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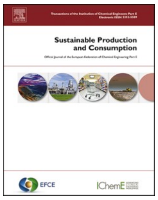

Mitigating the disproportionate environmental impacts and costs of dysprosium in Nd-Fe-B magnets through material efficiency

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ABSTRACT

Ultra-high-grade neodymium-iron-boron (Nd-Fe-B) magnets are essential components of clean energy technologies, including electric vehicles and wind turbines. However, they often contain dysprosium (Dy), a heavy rare earth whose extraction poses environmental, social and supply risks, and which is classified as a critical raw material by the European Union. Reducing Dy content while maintaining the magnetic performance required for these applications, enabled by material efficiency techniques, is therefore a critical step toward a sustainable energy transition. This study quantifies the life cycle environmental impact and raw material costs of manufacturing Nd-Fe-B magnets containing 1–8 wt% Dy. We modelled Nd and Dy as distinct upstream supply chains in the magnet life cycle. The results reveal that despite its low content, Dy contributes disproportionately to environmental impacts (e.g., 78% of freshwater ecotoxicity, 75% of marine eutrophication, and 78% of land use, for a baseline magnet composition with 4 wt% Dy), as well as magnet materials costs (25–44%). Reducing Dy content from 4 to 1 wt% would prevent the leaching of 480–840 kg of ore, avoid 12–17 kg CO_2-eq, reduce the fifteen other environmental impacts assessed by 11 to 64%, and save around €10 per kilogram of magnet. At the system level, without material efficiency (baseline 4 wt% Dy), cumulative Dy demand for magnets in a net-zero emissions scenario would be equivalent to two-thirds of present reserves by 2050. Limiting Dy content in magnets, whose technical feasibility has been demonstrated, represents a crucial solution to mitigate resource depletion, reduce environmental impacts and lower costs.

1. Introduction

Neodymium-iron-boron (Nd-Fe-B) magnets are essential components of clean energy technologies, such as electric vehicles (EVs) and wind turbines. Their unique magnetic performance explains their widespread use. Their composition depends on the required magnetic properties, such as coercivity (resistance to demagnetisation), remanence (magnetisation retained after removal of the external magnetic field) and maximum energy product (the maximum magnetic energy the magnet can deliver), as well as the operating conditions. To meet the requirements of high-temperature applications, such as motors and generators, heavy rare earths (HRE), particularly Dysprosium (Dy), are added to improve coercivity and prevent thermal demagnetisation (Chen et al., 2015; Dai et al., 2023). However, Dy content must be kept to a minimum, as Dy also reduces remanence and maximum energy product (Chen et al., 2015).

Additionally, the use of Dy raises ethical, environmental and geopolitical concerns. Following China's efforts to clean up its domestic rare earth (RE) industry – notably the closure of mines in Ganzhou, Jiangxi Province – Chinese producers have turned to neighbouring Myanmar for new sources of HRE. According to Global Witness, in Myanmar, RE mining consists of unregulated and illegal operations, controlled by militias. These activities cause serious environmental damage, including deforestation, landslides and water contamination (Global Witness, 2022). Currently, most Dy is produced from Ion-Adsorption Clay (IAC) deposits in Southern China and Myanmar (European Commission, n.d.). Processing of the mined materials is almost exclusively done by Chinese companies (Global Witness, 2022), increasing geographical supply risk, as illustrated by recent events. In April 2025, following new US tariffs, China imposed export licensing on seven RE elements, resulting in a sharp reduction of shipments (Jackson, 2025). This decision has reignited concerns about supply chain vulnerability, recalling the 2010 export restrictions to Japan, which led to a ten-fold price surge (Baskaran and Schwartz, 2025; Sprecher et al., 2015). At the same time, the growing global demand for low-carbon technologies, in response to climate targets, is leading to a rapid

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increase in Dy demand (Dai et al., 2023; Eheliyagoda et al., 2025). Dai et al. (2023) project that global Dy demand will rise by a factor of 5 to 10 between 2020 and 2050. Due to their limited availability, geopolitical supply risks and essential role in the energy transition, RE are recognised as critical raw materials by many countries, including the European Union (Carrara et al., 2023) and the United States (U.S. Geological Survey, 2022), with HRE such as Dy even scarcer than light RE.

Limiting Dy consumption is therefore a priority, and several studies, projects and companies have already investigated the technical feasibility of reducing its content, without compromising the high magnetic performance of magnets. Material efficiency techniques, such as those studied by Chen et al. (2015), Cheng et al. (2025), Huang and Mo (2024), Lee et al. (2016) and Wang et al. (2023), focus on optimising the microstructure, notably through grain boundary diffusion, to achieve high coercivity with less Dy (see Table A1). Research projects like RECO2MAG (Emilsson, 2025) and ROMEO (European Commission, 2016) have developed solutions to reduce HRE requirements, while the ongoing GREENE (2024) project continues this work. Other approaches include material substitution (Pavel et al., 2017) and improvement in recycling systems (SUSMAGPRO, 2019). This study focuses on material efficiency, as it effectively reduces HRE use while maintaining magnetic properties required for clean energy technologies and is compatible with current manufacturing processes, with material efficiency reflected in magnet composition.

While several studies have addressed the technical feasibility of reducing Dy content in magnets and others have examined the environmental (Marx et al., 2018), economic (Liu et al., 2021) and social (Werker et al., 2019) aspects of Nd-Fe-B magnet supply chains, none specifically address the sustainability implications of Dy reduction. This study aims to quantify the environmental and economic benefits of reducing Dy content in Ultra-High (UH)-grade sintered Nd-Fe-B magnets, intended for EVs and wind turbines. Across composition scenarios with 1 to 8 wt% Dy, we quantify the amount of Dy mining that could be avoided, the environmental benefits using LCA and the economic implications based on raw material costs.

2. Methodology

2.1. Scenarios

2.1.1. Dy range and magnet composition

We considered Nd-Fe-B permanent magnets with Dy contents ranging from 1 to 8 wt%. This range reflects the compositions reported in the literature for Dy-containing magnets. Magnets with 4 to 8 wt% Dy were assumed to be produced without grain boundary diffusion, with the 8 wt% upper limit reflecting the high Dy values reported in the literature for high-performance magnets (e.g. 7 wt% in Emilsson (2025) and Pavel et al. (2017), 7.7 wt% in Wang et al. (2023), 8 wt% in Vasilenko et al. (2022), and 8.7 wt% in Dai et al. (2023)). Magnets containing $<$ 4 wt% Dy were assumed to employ material efficiency techniques to maintain coercivity while reducing RE content, down to approximately 1 wt% as reported in the literature (e.g. 0.85 wt% in Chen et al. (2015), 0.9 wt% in Wang et al. (2023), 1 wt% in Emilsson (2025), and 1.4 wt% in Dai et al. (2023)). The total RE fraction was set at approximately 30 wt%, based on typical composition values reported in the literature (Kumari and Sahu, 2023; Vasilenko et al., 2022), which means that reducing the Dy content increases Nd content. Table 1 details the hypothetical compositions of the Nd-Fe-B magnets.

2.1.2. Variability in recovery rates for ion-adsorption clay deposits

Around 80% of global HREE supply comes from Ion-Adsorption Clay (IAC) deposits (Russo et al., 2025). The main method used to extract HRE from these deposits is in-situ leaching. This process involves injecting an ammonium sulfate-based leaching solution into the ore body to exchange and dissolve the RE ions into the leachate. In this study, we assume that the recovery rate, i.e. the proportion of RE that is successfully dissolved into the leachate during in-situ leaching, ranges between 40% and 70%, as in Schulze et al. (2017). Recovery depends both on ore characteristics, such as permeability, ore particle size and porosity, and on operating conditions, like leaching solution concentration, pH, leaching time and liquid-solid (leaching solution volume to IAC mass) ratio (Sobri et al., 2024). Furthermore, lower-grade ores tend to contain more impurities, which reduces leaching selectivity and the efficiency of the precipitation process, resulting in lower recovery rates (Schulze et al., 2017). The lower the recovery rate, the more ore needs to be leached and, therefore, the more chemicals, materials and energy are required to obtain a given amount of recovered RE, resulting in greater environmental impacts. Given the variability of the recovery rate and to ensure that its influence on the results is accounted for, two scenarios were defined: a ***high recovery scenario*** with a 70% recovery rate and a ***low recovery scenario*** with a 40% recovery rate.

