Environmental sustainability of NdFeB magnet recycling: foresight study on recycling systems and technologies

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4 Ex-ante LCA of magnet recycling: progressing towards sustainable industrial-scale technology

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Abstract

To alleviate the pressure on the rare earth supply chain, new technologies are under development for recovering, recycling and remanufacturing NdFeB magnets. In this study, the anticipated environmental performance of large-scale recycling is investigated and compared to the production of primary magnets. To do so, this ex-ante life cycle assessment combines input from measurements of pilot processes, expert technology forecasts, thermodynamic modeling, and equipment data from manufacturers. We examined the effect of four technology developments: process changes, size scaling, internal recycling, and optimization.

The results show that at pilot scale, recovered NdFeB powders have lower impacts than primary powders for almost all impact categories. This demonstrates that the recovery of NdFeB alloys is environmentally beneficial. Magnets from anticipated large-scale recycling have over 80% lower impacts than primary magnets in most of the impact categories analyzed. All four investigated types of technology development contributed to this improved performance. The final configuration was validated by comparison with an industrial reference and theoretical optimum configuration. Four magnet manufacturing routes (sintering, extrusion, metal injection molding, bonding) have distinct environmental profiles, but all can progress to similarly low levels of impact. The choice among routes should be primarily based on the functional requirements.

4.1 Introduction

4.1.1 Recycling technology development

To achieve a net-zero society, we need not only huge investments in clean technologies and new infrastructure, but also a sound circular economy for all materials involved. This requires new recycling technologies, complementing repair and reuse. For example, end-of-life (EoL) NdFeB magnets arise in increasing quantities from applications in rapidly growing markets like electric vehicles (EVs), data centers and wind turbines (van Nielen et al., 2023). Recycling is currently limited and small-scale, signaling a potential waste treatment issue and an opportunity for new recycling activities (Jowitt et al., 2018). Anticipating the introduction of industrial-scale NdFeB recycling, it is important to understand the technology and its environmental impacts.

Magnets can convert electric energy into motion and *vice versa*, e.g. in electricity generators, motors, and speakers. High performance magnets are made from NdFeB, consisting of iron, boron and about 32% REEs, including Nd, Pr and Dy. The high magnetic strength results from a fine-tuned composition of the magnet alloy and its microstructure, and is achieved by sintering, i.e. fusing fine NdFeB powders at high temperatures (Brown et al., 2002). Bonded magnets are composed of NdFeB powder and a polymer binder. Bonded magnets can be produced in complex shapes, but have lower magnetic strength (Brown et al., 2002).

Several types of magnet recycling technologies have been investigated: direct alloy (or short-loop) recycling, pyrometallurgy and hydrometallurgy (Binnemans et al., 2013; Yang et al., 2017). Direct alloy recycling recovers NdFeB material directly without separating its constituents, often by pulverizing magnets under hydrogen atmosphere. Pyrometallurgy employs high-temperature melting, while hydrometallurgy involves dissolving magnets. These technologies have the advantage of removing impurities, but require large amounts of energy and chemicals, respectively (Ormerod et al., 2023). Previous life cycle assessment (LCA) studies have indicated the environmental benefits of direct alloy recycling (Elwert et al., 2017; Jin et al., 2018, 2020; Sprecher et al., 2014; Walachowicz et al., 2014; Wang et al., 2022; Zakotnik et al., 2016) and hydrometallurgical recovery (Bailey, 2019; Beylot et al., 2020; Schulze et al., 2018), see Table 4.1. This study focusses on direct alloy recycling, as it shows lower impacts.

Direct alloy recycling consists of multiple processes, further explained in Section 4.2.1. The key stages are waste pre-processing, alloy recovery, and magnet manufacturing. Previous LCA studies have focused on the recovery stage, assuming a single processing pathway for waste pre-processing and manufacturing. However, a successful recycling system can handle a variety of waste inputs, and can manufacture multiple products depending on the needs of the market. It is important to model the entire recycling chain up to a new product, because this allows to assess the effectiveness of substituting primary magnets.

In all stages—pre-processing, alloy recovery and magnet manufacturing—recent efforts in research and development (R&D) have resulted in significant technology advancement. Experimental work has explored new ways to automate the liberation of magnets from waste (Burkhardt et al., 2023) and their recovery through hydrogen processing of magnetic scrap (HPMS) (Jönsson et al., 2020). Remelting opens a new route

TABLE 4.1: LCA studies and results (as greenhouse gas (GHG) emissions) for recycling of NdFeB magnets using direct alloy recycling (top) and hydrometallurgy (bottom). Not all numbers are comparable due to differences in scope.

Study	Used magnet source	Final product	GHG emissions of recycled product (kg CO_2-eq/kg)
Sprecher et al. (2014)	HDD	Sintered magnet	3.3–10
Jin et al. (2016)	HDD	Sintered magnet	12.5
Jin et al. (2020)	HDD	Sintered magnet	26.1
Bailey (2019)	EV motor	Sintered magnet	6.0
Walachowicz et al. (2014)	EV motor	Sintered magnet	178
Jin et al. (2018)	EV motor	Sintered magnet	18–41 (US), 25–56 (China)
Wang et al. (2022)	Small magnets	Sintered magnet	8.4
Bailey (2019)	EV motor	Sintered magnet	13–42
Schulze et al. (2018)	EV motor	Nd-Pr alloy	13–59
Walachowicz et al. (2014)	EV motor	Rare earth oxides	12.2–15.9
Beylot et al. (2020)	HDD	Rare earth oxides	5.93–6.55

for alloy recovery from partly oxidized magnets, as it removes metal oxides as slag (SUSMAGPRO, 2019). Hydrogenation–disproportionation–desorption–recombination (HDDR) yields powders suitable for bonded magnets (Gutfleisch & Harris, 1996; Lixandru et al., 2017). The 'shaping–debinding–sintering' approach produces magnets directly in the final shape, hence improving the material efficiency of magnet manufacturing (Gonzalez-Gutierrez et al., 2018). Even traditional sintered and bonded magnets have a relatively short history (Brown et al., 2002) and may also be developing efficiency-wise. These developments justify a renewed look at the environmental performance of NdFeB magnet recycling and manufacturing.

4.1.2 Towards industrial deployment

The maturity of recycling processes can be expressed using the commonly used technology readiness level (TRL) (ISO, 2013). At TRL 1, the basic principles of a technology are observed, and at TRL 9 the production is fully operational (EARTO, 2014). TRLs help to define the scope and approach of an LCA (Bergerson et al., 2020; Thomassen et al., 2019). In this paper, we use TRLs to indicate the maturity of processes, and 'small scale' refers to the maturity level at the time of data collection.

