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

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Introduction

1.1 The industrial ecosystem of magnets

The discovery of NdFeB magnets was a seemingly small event with large consequences. In a modest scientific publication, Sagawa et al. (1984) disclosed a permanent magnet made of neodymium, iron and boron. NdFeB is the strongest permanent magnetic material known to date, owing to a fine-tuned production process and an optimized composition that includes other rare earth elements (REEs). It enabled the development of HDDs, tiny speakers in almost every gadget, compact electric motors, and efficient wind turbines. This wide range of applications resulted in rapid growth of magnet demand. However, innovation does not end here. New solutions are needed to address two major drawbacks: the pollution caused by REE mining (Arshi et al., 2018), and the vulnerability of the supply chain to disruptions such as geopolitical struggles (Sprecher et al., 2017).

The supply chains of neodymium and other REEs used in magnets are of large geopolitical importance for two reasons. First, NdFeB magnets are a key enabler of electrified renewable energy systems, due to their use in electric vehicles (EVs) and wind turbines. These low-emission technologies require large amounts of materials for their expansion. The economic importance of NdFeB magnets is further increased by their application in drones, robots, and military equipment (Pavel et al., 2020). Second, in recent decades, China has established a dominant position in the magnet supply chain, from REE mining and refining to magnet manufacturing (Smith et al., 2022; Tukker, 2014). This is problematic for other countries that rely on imports with a risk of logistic or political interruptions. REEs are not geologically rare; in fact, reserves are over 400 times larger than the annual mining rate (USGS, 2023). Still, few mines outside of China have opened due to long lead times, economic infeasibility and in fear of damaging the local environment (Filho, 2015; Liu et al., 2016). The risk of material shortages threatens the deployment of EVs and wind turbines if the REE supply cannot ramp up in time (Watari et al., 2020). The combination of high economic importance and high supply risk means that REEs are considered critical raw materials (Blengini et al., 2020; USGS, 2022).

To reduce the need for mining and mitigate supply risks, recycling is a promising solution. It diversifies the supply of magnets by making secondary resources available. Therefore, the European Union aims to obtain 25% of its REE demand from recycling by 2030, to improve its strategic autonomy (European Commission, 2023). Several technologies for magnet recycling have been investigated in laboratories, aiming to provide a more sustainable alternative to primary magnet production. The recent growth in commercial and political interest in this technology raises a new question, which is the main question of this doctoral thesis:

> *What is the potential and the environmental consequence of deploying large-scale NdFeB magnet recycling?*

To answer this question, three challenges have to be addressed. These challenges connect to the large themes of *Industrial Ecology*, as decribed in this chapter. Firstly, although recycling is conceptually simple, large-scale recycling systems can be complex to build and understand (see §1.3). Secondly, the wide range of magnet applications gives rise to an opaque societal metabolism, and tracing the waste flows is challenging (see §1.4). Thirdly, magnet recycling and other emerging technologies are constantly evolving, and therefore require a prospective approach to assessing their future sustainability benefits (see §1.5, §1.6). After summarizing the current status of magnet recycling in §1.2, the following sections introduce the research opportunities and research questions that guided the investigation into the recycling of NdFeB magnets.

1.2 Current status of magnet recycling technology

The recycling rates of NdFeB magnets are presently low due to various challenges in waste collection and recovery (Balaram, 2019; Jowitt et al., 2018; §1.3). Until recently, NdFeB magnets were rarely collected or sorted, consequently ending up in ferrous scrap after shredding (Bandara et al., 2014). This is how most small magnets, which are found in consumer electronics and vehicles, are lost. In most countries, the recovery of NdFeB material has until now been uneconomical (Binnemans et al., 2021), because labor-intensive recycling processes cannot compete with the price of primary production.

Figure 1.1 outlines various technologies that have been explored for the recovery and recycling of waste NdFeB (Yang et al., 2017). If devices are disassembled properly, magnets may be reused directly. The shortest recycling loop is through powder metallurgy, which recovers NdFeB powders from scrap magnets. Powder metallurgical recycling is also known as direct alloy recycling, because the magnet alloy is not separated into its constituent elements but used directly to make new magnets. A notable example is *hydrogen processing of magnet scrap* (HPMS), which uses hydrogen gas to pulverize magnets (Walton et al., 2015). Other recycling technologies, including hydrometallurgy (dissolution in acids) and pyrometallurgy (melting), purify and recover individual elements. However, this requires large amounts of either chemicals or energy. In contrast, HPMS is a promising technology from an environmental perspective because it operates at room temperature and uses no solvents (Ormerod et al., 2023; Yang et al., 2017).