Table 1
Hypothetical magnet compositions for different Dy contents (Nd: Neodymium, Pr: Praseodymium, Dy: Dysprosium, Fe: Iron, B: Boron, Co: Cobalt, Al: Aluminium, Cu: Copper, Ga: Gallium).

Nd/Pr	Dy	Fe	B	Co	Al	Cu	Ga
28%	1%	68.5%	1%	1%	0.2%	0.2%	0.1%
28%	2%	68.5%					
27%	3%	68.5%					
26%	4%	68.5%					
25%	6%	67.5%					
23%	8%	67.5%					

2.2. Mining resources

We quantified the amount of ore mining that could be avoided by reducing Dy content in Nd-Fe-B magnets. The Dy content in the ore was estimated at 99.4 mg_{Dy}/kg_{ore}, using the following equation:

$$C_{Dy,in\ ore} = C_{REO,in\ ore} \times C_{Dy_2O_{3,REO}} \times \frac{n \times M_{Dy}}{M_{Dy_2O_3}}$$

Where $C_{REO,in\ ore}$ represents the fraction of Rare Earth Oxides (REO) in the ore, $C_{Dy_2O_{3,REO}}$ the fraction of Dy oxide within REO, n the number of Dy atoms per oxide molecule and M_{Dy} and $M_{Dy_2O_3}$ the molar mass of Dy and its oxide, respectively. IAC typically contain 0.05–0.5 wt% REO, but mining is considered viable only between 0.2 and 0.4 wt% REO (Schulze et al., 2017). This study assumes an average REO concentration of 0.3 wt %, with Dy_2O_3 constituting 3.8 wt% of the REO content.

Based on the estimated Dy content, the amount of ore required to extract 1 kg of Dy was estimated at 14.4–25.1 t (*high-low recovery scenarios)*. These values were used to quantify the ore savings associated with reducing Dy content in magnets. In addition, we quantified the amount of chemical inputs to mining that could be avoided through Dy reduction. Chemical requirements for mining were derived from the life cycle inventory (LCI) compiled for this study (see Section 2.3.2). The two primary chemicals used in the in-situ leaching process are ammonium bicarbonate and ammonium sulfate. Their respective demands per kilogram of RE concentrate (*high to low recovery*) range from 3.00 to 4.10 kg for ammonium bicarbonate and 6.08 to 10.4 kg for ammonium sulfate. According to the LCI, 0.106 kg of RE concentrate leached is required for each 1 wt% of Dy contained in 1 kg of magnet.

2.3. Life cycle assessment

2.3.1. Goal and scope

This study quantifies and compares the environmental impacts of producing sintered Nd-Fe-B magnets with different Dy contents (1–8 wt %) through an attributional LCA following ISO 14040/14044 standards (ISO, 2006a, 2006b). The LCA adopts a cradle-to-gate approach, covering all processes from raw material extraction – including Nd from the Bayan Obo (BO) mine in China and Dy from IAC deposits in Myanmar – to the production of a shaped magnet. The coating stage is excluded, as the coating-to-magnet mass ratio depends on the size and geometry of the magnet, as well as the use and end-of-life phases, which are considered identical for the different magnet compositions. All materials are assumed to come from primary extraction; recycled feedstock is not considered as this is not yet common practice in the industry. Thus, the system boundary includes four main production stages: RE mining, metal refining, alloying and magnet shaping. A detailed flowchart of the modelled processes is provided in Fig. A1. The functional unit is the production of 1 kg of sintered UH-grade Nd-Fe-B magnet. The LCA was conducted for six magnet compositions (see Table 1), each modelled under the *low* and *high recovery scenarios* described in Section 2.1.2.

2.3.2. Life cycle inventory

The LCI combines foreground data from previous LCA studies for the production stages defined in the system boundary, with background data (e.g. electricity mixes or chemicals production) from the ecoinvent v3.11 database, cut-off system model. It was modelled using Activity Browser, an interface of the Brightway LCA framework (Steubing et al., 2020). The LCIs developed by Miranda Xicotencatl et al. (2021) served as a starting point, and were complemented by other relevant sources including Bailey et al. (2020), Lee, J.C.K and Wen (2017), Marx et al. (2018), Schulze et al. (2017), Sprecher et al. (2014), Vahidi and Zhao (2017) and Zapp et al. (2018).

RE metal production is a multi-product system. To allocate environmental burdens among co-produced oxides, economic allocation was applied at the solvent-extraction stage, as recommended by Santero and Hendry (2016) for co-produced metals with large differences in market values. They further note that, for metals, refining downstream processes (such as solvent extraction) are best characterised using economic allocation. The allocation factors were calculated using the average REO market prices from the last three years (2022–2024), as recommended by Guinée et al. (2004). Deposit-specific factors were calculated for BO and IAC ores to reflect their different compositions.

Nd and Dy are modelled as distinct upstream supply chains in the magnet life cycle. Given that different scenarios are studied, the LCI differs for two production stages: the alloying process ("NdFeB strip casting"), where the proportions of Dy, Nd and iron vary according to the magnet composition; and the Dy oxide production processes, for which two *scenarios* were modelled to account for differences in recovery rates of IAC deposits. Due to the lack of LCI data on HRE mining from IAC deposits in Myanmar, literature data from Chinese operations (Schulze et al., 2017) were used as a proxy. Both Southern China and Myanmar operations employ the same extraction processes under comparable operating conditions, namely in-situ leaching using ammonium-based leaching agents through holes drilled into the ore body and precipitation in ponds. Moreover, subsequent processing operations are carried out in China (Meehan et al., 2025). The detailed LCI, including REO prices and concentrations, a comparison of economic and mass allocation factors, unit process descriptions and data sources is provided in Supplementary material 1.

2.3.3. Life cycle impact assessment

The impact assessment was conducted for the 16 impact categories of the Environmental Footprint method v3.1, as recommended by the European Commission (2021). The categories include climate change, ozone depletion, human toxicity, particulate matter, ionising radiation, photochemical ozone formation, acidification, eutrophication, ecotoxicity, land, water and resource use (see Table A2). Normalization and weighting were not applied.

2.3.4. Interpretation

The environmental benefits of Dy reduction were assessed both in relative terms (percentage change compared to a baseline) and in absolute terms (impact reduction per 1 wt% Dy decrease). Moreover, three contribution analyses were carried out to identify hotspots in the production of Nd-Fe-B magnets. The first quantifies the relative contributions of the main production stages to each impact category. The second and third examine in detail the climate change and freshwater ecotoxicity categories, specifying the contributions of the various foreground processes. We focused on climate change as it is the most widely recognised, interpretable and policy-relevant impact category, and on freshwater ecotoxicity in order to acknowledge the potential toxicological impacts associated with Dy production. The contribution analyses use an average scenario (55% recovery rate) because the objective is to identify hotspots rather than differences between recovery rates, and were performed for three magnet compositions (1, 4 and 8 wt% Dy).

2.4. Economic assessment

The economic assessment evaluates the influence of Dy on raw material costs for the six magnet compositions (Table 1), with a reference unit of 1 kg of Nd-Fe-B magnet. The study covers the period from January 2020 to June 2025. Average monthly market prices of raw materials for this period were obtained from ISE (2025). Raw material costs were calculated as the sum of each element's price multiplied by its respective mass fractions in the magnet composition. The final costs were adjusted to account for a 10% grinding loss. For the Boron content, Ferroboron (FeB) was considered instead of the pure element, in line with industrial practice. As FeB contains 18 wt% B, 1 wt% B in the magnet corresponds to 0.0556 kg of FeB. Because FeB also contains 82 wt% Fe, it contributes to 0.0456 kg of Fe, which was deducted from the pure Fe share. Two complementary analyses were carried out. The first assesses the evolution of raw material costs for the different magnet compositions over the period January 2020 to June 2025. The second quantifies the contributions of Nd, Dy and other alloying elements to the overall raw material costs.