On the path towards industrial-scale recycling of NdFeB magnets, technology developers will face fundamental decisions regarding process design and the overall layout of the recycling system. It is unknown how these choices affect the future industrial operation and its environmental performance. Current R&D efforts are mainly focused on smoothing the way to commercial implementation, whereas this may entail unforeseen but profound consequences for future operations.

4.1.3 Environmental impacts of future magnet recycling

To calculate the anticipated future environmental impacts of an emerging technology at large-scale, the method of ex-ante LCA has been developed (Cucurachi et al., 2018). Ex-ante LCA acknowledges that inventories of small-scale processes are not representative for industrial operation, since fundamental process changes, technology optimization, and changes in the wider economy are expected. Multiple studies have contributed to the conceptual development of methods for upscaling from small to industrial scale (Balgobin & Evrard, 2020; Buyle et al., 2019; Cucurachi et al., 2018; Langkau et al., 2023; Piccinno et al., 2016; Tsoy et al., 2020; van der Giesen et al., 2020; van der Hulst et al., 2020; Villares et al., 2017). Methods include process simulation, physics-based models, proxy technologies, participatory methods, and scaling relations. The preferred approach depends on the case at hand and the data availability. When small-scale data is available, the upscaled technology performance can be estimated, as demonstrated by case studies on e.g. chemicals (Piccinno et al., 2016), photovoltaics (Blanco et al., 2020), energy technologies (Caduff et al., 2014), and steel slag (Buyle et al., 2021). For some process types, upscaling guidelines are available, but this is not the case for powder metallurgy and magnet production.

This research aims to quantify the environmental impacts of industrial-scale magnet recycling, based on information available from current small-scale processes and envisioned technology developments. We apply ex-ante LCA to compare recycled magnets to magnets from primary materials, as well as to pinpoint specific areas of concern within the recycling chain. By identifying environmental hotspots, we aim to support technology developers in developing more sustainable solutions. To validate the results, we aim to compare the projected impacts with an industrial reference configuration and a theoretical, thermodynamic minimum impact. Moreover, we aim to find the kind of changes that contribute most to the improvement of environmental performance, by systematically assessing different mechanisms of technology development. This may provide research priorities for other ex-ante LCA studies, while also paving the way for a sustainability-focused R&D agenda.

As opposed to previous research, we aim to study recycling that starts from a range of waste flows and includes the manufacturing of various new magnet types. The processes that are part of the recycling chain were modeled in collaboration with technology developers participating in the SUSMAGPRO project (SUSMAGPRO, 2019). We determined the future performance of each process by considering fundamental process changes, size scaling, internal recycling and process optimization (as described in Section 4.2.4). Moreover, we compared secondary and primary production at the level of NdFeB powders and of finished magnets.

4.2 Methods

4.2.1 Goal & Scope

This ex-ante LCA studied the environmental performance of developing processes for direct alloy recycling of NdFeB magnets. The recycling chain is defined as spanning from waste sorting to secondary magnet manufacturing, resulting in the foreground system

TABLE 4.2: Definition of demonstrator magnets.

	Type of magnet	Application	Dimensions (mm)	Shape	Coating
1	Extruded	EV drive rotor	$25 \times 14 \times 4$	Rectangular	Epoxy
2	MIM	Sensor	$18 \times 16.5 \times 2.5$	Disk	Phosphate + epoxy
3	Sintered	EV drive rotor	$30 \times 30 \times 50$	Block	Epoxy
4	Bonded	Water pump	$46.5 \times 11 \times 2.7$	Rectangular	None

depicted in Figure 4.1. We evaluated the life cycle impacts for recovered alloy powders and for magnets made from recycled material (demonstrators). We defined two functional units and investigated alternative processing routes for each. These routes yield products that differ in shape and functionality, making some products incomparable. The first functional unit is 1 kg NdFeB alloy powders, an intermediate output produced by fine-tuning (Figure 4.1b). Six alternative sources of waste magnets (listed in Table C.1) were compared, to assess the effectiveness of recovery. To evaluate magnet remanufacturing, the second functional unit is an amount of magnets containing 1 kg NdFeB, at factory gate. Table 4.2 presents the product alternatives. Note that the reference flow for bonded magnets weighs 1.125 kg including the polymer binder, and the weight of coated magnets also exceeds 1 kg.

The recycling feedstock consists of EoL hard disk drives (HDDs), EV rotors, loudspeakers, industrial pumps, TV speakers and wind turbine magnets (see Appendix C.1, Table C.1). These waste flows were selected for their prominent contribution to NdFeB magnet consumption and waste production (Appendix C.1; van Nielen et al. (2023)). The recycling feedstock is assumed to comprise equal shares of waste magnets from these six sources.

The demonstrator magnets in Table 4.2 represent magnets for specific applications, e.g. an EV drive rotor, as produced and tested in pilot settings. Each demonstrator is the product of a distinct production route in Figure 4.1c, yielding 1) extruded 2) metal injection molding (MIM), 3) sintered and 4) bonded magnets. The studied processes had a TRL of around 4–6, and approached TRL 7 or 8 at the end of the project. Routes 1 and 2 have a lower TRL than the other routes. After extrusion or injection molding, both follow a similar procedure of debinding and sintering.

4.2.2 General inventory data

This study focused on magnet recycling in Europe, and assumed the European average market mix in 2018 for all inputs, as modeled in Ecoinvent 3.8. In Europe, waste is already collected independently of magnet recycling. Therefore, waste collection was excluded from our scope (while magnet liberation was included). Changes in the background system were not considered, as the focus is on changes in the foreground technology. To establish a baseline for comparison, we calculated the environmental impacts of primary magnets produced in Europe. The main raw materials for primary magnets are rare earth metals, for which we adopted the global average market mix (see Section 4.2.5).