During this doctoral research project, the development of magnet recycling has accelerated remarkably. The public awareness increased due to a growing media attention. News media reported on business efforts to recycle magnets, from the securing of funding to the opening of pilot plants (Figure 1.2). These business activities have been enabled by previous research efforts and are encouraged by policy plans (Koese et al., 2024). Specifically, if the EU Critical Raw Materials Act is implemented, it can stimulate the demand for recycled REEs. This combination of trends is likely to result in more widespread recycling in the future.

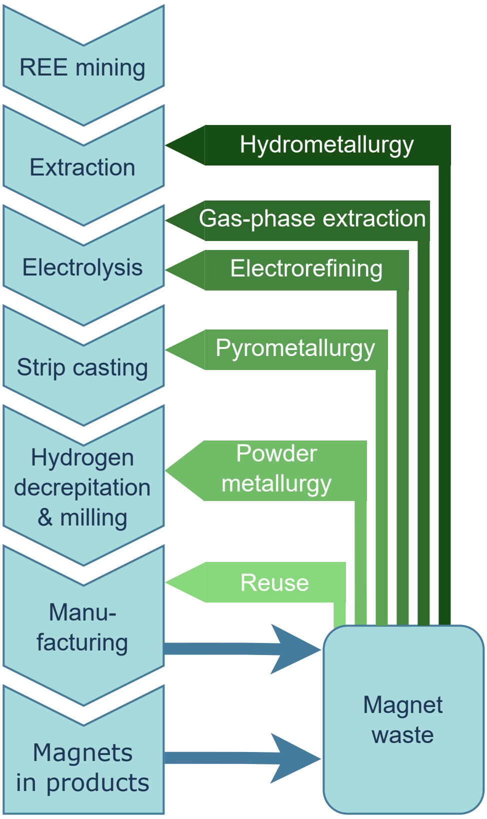

FIGURE 1.1: Overview of NdFeB recovery methods, and the point of entry of material into the primary supply chain. For completeness, direct reuse is included as a short-loop alternative to recycling. Reproduced from Koese et al. (2024).

This study aims to fill important knowledge gaps for the emerging magnet recycling sector. Scientific research can guide the advancement of new magnet recycling systems and technologies. An example of a new recycling initiative is the SUSMAGPRO project, which aimed to implement direct alloy recycling. SUSMAGPRO was a European Horizon-2020 research project[1] that lasted 4 ½ year and brought together a consortium of 19 organizations. This thesis was largely written in the context of SUSMAGPRO. The collaboration with SUSMAGPRO technology developers has created unique opportunities for interaction and data collection. This enabled us to model recycling technologies in great detail and gain more insights into the practical challenges of recycling. Chapter 4 describes SUSMAGPRO technologies in more detail.

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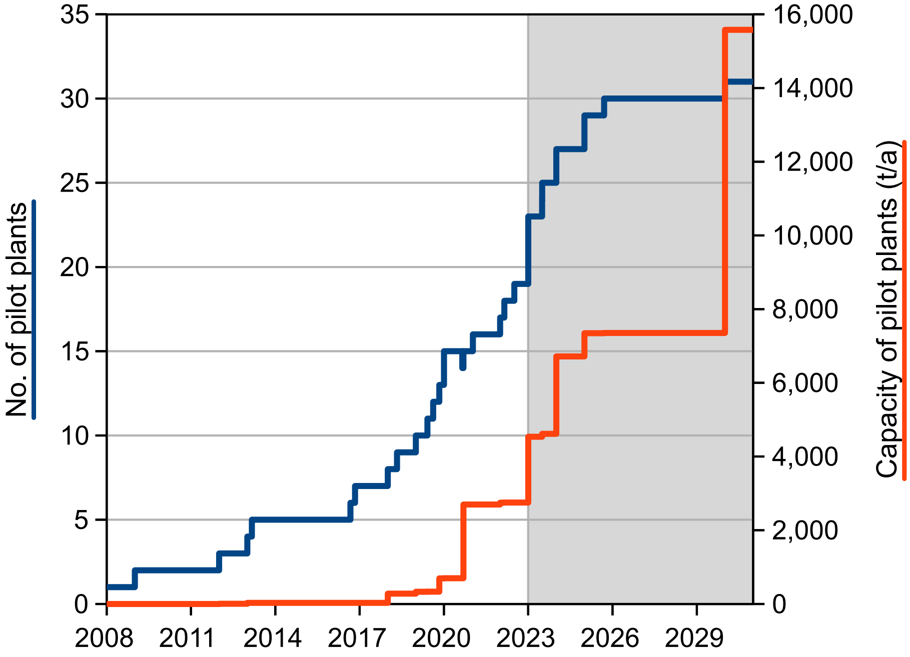