2.5. Extrapolation to the global level

To explore the potential benefits of Dy content reduction on a global level in the future, we first estimated the demand for Nd-Fe-B magnets between 2024 and 2050 using the International Energy Agency (IEA) scenarios: Stated Policies (STEPS), Announced Pledges (APS) and Net Zero Emissions by 2050 (NZE). To convert the demand for "magnet rare earth elements" provided by the IEA (2025) into magnet demand, we assumed a RE fraction of 30 wt% in Nd-Fe-B (Kumari and Sahu, 2023; Vasilenko et al., 2022). Based on this, magnet demand is estimated at 269 kt in 2024 and is projected to increase to 592–688 kt by 2050, depending on the scenario (Fig. 1A). Cumulative magnet demand was calculated for 2024–2050 (Fig. 1B), resulting in a range between 12.5 (STEPS) and 14.4 Mt (NZE).

In 2024, clean energy applications (EVs and wind turbines) accounted for about 21% (IEA, 2025) of global Nd-Fe-B magnets demand. Since these applications require HRE, we use this 21% share as a proxy for the proportion of Nd-Fe-B magnets containing Dy in 2024. Given the projected growth of clean energy technologies, we assume an average long-term share of Dy-containing magnets of 36%. These estimates are conservative, as Dy can also be used in other applications (e.g., industrial motors), but no other reliable data was found. The actual share of magnets containing Dy is therefore likely higher.

3. Results

3.1. Environmental assessment

3.1.1. Mining resources

Each 1 wt% of Dy in 1 kg of Nd-Fe-B magnet requires 0.0111 kg of Dy (assuming a 10% grinding loss). This demand corresponds to the leaching of 160–279 kg of ore (*high-low recovery scenarios*). Reducing the

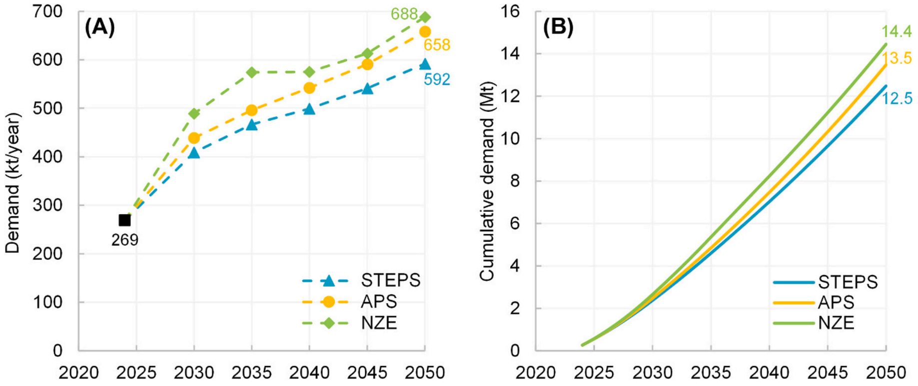

Fig. 1. Estimated global demand for Nd-Fe-B magnets (2024–2050) under IEA (International Energy Agency) scenarios: Stated Policies (STEPS), Announced Pledges (APS) and Net Zero Emissions by 2050 (NZE). (A) Annual demand projections in 2024 and every five years until 2050 and (B) Cumulative demand calculated over the period. Raw data in Supplementary material 2.

Dy content in magnets proportionally decreases the resource requirements for in-situ leaching, including chemicals. For each 1 wt% reduction in Dy, 0.646 kg to 1.10 kg of ammonium sulphate and 0.318 kg to 0.435 kg of ammonium bicarbonate are saved (*high to low recovery scenarios*) per kilogram of magnet. Next, we present the potential environmental benefits associated with these savings through LCA.

3.1.2. *Life cycle assessment*

Fig. 2 compares the environmental performance of each magnet composition with a baseline magnet containing 4 wt% Dy, representing the current average content of UH-grade magnets. Results are given for the *low* and *high recovery rate scenarios*. Table A3 reports the corresponding absolute reductions in environmental impacts per 1 wt% Dy reduction. Both confirm that lowering Dy content reduces impacts in all categories despite increased Nd content. The most notable reductions are observed for terrestrial eutrophication, freshwater ecotoxicity, photochemical oxidant formation, acidification, marine eutrophication and land use (especially for the *low recovery scenario*). For freshwater ecotoxicity, reducing Dy from 4 wt% to 3 wt% decreases the impact by 12% in the *high recovery scenario* and 21% in the *low*; reducing it to 1 wt

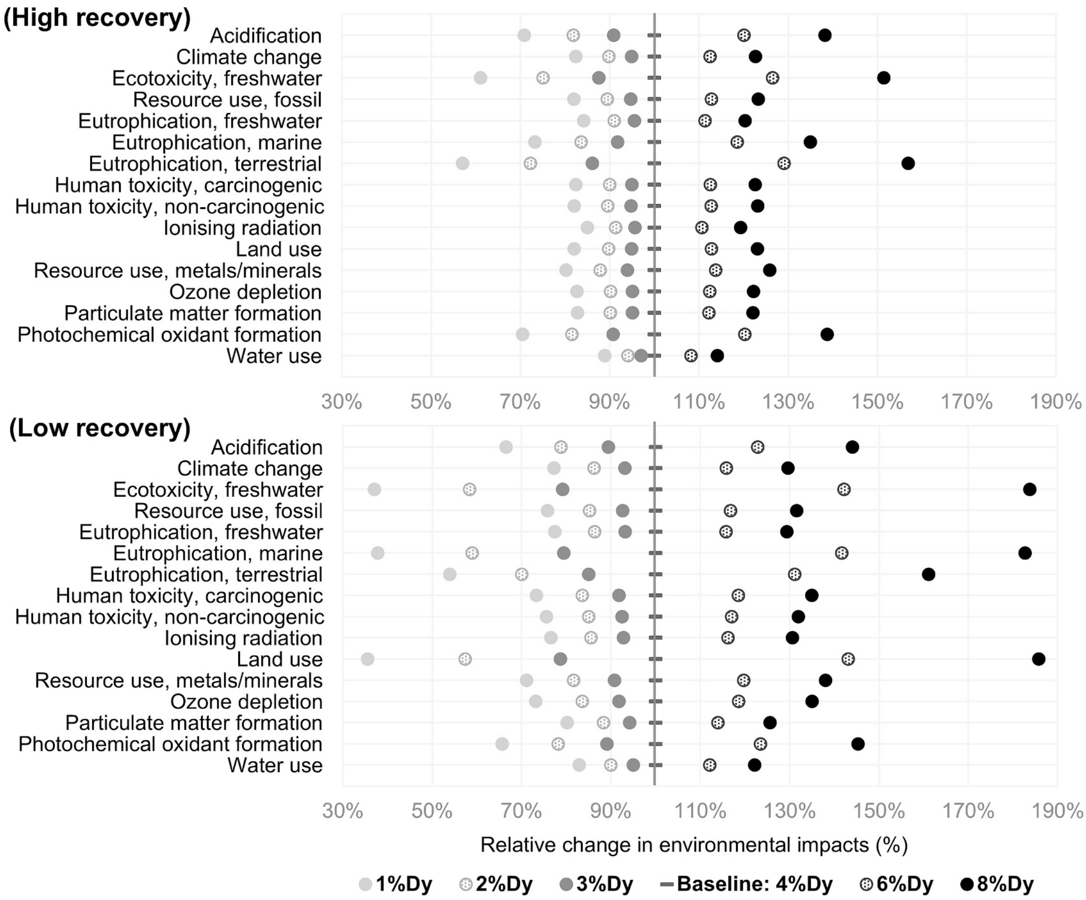

Fig. 2. Relative environmental benefits of reducing Dy content in Nd-Fe-B magnets, expressed as a percentage change in impacts compared to the baseline composition (4 wt% Dy). Results are given for the *high recovery* (upper figure, recovery rate of 70%, lower impact) and *low recovery* (lower figure, recovery rate of 40%, higher impact) scenarios. Values below 100% indicate reduced impacts compared with the baseline, while values above 100% indicate increased impacts.