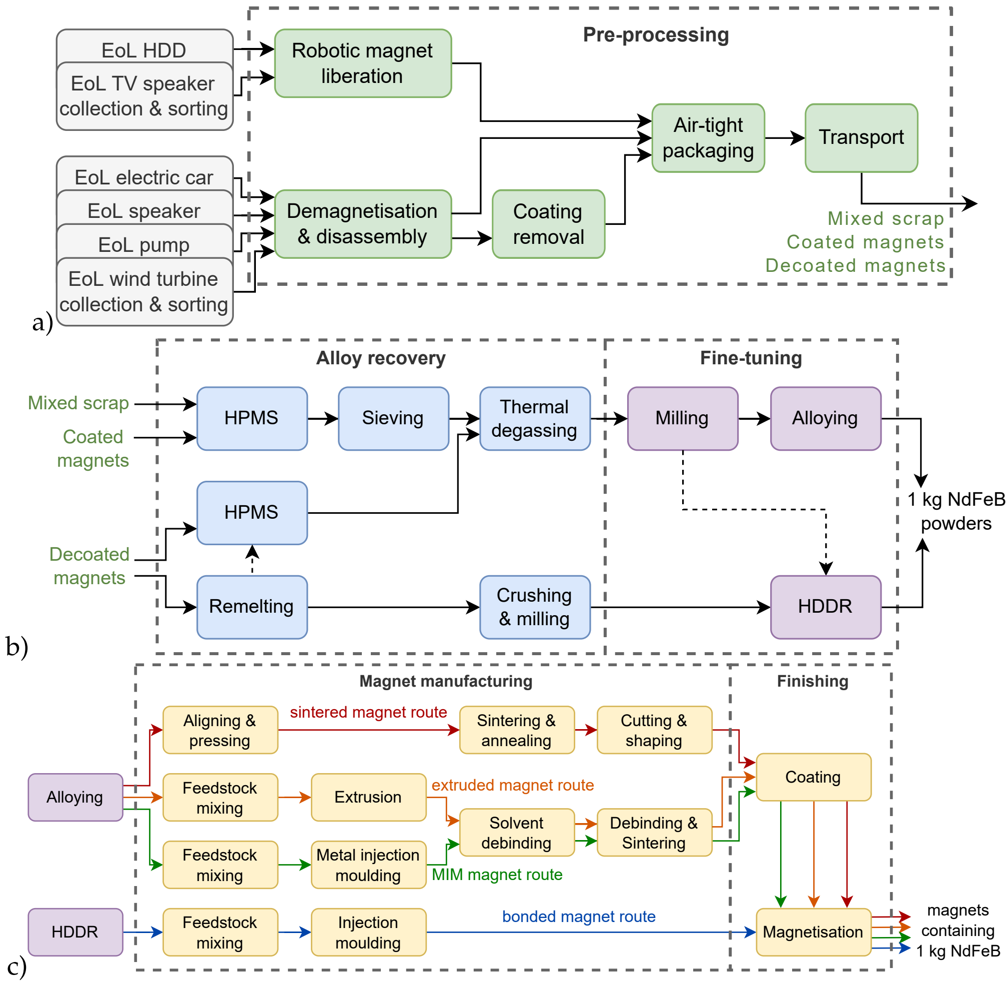

FIGURE 4.1: Flowcharts of the studied recycling routes. The functional units (on the right) are 1 kg NdFeB powders and magnets containing 1 kg NdFeB. The system boundaries include five recycling stages, indicated by dashed outlines. Dashed arrows indicate feasible routes not fully explored in this study. HPMS: hydrogen processing of magnetic scrap; HDDR: hydrogenation–disproportionation–desorption–recombination.

To allow for the evaluation of all possible combinations of process alternatives, a parametrized model was built in ActivityBrowser version 2023.03.03 (Steubing et al., 2020) using Ecoinvent 3.8 (cut-off version) as background database (Wernet et al., 2016). The various waste inputs, recycling routes, output magnets, and technology developments were implemented as flow-scenarios.

4.2.3 Data on small-scale recycling

Data on the current performance of recycling technology was obtained from SUSMAGPRO partners [1] through site visits, measurements, and interviews with technology experts. This resulted in a good understanding of the pilot unit processes and their interdependencies. Experimental process trials allowed to identify technically feasible processes and conditions. Processes with poor performance were discarded and promising processes were developed further. Next, interviews and workshops were conducted, again involving technology developers, to explore potential changes and improvements towards large-scale operation.

4.2.4 Projecting industrial-scale recycling

Impacts of lab-scale technology are not representative for industrial operation (Tsalidis & Korevaar, 2022). Therefore, we aimed to estimate life cycle inventory data for a recycling chain at industrial scale, based on experience with lab-scale processes and initial tests at pilot-scale. This addresses an important and challenging step in prospective technology assessment, as technological reconfigurations are most likely during this phase of development. Given the current maturity of magnet recycling technology, our approach is mostly based on van der Hulst et al. (2020).

We calculated the environmental pressures for a base case and four anticipated configurations. The base case represents recycling at pilot scale, which is close to the present process implementations but with higher operating hours. The anticipated configurations were derived from the pilot set-up by accounting for four developments towards industrial recycling (van der Hulst et al., 2020): process changes, size scaling, internal recycling (a process synergy), and optimization (combining technological learning and economies of scale) (Figure 4.2). The definition and the general approach for each configuration are outlined below, along with a general indication of data sources.

Pilot process is a pre-industrial prototype process, with a TRL around 6. This is close to the TRL of processes for which data was collected, although some processes had a different TRL. The equipment is operated 8 hours per day and 240 days per year. For processes that take more than 8 h per batch, 240 batches per year were assumed. The lifespan of machines was estimated by technical experts, and varies between 8 and 30 years. *Process change* includes fundamental changes of the process or materials. Process changes were identified in exchanges with SUSMAGPRO technology experts. Information on the energy consumption and the weight of some equipment was obtained from equipment manufacturers. *Size scaling* involves increasing dimensions of equipment (upscaling), to achieve higher throughput. The general target capacity for equipment

[1] A list of the SUSMAGPRO participants is available at https://doi.org/10.3030/821114.

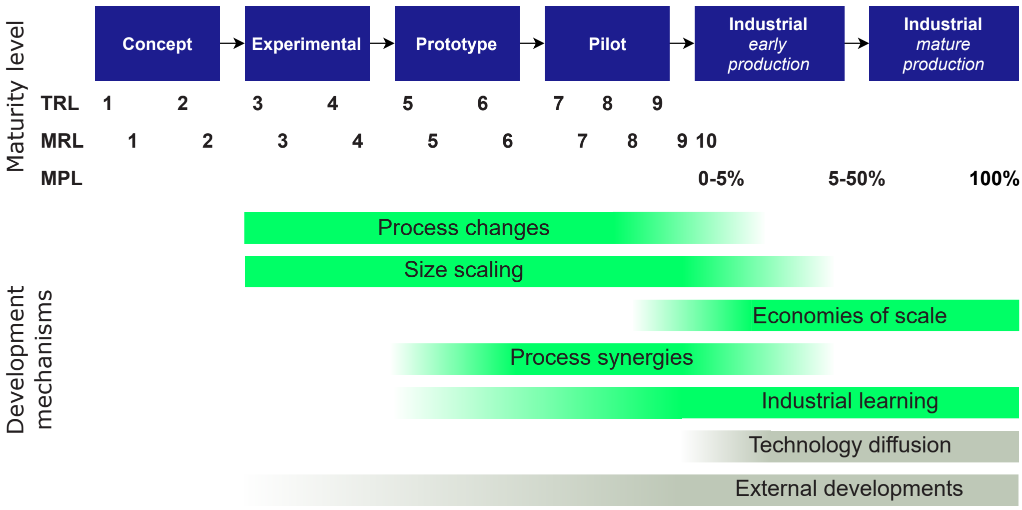

FIGURE 4.2: Mechanisms for technology development, adapted from (Buyle et al., 2019; van der Hulst et al., 2020). Mechanisms in green are addressed in this study; economies of scale and industrial learning are assessed jointly. Mechanisms in grey apply to a broader level of analysis. TRL: technology readiness level; MRL: manufacturing readiness level; MPL: market penetration level.

is 200 t/a. Further scaling beyond 200 t/a is achieved mostly by parallel processing, therefore it would only marginally change the process performance. 16 operating hours per working day are assumed. In some cases, the pilot process performance was extrapolated using scaling relations. *Internal recycling* refers to recycling of waste flows, like solvents and inert gases, and production of NdH_2 from recovered materials. Other process synergies were not considered. *Optimization* accounts for small or difficult improvements, achieved through ongoing industrial learning and economies of scale. The optimized processes operate 24 h per day.

