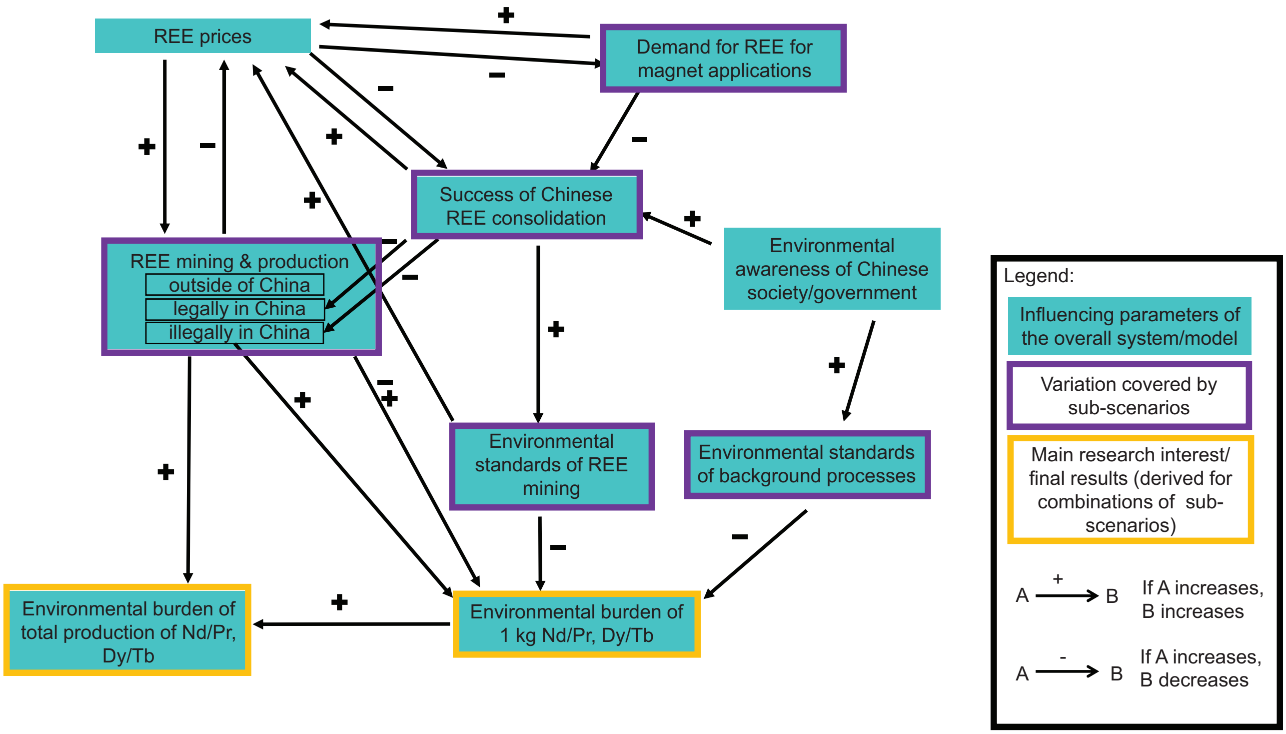

FIGURE 1 Causal loop diagram (CLD) displaying the different parameters relevant for the future change in environmental impacts of production of Nd, Pr, Dy, Tb as well as their various interdependencies

2.2 | Sub-scenarios of influential parameters

2.2.1 | Metal demand and supply

Due to their high performance, NdFeB magnets are used in future technologies such as traction motors in electric cars and generators in wind power plants (Marscheider-Weidemann et al., 2016; Roskill Information Services, 2011). The magnets generally contain the rare earth element Nd (about 33 mass percent), while Dy may substitute small quantities of Nd (<10%) to improve their properties (Glöser-Chahoud, 2017; Hoenderdaal, Tercero Espinoza, Marscheider-Weidemann, & Graus, 2013). Furthermore, Nd can be replaced by Pr up to a ratio of 3:1 without negative impacts on performance (Buchert, Manhart, Bleher, & Pingel, 2012). The typically used ratio is 5:1 (Glöser-Chahoud, 2017). Likewise, substitution of Dy by Tb is possible (Schüler, Buchert, Liu, Dittrich, & Merz, 2011). Therefore, we considered the four elements Nd, Pr, Dy, and Tb in our demand analysis. Nd and Pr belong to the more abundant light rare earth elements (LRE), while Dy and Tb are assigned to the less abundant heavy rare earth elements (HRE) (Elsner, 2011). *Based on typically applied substitution ratios and the average composition of RE ores* (BGR, 2019)*, we assume that the LRE demand for magnets will be met by 23% Pr and 77% Nd, while HRE demand will be covered by 14% Tb and 86% Dy.*

In 2013, the total demand for NdFeB applications was 28,900 t of Nd/Pr and 2,000 t of Dy/Tb (Marscheider-Weidemann et al., 2016). For comparison, data on the global production of Nd/Pr and Dy/Tb can be found in Supporting Information S1 for the years 2013 and 2018 (BGR, 2019). To estimate the future demand for Nd/Pr and Dy/Tb for NdFeB magnets, we used scenarios published in Marscheider-Weidemann et al. (2016). The scenarios include detailed analyses of the demand for electric cars, wind power plants, and electric bikes as well as general assumptions for other magnet applications. Moreover, they consider technological alternatives competing with the NdFeB magnet technology, which are especially widespread for wind power plants. Different assumptions concerning market diffusion of applications, market share of the NdFeB magnet technology, and success of material efficiency measures resulted in 27 scenarios. For this study, we chose three of those scenarios to reflect high, medium, and low demand increases. The respective values for the annual global demand in 2035 are:

- low demand (A1)*: Nd/Pr: 42,100 t, Dy/Tb: 3,200 t*
- medium demand (A2)*: Nd/Pr: 62,400 t, Dy/Tb: 7,200 t*
- high demand (A3)*: Nd/Pr: 81,700 t, Dy/Tb: 13,700 t*

Nd, Pr, Dy, and Tb are more expensive than other RE (e.g., lanthanum (La) and cerium (Ce)) since they are a main target of the mining of RE, which usually occur together in mining sites (Elsner, 2011). Consequently, other RE are often mined in excess and can be considered a by-product. Furthermore, the strongest demand increase in the future is expected for magnet applications (due to the growing demand for electric cars, wind power, and others) (Marscheider-Weidemann et al., 2016; Roskill Information Services, 2011). Consequently, we make the following assumptions:

Assumptions A: *Mining and production of various RE is determined mainly by the demand for Nd, Pr, Dy, and Tb for magnet applications in the future. The total amount of Nd, Pr, Dy, Tb mined and produced in 2035 is equal to the demand for these metals in 2035. Total supply of Nd/Pr and Dy/Tb in 2035 is therefore assumed to be equal to the demand values given above.*

For simplification, these assumptions neglect misfits between demand and production, for example, due to stock piling, surplus capacities, or supply shortages.

2.2.2 | Framing conditions for mining and production

China has been dominating the global RE market since the late 1990s. China's contribution to global mining production exceeded 90% in 2013 (BGR, 2019). According to the official figures, mining production outside China had increased to 22% by 2018, but illegal production in China had a high share of more than 50% in global production (Schüler-Zhou, 2018). In the case of HRE like Dy and Tb, temporary mining in Myanmar does not curtail the quasi monopoly of China because the ores are processed at Chinese plants, leaving production under Chinese control (BGR, 2019). More details on the global mining production between 2010 and 2018 can be found in Supporting Information S1.

According to systemic and game-theoretical analyses, China will probably sustain its dominant position in RE supply. Among others, Han, Ge, and Lei (2015) conclude that Chinese export restrictions alone will decide to what extent future mining will take place outside China. Additionally, Machacek and Fold (2014) argue that Chinese companies will always dominate the global production of RE, though mining will not necessarily take place mainly inside China, but rather Chinese companies will control mining sites abroad. Furthermore, Klossek, Kullik, and van den Boogaart (2016) conclude that none of the strategies proposed so far will enable the United States, European Union, or Japan to prevent the shift of higher value parts of the RE value chain to China. Therefore, we make the following basic assumption:

Assumption B: *China will sustain its dominance of RE supply in the future. Mining and processing will remain mainly under the control of Chinese companies, even if they take place in other countries. At the same time, higher value parts of the value chain will be established within China. Consequently, mining sites as well as the environmental conditions of RE production are mainly dependent on decisions made in China, that is, agreements made and enforced within the Chinese consolidation strategy*.

In 2011, the Chinese government implemented numerous official regulatory measures for a consolidation of the RE market. These measures address surplus production and price decay as well as environmental concerns. They include closing illegal mines, raising environmental standards, increasing mining fees, and R&D for environmentally friendlier mining and recycling. It was particularly difficult for small enterprises to meet the new environmental standards. Hence, the consolidation strategy so far has led to the so-called 1 + 5 structure (China Northern Rare Earth Group + five companies from Southern China). These six large companies control 22 of 23 (official) mines and 54 of 59 processing facilities (Schüler-Zhou, 2018).