% lowers the impact by 39% and 63%, respectively.

The environmental benefits are consistently more significant in the *low recovery scenario*, reflecting the higher impacts associated with Dy production when IAC recovery rates are lower (40% for the *low scenario*, versus 70% for the *high*). This effect is particularly pronounced for land use, marine eutrophication and freshwater ecotoxicity. For example, reducing Dy content from 4 wt% to 3 wt% decreases land use impact by 5.1% in the *high recovery scenario* but by 21% in the *low scenario* (Fig. 2). Therefore, under *low recovery* conditions, the potential for impact reduction is amplified, making Dy content reduction even more crucial.

3.1.3. LCA contribution analysis

The Dy content largely influences the environmental hotspots in the Nd-Fe-B magnet supply chain (Fig. 3). For magnets containing only 1 wt % Dy, the production of Nd oxide is the most significant contributor to all impact categories, accounting for 85% of ozone depletion and 82% of carcinogenic human toxicity. These high contributions are mainly due to the use of hydrochloric acid in the solvent extraction process and, to a lesser extent, in the leaching of RE sulfate. Even at low Dy content (1 wt %), Dy oxide production contributes disproportionately to some impact categories such as freshwater ecotoxicity (45%) and marine eutrophication (41%) due to the chemicals used during in-situ leaching and solvent extraction, as well as land use (46%). The higher the Dy content of the magnet, the more the production of Dy oxide contributes to environmental impacts, eventually becoming the main hotspot in several categories.

Refining of Nd and Dy metals contributes significantly to terrestrial eutrophication (12–22%, for 1 wt% Dy and 8 wt% Dy, respectively) and particulate matter formation (20–26%). The contribution to terrestrial eutrophication is mainly due to ammonia emissions during the fluorination of the oxides, with no mitigation from air filtration considered in literature sources. The particulate matter emissions come from the molten salt electrolysis process of Nd refining and ammonia emissions during fluorination. Alloying notably affects minerals and metals resource use (19–33% for 8 wt% Dy and 1 wt% Dy, respectively) and water use (15–20%) due to the inclusion of cobalt and other raw

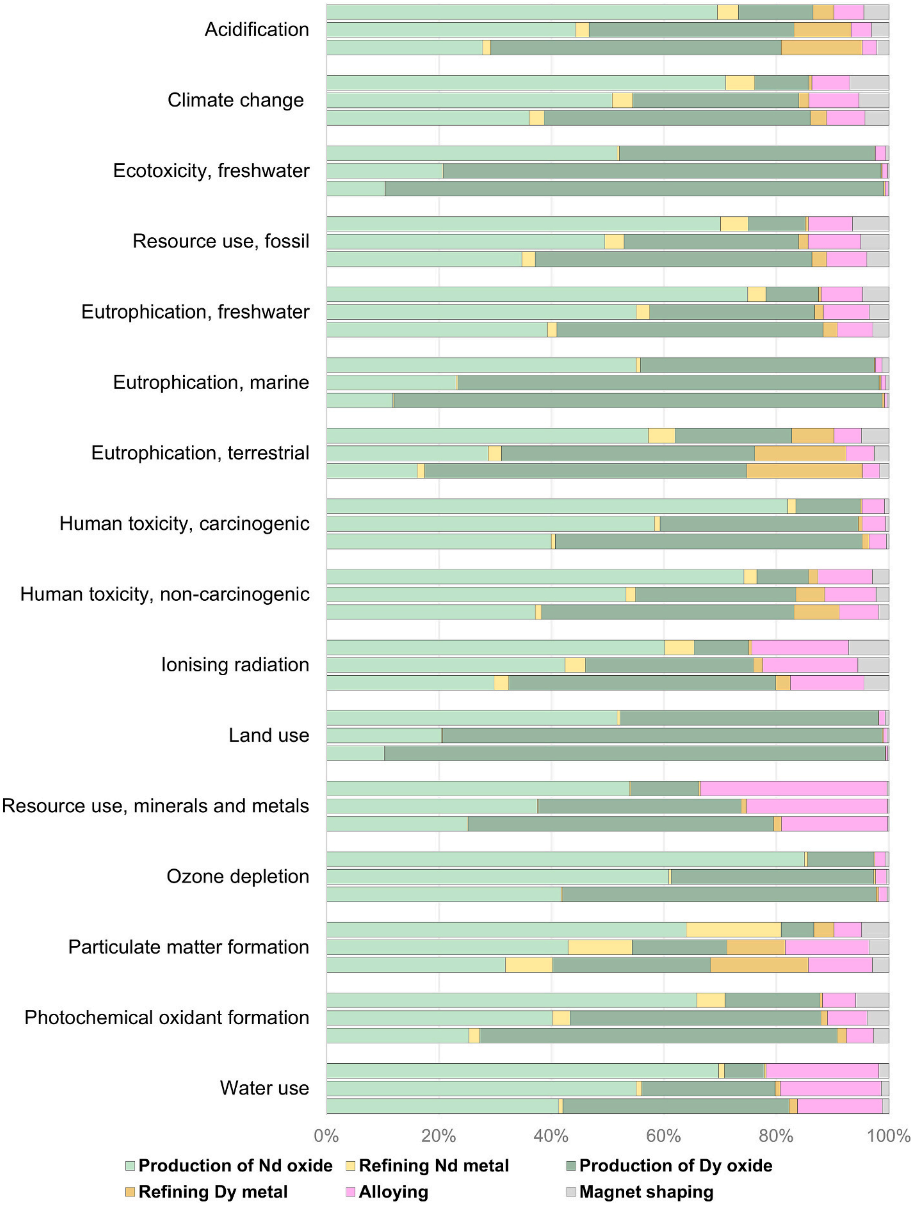

Fig. 3. Contribution of production stages to environmental impacts for Nd-Fe-B magnets with different Dy content. For each impact category, three stacked bars are shown corresponding to magnets containing 1 wt% Dy (top bar), 4 wt% Dy (middle bar) and 8 wt% Dy (bottom bar). The recovery rate of RE from the IAC ore applied is 55% (Average scenario). Raw data in Supplementary material 2.

materials. Magnet shaping has minimal influence across all categories, confirming that most environmental impacts occur at earlier stages, particularly during RE mining and refining. Next, we provide a more detailed contribution analysis for climate change and freshwater ecotoxicity.

3.1.3.1. Climate change. Although Nd-Fe-B magnets are essential to energy transition technologies, their production is GHG-intensive. The results indicate that producing 1 kg of Nd-Fe-B UH-grade magnet generates between 55.4 kg CO_2-eq (corresponding to 1 wt% Dy and *high recovery scenario*) and 95.7 kg CO_2-eq (for the 8 wt% Dy and *low recovery scenario*). Climate change is one of the impact categories that is moderately sensitive to Dy content reduction (Fig. 2). Reducing Dy content from 4 wt% to 1 wt% lowers climate change impacts by 18% in the *high recovery scenario* and 23% in the *low*. Each 1 wt% Dy reduction avoids 3.43–4.95 kg CO_2-eq (*high recovery*) to 5.09–6.61 kg CO_2-eq (*low*). Although proportionally smaller than for other categories, these reductions remain significant given the projected scale of global magnet demand and the importance of climate change mitigation.