Furthermore, two reference configurations were evaluated. The *industrial reference* processes are mostly modeled after a similar unit process from a comparable sector. For example, MIM of steel powders was used as a proxy for MIM of NdFeB powders. Internal recycling is assumed in the magnet industry. The *theoretical optimum* describes a thermodynamically ideal process, with an energy efficiency of 100%, and no material loss. For all processes with high operating temperatures, a thermodynamic model was constructed to calculate the energy use at large scale and at the theoretical optimum.

All development steps were modeled as cumulative improvements. When no changes were expected for a certain flow or parameter, the performance of the preceding step was applied. The data and assumptions are detailed per process in Appendix C.2 and ESI 1[2]. Using the pedigree matrix by Weidema (1998), we determined data quality indicators between 1.6 for pilot processes and 3.6 for the optimized configuration, see Appendix C.2.1.

[2]https://www.sciencedirect.com/science/article/pii/S0959652624019012#appSC

4.2.5 Data on primary REE and magnet production

Primary rare earth elements (REEs) are used for two processes: for the production of neodymium hydride (NdH_2) (added during alloying [3]), and for the production of primary magnets (the baseline). The primary supply chain of REEs is modeled after Miranda Xicotencatl et al. (2021). As REE ore sources, we assume the average market mix for 2021–2022, consisting of 10% monazite from Australia, and 82% bastnäsite–monazite and 8% ion adsorption clays from China (USGS, 2023). For simplicity, NdFeB alloy is assumed to consist of 27% neodymium, 72% iron pellets and 1.3% boron carbide (Sprecher et al., 2014). In reality, the alloy also contains other REEs co-produced with Nd such as Dy and Pr.

4.2.6 Impact assessment

We calculated the environmental impacts for 16 impact categories. All except one were calculated with the Environmental Footprint v3.0 impact assessment method (EF) (Fazio et al., 2018), as listed in Appendix C.3. We only deviate from EF for water use impacts, because water extractions and emissions are regionalized in EF but not in Ecoinvent. Water use was assessed using the characterization factors in Appendix C.4.

4.3 Results

4.3.1 Hotspots in magnet recycling at pilot scale

Analysis of the pilot-scale recycling system shows that most impacts arise from alloy fine-tuning and magnet manufacturing. Figure 4.3 shows the environmental hotspots for the sintered demonstrator magnets for EVs. The contribution of fine-tuning stems from jet milling and primary neodymium, added in the form of NdH_2 to ensure good magnetic properties. Other burdens are linked to the production of electricity (36% of climate change impacts) and equipment (52% of human cancer effects). Besides, significant material losses occur during sieving (35%) and cutting magnets to shape (21%). These hotspots were used as guidance for identifying areas of technology improvement. Although pre-processing and finishing have limited impacts, process developments were also investigated within these stages.

4.3.2 Projected impacts of recovering magnet alloys

NdFeB powders can be produced by jet milling, by vibratory milling and by HDDR. Each process yields powders with distinct characteristics; e.g. HDDR powders are suited best for bonded magnet production. Their greenhouse gas (GHG) emissions are compared in Figure 4.4. The impacts are plotted for six waste sources, revealing that the effect of starting material is only small.

All recycled powders have lower GHG emissions than primary powder already at pilot scale. The impacts of jet milling, mainly stemming from inert gases, are closest

[3] Alloying means mixing metal powders to form an alloy.

4

	Pre-processing	Coating removal	Alloy recovery	Fine-tuning	Magnet manufacturing	Finishing
Resource use, minerals and metals	1%	3%	4%	13%	72%	8%
Human toxicity, cancer effects	1%	5%	8%	17%	63%	6%
Human toxicity, non-cancer effects	1%	3%	6%	33%	52%	5%
Freshwater ecotoxicity	1%	3%	6%	43%	43%	4%
Photochemical ozone formation	1%	7%	8%	40%	41%	2%
Eutrophication, aquatic freshwater	2%	4%	13%	40%	39%	2%
Acidification	1%	5%	10%	44%	38%	3%
Resource use, energy carriers	2%	6%	14%	42%	35%	2%
Ionising radiation, human health	2%	4%	15%	44%	34%	1%
Climate change	2%	6%	13%	44%	33%	2%
Ozone depletion	1%	10%	10%	45%	32%	2%
Eutrophication, terrestrial	1%	6%	10%	50%	30%	2%
Water use	1%	2%	7%	61%	28%	1%
Land use	1%	5%	8%	57%	27%	2%
Respiratory inorganics	1%	7%	7%	58%	26%	2%
Eutrophication, aquatic marine	1%	4%	8%	64%	21%	1%

FIGURE 4.3: Contribution of recycling stages to the environmental impacts of 1 kg sintered magnets for an EV drive rotor, as calculated for the pilot-scale processes. Stages are defined in Figure 4.1. Coating removal is part of pre-processing.

to primary production, with higher impacts for ionizing radiation and freshwater eutrophication (see ESI 6[4]). When improvements up to internal recycling are implemented, recycling performs better on all environmental indicators. Drivers for impact reduction include energy-efficient equipment and recovery of inert gases.

Vibratory milling and HDDR cause lower impacts than jet milling. The lowest impacts are achieved by combining remelting and HDDR. This is largely because small-scale HPMS uses more energy than remelting, and because no alloying additions are needed for HDDR powder. For comparison, the combination of HPMS and HDDR has impacts similar to remelting with HDDR after size scaling (4.9 and 4.6 kg CO_2-eq.), indicating that the upscaled HPMS process performs similar to remelting. The optimized large-scale recovery processes all have comparable impacts ($\sim$ 3.4 kg CO_2-eq.).

Having analyzed alloy recovery, we now examine the effect of technology development on the whole magnet recycling chain. These further analyses assume equal shares of scrap magnets from each of the six EoL applications, and only consider HDDR applied to remelted material.