The potential future success of the consolidation strategy is a subject of controversial discussion (e.g., Han et al., 2015; Wübbeke, 2013). We summarized the influencing parameters in Supporting Information S1. Based on those considerations, we constructed three basic scenarios B1–B3 to cover possible developments. *Within the three* basic scenarios B1–B3 *we assumed the success of the Chinese consolidation strategy to be great (B1), moderate (B2), or little (B3), respectively. Associated sub-scenarios of the contribution of mining sites outside China and environmental conditions will be outlined in the following sections.*

2.2.3 | Share of different mining sites and illegal production

Data on the shares of different mining sites in the global supply of Nd/Pr and Dy/Tb can be found in Supporting Information S1 for the years 2013 and 2018. For the future shares of different mining sites, an important parameter within the Chinese consolidation strategy is the mining and processing quota, which is the official limit to the total amount that can be produced within China. This quota is supposed to avoid surplus production and the related price decay and environmental burden. However, despite an official production quota of 105,000 metric tons per annum (tpa) REO from 2014–2017, processing capacities of 300,000 tpa were still in place in 2016 (Schüler-Zhou, 2018). Companies filled the surplus capacities by processing illegally mined RE ores in order to increase their profitability, thus undermining the official quota.

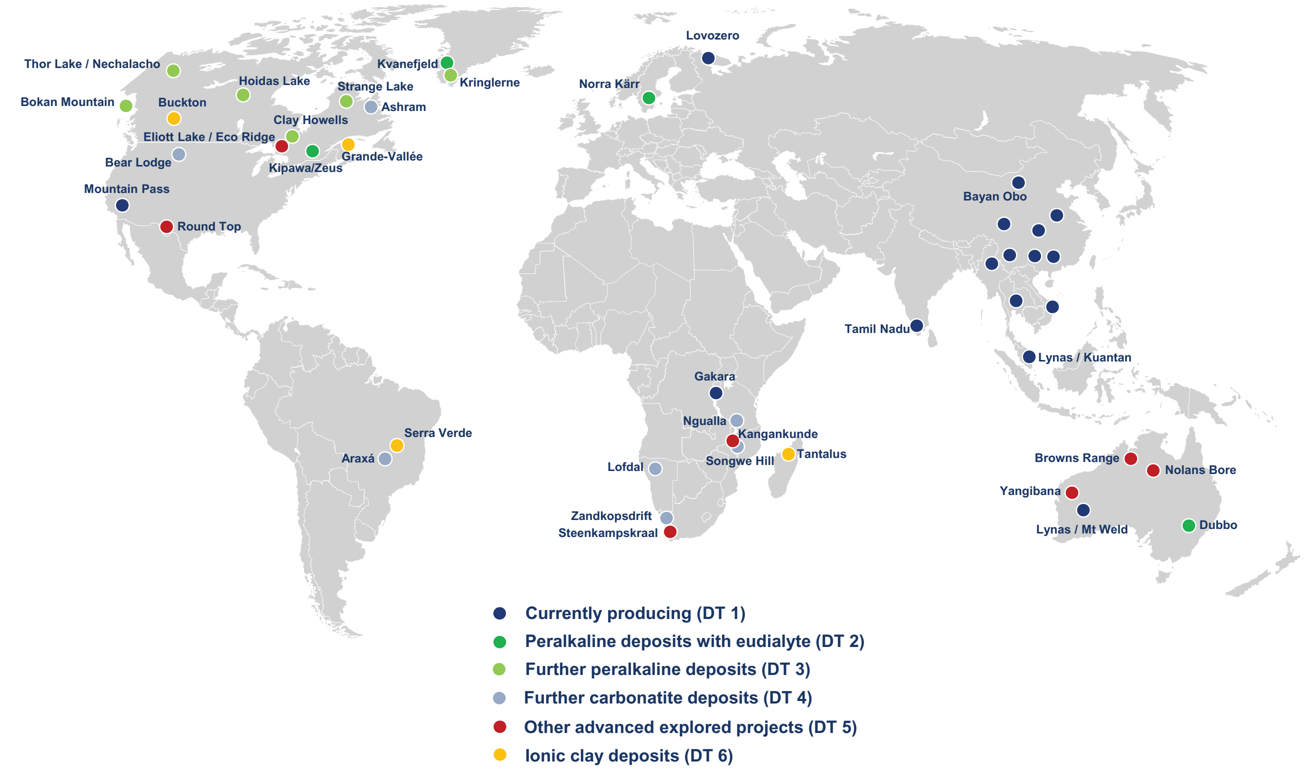

FIGURE 2 Close up of mines currently producing REO and potential new mining sites outside China (BGR, 2019). For a detailed description of the possible contribution from different deposit types (DT 1–6) see text

The target processing capacity of 200,000 tpa is to be reached by 2020 according to the Chinese development plan for the RE industry (MIIT, 2016). Since global demand and Chinese demand are expected to grow, mining and processing quotas are likely to increase as well. *Hence, for the* official mining and processing quota in 2035, *we assumed 200,000 metric tpa in the scenario of great consolidation success, 250,000 tpa in the scenario of moderate consolidation success, and 300,000 tpa in the scenario of little consolidation success.*

The share of illegal or unofficial mining did not change significantly between 2013 and 2018 (BGR, 2019; for details see Supporting Information S2). For Dy and Tb from ionic clay deposits in Southern China, the illegal mining share was still about 60% in 2018; for Nd and Pr from carbonatite deposits the unofficial contribution was about 15% (BGR, 2019). The future share of illegal mining depends strongly on the success of the consolidation strategy. *We assumed that illegal mining is entirely eliminated only in the scenario of great consolidation success, while it remains at 26% and 42% for Dy/Tb from ionic clays in scenarios of moderate and little success, respectively. All further assumptions can be found in Supporting Information S2.*

Mining sites outside China are assumed to cover demand, which is not covered by legal or illegal mining within China. These might be mining sites already in production today (e.g., Mount Weld, Australia), or newly developed sites (e.g., Norra Kärr, Sweden). For each of the nine possible combinations of the scenarios of demand (A1–A3) and consolidation success (B1–B3), mining sites most likely to contribute to global production were combined into sub-scenarios of supply according to the following characteristics:

1. Development stage of new mining projects (operating and potential increase in production > preproduction > feasibility > prefeasibility/scoping)
2. Approved mining and processing techniques, existing infrastructure (or expenditure for its construction)
3. Best fit of deposit composition to demand, RE content in general (especially ratio of heavy RE like Dy, Tb to light RE like Nd, Pr)
4. Amount of potential annual production/measured resources
5. Th and U contamination, environmental burden in general

Figure 2 shows the currently producing sites as well as the most promising projects outside of China selected using these five criteria. They are grouped into deposit types (DT) according to similarities in their potential contribution. Assumptions about potential annual production rates and composition of the deposits are based on data from (pre)feasibility studies, annual reports, commercial databases, and further literature (S&P Global 2019; Weng, Haque, Mudd, & Jowitt, 2016; Zhou, Zhongxue, & Congcong, 2017). In the following, we briefly describe the properties of deposit types 1–6 with special regards to selection criteria 1–5.

Deposit type 1: Increasing the production of currently producing mines is the easiest option to implement. Mt. Weld (AUS; from 18,500 t in 2018 to a maximum of 45,000 tpa) and Mt. Pass (USA; from 11,000 t in 2018 to a maximum of 20,000 tpa) could quickly double their production according to company information. However, these deposits provide only small amounts of HRE.

Deposit type 2: Peralkaline deposits bear numerous complex rare earth minerals, so processing the ores is very difficult, which is why these deposits are currently not industrially exploited. However, peralkaline deposits have significant advantages over other deposits: With comparatively large amounts of HRE, their composition is ideal for the ratio of HRE/LRE demanded for magnets. Moreover, they contain only small amounts of thorium and uranium and their processing has a comparatively low environmental impact (Weng et al., 2016). Thus, various research efforts are dedicated to developing an effective processing route for ores from peralkaline deposits. While DT 2 summarizes deposits with eudialyte as the main RE mineral (Schreiber et al., 2016).

Deposit type 3: It includes further peralkaline deposits, mainly with the RE mineral allanite. We have separated these deposit types, because an initial breakthrough in establishing a processing route for one of the above-mentioned RE minerals would lead to exploitation of deposits with that RE mineral.

Deposit type 4: Besides the large carbonatite deposits that are currently in production (e.g., Bayan Obo, CHN, Mt. Weld, AUS, Mt. Pass, USA), several other deposits are known. Processing techniques for their main RE minerals monazite and bastnaesite are well established. Thus, it would be comparatively easy to start production. However, especially monazite ore may be rich in thorium that could raise environmental concerns. Moreover, this deposit type provides only minor amounts of HRE. Therefore, a strong production increase in these deposits would exacerbatethe supply imbalance of the mainly required RE (Nd/Pr and Dy/Tb).

Deposit type 5: A limited number of other advanced explored deposits with different characteristics is known (cf., Supporting Information S1).They are selected according to the method described above.

Deposit type 6: Ionic clay deposits supply a major amount of the presently available HRE. Exploitation takes place mainly in China with a high share of illegal mining, enabled by the low technical requirements for producing high-grade RE concentrates from these deposits. Outside China, ionic clay RE deposits are rare and at a relatively low development stage. Nevertheless, we found these deposits are needed to meet high HRE demand in the respective future scenarios (A3).

Detailed information on all the deposits considered is listed in Supplementary Information S1.