FIGURE 1.2: Number of new plants (blue) and their total recycling capacity (red) for NdFeB magnet recycling. The (expected) start of operation is displayed; when only the starting year was communicated, January 1st was assumed. For 7 of 28 facilities, no (estimated) capacity was released. The shaded area indicates announced facilities. Reproduced from Koese et al. (2024).

1.3 The role and complexity of recycling systems

Large-scale recycling is achieved through recycling systems, consisting of technical processes, physical infrastructure[2] and organizational structures. The societal benefits of metal recycling are much broader than waste management, as it contributes to a diversified metal supply, reduces price volatility, minimizes environmental impacts, and reduces pollution from landfills (Hagelüken & Goldmann, 2022; Hagelüken et al., 2016). In a circular economy, recycling is one of the strategies to close material loops; recycling enables the recovery of materials from EoL products that cannot be repaired or reused. Recycling and other circular strategies also compete for a limited supply of EoL products. Extending this concept, waste management was studied as a reverse market, where classical economic market forces apply (Stindt et al., 2017). The dynamics of reverse supply chains are shaped by the available resources and by interactions of involved stakeholders.

Improving a recycling system starts with measuring its current status and identifying

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[2] Technical processes refer to the specific methods and procedures involved in recycling. Physical infrastructure refers to supporting facilities, such as buildings, machinery, and transportation networks

any problems. Three common indicators are widely used to measure the success of recycling: end-of-life (EoL) recycling rate, recycled content, and old scrap ratio[3] (Graedel et al., 2011a). Recycling rates are low for many metals, especially for minor metals (Graedel et al., 2011a,b; Hagelüken & Meskers, 2010). This is a concern because minor metals such as REEs are key enablers of specialized technologies, and are therefore also referred to as technology metals or specialty metals (Graedel et al., 2011b). This motivates research into the recycling of these metals.

Previous research has documented several challenges for the implementation of effective recycling. Cramer (2018) categorized these as economic and business barriers (e.g. upfront investment costs for recycling infrastructure), regulatory barriers (e.g. standards and certifications), and social barriers (e.g. throw-away mentality). Minor metals face additional obstacles due to their dispersed use in numerous components and devices, and limited technology options for recycling emerging applications (Mathieux et al., 2018). In addition, tracing these metals can be challenging due to complex global trade networks (Nansai et al., 2014). The interpretation of recycling indicators for emerging minor metal waste flows requires caution (Hagelüken & Goldmann, 2022). While demand increases, high recycled content and old scrap ratios cannot be achieved. A low EoL recycling rate suggests that some parts of the recycling system have yet to be established, without specifying which parts. More specific indicators would help to identify the limiting factors of minor metal recycling. In fact, to establish effective recycling systems requires a holistic approach and an understanding of the role of all stakeholders (Reuter et al., 2013). Therefore, this thesis aims to answer the following research question (RQ).

RQ 1. *What factors determine the success of recycling minor metals and their recycling systems?*

This research question aims to look beyond current recycling rates, and create an overview of economic, technical and societal factors that play a role. The objective is to develop a recyclability assessment framework for minor metals in general, and later apply the insights to neodymium in NdFeB magnets. ‘Recyclability’ refers to the feasibility of recovering materials from discarded products (Henstock, 1988). To evaluate recyclability, multiple indicators are needed, addressing barriers and drivers throughout the recycling value chain.