[4]https://ars.els-cdn.com/content/image/1-s2.0-S0959652624019012-mmc2.xlsx

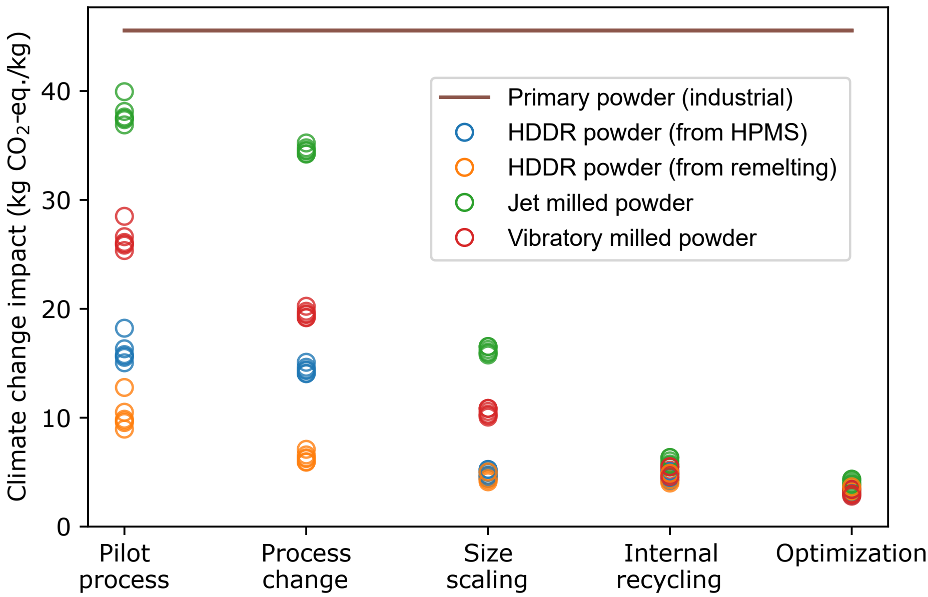

FIGURE 4.4: Climate change impacts of NdFeB powders, from primary origin and recovered from any of six waste sources. Recovery impacts are shown for six waste sources, for the pilot scale and after four cumulative technology improvements (described in Appendix C.2). All outputs are 1 kg of fine powders, hence milled powders have been alloyed with NdH_2.

4.3.3 Projected impacts of magnet recycling

The climate change impacts of recycled magnets are compared on a mass basis in Figure 4.5. For all demonstrator magnets, technology improvements can lower the emissions, possibly even below the industrial reference performance. At pilot scale, the highest GHG emissions are associated with the production of extruded EV demonstrator magnets. MIM magnets are second, followed by sintered magnets. Finally bonded pump magnets have the lowest emissions. The demonstrators with the highest emissions at pilot scale also have the greatest potential for impact reduction. In a large-scale, optimized plant, MIM and extruded magnets have emissions close to those of sintered magnets (10.6, 8.8, and 7.4 kg CO_2-eq. respectively).

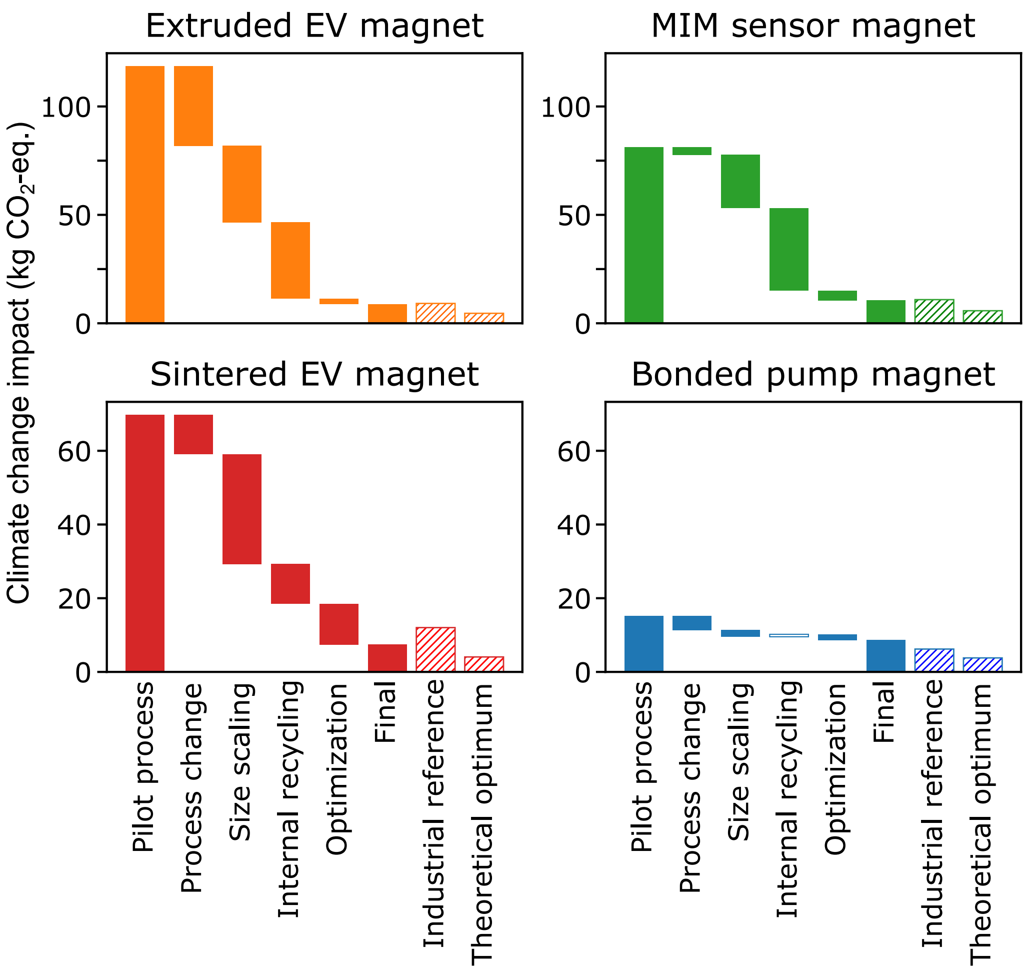

FIGURE 4.5: Climate change impacts of 1 kg recycled demonstrator magnets. Impacts are presented for the pilot scale, after four cumulative technology improvements, and two reference configurations (dashed bars). Note that the *x*-axes are shared.

Figure 4.6 shows that recycled magnets can achieve lower environmental impacts than primary magnets. The reference values for primary magnet production are only plotted for sintered and bonded magnets, because the other two types are currently not produced industrially. For at least 6 of 16 impact categories, recycling already performs superior at pilot scale, e.g. for freshwater ecotoxicity and land use.[5] However, pilot-scale recycling has high climate change impacts, and several improvements are needed to reduce impacts to below primary levels.