Tables 1 and 2 summarize the supply scenarios with production shares of mining sites outside China (DT 1–6) for the different combinations of sub-scenarios of demand (A1–A3) and success of consolidation (B1–B3). In order to supply the expected market for Nd/Pr and Dy/Tb, and to avoid an imbalance, the mining supply of the different rare earth elements has to be considered (selection criteria 3). Thus, exploitation of peralkaline deposits with relatively high HRE content is more likely than an unlimited production increase in mines currently producing carbonatite deposits with low HRE contents. The balance problem that results with high demand (A3) combined with limited success of Chinese consolidation (B3) leads to significant changes in the share of different mining sites. Mines currently producing such as Mt. Weld (AUS) and Mt. Pass (USA) then become potentially uneconomic due to decreasing prices of LRE and are not considered in the scenario A3B3.

2.2.4 | LCA data on environmental impacts

Basic data

LCA data from three different references were incorporated into the scenarios. Lee and Wen (2017) provide LCA data for RE mining in China, distinguishing between three Chinese mining regions: Inner Mongolia (Bayan Obo), Sichuan, and Southern China. Zapp et al. (2018) provide a comparison of LCA data for Dy mining in the Chinese Southern Provinces versus the European mining site Norra Kärr. Data from (Marx et al., 2018) allows a comparison of Nd mining at three different mining sites: Bayan Obo (China), Mountain Pass (USA), and Mount Weld (Australia).

Chinese mining sites have the highest share of overall production at present and in all future scenarios except for one (cf. Tables 1 and 2). Therefore, environmental conditions at these sites have the biggest influence on the results and required the most attention within the analysis. This is the reason that data from Lee and Wen (2017) were adopted, since their work provides the best insights into the situation inside China and allows for a differentiation of deposits/mining sites, as well as varying environmental conditions within China. For the last point, three self-consistent cases are given in Lee and Wen (2017):

- the "lower bound," referring to the best facilities in China in 2013,
- the "upper bound," referring to the worst environmental conditions,
- the "average," referring to average Chinese industry conditions (but not statistical averages).

Data given in Zapp et al. (2018) and Marx et al. (2018) for Mt. Pass, Mt. Weld, and Norra Kärr are not directly comparable with the data given in Lee and Wen (2017) because of differences in methods, especially allocation. As the data on Mt. Pass, Mt. Weld, and Norra Kärr are needed to show

TABLE 1 Share in potential production of Nd and Pr outside China depending on different scenarios of future demand (A1–A3) and the success of the Chinese consolidation process (B1–B3). The location of the mines in the different scenarios is shown in Figure 2. Details for the deposit types (DT1–6) are given in the text and in Supporting Information S1

NdO + PrO	B1 great consolidation success	B2 moderate consolidation success	B3 little consolidation success
A1 low demand	**14.8% production outside China** *Reduced production compared to current state (2018), no additional deposits necessary* • 9.9% Mt. Weld (AUS) • 3.9% Mt. Pass (USA) • 1.0% others ***Surplus production of 1,700 tpa***	**11.8% production outside China** *Reduced production compared to current state (2018), no additional deposits necessary* • 7.9% Mt. Weld (AUS) • 3.1% Mt. Pass (USA) • 0.8% others ***Surplus production of 13,000 tpa***	**9.8% production outside China** *Reduced production compared to current state (2018), no additional deposits necessary* • 6.5% Mt. Weld (AUS) • 2.6% Mt. Pass (USA) • 0.7% others ***Surplus production of 24,400 tpa***
A2 medium demand	**40.7% production outside China** 21.6% current + increasing production of Mt. Weld (AUS) and Mt. Pass (USA)—DT 1 • 18.1% peralkaline deposits—DT 2 + 3 • 0.2% other advanced projects—DT 5 • 0.7% other currently producing deposits	**23.6% production outside China** • 21.4% current + increasing production of Mt. Weld (AUS) and Mt. Pass (USA)—DT 1 • 1.5% peralkaline deposits—DT 2 • 0.7% other currently producing deposits	**9.8% production outside China** *Reduced production compared to current state (2018), no additional deposits necessary* • 6.5% Mt. Weld • 2.6% Mt. Pass • 0.7% others ***Surplus production of 4,000 tpa***
A3 high demand	**54.9% production outside China** • 16.6% current + increasing production of Mt. Weld (AUS) and Mt. Pass (USA)—DT 1 • 17.7% peralkaline deposits—DT 2 + 3 • 10.6% further carbonatite deposits—DT 4 • 7.9% other advanced projects—DT 5 • 2.1% ionic clay—DT 6	**41.6% production outside China** • 14.8% current + increasing production of Mt. Weld (AUS) and Mt. Pass (USA)—DT 1 • 16.2% peralkaline deposits—DT 2 + 3 • 8.0% further carbonatite deposits—DT 4 • 0.5% other advanced projects—DT 5 • 2.1% ionic clay—DT 6	**27.0% production outside China** • *No production at currently active mines outside of China due to balance problems (see text)* • 16.4% peralkaline deposits —DT 2 + 3 • 8.1% further carbonatite deposits—DT 4 • 0.4% other advanced projects—DT 5 • 2.1% ionic clay—DT 6

TABLE 2 Share in potential production of Dy and Tb outside China depending on different scenarios of future demand (A1–A3) and success of the Chinese consolidation process (B1–B3). Details for the deposit types (DT 1–6) are given in the text and in Supporting Information S1

DyO + TbO	B1 great consolidation success	B2 moderate consolidation success	B3 little consolidation success
A1 low demand	**0% production outside China** *No additional deposits necessary* ***Surplus production of 2,000 tpa***	**0% production outside China** *No additional deposits necessary* ***Surplus production of 3,700 tpa***	**0% production outside China** *No additional deposits necessary* ***Surplus production of 5,500 tpa***
A2 medium demand	**30.8% production outside China** • 2.3% current + increasing production of Mt. Weld (AUS) and Mt. Pass (USA)—DT 1 • 24.0% peralkaline deposits—DT 2 + 3 • 4.5% other advanced projects—DT 5	**7.1% production outside China** • 2.2% current + increasing production of Mt. Weld (AUS) and Mt. Pass (USA)—DT 1 • 4.9% peralkaline deposits—DT	**0% production outside China** *No additional deposits necessary* ***Surplus production of 1,300 tpa***
A3 high demand	**41.2% production outside China** • 2.0% current + increasing production of Mt. Weld (AUS) and Mt. Pass (USA)—DT 1 • 24.0% peralkaline deposits—DT 2 + 3 • 4.6% further carbonatite deposits—DT 4 • 7.0% other advanced projects—DT 5 • 3.6% ionic clay—DT 6 ***under-supply of 5,700 tpa***	**33.3% production outside China** • 1.5% current + increasing production of Mt. Weld (AUS) and Mt. Pass (USA)—DT 1 • 19.9% peralkaline deposits—DT 2 + 3 • 3.6% further carbonatite deposits—DT 4 • 5.3% other advanced projects—DT 5 • 3.0% ionic clay—**DT 6** ***under-supply of 4,000 tpa***	**27.4% production outside China** *No production at currently active mines outside of China due to balance problems (see text)* • 17.1% peralkaline deposits—**DT** 2 + 3 • 3.1% further carbonatite deposits—DT 4 • 4.6% other advanced projects—DT 5 • 2.6% ionic clay—DT 6 ***under-supply of 2,400 tpa***

the potential changes due to a higher share of total production of these mining sites in the future, the difference in relation to the main mining sites Bayan Obo, Sichuan, Southern China are more important than the absolute values. Thus, ratios given in these references were used to calculate changes due to production shifting toward these mining sites, while no LCA data were taken directly from these sources. The respective ratios and data sources are:

- Mt Pass/Bayan Obo from Marx et al. (2018)
- Mt. Weld/Bayan Obo from Marx et al. (2018)
- Norra Kärr/Southern China from Zapp et al. (2018)

We needed to consider other mining sites as well (cf. Tables 1 and 2), but no specific data could be found for them. Therefore, data for ionic clay mining in the Southern Chinese Provinces available in Lee and Wen (2017) was taken as an approximation to assess ionic clay mining outside China. Differences in environmental standards were covered by choosing the most suitable of the three data sets given in Lee and Wen (2017). Likewise, carbonatite mining outside China was approximated using data for carbonatite mining inside China (Lee & Wen, 2017) considering different environmental standards. Peralkaline deposits were assumed to be similar to the Norra Kärr deposit (Zapp et al., 2018). Other deposits had a share of less than 5% and were thus neglected.

Since the LCA data sets were adopted from references, only the impact categories assessed therein can be taken into account within this study. We present results for the impact categories fossil fuel depletion, acidification, eutrophication, freshwater ecotoxicity, terrestrial ecotoxicity, global warming potential, human toxicity, ozone depletion, and photochemical oxidation. Allocation is done by mass in accordance with Lee and Wen (2017).

Scenarios

Starting from the baseline year 2013, we derived scenarios for changes in the LCA foreground system (mining processes) and background system (supply chains) until 2035.