The contribution analysis (Fig. 3) shows that REO production is the main source of GHG emissions, accounting for over 80% of climate change impacts for all the hypothetical magnet compositions. At the process-level (Fig. 4A), solvent extraction is the principal contributor, representing about 58% of total emissions, equivalent to 33.3 (1%Dy) to 51.2 (8%Dy) kg CO_2-eq. These emissions are mainly caused by electricity and chemicals use. Solvent extraction separates individual RE chlorides from a hydrochloric acid leachate containing a mixture of $RECl_3$. Ammonium bicarbonate or oxalic acid is then used to precipitate the RE chloride to form RE carbonates (Lee, J.C.K and Wen, 2017; Schulze et al., 2017). Finally, the precipitate is heated to obtain REO, which explains the need for electricity. Mining and in-situ leaching of IAC ore, linked to Dy production, is the second largest source of GHG emissions, but its contribution decreases at lower Dy contents. For magnets with 8 wt% Dy, it can generate up to 16.2 kg CO_2-eq. Emissions come from heat production and chemical use, as the process covers the leaching with ammonium sulfate-based solution, precipitation with ammonium bicarbonate and roasting (Schulze et al., 2017).

3.1.3.2. Freshwater ecotoxicity. Freshwater ecotoxicity quantifies the toxic impacts of chemical emissions on aquatic ecosystems. Results are expressed in comparative toxic units (CTUe) representing the potentially affected fraction of freshwater species integrated over time and volume per kilogram of chemical emitted. This category is highly sensitive to the production of Dy oxide (Fig. 3) and is therefore strongly affected by Dy content (Fig. 2). The freshwater ecotoxicity impact results range from 1320 CTUe (1 wt% Dy, *high recovery scenario*) to 11,900 CTUe (8 wt%

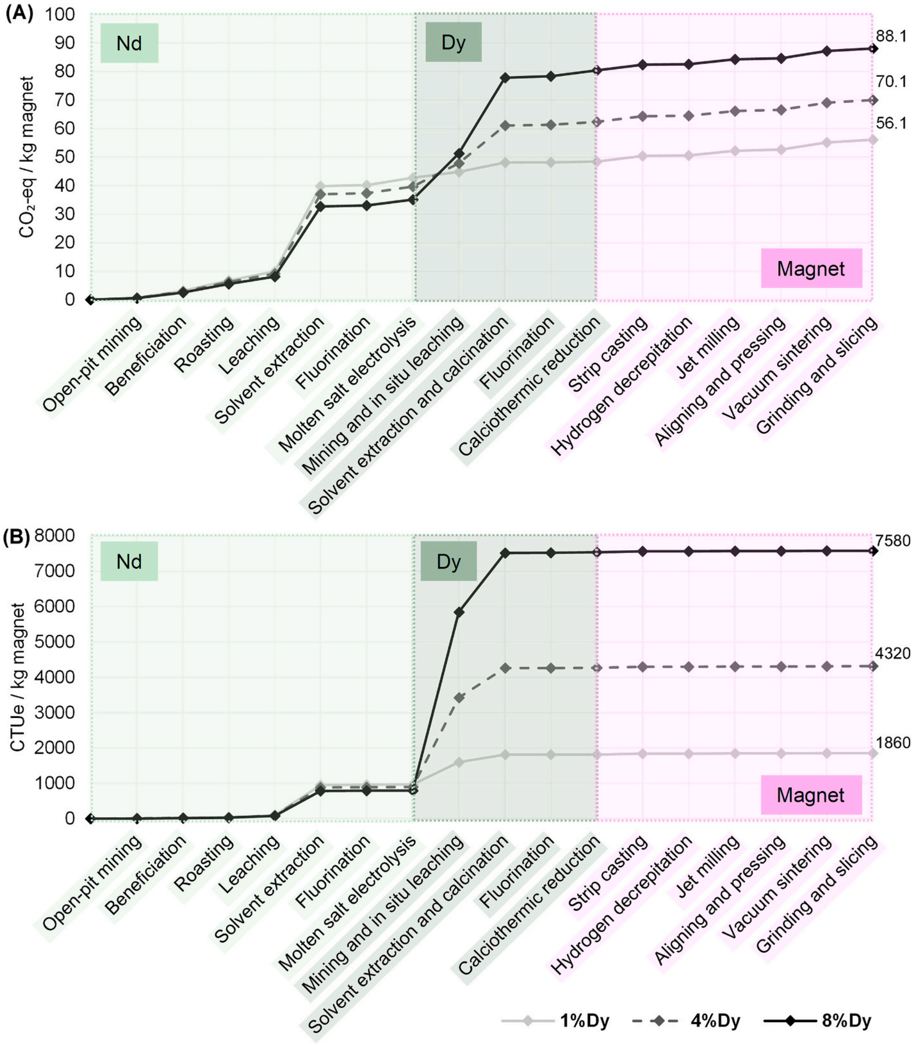

Fig. 4. Cumulative contribution of foreground processes of Nd-Fe-B magnet production to (A) Climate Change (kg CO_2-eq/kg magnet) and (B) Freshwater ecotoxicity (CTUe/kg magnet), for magnets composed of 1 wt%, 4 wt% and 8 wt% Dy. The recovery rate of RE from the IAC ore applied is 55% (Average scenario). Raw data in Supplementary material 2.

Dy, *low recovery scenario*) per kilogram of magnet.

For magnets containing 1 wt% Dy, solvent extraction is the largest contributor (57%) to freshwater ecotoxicity, while in-situ leaching accounts for 34%. As Dy content rises, the relative contribution of leaching grows substantially, representing 59% at 4 wt% Dy and 67% at 8 wt% Dy, while solvent extraction's share decreases (Fig. 4B). The high contribution of these two processes to freshwater ecotoxicity is mainly due to emissions of ammonium, chloride and sulfuric acid into water. These emissions have a direct impact on freshwater ecosystems in mining regions such as Myanmar and Southern China, illustrating some of the local ecological risks associated with Dy production.

3.2. Economic assessment

The raw material cost per kilogram of Nd-Fe-B magnets is significantly influenced by the Dy content (Fig. 5A). Considering raw material market prices between January 2020 and June 2025, the associated costs for a magnet containing 8 wt% Dy are, on average, 1.3 times higher than for a magnet with 4 wt% Dy and 1.7 times higher than for one with 1 wt% Dy. Between January and October 2020, raw material costs were stable, with minimum values in January 2020 of €18.7 (1 wt% Dy) and €39.1 (8 wt% Dy), before rising sharply to their maximum in March 2022, when they reached €69.6 and €99.4. After this peak, costs gradually declined, stabilising again in early 2024 to mid-2025. Current raw material costs (June 2025) range from €24.4 to €40.3 (Fig. 5B). During the period studied, the relative difference between the minimum and maximum costs was 272% (1% Dy) and 154% (8% Dy). This illustrates the strong influence of Dy market price on the volatility of magnet costs.

Nd and Dy are the main contributors to raw material costs (Fig. 5B), while the contribution of other alloying elements is negligible. Considering market prices as of June 2025, only 1 wt% of Dy already accounted for 12% of the total raw material cost, whereas 8 wt% of Dy represented 56%. This confirms the disproportionate impact of Dy on magnet raw material costs compared to its content in the alloy. However, although reducing Dy content lowers the absolute cost of magnet raw materials, it does not mitigate cost volatility. The different magnet compositions broadly follow the same trend over time (Fig. 5A). Therefore, reducing Dy content is not sufficient to protect the cost of magnets from raw materials market fluctuations.

Nonetheless, even slight reductions in Dy content can lead to significant savings. Over the period studied, each 1 wt% Dy reduction results in savings of €2.07–5.83 per kilogram of magnet, with an average saving of €3.39/kg. In 2024, the savings per 1 wt% Dy were slightly lower, at €2.31–3.73/kg (average €2.86/kg). These reductions could be economically relevant on a large-scale, given the high global demand for Nd-Fe-B magnets (as shown in Section 4.1).