Figure 4.6 also illustrates that the results for some impact categories look different from climate change effects. Although extruded magnets have the highest GHG emission at pilot scale, their impact is similar to sintered magnets for freshwater ecotoxicity and land use. Moreover, extruded magnets show a significant decline in impacts as technology improves, highlighting the potential for optimization in this less mature magnet production route.

All types of technology development can contribute to lower impacts (Figure 4.6 and 4.7). The largest reductions are achieved by size scaling and internal recycling, although this depends on the demonstrator magnet. For sintered magnets, a remarkable drop in water use (−88%) is observed due to process changes. This was achieved by improving the insulation of the sintering furnace and thus reducing the cooling water use. Although most process changes are required to enable upscaling, some cause little impact reduction. Specifically for extruded magnets, a major process change is the reduced energy use for degassing of feedstock.

Sintered magnets use more water than other types, especially at pilot scale. Most water is used directly as cooling water, which can be reduced by better insulation and water recirculation. Land use impacts are low for bonded magnets and are very similar for the other three demonstrators. Land use is mostly related to electricity production and REE mining.

Bonded magnets have low impacts in every impact category. This is because bonded magnet manufacturing does not require sintering and annealing, which are very energy-intensive processes. The manufacturing of bonded magnets is already well-developed and leaves little room for improvement. Moreover, bonded magnets do not require additions of (virgin) NdH_2. Most improvements occur in the recovery and fine-tuning (remelting and HDDR). Bonded magnets are produced via the remelting route, which causes less impacts than the HPMS route at pilot scale. After upscaling and optimization, the HPMS route had similar impacts, due to improvements in jet milling, optimization of the HPMS motor and replacement of virgin NdH_2 inputs. These and other major drivers of emission reduction are analyzed in Section 4.3.4.

4.3.4 Key strategies to reduce impacts

This section examines the changes that contribute most to impact reduction and the effect of recycling technology development on four impact categories. At the level of inflows and outflows, impact reduction is mostly driven by electricity, inert gases, and NdFeB

[5]Depending on the demonstrator, impacts are lower in 6–15 categories. For recycled sintered magnets, the impacts are higher at pilot scale for: ionizing radiation, freshwater eutrophication, human toxicity (cancer effects), energy use, water use, resource use (minerals and metals), and climate change. See also ESI 6.

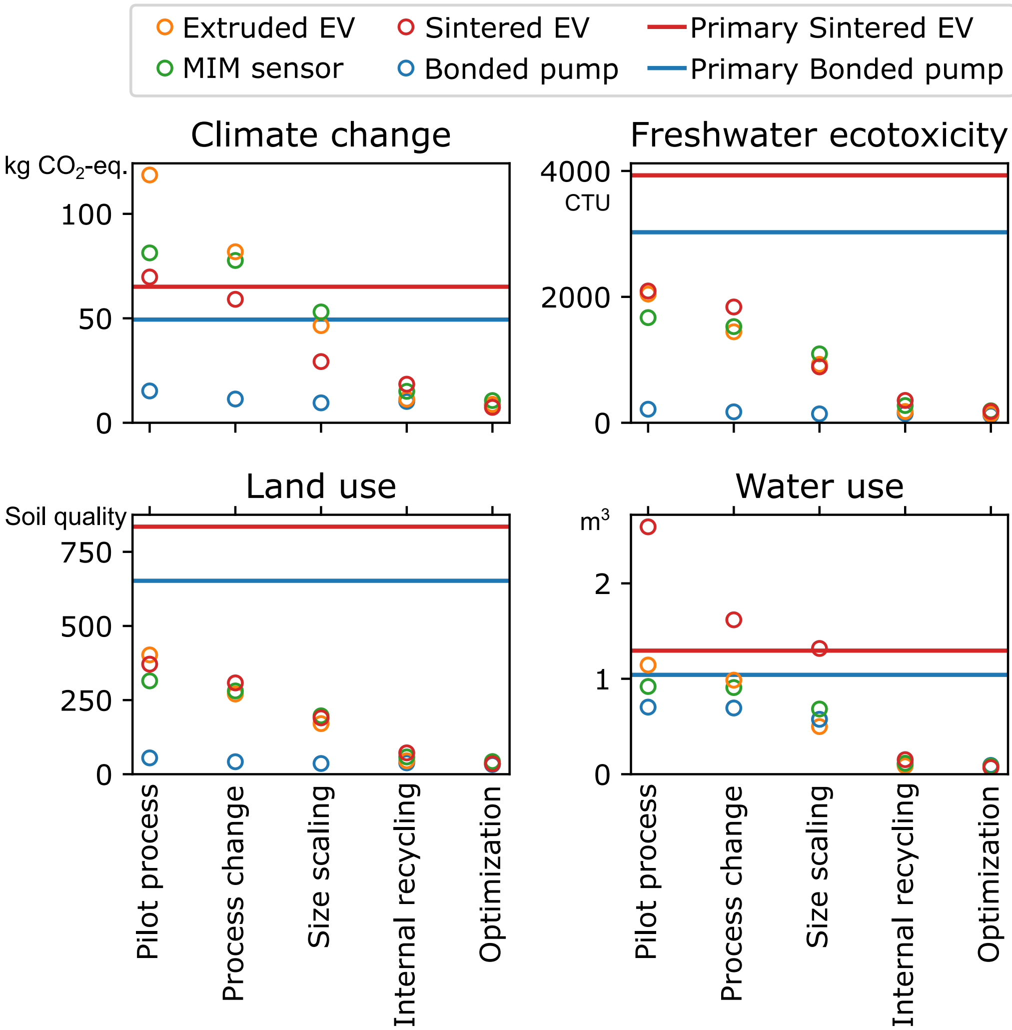

FIGURE 4.6: Environmental impact changes due to cumulative technology developments in recycling, for four impact categories. The impacts of industrial primary magnets are shown as lines for comparison. The reference flow of each demonstrator magnet contains 1 kg NdFeB. The *x*-axes are shared.

losses. Electricity is used in all processes, and energy savings are often possible by applying optimization measures (see ESI 1). For instance, the HPMS vessel can be rotated at lower speed or less often. Furnaces are more energy-efficient if they are larger or have better insulation. Secondly, inert gases prevent oxidation of NdFeB powder. Recovering these gases, notably from jet milling, avoids energy-intensive gas production and saves 15.9 kWh. Some fresh gas remains needed, to compensate for leakage and for contaminant removal.