Regarding the foreground system, we constructed *sub-scenarios for how the environmental conditions of Chinese mining and processing facilities develop*, deduced from the three scenarios on the success of the Chinese consolidation strategy (B1–B3). To do so, we assumed different shares of the three data sets on worst, best and average environmental conditions given in Lee and Wen (2017):

- *2013: 80% of illegal mining took place under the worst conditions (upper bound), 20% of illegal mining took place under average conditions; 80% of legal mining took place under average conditions, 20% of legal mining took place under best case conditions (lower bound)*
- *great consolidation success (B1): no illegal mining; 10% of legal mining average, 90% of legal mining lower bound*
- *moderate consolidation success (B2): 50% of illegal mining upper bound, 50% of illegal mining average; 20% of legal mining average, 80% of legal mining lower bound*
- *little consolidation success (B3): 70% of illegal mining upper bound, 30% of illegal mining average; 70% of legal mining average, 30% of legal mining lower bound*

More details on the assumptions can be found in Supporting Information S2.

Mendoza Beltran et al. (2018) pointed out the importance of including future changes in the background processes of the LCA model for prospective LCA studies. In case of RE mining, the electricity supply was found to have little influence on the total environmental impacts by Lee and Wen (2017). Instead, the supply chains of the chemicals used have the largest share in environmental impacts. More than 50% of impacts can be attributed to the supply with chemicals in almost all impact categories, and a 95% share is reached for some categories (Marx et al., 2018; Zapp et al., 2018). Therefore, we constructed future scenarios for the production of the most relevant chemicals, that is:

- ammonium sulfate for ion adsorption clays
- sulfuric acid and hydrochloric acid for carbonatites

The scenarios cover potential improvements by applying the currently best available technology (BAT) to an increasing number of production facilities. As a rough estimation, we simulated the relative improvement possible by increasing the share of the ecoinvent data set RER (Europe, currently high in environmental standards) versus RoW (rest of world). The *three sub-scenarios of development of background processes* were constructed as follows:

- *great improvement (C1): 100% RER*
- *moderate improvement (C2): 60% RER*
- *little improvement (C3): 10% RER*

2.3 | Combination of sub-scenarios into overall scenarios

After the relevant influencing parameters (Figure 1) had been analyzed and assumptions and sub-scenarios had been derived, they had to be combined into consistent overall scenarios. Cross-consistency assessment (CCA) is a method to choose consistent or most plausible combinations of sub-scenarios out of all the theoretically possible combinations of sub-scenarios (Ritchey, 2002; Zwicky & Wilson 1967).

Regarding *demand (A1–A3)* and *consolidation success (B1–B3)*, a great success of the Chinese consolidation strategy will result in higher prices for RE by preventing illegal mining (which is depressing prices) and additional costs for higher environmental standards and higher mining fees (Figure 1). Higher prices might encourage measures supporting the substitution and recycling of RE and thereby lower the demand for RE. Likewise, high demand will be a major incentive to be less strict about consolidation measures, especially since Chinese demand will account for a large share of global demand. These considerations suggest that the combinations *low demand—great consolidation success (A1B1)*, *medium demand—moderate consolidation success (A2B2)*, *high demand—little consolidation success (A3B3)* seem more plausible and consistent than other combinations. On the other hand, the costs for NdFeB magnets often play a minor role in the overall prices of the final products (e.g., electric cars) (Glöser-Chahoud, 2017), so that the correlations described might not have significant impacts. Therefore, we decided to analyze all nine possible combinations of sub-scenarios A and B in the results section.

Concerning the *environmental conditions of background processes/chemical supply chains* (*C1–3*), improvements will likely develop in the same manner as the *Chinese consolidation strategy (B1–3)*, as both depend on general environmental awareness in China (Figure 1). Therefore, only the combinations *B1C1 (great improvement of background processes + great success of consolidation success → great improvement)*, *B2C2 (moderate improvement)*, *B3C3 (little improvement)* were chosen as consistent combinations for the overall scenarios. As a result, only nine consistent overall scenarios were analyzed, instead of the 27 theoretically possible combinations of sub-scenarios, which also enhances the clarity of presenting the results. Nonetheless, the remaining combinations can be created with the help of Supporting Information S3. The consistency check table can be found in Supporting Information S1.

2.4 | Deriving results, conclusions, and recommendations

Details on the calculation of results can be retraced with Supporting Information S3. For the environmental impacts of global production, the environmental impacts of 1 kg of metal were multiplied by the global production/demand, as suggested in van der Voet et al. (2019). Conclusions about future developments were drawn from similarities among all scenarios. Recommendations for the most suitable measures to influence these developments were derived from differences between the scenarios. More details can be found in the results section.

3 | RESULTS AND DISCUSSION

3.1 | Changes in environmental impacts per kilogram from 2013 to 2035

Figures 3 and 4 display the ratio of environmental impacts of 1 kg metal in 2035 to 1 kg metal in 2013 for Nd and Dy, respectively. Values for 2035 are depicted for nine future scenarios resulting from a combination of sub-scenarios (cf. Section 2). *Improvement* scenarios summarize sub-scenarios on the future success of the Chinese consolidation strategy (including prevention of illegal mining, limitation of legal mining, and enhancement of environmental standards) as well as on the environmental improvement of background processes. *Demand* scenarios describe the future global demand for these metals, which affects the environmental impact of 1 kg of metal by influencing the contribution from different mining sites.

Figures 3 and 4 show that the environmental impacts per kilogram decrease for all impact categories in all scenarios, with the largest improvements for human toxicity. Comparing different scenarios highlights how different parameters influence this general trend. *Improvement*, summarizing the success of the consolidation strategy and the improvement of background processes, has the strongest influence on the environmental impacts of 1 kg metal, so differences between scenarios with equal *demand* but varying *improvement* are larger than vice versa. Furthermore, greater *improvement* leads to smaller environmental impacts in all impact categories, that is, there are no trade-offs between the different environmental impact categories connected with these measures. Thus, greater success of these improvement measures will lead to lower environmental impacts per kilogram in general. However, exceptions to this general trend can be seen for ozone depletion in case of Dy as well as for fossil fuel depletion and global warming potential in case of Nd (Figures 3 and 4). For these exceptions, differences in demand have a stronger influence on the environmental impacts per kilogram than improvement measures.

Differences in demand affect the environmental performance per kilogram as they lead to different contributions to global production from different mining sites (cf. Tables 1 and 2). In general, higher demand leads to a larger contribution from new mining sites outside China. By comparing scenarios with equal *improvement* but different *demand* (Figures 3 and 4), it can be concluded that these shifts significantly influence the

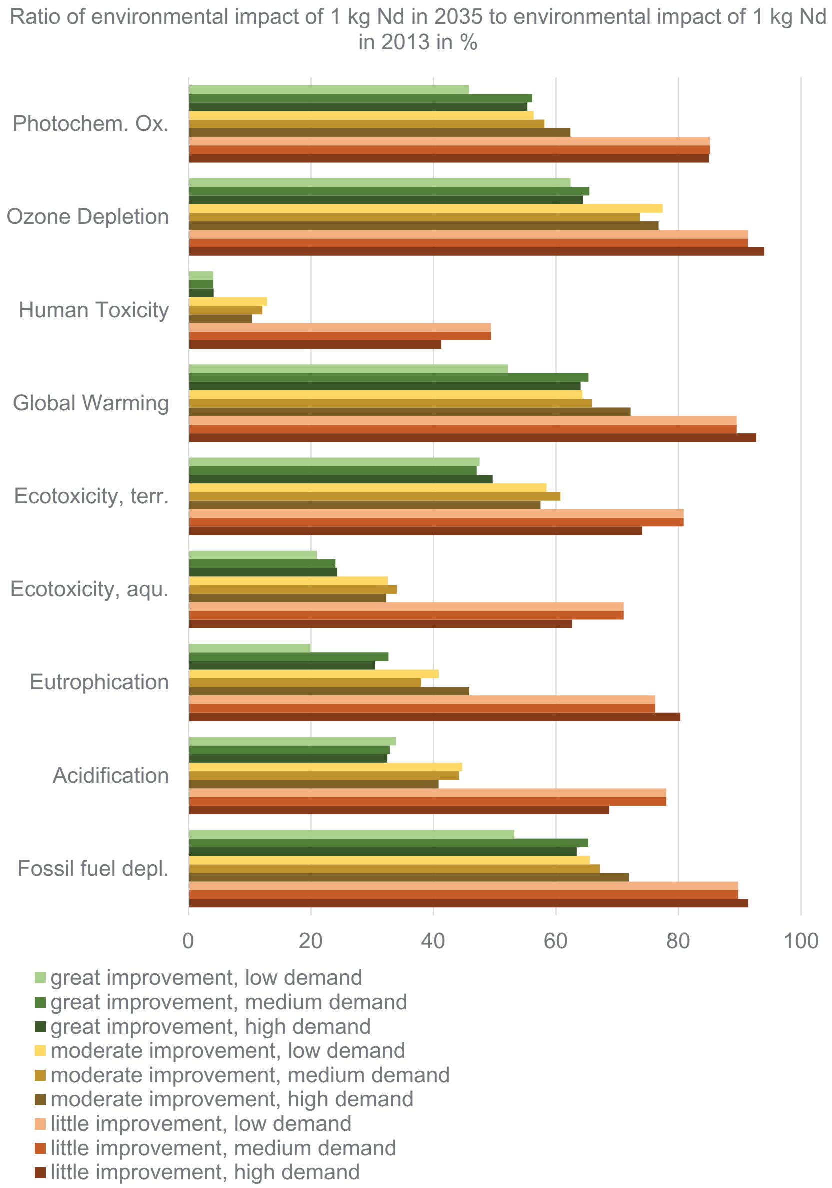

FIGURE 3 Ratio of environmental impacts of 1 kg Nd in 2035 to environmental impacts of 1 kg Nd in 2013. Values for 2035 are taken from nine future scenarios resulting from a combination of sub-scenarios. "Improvement" summarizes assumptions on the future success of the Chinese consolidation strategy as well as environmental improvement of background processes. Demand relates to the future global demand for these metals, which affects the environmental impact of 1 kg of metal by influencing the contribution from different mining sites. Underlying data used to create this figure can be found in Supporting Information S3a