4. Discussion

4.1. Global implications of reducing Dy content

In 2024, global demand for Nd-Fe-B magnets was estimated at 269 kt (Fig. 1A), of which 21% were assumed to contain Dy (Section 2.5). Reducing Dy content by 1 wt% in these magnets would avoid 628 t of Dy, corresponding to 9.05–15.8 Mt (*high-low recovery scenarios*) of ore that would not need to be leached. Applying 2021 mining country shares (European Commission, n.d.), approximately 31% of Dy supply came from Myanmar. Under these conditions, a 1 wt% reduction could

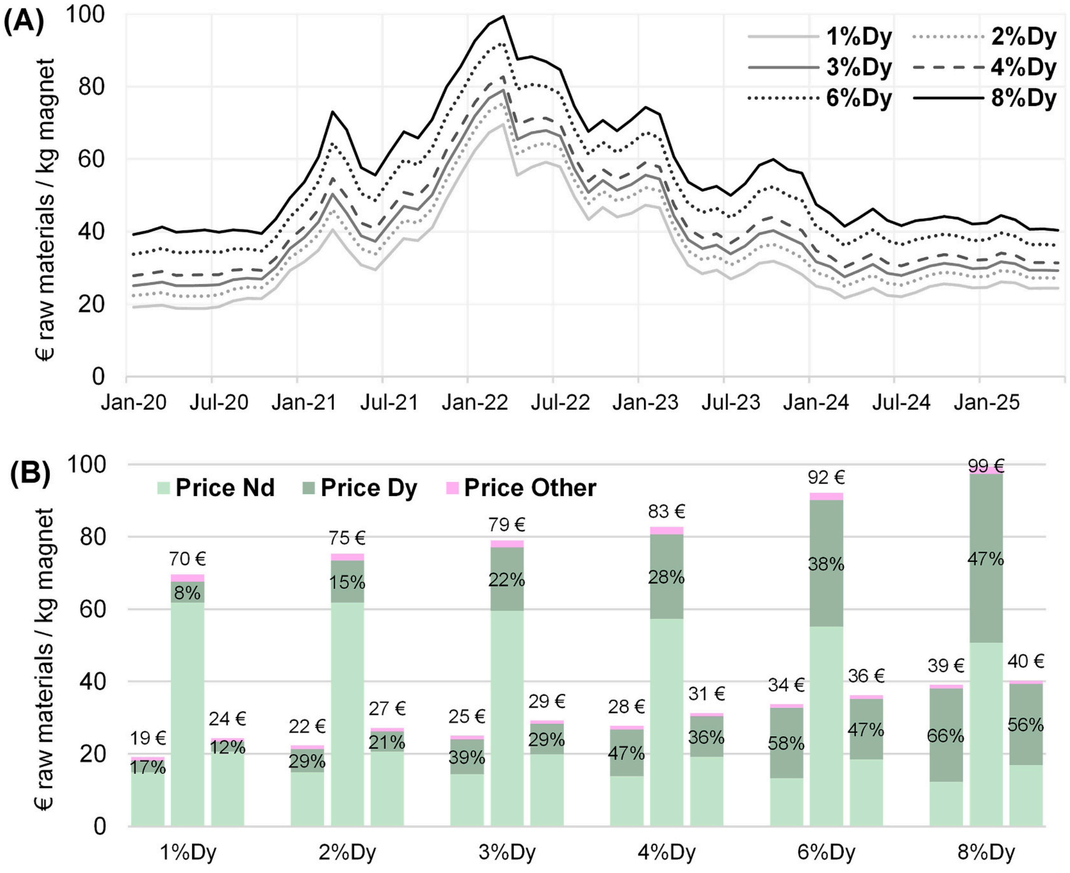

Fig. 5. Estimated raw material costs (€ raw materials / kg magnet) for 1 kg of Nd-Fe-B magnet. (A) Evolution of costs from January 2020 to June 2025, for the different magnet composition (1–8 wt% Dy). (B) Contribution of Nd and Dy to raw material costs. For each Dy content, three bars are shown corresponding to January 2020 (minimum price), March 2022 (maximum price) and June 2025. Raw data and contribution of raw materials to costs for each month from 2020 to June 2025 in Supplementary material 2.

prevent the leaching of 2.8–4.9 Mt of ore in Myanmar. Lower Dy content also decreases the chemical inputs required for in-situ leaching. Scaled to 2024 magnet production, each 1 wt% Dy reduction saves 36.5–62.2 kt of ammonium sulfate and 18.0–24.6 kt of ammonium bicarbonate (*high-low recovery scenarios*). These chemicals are at the core of the environmental problems observed in Myanmar's RE mining regions. Meehan et al. (2025) report severe water pollution with heavily contaminated rivers and streams, dried-out soils and abandoned toxic wastewater pools causing long-term risks. In this context, chemical savings may also mitigate the potential impact of mining on local environmental damage. Although Dy savings are partly compensated by additional Nd requirements, the contribution analysis (Fig. 3) shows that Dy mining has disproportionate environmental impacts relative to its content. Consequently, reducing Dy by 1 wt% in all Dy-containing magnets would avoid 194 to 374 kt of CO_2-eq emissions in 2024, equivalent to the annual emissions of 27 to 52 thousand European citizens (Crippa et al., 2025).

Long-term implications were assessed using cumulative magnet demand over 2024–2050, estimated at 12.5 Mt under STEPS to 14.4 Mt under NZE (Fig. 1B), representing a 16% increase over STEPS. Considering all Dy-containing magnets (36%), cumulative Dy demand is estimated at 50.0–57.8 kt (STEPS-NZE) if they all contain 1 wt% Dy, at 125–144 kt for a mixed distribution (equal shares of 1, 2, 3, 4 wt% Dy) and at 200–231 kt if they contain 4 wt% Dy. These demands represent 15–17%, 37–43% and 59–68% of global present reserves (338 kt, Dai et al., 2023), respectively. Other studies predict future supply constraints: Eheliyagoda et al. (2025) expect Dy demand to exceed primary supply capacity, and Wang et al. (2024) project that present reserves could be exhausted around 2035–2045 under NZE. Furthermore, the potential climate impact is considerable. The cumulative demand for Dy-containing magnets could emit between 249 Mt CO_2-eq. (1 wt% Dy, *high recovery scenario*, STEPS) and 384 Mt CO_2-eq. (4 wt% Dy, *low recovery*, NZE), comparable to the 2024 emissions of Algeria and the United Kingdom (Crippa et al., 2025). Since these figures only cover the conservative proportion of magnets containing Dy, total Nd-Fe-B production would generate significantly higher emissions. Although future decarbonisation of energy systems will reduce the environmental impacts, it will have limited influence on those related to mining and the use of chemicals.

The economic benefits are also noteworthy. Based on 2024 average savings of €2.86 per kilogram of magnet, a 1 wt% Dy reduction would avoid about €161 million in raw material costs, highlighting the substantial economic implications of even modest reductions. Over 2024–2050, each 1 wt% Dy reduction could save €15.3–17.6 billion (STEPS-NZE) in material costs. A shift from 4 wt% to 1 wt% Dy, across Dy-containing magnets, would therefore save around €50 billion globally.

In the context of the clean energy transition, these findings highlight the importance of reducing Dy content in order to limit the growth in critical mineral demand and its associated environmental, economic and supply disruption risks. From a business perspective, reducing raw material costs and exposure to volatile Dy prices already provides a strong financial incentive to adopt material efficiency strategies that lower HRE content. From a policy perspective, continued support for research, innovation and the industrial scaling-up of low-HRE magnets is important. Relevant policies could include establishing targets for HRE content in strategic applications to encourage progress in material efficiency techniques, prioritising funding for or procurement of low-HRE magnets, and strengthening traceability and responsible sourcing requirements throughout magnet supply chains.

4.2. Limitations and future research

This study has several limitations that should be acknowledged. Uncertainties in LCI data are inherent to LCAs. Notably, variations in recovery rates and ore grades can affect estimated material and energy requirements, influencing both LCA results and quantified mining resource savings. Recovery rates depend on leaching efficiency, local conditions and ore composition, which are often undocumented, particularly in Myanmar. The potential future ore depletion, resulting in a decline in REO grades in deposits, could further increase impacts. Future improvements in recovery efficiency or changes in Dy supply sources may also affect the results, but such developments were not considered in this study. However, using the current average ore grade (0.3 wt% REO), this study provides an indication of the potential benefits of reducing Dy content for current production conditions. Furthermore, applying a range of recovery rates (40–70%) ensures that the results reflect plausible conditions at different mining sites and variability in recovery efficiency. Methodological choices, such as the allocation method used, could also influence the absolute results of the LCA, but the main conclusion regarding Dy's disproportionate contribution to environmental impacts would remain unchanged under mass allocation. The LCA results also depend on the quality and representativeness of LCI data. Both background inventories from ecoinvent and foreground data from literature sources involve methodological choices, simplifications and combined production routes that may not reflect actual conditions. For example, emissions during fluorination are likely overestimated as abatement technologies were not considered (Marx et al., 2018). This limitation is especially relevant in regions like Myanmar where data scarcity means that the actual environmental impacts of unregulated mining activities are potentially underestimated and, consequently, so may be the environmental benefits associated with reducing Dy content. Nevertheless, comprehensive LCIs based on primary data for informal HRE mining in Myanmar are urgently needed.