1.4 Gauging the potential of magnet recycling

Conceptualizing recycling as a reverse supply chain (see §1.3) highlights the importance of secondary resources, namely the waste flows that serve as feedstock. For NdFeB, neodymium, and other minor metals, the availability of secondary resources can be a major limiting factor. In order to design and optimize reverse logistics of used NdFeB magnets, for instance using an optimization algorithm (Jin et al., 2018b), it is essential to quantify the waste flows. This is a challenge because NdFeB magnets are applied in a wide variety of products and components. For example, a passenger car has magnets in ten types of components, ranging from speakers to radiator fans (Restrepo et al., 2017).

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[3] The old scrap ratio describes the fraction of old scrap in the total recycling flow. Recycled content includes old scrap and pre-consumer scrap.

Moreover, in most electrical and electronic devices, magnets only account for a small fraction of the device's weight (Nansai et al., 2014). To address the potential for magnet recycling in European context, research question 2 was formulated.

RQ 2. *What is the volume of NdFeB magnet waste in Europe? Which waste flows are most suitable for recycling?*

This question can be answered by combining two approaches, material flow analysis (MFA) and recyclability assessment (see §1.3). MFA is introduced below. By combining these two quantitative assessments, a holistic view on the recycling system is pursued, covering material flows, recycling processes, and stakeholders.

Material flow analysis is the study of stocks and flows of materials and substances in society (van der Voet, 1996). To quantify the evolving flows of neodymium, a valuable approach is dynamic MFA. Dynamic MFA quantifies the flows into and out of the use phase, using either a stock-driven or an input-driven model (Müller et al., 2014). Stock-driven models calculate the flow into use based on observed or projected stock growth while accounting for discarded products. This approach is useful when precise information about the in-use stock is available, or when studying bulk metals (Fishman et al., 2014). Input-driven models start from product consumption and waste flows. Stocks are derived from the difference in in- and outflows, requiring an initial stock estimate and long time series. This approach is more suited for studying products that are weakly linked to population size, and for substances that only occur in specific product types. Both models typically calculate waste flows using lifespan distributions or averages, derived from e.g. surveys on electronic products (Forti et al., 2018; Thiébaud et al., 2018).

This thesis employs an input-driven MFA model to conduct a detailed analysis, aiming to disaggregate neodymium flows by product and country. To accurately model these material flows, this research accounts for two particularities of magnets. First, NdFeB magnets have been applied in an increasing number of applications over the last decades. It is therefore important to consider the changing market share of NdFeB magnets compared to other magnet types. Second, the wide scope of this study addresses the diversity of magnet types and applications, including those with a small associated Nd flow. In contrast, prior studies have either omitted certain magnet applications or assumed a constant market share of NdFeB magnets. The diversity of magnets is also acknowledged in the next section by considering recycling as a system with multiple inputs and outputs.

1.5 Environmental analysis of technological innovations

Recycling is often assumed to be environmentally beneficial. In industrial ecology, this assertion is tested by comparing different waste management options. Unfortunately, it was not possible to make a complete environmental comparison between NdFeB recycling and other types of waste treatment, because there are no characterisation factors for the extraction (resource depletion potential) and emission (toxicity) of REEs used in magnets (Edahbi et al., 2019; Fazio et al., 2018). A related question is whether the benefits of recycling outweigh the impacts of waste collection. However, the decision to collect waste is mostly motivated by the societal aversion of waste dumping, landfilling and incineration. From a life cycle perspective, the emissions of waste collection are therefore attributed to the use of a product rather than its recycling. Hence the scope can be limited to waste sorting and recycling.

Magnet recycling and other technological innovations contribute to the decoupling of environmental degradation from human wellbeing. As indicated by the $IPAT$ equation, innovations contribute to technological efficiency (T), and can be complemented by moderating population growth (P) and shifting from materialistic affluence to wellbeing (A) (Chertow, 2000). For technology developers, consumers and policy makers, it is important to understand the development prospects of a new innovation before its introduction to the commercial market. This foresight allows to direct investments towards the most promising technologies, and underlines the need for ex-ante life cycle assessment (LCA) (Cucurachi et al., 2018; van der Giesen et al., 2020).

For the magnet recycling processes introduced in §1.2, several studies have investigated the environmental impacts using LCA. Comparative studies indicated that recycling has lower environmental impacts than primary magnet production. Shorter recycling loops, as shown in Figure 1.1, generally perform better (Elwert et al., 2017; Wang et al., 2022). Recent advances in direct alloy recycling technologies justify a renewed investigation of environmental impacts, including an outlook on industrial-scale performance. This motivated the formulation of RQ 3.