environmental performance. Whether such future shifts in mining sites increase or decrease the environmental impacts depends on the individual mining sites and the impact categories, that is, it is not possible to outline a general trend for these influences. In case of the aforementioned exceptions, the unsystematic influence of shifts in mining sites outweigh the general systematic trend of decreasing environmental impacts with enhanced improvement measures (Figures 3 and 4). This comparison also indicates that the potential of improving environmental performance by shifting mining outside China is limited. However, Figures 3 and 4 also show that significant improvements in the most relevant impact category human toxicity are possible by shifting mining sites, that is, this might still be a relevant measure, especially if measures included in *improvement* fail. A further differentiation between those measures will be outlined in the next section. Data sets for the environmental impacts of 1 kg Nd, Dy, Pr, and Tb in 2035 can be found in Supporting Information S3.

3.2 | Foreground versus background

Among the measures within the *improvement* scenarios, environmental conditions along the supply chains of the chemicals used for mining are included as the most influential aspects of the background of the life cycle inventory (LCI) model (sub-scenarios C1–3, cf., Section 2.2). All other analyzed parameters and sub-scenarios are related to the foreground of the LCI model: success of the Chinese consolidation strategy including prevention of illegal mining and improvement of environmental standards (sub-scenarios B1–3) as well as demand induced shifts in mining sites (sub-scenarios A1–3, Tables 1 and 2). Figure 5 differentiates the influence of changes in the foreground and background for the example of the

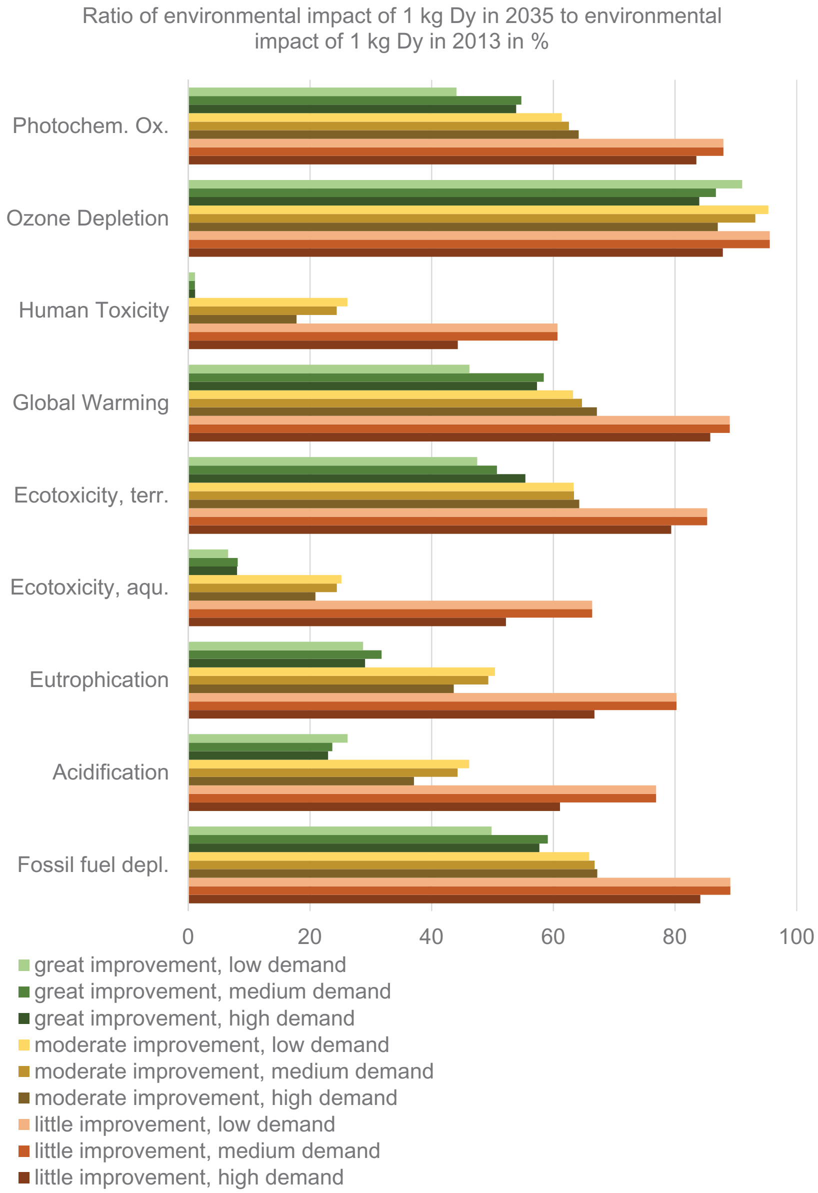

FIGURE 4 Ratio of environmental impacts of 1 kg Dy in 2035 to environmental impacts of 1 kg Dy in 2013. Underlying data used to create this figure can be found in Supporting Information S3b

human toxicity potential of the production of 1 kg Dy in 2035. The comparison shows that changes in the foreground processes make a larger contribution to mitigating the environmental impacts. Similar graphs for all impact categories can be found in Supporting Information S3. Environmental improvements in the background processes were found to have a smaller influence than changes in foreground processes for most impact categories, including human toxicity (Figure 5), acidification, eutrophication, and aquatic ecotoxicity for both Nd and Dy. Although the main environmental impacts occur along the supply chain of chemicals, for some of these categories (e.g., eutrophication of Dy; Yang et al., 2013), the most promising mitigation measure is to reduce the required amount of these chemicals by improving foreground processes.

3.3 | Environmental impacts of the world production of Nd/Pr and Dy/Tb for magnet applications in 2013 and 2035

Figures 6 and 7 display the environmental impacts of the world production of Nd/Pr and Dy/Tb for magnet applications in 2013 and 2035. To assess the relevant importance of different impact categories, the results were normalized using total global environmental impacts in the year 2000 (van Oers, 2015). Absolute values are included in Supporting Information S3. Clearly, human toxicity will remain the most relevant environmental problem associated with the production of Nd/Pr (Figure 6) and Dy/Tb (Figure 7). In contrast, terrestrial ecotoxicity and ozone depletion are of comparatively little importance. Overall, the contributions to most impact categories of producing Nd/Pr and Dy/Tb for magnet applications appear

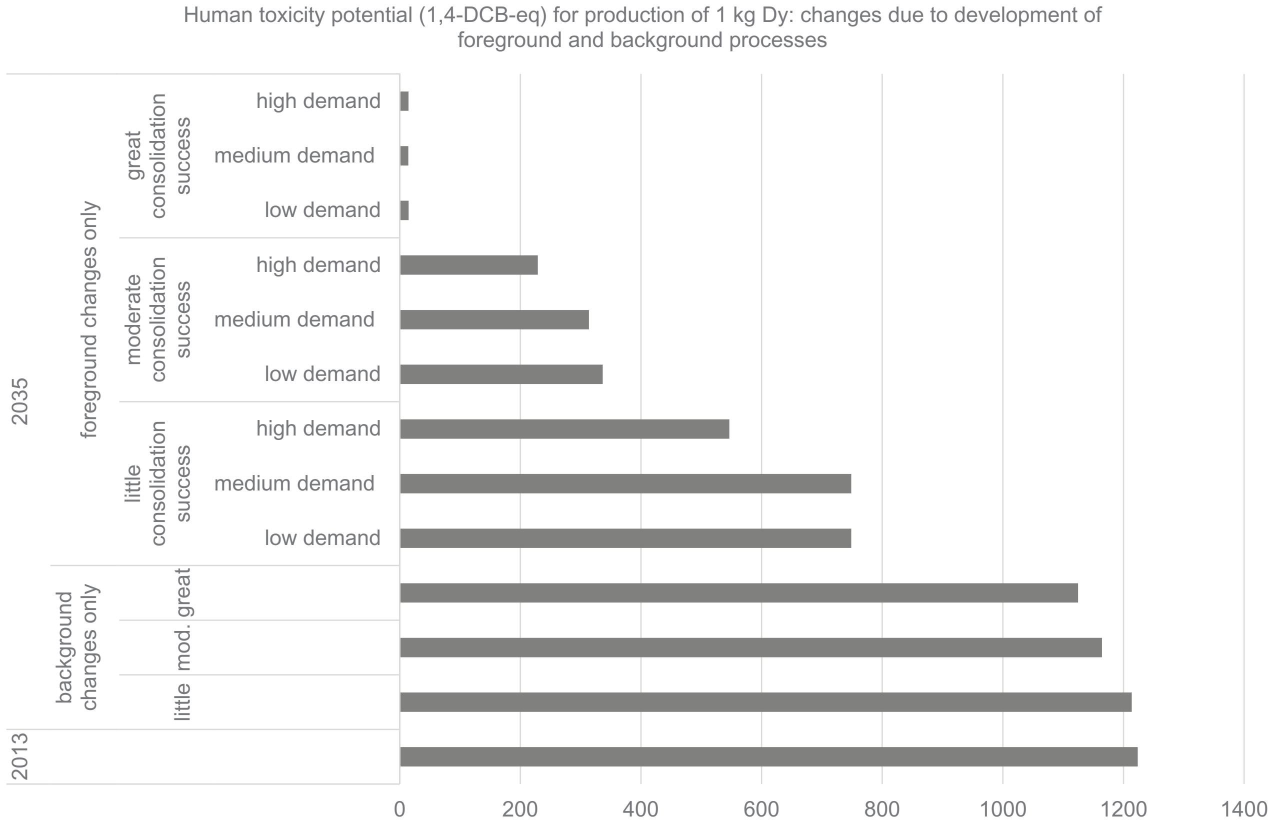

FIGURE 5 Comparison of changes in the human toxicity potential of producing 1 kg Dy due to changes in the background system versus changes in the foreground system. Underlying data used to create this figure can be found in Supporting Information S3b

small when compared to the overall environmental burden of human activities in the year 2000, which is not surprising, as these are only four specialty metals among many others (see, e.g., Nuss & Eckelman, 2014).