Thirdly, a key process improvement is the reduction of NdFeB losses. The highest losses occur in sieving (although the loss is uncertain) and shaping the magnet. Powder sticking to coating residues and too fine powders are lost. These losses can be reduced by optimizing preceding processes. Regarding shaping, the MIM and extrusion routes have a clear advantage: because the shaping process occurs before sintering, internal recycling of shaping losses is easy and no excess material is sintered. Further significant improvements address the use of raw materials, notably NdH_2 by using less or using recycled NdH_2, and solvents by distillation. The NdH_2 content can be minimized without compromising the magnet's performance. To a lesser extent, higher utilization rates of machines reduce toxicity impacts related to their production.

Some process improvements had only marginal environmental benefits. For instance, low impacts are associated with ICP-OES measurements, QR-code scanning (both aim to determine a magnet's composition), magnetization, coating of magnets, and H_2 use. Consequently, additional measurements are worthwhile if they help to reduce material losses. Changing the mentioned processes may bring some benefits, but would not change the overall outcomes.

For each recycled magnet type, the trend of impact categories is remarkably similar (Figure 4.7). This demonstrates that all impacts are reduced by the process improvements. For the bonded magnet demonstrator, the implementation of internal recycling of cooling water has mixed effects. While the water use is reduced (−82%), the impacts of all other indicators increase, albeit slightly. The effect of cooling water recycling also affects other demonstrators, although less visible in Figure 4.7 because of the positive effect of other internal recycling solutions.

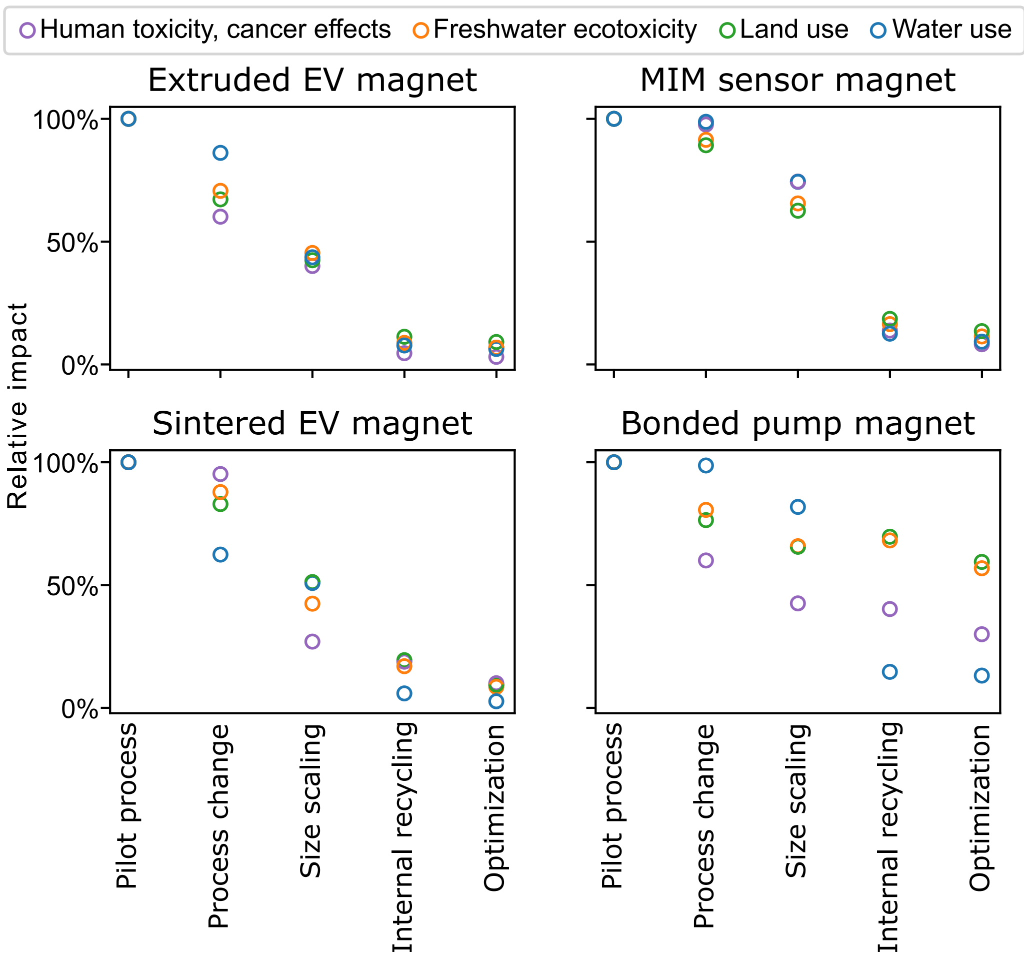

FIGURE 4.7: Environmental impact changes due to projected technology developments for recycled demonstrator magnets, for selected impact categories. Other impact categories are provided in Appendix C.5. The values are plotted relative to the impacts at pilot scale and the x-axes are shared.

4.4 Discussion

4.4.1 Validation

The high impact of pilot-scale recycling is due to inefficient small-scale processing, as observed throughout manufacturing (Gutowski et al., 2017, 2009). After implementing all projected technology developments, the emissions of recycling are close to the industrial reference values and still above the theoretical optimum (see Figure 4.5). This comparison suggests that the projections provide a realistic endpoint. However, the final GHG emissions of recycled sintered EV magnets fall below the industrial reference. This may indicate overly optimistic assumptions, e.g. regarding cutting and shaping losses.

In line with the low impacts of bonded magnets, these demonstrators also have the lowest theoretical optimum impact in all impact categories. This is due to the low number of high-temperature processes needed for recycled bonded magnets (see Section 4.2.4).

4.4.2 Uncertainties and limitations

The characterized results are in agreement with previous studies for recycled sintered magnets. Using pilot-scale data, 1 kg recycled sintered magnets cause 70 kg CO_2-eq. emissions. When implementing anticipated process changes, size scaling and internal recycling, the impact reduces to 22.9 kg CO_2-eq./kg. With further optimization, 8.9 kg CO_2-eq./kg may be achieved (Figure 4.5). The latter two numbers are in line with the values in Table 4.1. Although some previous studies were not explicit about the technology scale, it seems that they assumed industrialization. It was not possible to identify the origin of the large difference with the findings by Walachowicz et al. (2014).

Waste collection is excluded from the scope of this study. This is justified for the environmental impact assessment, because waste is already collected in Europe, independent of magnet recycling. Only in identification and disassembly (covered by this study), additional efforts are needed. In other regions, waste collection needs to be set up before recycling is possible. This results in additional impacts, that should be divided over the recovered materials.

To address the inherent uncertainty associated with an emerging technology, this research presented the effect of different developments separately. Not all changes might be implemented as anticipated, therefore the final performance could deviate from the impact after the ‘optimization’ step. Although ‘process changes’ are fundamental and uncertain, several changes have been tested successfully in SUSMAGPRO pilots. Size scaling comes with the challenge to guarantee consistency throughout a batch. This could, for example, limit the scale of HDDR. Internal recycling is often only feasible for large-scale facilities. Optimization might take more time and effort, particularly for processes with a low TRL.