The economic assessment focuses on raw material costs, which represent a significant portion of the total production cost of Nd-Fe-B magnets. Nevertheless, extending the analysis to include all production costs (processing, manufacturing, labour, transport, etc.) and possibly estimating the monetisation of environmental externalities would reinforce the robustness of the economic assessment. Additionally, future research could compare material efficiency with other circular strategies, such as material substitution and improvements in recycling systems, in order to assess their respective contributions to reducing primary Dy demand and its associated impacts. Finally, the social implications of HRE mining are particularly severe in Myanmar's Kachin state, where mining is closely linked to the war economy (Meehan et al., 2025). RE extraction in Myanmar affects local communities through the contamination of the water and soil on which they depend for drinking and agriculture, impacts local livelihoods and community well-being, and leads to occupational exposure to leaching chemicals (ISP-Myanmar, 2025; Meehan et al., 2025). Reducing Dy content may therefore mitigate local consequences (e.g. toxic exposure from leaching agents, health risks, deterioration of living conditions for local communities) and generate potential social co-benefits that are not accounted for in this study. Future research should develop and apply methods to assess the social impacts associated with Dy mining, alongside environmental and economic ones, to enable a comprehensive assessment of the sustainable benefits of its reduction.

5. Conclusion

Reducing the Dy content from 4% to 1% in high-performance Nd-Fe-B magnets is technically conceivable by optimising their microstructure, using material efficiency techniques such as grain boundary diffusion. This study quantified the environmental and economic implications of such a reduction, demonstrating that engineering lower Dy content magnets can significantly improve the sustainability of magnet production for clean energy technologies. Lowering Dy content reduces environmental impacts across all sixteen impact categories assessed in this study, even despite increased Nd content. Given the disproportionate environmental impact of Dy oxide production compared to HRE content in the alloy, even modest reductions lead to significant environmental improvements. The most notable benefits were observed in categories related to ecosystem pressure, such as freshwater ecotoxicity, marine eutrophication and land use. Economically, Dy also has a disproportionate influence on the cost of raw materials for Nd-Fe-B magnets, meaning that small reductions in its content can lead to significant savings on a large scale. Although cost volatility remains, lowering Dy content will always improve cost resilience and reduce exposure to supply disruptions. Without reducing Dy content (baseline composition of 4 wt% Dy), the cumulative demand for magnet in a net-zero emissions scenario is equivalent to two-thirds of present Dy reserves by 2050 and generates, between 2024 and 2050, GHG emissions comparable to the annual emissions of an industrialised country. Material efficiency techniques, which reduce HRE content, therefore appear to be a crucial strategy: it limits resource depletion, reduces global cumulative environmental impacts, cuts raw material costs by several billion euros, may also mitigate local consequences associated with mining, reduces geopolitical dependency, and is essential for aligning the energy transition with global sustainability goals.

CRediT authorship contribution statement

Stellina Samuel: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Robert Istrate:** Writing – review & editing, Supervision, Conceptualization. **René Kleijn:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the corresponding author used ChatGPT (OpenAI, GPT 5.0) to ensure an academic tone, improve conciseness and refine sentence fluency. After using this tool, the author reviewed and edited the content as needed and take full responsibility for the content of the published article.

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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.

Appendix A

Table A1
Overview and description of papers and projects on material efficiency techniques, including Grain Boundary Diffusion (GBD), for Nd-Fe-B magnets.

Type	Reference	Short description
Paper	Chen et al. (2015)	Developed a new GBD process for sintered Nd-Fe-B magnets for application in EV traction machines, with reduced Dy content.
Paper	Cheng et al. (2025)	Investigated coercivity and magnet performance of sintered Nd-Fe-B magnets, treated with GBD.
Paper	Huang and Mo (2024)	Proposed a novel vacuum diffusion heat treatment GBD process, to improve the utilization of HRE and increase coercivity.
Paper	Lee et al. (2016)	Introduced an improved GBD method to address problems of conventional diffusion processes and improve magnet properties.
Paper	Wang et al. (2023)	Developed a two-step GBD process, achieving very high coercivity while using only 0.9 wt% Dy.
Project	RECO2MAG (Emilsson, 2025)	Explored Dy reduction in Nd-Fe-B magnets using GBD, then switched to an improved milling technique that reduced the material particles size and Dy content to 1%.
Project	ROMEO (European Commission, 2016)	Produced Nd-Fe-B magnets with drastically reduced HRE content (0.6 wt%) using techniques like electrophoretic deposition, GBD and novel microstructural engineering. Explored RE-free materials close to the magnetic properties of Nd-Fe-B magnets, such as $YCo_{5-x}Fe_x$ and Co_2MnTi.
Project	GREENE (2024)	Developed high-performance Single-Grain *Re*-Engineered Nd-Fe-B magnets, by creating a new interface between the $Nd_2Fe_{14}B$ magnetic grains and the grain-boundary phase, to make them more powerful while reducing rare earth content.