The comparison of global RE production for magnet applications in 2013 and 2035 shows that decreasing environmental impacts are only possible in the best case scenario for the majority of impact categories, namely global warming potential, fossil fuel depletion, photochemical oxidation, ozone depletion, and terrestrial ecotoxicity. For the remaining impact categories, some scenarios result in increasing and others in decreasing environmental impacts, although the human toxicity potential of Nd/Pr production decreases for all but two scenarios (Figures 6 and 7).

3.4 | Key parameters and mitigation measures

Figures 6 and 7 also show that the variation of environmental impacts between different scenarios for 2035 exceeds the total environmental impacts in 2013. Therefore, it is very useful to compare scenario results in order to identify the most influential parameters and derive conclusions about the most effective mitigation measures to reduce future environmental impacts. In case of human toxicity, a *high demand* increase combined with a *great improvement* of conditions (great success of consolidation strategy + great improvement of background processes) leads to much smaller environmental impacts than a *low demand* increase combined with *little improvement* (cf. Figures 6 and 7). Hence, improvement measures are most promising for this impact category. An opposite example is the eutrophication potential of Dy/Tb. In this case, *high demand* combined with *great improvement* of conditions leads to bigger environmental impacts than *low demand* with *little improvement* of conditions (cf., Figure 7). Consequently, *demand* is the most important factor here and the most promising measures to reduce the overall impacts are those that lower demand, for example, material efficiency improvements or sufficiency efforts.

In this manner, measures to *improve* conditions were found to have a stronger influence than *demand* mitigation for human toxicity and freshwater ecotoxicity in all four metals, and for acidification and eutrophication in the case of Nd/Pr. For all other impact categories, *demand*-mitigating measures were found to be more influential. Therefore, measures to lower demand are important to mitigate future environmental impacts in most impact categories. Additionally, measures summarized in the *improvement* sub-scenarios, that is, success of the Chinese consolidation strategy (including prevention of illegal mining, limitation of legal mining, and enhancement of environmental standards) and environmental improvement

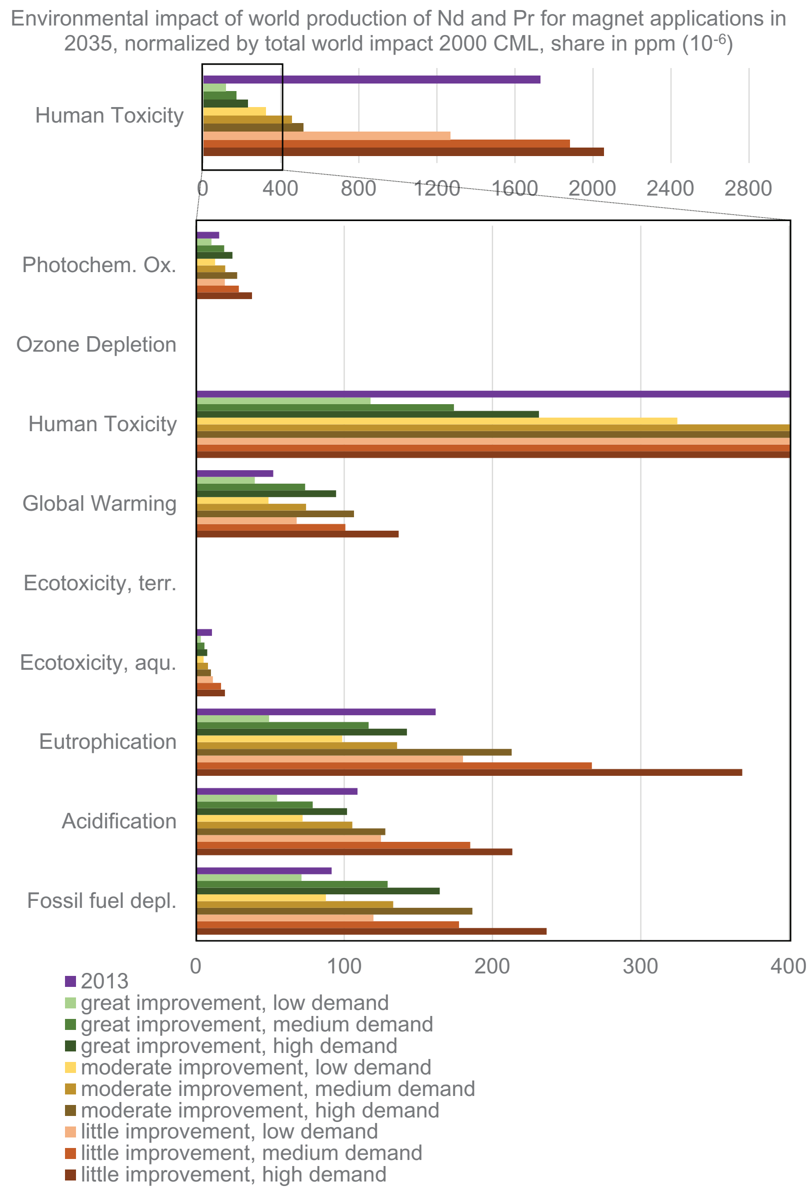

FIGURE 6 Environmental impact of world production of Nd and Pr for magnet applications in 2013 and in 2035. All values are normalized using CML data sets for the overall global impacts in the considered impact categories in 2000 (van Oers, 2015), shares are given in parts per million (ppm). Values for 2035 are taken from nine future scenarios resulting from a combination of sub-scenarios. "Improvement" summarizes assumptions on the future success of the Chinese consolidation strategy as well as environmental improvement of background processes. Demand describes the future global demand for these metals. Underlying data used to create this figure can be found in Supporting Information S3a and S3c

of background processes are essential to mitigate environmental impacts in the most relevant impact category of human toxicity. Among these measures, the success of the Chinese consolidation strategy has the strongest influence, as outlined in Section 3.2.

3.5 | Discussion of uncertainties

Unavoidable uncertainties may arise due to the limited accuracy of data, ambiguities within LCA methods (especially allocation), and uncertainties concerning future assumptions. The accuracy of the used data sets is discussed in the respective references. Additional uncertainties arise from the approximation of missing data sets for mining sites based on data sets available for similar sites.

Regarding the choice of the allocation method, a comparison between mass allocation and economic allocation by Marx et al. (2018) shows a strong influence on the results. Depending on the impact category, the environmental impacts of producing 1 kg of Nd are 10–75% lower when choosing mass allocation, due to the high (Nd/Pr) and very high (Dy/Tb) prices in comparison to other RE or even other accompanying elements (e.g., Fe in Bayan Obo). However, the main objective of this study was to compare the environmental impacts of Nd, Pr, Dy, and Tb between 2013 and different scenarios for 2035. The results of this comparison would not be affected by changing from mass to economic allocation based on constant prices. Additionally, the high temporal fluctuations of RE prices (DERA, 2017) render an economic allocation unsuitable. Another criticism is that a normalization of data for 2013 and 2035 should not be preformed using normalization data for 2000, but normalization data were not available for 2013 and obviously not for 2035.