This study evaluated changes in recycling processes, not in the wider economy. The effect of background system changes is illustrated by Appendix C.5, which shows that a switch to electricity from other countries can significantly increase environmental impacts. Additionally, it shows the important contribution of renewable electricity to cleaner recycling (further investigated by Miranda Xicotencatl et al. (2024)). Since recovery relies more on electricity than REE mining, recycling benefits most, and the advantage over primary magnets remains.

A relatively uncertain part of the LCA model is the equipment. While the best available estimates for the weight of machines were used, their production capacity and technical lifespan are uncertain for the novel processes considered here. Besides, the Ecoinvent data for machine compositions may not be representative. For the shaping process, a metal working machine was assumed. This machine contains 10% copper by weight, whereas an unspecified industrial machine (1.4% copper) was deemed more representative for other processes. These uncertainties mainly affect abiotic resource depletion and to a lesser extent toxicity impacts.

Uncertainties also exist in the production of primary magnets, mainly related to the source of REEs. Different rare earth deposits vary in their environmental impacts, as shown by previous research (Bailey et al., 2020; Marx et al., 2018; Miranda Xicotencatl et al., 2021). This research assumed the current market mix of REE production, but shifts in this mix can significantly alter the future environmental profile.

4.4.3 Methodological reflection

Notwithstanding the large number of processes involved in magnet recycling and manufacturing, we obtained a comprehensive insight in the development prospects. The modeling of processes became structured because the same types of technology developments were assessed for each process. At the same time, the grouping by type of development facilitated the interpretation of results.

The reliability of the outcomes was improved by combining different approaches for estimating process performance: lab-scale data, pilot process measurements, industrial reference values, and thermodynamic models. Lab-scale and pilot-scale data were useful for determining the focus of further analysis and for calibrating upscaling models. Industrial proxies supported estimations of the optimization potential. Thermodynamic models helped to identify the drivers for energy use, somewhat similar to exergy analysis (Dincer & Rosen, 2013; Granovskii et al., 2008). By contrasting process data from all three sources, inconsistencies were identified and corrected. This allowed for selective collection of additional data.

Environmental assessments have a rather different approach to dealing with uncertainty compared to cost studies. An environmental assessment model usually assumes a 'flawless' process operation. Material losses are accounted for, but this is not the case for equipment down-time, energy use during idling, additional steps, or safety measures. All these unexpected setbacks are typically accounted for in cost calculations by a contingency factor. The less mature a technology is, the higher the contingency costs. For a small pilot plant (TRL 6), a contingency factor of 20–35% is recommended (AACE, 1991). In the case of NdFeB magnet recycling, two occurrences could negatively influence the process performance. Firstly, some batches might be discarded because the quality criteria are not met. This can significantly lower the net output. Secondly, safety measures are needed to handle magnetized magnets and fine pyrophoric NdFeB powders. These effects can be included in future studies for a more complete environmental profile.

The relative effect of various technology developments differs from the results in a case study on photovoltaic laminate (van der Hulst et al., 2020). In the present study, all types of technology developments contributed to improvements in environmental performance. The relevance of each differs per demonstrator and impact category. van der Hulst et al. (2020) concluded that process changes have the largest effect. Hence no generalizations from one ex-ante LCA study to the next can be made. Future studies of other technologies should therefore assess all development mechanisms.

4.4.4 Recommendations for recycling technology

This study yielded new scalable unit process models, applicable beyond the case of magnet recycling. Specifically, thermodynamic models were created for jet milling, feedstock mixing (mixing powders with polymer binders), and solvent debinding (see ESI 1). Hereby, we extended the available set LCA models of powder metallurgical processes (Azevedo et al., 2018; Raoufi et al., 2020).

This research contributed to the development of NdFeB magnet recycling by providing guidance for more sustainable process improvements. Section 4.3.4 provided guidance for technology developers to define a focus for further improvements. Most improvements apply to multiple magnet production routes, signaling opportunities for knowledge cross-over. For example, the large-scale pelletizing process used for bonded magnets can be adapted and adopted to improve the feedstock preparation for MIM and extruded magnets. Sintering is applied in three manufacturing routes, and although the settings depend on the presence of a binder, best practices could be exchanged for energy-efficient design and operation.

The four routes for manufacturing NdFeB magnets have distinct environmental profiles. At current technology levels, recycled bonded magnets offer the largest environmental benefits. The demonstrator that has the highest impact is different per impact category. Due to the anticipated technology developments, the impacts of the manufacturing routes will converge. Consequently, the industrial-scale versions of all routes perform significantly better than their primary production counterparts. The choice for either manufacturing route should not be based on the current performance, but rather on the functional requirements and on the expected ease of improvement.

Future research could investigate the profitability of recycling, while considering fluctuating REE prices. Profitability is likely to increase through upscaling and efficiency gains. Prospective assessments suggest that hydrometallurgical recycling is cost-competitive (Beylot et al., 2020; Chowdhury et al., 2021; Elwert et al., 2017).

4.5 Conclusion

This study investigated how advancements in magnet recycling technology can reduce its environmental impacts, and compared these impacts to those of the primary production route. Recycled NdFeB powders were shown to have lower environmental impacts than powders from primary sources, already for pilot-scale recovery. For recycling and magnet manufacturing combined, all improvements together can result in 80% lower environmental impacts compared to primary magnets for most impact categories. The industrial-scale performance is achieved by upscaling and optimizing the unit processes, as quantified in this study.

The most effective identified improvements address three environmental hotspots: electricity use, inert gas use, and losses of NdFeB material (Section 4.3.4). Therefore, large impact reduction can be achieved through internal recycling and by minimizing losses of NdFeB material. Size scaling effects contribute to lower heat losses, significantly minimizing the energy consumption. Process changes and optimization also contributed to lower impacts. While the major improvements address the magnet manufacturing stage, the relative importance of pre-processing increases in optimized recycling systems.

This case study shows that innovation and emerging technology development can result in large reductions of environmental impacts. Although most changes are motivated by efficiency and costs, the environment also benefits. An exception could be internal recycling measures, which require additional investments in recovery equipment, and only become financially viable at larger scales.

Based on our findings, the rare earth permanent magnet industry can reduce its environmental impacts in three ways. First, by incorporating more recycled materials in magnets. Second, by investing in process innovation for cleaner production and recycling. Third, by upscaling and applying more resource-efficient manufacturing routes like MIM and extrusion when suitable. With these focus points, NdFeB magnets can continue to enable clean electricity production and consumption.

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