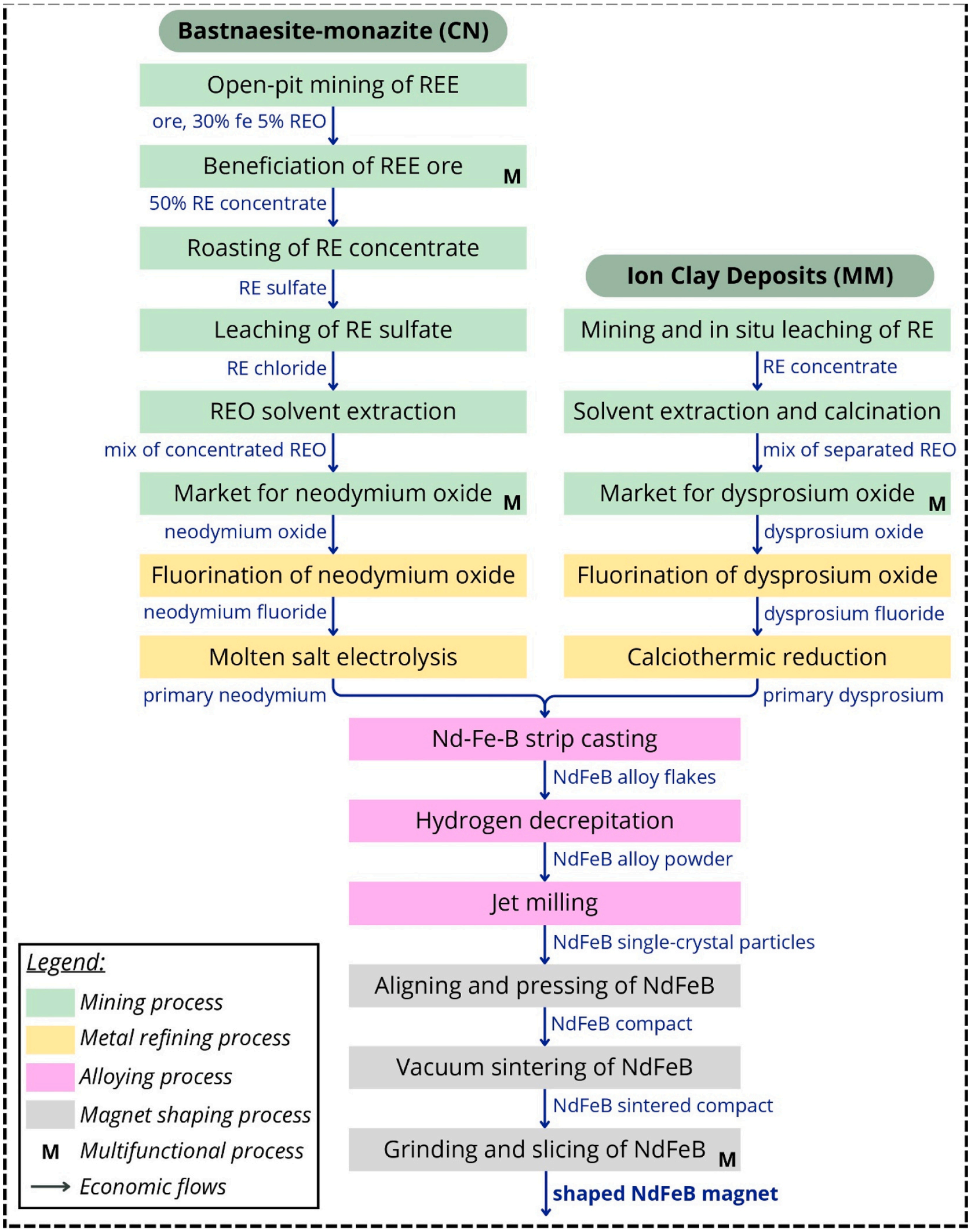

Fig. A1. Flowchart of the production of sintered Nd-Fe-B permanent magnets.

Table A2
Environmental Footprint v3.1 midpoint impact categories with their indicator and unit (European Commission, 2021).

Impact category	Indicator	Unit
Acidification	Accumulated Exceedance (AE)	mol H^+_{eq}
Climate change	Global Warming Potential (GWP100)	kg CO_2 $_{eq}$
Ecotoxicity, freshwater	Comparative Toxic Unit for ecosystems (CTUe)	CTUe
Resource use, fossil	Abiotic depletion resource – fossil fuels (ADP-fossil)	MJ
Eutrophication, freshwater	Fraction of nutrients reaching freshwater end compartment (P)	kg P_{eq}
Eutrophication, marine	Fraction of nutrients reaching marine end compartment (N)	kg N_{eq}
Eutrophication, terrestrial	Accumulated Exceedance (AE)	mol N_{eq}
Human toxicity, carcinogenic	Comparative Toxic Unit for humans (CTUh)	CTUh
Human toxicity, non-carcinogenic	Comparative Toxic Unit for humans (CTUh)	CTUh
Ionising radiation, human health	Human exposure efficiency relative to U^{235}	kBq U^{235}

(*continued on next page*)

Table A2 (*continued*)

Impact category	Indicator	Unit
Land use	Soil quality index	Dimensionless (pt)
Resource use, minerals and metals	Abiotic depletion resource (ADP ultimate reserves)	kg Sb_{eq}
Ozone depletion	Ozone Depletion Potential (ODP)	kg CFC-11_{eq}
Particulate matter formation	Impact on human health	Disease incidences
Photochemical oxidant formation, human health	Tropospheric ozone concentration increase	kg $NMVOC_{eq}$
Water use	User deprivation potential (deprivation weighted water consumption)	m^3 world eq. deprived water

Table A3

Absolute environmental benefits (impact reductions) associated with 1 wt% Dy reduction in 1 kg of Nd-Fe-B magnets, for the high and low recovery scenarios.

Impact category	HIGH recovery scenario	LOW recovery scenario	Unit
Acidification	0.0620–0.0749	0.0798–0.0926	mol H^+_{eq}
Climate change	3.43–4.95	5.09–6.61	kg $CO_{2\ eq}$
Ecotoxicity, freshwater	269–304	1347–1381	CTUe
Resource use, fossil	37.1–52.8	58.3–74.0	MJ
Eutrophication, freshwater	7.81E-04 - 1.20E-03	1.34E-03 - 1.76E-03	kg P_{eq}
Eutrophication, marine	0.0315–0.0398	0.297–0.305	kg N_{eq}
Eutrophication, terrestrial	0.244–0.266	0.291–0.314	mol N_{eq}
Human toxicity, carcinogenic	2.96E-09 - 4.46E-09	5.77E-09 - 7.27E-09	CTUh
Human toxicity, non-carcinogenic	4.64E-08 - 6.67E-08	7.51E-08 - 9.51E-08	CTUh
Ionising radiation	0.118–0.173	0.229–0.284	kBq U^{235}
Land use	37.4–56.0	841–859	Dimensionless (pt)
Resource use, metals/minerals	6.09E-05 - 7.69E-05	1.10E-04 - 1.26E-04	kg Sb_{eq}
Ozone depletion	7.60E-08 - 1.16E-07	1.53E-07 - 1.93E-07	kg CFC-11_{eq}
Particulate matter formation	4.04E-07 - 6.01E-07	5.01E-07 - 6.98E-07	Disease incidences
Photochemical oxidant formation	0.0306–0.0366	0.0405–0.0465	kg $NMVOC_{eq}$
Water use	0.925–1.64	1.74–2.45	m^3 world eq. deprived water

Appendix B. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.spc.2026.04.006.

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Glossary

Dy (Dysprosium): Heavy rare earth element added to Nd-Fe-B magnets to improve coercivity and prevent thermal demagnetisation in high-temperature applications.

Grain boundary diffusion: Processing method in which dysprosium (or other HREs) is diffused along the grain boundaries of Nd-Fe-B magnets, forming a thin shell around the $Nd_2Fe_{14}B$ grains (Chen et al., 2015). It is a material efficiency technique that ensures high coercivity while reducing overall Dy consumption.

Economic allocation: An allocation method used in LCA that partitions the inputs and outputs of a multifunctional process among its co-products according to their share of the total economic value (Guinée et al., 2004).

Functional unit: In LCA, the quantified primary function performed by the product system (Guinée et al., 2002); in this study, 1 kg of sintered Nd-Fe-B magnet.

HRE (Heavy Rare Earths): Rare earths with higher atomic numbers (Gadolinium, Terbium, Dysprosium, Holmium, Erbium, Thulium, Ytterbium, Lutetium and Yttrium), used for their magnetic and thermal properties in Nd-Fe-B magnets. They are mainly mined from ion-adsorption clay deposits in Southern China and Myanmar.

IAC (Ion-Adsorption Clay): Type of deposit where rare earth elements are weakly adsorbed onto clay minerals and can be extracted by leaching. Due to higher concentrations than in monazite or bastnaesite, IACs are the main source of heavy rare earths.

In-situ leaching: Mining process used for ion-adsorption clay deposits, which involves injecting a leaching solution (e.g., ammonium sulfate) into the ore body to dissolve and recover rare earths.

LCA (Life Cycle Assessment): Method for assessing the potential environmental impacts of a products system throughout its life cycle.

LCI (Life Cycle Inventory): Compilation and quantification of inputs (resources, energy) and outputs (emissions, waste) associated with each process of a product system throughout its life cycle (Guinée et al., 2002).

LCIA (Life Cycle Impact Assessment): Assesses the potential environmental impacts of the product system by assigning inputs and outputs (identified in the LCI) to impact categories (e.g., climate change, freshwater ecotoxicity) and quantifying their contribution (Guinée et al., 2002).

Nd-Fe-B magnets (Neodymium-Iron-Boron magnets): High-performance permanent magnets widely used in clean energy technologies such as electric vehicles and wind turbines.

Recovery rate: In this study, the percentage of rare earth content in the ore that is successfully dissolved into the leachate during in-situ leaching (Schulze et al., 2017).

Solvent extraction: A hydrometallurgical refining process that separates individual rare earths from a mixed leachate by exploiting their different solubilities across two immiscible phases, typically an aqueous hydrochloric acid-based leachate and an organic solvent containing a selective extractant (Merroune et al., 2024). Through multiple extraction stages, the lighter RE are removed first (in order of atomic weight), followed by selective separation of the heavier RE.