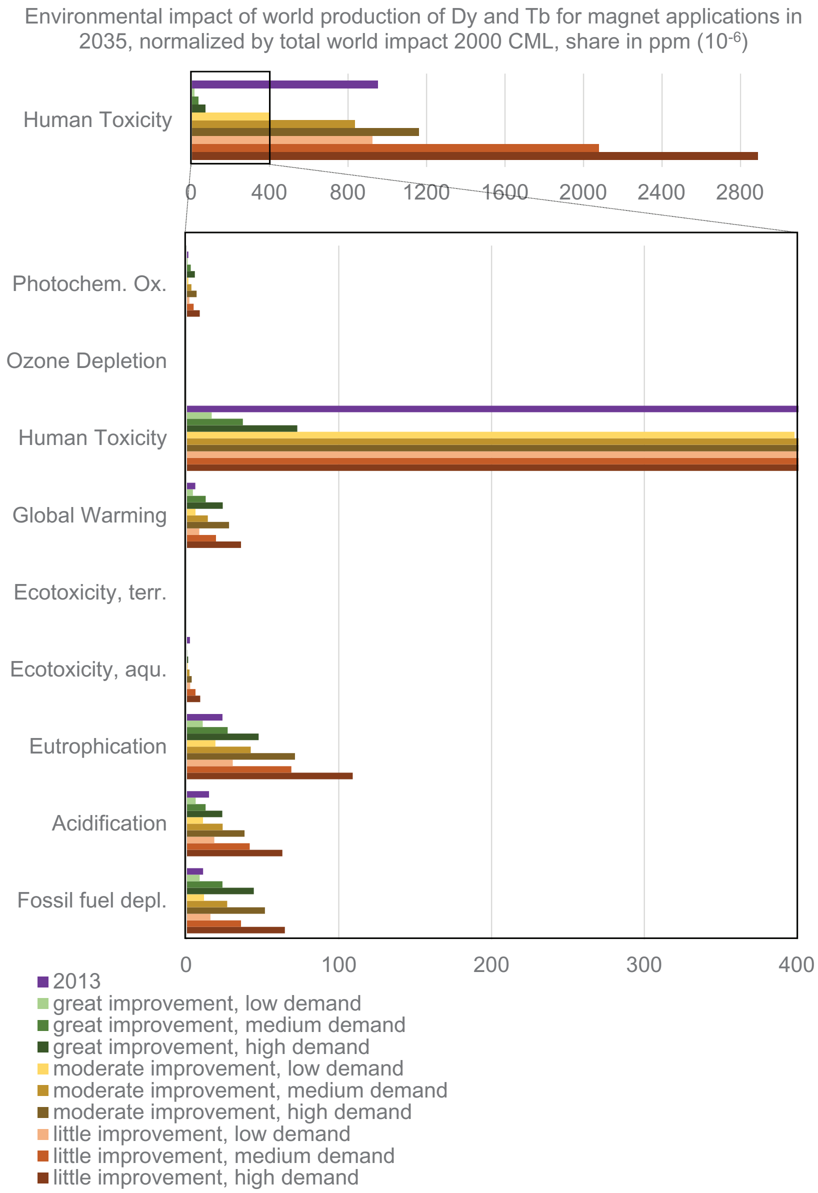

FIGURE 7 Environmental impact of world production of Dy and Tb in 2013 and 2035. All values are normalized using CML data sets for the overall global burden in the considered impact categories in 2000 (van Oers, 2015), shares are given in ppm. Underlying data used to create this figure can be found in Supporting Information S3b and S3d

Among the assumptions necessary for the future scenarios, assumption A supposes that the total amount of Nd, Pr, Dy, and Tb mined and produced in 2035 is equal to the demand for these metals in 2035 (cf. Section 2). Alternatively, it is also conceivable that the production of Nd, Pr, Tb, and Dy will not meet demand in 2035, for example, because the demand for these four metals is insufficient to promote rare earth mining (assumption A'). It is also conceivable that production amounts of Nd, Pr, Tb, and Dy will surpass demand in 2035, for example, because a newly developed future technology increases the demand for another rare earth, leading to more RE mining with Nd, Dy, Pr, and Tb as by-products (A''). Both would affect the environmental burden per kilogram due to a different relative contribution from different mining sites. Lower demand would mean fewer incentives for additional mining sites to go into production, since the existing ones already meet demand, and vice versa. These variations also affect the environmental impacts of the total global production. Additionally, the environmental impacts of total world production change linearly with the total amount produced. Since the results presented in Figures 3–7 already display a variation in total production due to three sub-scenarios of demand, they allow an estimation of the changes due to variations of total production in line with assumption A' or A''. In case of A'', it might also be argued that the environmental impacts of surplus production of Nd, Pr, Dy, and Nd should partly be allocated to the element causing the surplus production. Likewise, under assumption A, the demand for Nd, Pr, Dy, and Tb will probably cause excess production of other RE, for example, Ce and La. More work needs to be done on possible future applications of those metals to determine to what extent the environmental impacts connected with their production should be allocated to Nd, Pr, Dy, and Tb, thereby increasing the environmental impacts displayed in Figures 3–7.

Sub-scenarios of the future development of environmental conditions are based on a broader diffusion of currently available, environmentally friendly technologies, while a possible further improvement of such technologies was neglected. Though this is uncertain, many of the key environmental technologies (e.g., waste gas cleaning) have been used for decades and have already achieved a high degree of effectiveness, making frequent and major technical improvements in the future unlikely. In contrast, there are still large differences in environmental standards between different regions of the world, so that a broader diffusion of BATs has the largest potential for improvement.

Furthermore, we neglected mining site depletion, which is known to increase the environmental impact per kilogram mined (Kuipers et al., 2018; van der Voet et al., 2019). Unfortunately, no reliable data on mining site depletion was available to us.

Finally, we neglected the contribution of recycling to supply. However, recycling contributes less than 1% at present (UNEP, 2011). A significant contribution in 2035 is unlikely, as demand is assumed to grow strongly from year to year due to the increasing market diffusion of future technologies. At the same time, those future technologies (e.g., electric cars) will be in use for several years, so by the time products might be available for recycling, the demand for new products will already have multiplied. Thus, recycling can only contribute significantly to raw material supply once the diffusion of the technologies involved has reached a saturation level.

4 | CONCLUSION

Figures 3–7 show how the environmental impacts of producing Nd, Dy, Pr, and Tb might develop due to possible changes in the demand for these specialty metals, policy measures, mining sites, and environmental conditions. The environmental impacts of producing 1 kg of Nd, Dy, Pr, and Tb decrease in all analyzed future scenarios, with the magnitude of this improvement depending primarily on the success of consolidation measures. However, regarding the global production of these metals for magnet applications, decreasing environmental impacts are only possible in the best case scenario for the majority of impact categories. Therefore, strong mitigation efforts are necessary to reduce the environmental consequences of the global production of these RE for magnets in the future.

By comparing the different scenarios, we drew the following conclusions about the most relevant mitigation measures. Supporting consolidation attempts, especially the closure of illegal mines and raising environmental standards, should be assigned high priority, as these are the most promising measures to reduce the human toxicity potential of the global production of RE for magnet applications, which is the most relevant impact category following normalization. However, variations in future demand have the strongest influence on the environmental impacts in most other impact categories. Therefore, high priority should also be given to R&D efforts to improve material efficiency. Furthermore, instead of relying on technological improvements alone, changes in the society in the direction of sufficiency in consumption appear indispensable to mitigate environmental burdens.

As a final remark, the data derived in this study is not suitable to judge the environmental performance of future technologies using RE, since it does not consider any potential environmental or social benefits from applying those technologies.

ACKNOWLEDGEMENTS

The authors thank Simon Glöser-Chahoud for his idea to combine their research efforts that led to this publication. The authors also thank the anonymous reviewers for their excellent comments.

Open access funding enabled and organized by Projekt DEAL.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

ORCID

Sabine Langkau https://orcid.org/0000-0003-3443-2920

REFERENCES

Ad-Hoc Working Group on Defining Critical Raw Materials. (2010). Critical raw materials for the European Commission. http://ec.europa.eu/enterprise/policies/raw-materials/files/docs/report-b_en.pdf

Amnesty International. (2016). This is what we die for. Human rights abuses in the democratic republic of the Congo power the global trade in cobalt. https://www.amnestyusa.org/files/this_what_we_die_for_-_report.pdf

BGR. (2019). Fachinformationssystem Rohstoffe. unpublished. data status Jun 30. Hannover, Germany.

Bodenheimer, M. (2014). *Certifying Improvement, Improving Certification. An Analysis Based on the Artisanal and Small-Scale Mining Sector* Karlsruhe: Fraunhofer Institut für System-und Innovationsforschung-ISI, ISIP, ISI-CC N, Fraunhofer ISI; Working Paper Sustainability and Innovation, S 9/2014.

Bontron, C. (2012). Rare-earth mining in China comes at a heavy cost for local villages. *The Guardian*. Retrieved from https://www.theguardian.com/environment/2012/aug/07/china-rare-earth-village-pollution

Buchert, M., Manhart, A., Bleher, D., & Pingel, D. (2012). Recycling critical raw materials from waste electronic equipment. Oeko-Institut e.V. https://www.oeko.de/oekodoc/1375/2012-010-en.pdf

DERA. *Rohstoffinformationssystem ROSYS*. Retrieved from https://www.deutsche-rohstoffagentur.de/DERA/DE/ROSYS/rosys_node.html

DERA. (2017): *Chart des Monats, August 2017*. Retrieved from https://www.deutsche-rohstoffagentur.de/DERA/DE/Downloads/DERA%202017_cdm_08_Preisverlauf.pdf?__blob=publicationFile&v=4

de Vries, B. J. M. (2012). *Sustainability Science*. Cambridge: Cambridge University Press.

Elsner, H. (2011). Kritische Versorgungslage mit schweren Seltenen Erden - Entwicklung “Grüner Technologien” gefährdet? *Commodity Top News* (36), 1–8. https://www.bgr.bund.de/DE/Gemeinsames/Produkte/Downloads/Commodity_Top_News/Rohstoffwirtschaft/36_kritische-versorgungslage.html;jsessionid=5157AD877A1546E199246F096237F8F1.1_cid321?nn=1544716

Gerhold, L., Holtmannspötter, D., Neuhaus, C., Schüll, E., Schulz-Montag, B., Steinmüller, K., & Zweck, A. (Eds.). (2015). *Standards und Gütekriterien der Zukunftsforschung. Ein Handbuch für Wissenschaft und Praxis*. Wiesbaden: Springer VS. (Wissenschaftliche Schriftenreihe Zukunft und Forschung des Zentrums für Zukunftsstudien Salzburg, Bd. 4).

Glöser-Chahoud, S. (2017). *Quantitative Analyse der Kritikalität mineralischer und metallischer Rohstoffe unter Verwendung eines systemdynamischen Modell-Ansatzes*. Dissertation. Technische Universität Clausthal, Clausthal. Fakultät für Energie- und Wirtschaftswissenschaften. Retrieved from https://dokumente.ub.tu-clausthal.de/servlets/MCRFileNodeServlet/clausthal_derivate_00000303/Db113324.pdf

Guinée, J. B. &; Heijungs, R. (2011). Life cycle sustainability analysis: Framing questions for approaches. *Journal of Industrial Ecology*, *15*(5), 656–658.

Han, A., Ge, J., & Lei, Y. (2015). An adjustment in regulation policies and its effects on market supply: Game analysis for China’s rare earths. *Resources Policy*, *46*, 30–42. https://doi.org/10.1016/j.resourpol.2015.07.007

Hoenderdaal, S., Tercero Espinoza, L., Marscheider-Weidemann, F., & Graus, W. (2013). Can a dysprosium shortage threaten green energy technologies? *Energy*, *49*, 344–355. https://doi.org/10.1016/j.energy.2012.10.043

Klossek, P., Kullik, J., & van den Boogaart, K. G. (2016). A systemic approach to the problems of the rare earth market. *Resources Policy*, *50*, 131–140. https://doi.org/10.1016/j.resourpol.2016.09.005

Kuipers, K. J .J., van Oers, L. F. C. M., Verboon, M., & van der Voet, E. (2018). Assessing environmental implications associated with global copper demand and supply scenarios from 2010 to 2050. *Global Environmental Change*, *49*, 106–115. https://doi.org/10.1016/j.gloenvcha.2018.02.008

Langkau, S., & Tercero Espinoza, L. A. (2018). Technological change and metal demand over time. What can we learn from the past? *Sustainable Materials and Technologies*, *16*, 54–59. https://doi.org/10.1016/j.susmat.2018.02.001

Lee, J. C. K., & Wen, Z. (2017). Rare earths from mines to metals. Comparing environmental impacts from China’s main production pathways. *Journal of Industrial Ecology*, *21*(5), 1277–1290. https://doi.org/10.1111/jiec.12491

Machacek, E., & Fold, N. (2014). Alternative value chains for rare earths: The Anglo-deposit developers. *Resources Policy*, *42*, 53–64. https://doi.org/10.1016/j.resourpol.2014.09.003

Marscheider-Weidemann, F., Langkau, S., Hummen, T., Erdmann, L., Tercero Espinoza, L., Angerer, G. … Benecke, S. (2016). Rohstoffe für Zukunftstechnologien 2016. Edited by Deutsche Rohstoffagentur (DERA) in der Bundesanstalt für Geowissenschaften und Rohstoffe (BGR). Berlin (DERA Rohstoffinformationen, 28). Retrieved from http://www.deutsche-rohstoffagentur.de/DERA/DE/Downloads/Studie_Zukunftstechnologien-2016.pdf

Marx, J., Schreiber, A., Zapp, P., & Walachowicz, F. (2018). Comparative life cycle assessment of NdFeB permanent magnet production from different rare earth deposits. *ACS Sustainable Chemical Engineering* *6*(5), 5858–5867. https://doi.org/10.1021/acssuschemeng.7b04165

Mendoza Beltran, A., Cox, B., Mutel, C., Vuuren, D. P., Font Vivanco, D., Deetman, S., … Tukker, A. (2018). When the background matters. Using scenarios from integrated assessment models in prospective life cycle assessment. *Journal of Industrial Ecology*, *24*(1), 64–79. https://doi.org/10.1111/jiec.12825

MIIT. (2016). 稀土行业发展规划 (2016–2020). Development Plan for the rare earth industry. http://www.gov.cn/xinwen/2016-10/18/content_5120998.htm

Nuss, P., & Eckelman, M. J. (2014). Life cycle assessment of metals. A scientific synthesis. *PloS ONE*, *9*(7), e101298. https://doi.org/10.1371/journal.pone.0101298

Ritchey, T. (2002). General morphological analysis. A general method for non-quantified modelling. *Swedish Morphological Society*.

Roskill Information Services. (2011). Rare Earths & Yttrium: Market Outlook to 2015. A quick introductory guide to rare earths. https://ia600207.us.archive.org/27/items/ritchey_swemorph_Gma/gma.pdf

S&P Global. (2019). *SNL Database. Online database with costs.* Retrieved from https://platform.marketintelligence.spglobal.com

Schreiber, A., Marx, J., Zapp, P., Hake, J.-F., Voßenkaul, D., & Friedrich, B. (2016). Environmental impacts of rare earth mining and separation based on eudialyte. *A new European way Resources*, *5*(4), 32. https://doi.org/10.3390/resources5040032

Schrijvers, D., Hool, A., Blengini, G. A., Chen, W.-Q., Dewulf, J., Eggert, R., … Wäger, P. A. (2020). A review of methods and data to determine raw material criticality. *Resources, Conservation and Recycling*, *155*, 104617. https://doi.org/10.1016/j.resconrec.2019.104617

Schüler, D., Buchert, M., Liu, R., Dittrich, S., & Merz, C. (2011). Study on rare earths and their recycling. Final report for the greens/EFA group in the European Parliament. Edited by The Greens/European Free Alliance, Öko-Institut e.V. Darmstadt. https://www.oeko.de/oekodoc/1112/2011-003-en.pdf

Schüler-Zhou, Y. (2018). *Chinas Rohstoffpolitik für Seltene Erden. Edited by DERA. BGR (Commodity Top News, 57).* Retrieved from https://www.bgr.bund.de/DERA/DE/Aktuelles/rohstoff_seltene_erden.html

Tercero Espinoza, L., Schrijvers, D., Chen, W.-Q., Dewulf, J., Eggert, R., Goddin, J., … Hool, A. (2020). Greater circularity leads to lower criticality, and other links between criticality and the circular economy. *Resources, Conservation and Recycling*, *159*, 104718. https://doi.org/10.1016/j.resconrec.2020.104718

UNEP. (2011). Recycling rates of metals – A status report. With assistance of Thomas E. Graedel, Julian Allwood, Jean-Pierre Birat, Matthias Buchert, Christian Hagelüken, Barbara Reck et al. Edited by United Nations Environment Programme. UNEP. Retrieved from http://www.unep.org/resourcepanel/Portals/24102/PDFs/Metals_Recycling_Rates_110412-1.pdf

van der Voet, E., van Oers, L., Verboon, M., & Kuipers, K. (2019). Environmental implications of future demand scenarios for metals. Methodology and application to the case of seven major metals. *Journal of Industrial Ecology*, *23*(1), 141–155. https://doi.org/10.1111/jiec.12722

van Oers, L. (2015). *CML-IA database, characterisation and normalisation factors for midpoint impact category indicators. Version 4.5.* Retrieved from http://www.cml.leiden.edu/software/data-cmlia.html

Walz, R., Bodenheimer, M., & Gandenberger, C. (2016). Kritikalität und Positionalität. Was ist kritisch für wen - und weshalb? *Kritische Metalle in der Grossen Transformation*, *S*, 19–38. https://doi.org/10.1007/978-3-662-44839-7_2

Weng, Z., Haque, N., Mudd, G. M., & Jowitt, S. M. (2016). Assessing the energy requirements and global warming potential of the production of rare earth elements. *Journal of Cleaner Production*, *139*, 1282–1297. https://doi.org/10.1016/j.jclepro.2016.08.132

Wübbeke, J. (2013). Rare earth elements in China. Policies and narratives of reinventing an industry. *Resources Policy*, *38*(3), 384–394. https://doi.org/10.1016/j.resourpol.2013.05.005

Yang, X. J., Lin, A., Li, X.-L., Wu, Y., Zhou, W., & Chen, Z. (2013). China’s ion-adsorption rare earth resources, mining consequences and preservation. *Environmental Development*, *8*, 131–136. https://doi.org/10.1016/j.envdev.2013.03.006

Zapp, P., Marx, J., Schreiber, A., Friedrich, B., & Voßenkaul, D. (2018). Comparison of dysprosium production from different resources by life cycle assessment. *Resources, Conservation and Recycling*, *130*, 248–259. https://doi.org/10.1016/j.resconrec.2017.12.006

Zhou, B., Zhongxue, L., & Congcong, C. (2017). Global potential of rare earth re-sources and rare earth demand from clean technologies. *Minerals*, *7*(11), 203.

Zwicky, F., & Wilson, A. (Eds.). (1967). New methods of thought and procedure. *Contributions to the Symposium on Methodologies.* Berlin: Springer.

SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

How to cite this article: Langkau S, Erdmann M. Environmental impacts of the future supply of rare earths for magnet applications. *J Ind Ecol*. 2020;1–17. https://doi.org/10.1111/jiec.13090