RQ 3. *What are the environmental impacts of industrial-scale recycling processes for NdFeB magnets?*

This research question seeks to explore the role of technological changes that occur when direct alloy recycling develops from lab-scale and pilot-scale to industrial scale. By assessing various anticipated technological advancements and recycling routes, the potential for environmental impact reduction can be revealed.

The approach to answering RQ 3 builds upon the established LCA methodology, which allows to quantify the environmental impacts along the life cycle of a product, process or service. LCA studies quantify the contribution of a product's life cycle to global environmental issues, using a set of impact assessment methods (Guinée et al., 2002). Conducting an *ex-ante* LCA, i.e. before a technology is fully developed and implemented, allows to anticipate improvements in sustainability performance and identify areas of concern, guiding the technology's further R&D trajectory (van der Giesen et al., 2020). Therefore, ex-ante LCA is relevant for studying the developing magnet recycling technology. We aim for a detailed outlook by incorporating the latest information on technology performance from developers.

To conduct the ex-ante LCA, we can refer to existing guidelines. These guidelines provide general procedures, despite the wide variety of technological domains. Some approaches focus on inventory modelling (Tsoy et al., 2019), while others take a broader perspective (Langkau et al., 2023). The guidelines implicitly or explicitly draw from other forward-looking methods, such as cost projections, scenario building, and technology forecasting (Cho & Daim, 2013; Langkau et al., 2023). This research used scenario thinking and various unit process modeling techniques to explore the future impacts of magnet recycling.

Previous ex-ante LCA studies have primarily focused on the future technology performance (Jin et al., 2018a; Sprecher et al., 2014; Wang et al., 2022). It is much less explored how the environmental impacts would evolve during the technology development from small-scale to industrial scale. Such analysis would enhance the usefulness of ex-ante LCA, by explicitly highlighting the gap between small-scale and large-scale technology, and by indentifying the most effective improvements. We have pursued this approach, following the example of van der Hulst et al. (2020). Scenarios in ex-ante LCA typically consider external developments. This study only briefly touches on external developments, as extensively researched by my colleague (Miranda Xicotencatl et al., 2023).

1.6 Anticipating environmental impact trends after commercial introduction

Next to the development from lab-scale and pilot-scale to industrial recycling, it would be great to extend the outlook to development during industrial operation. Current ex-ante LCA approaches help to explore future technology performance. It would be great to also have insight in the time it takes to reach anticipated future performance levels. While early technology innovation is unpredictable, research has shown that after the initial industrial introduction, costs follow a predictable trend, described by a learning curve. This inspired an investigation of the effect of learning on environmental impacts.

Learning plays a key role in the improvement of mature industrial processes (Feeney et al., 2023), therefore LCAs should consider learning when technologies are studied beyond their first commercial introduction. In their definition of ex-ante LCA, Cucurachi et al. (2018) refer to learning curves as a possible approach to derive technology development scenarios. Some studies have modeled environmental learning (Thomassen et al., 2020; van der Hulst et al., 2020) on the assumption that cost-based learning trends can be applied to the environmental domain. However, this assertion is not supported by, for example, identifying the drivers or mechanisms of learning. Furthermore, the possibility that learning may have different implications for different impact categories has largely been disregarded, with only one study indicating differentiated trends (Stamford & Azapagic, 2018). In short, there is a lack of conceptual underpinning and robust methods for the applicaton of environmental learning curves. This gap is addressed by RQ 4.

RQ 4. *How does technological learning affect environmental impacts, and how can LCA studies address this effect?*

By developing a method to assess environmental learning, this research aims to enable temporally-explicit outlooks in ex-ante LCA. The procedure is developed based on organizational learning theory, eco-innovations literature, evidence from case studies, and cost forecasting methods. The latter also inspired the use of contingency factors to improve future impact projections (see §5.3.6).

Thus far, learning curves have mainly been used in environmental sciences to study energy technologies, resulting in a focus on costs and CO_2 emissions. This contributed to insight into the development of renewable energy technologies, including their costs and efficiency. However, RQ 4 seeks to broaden this scope by aiming for a methodology that addresses all environmental impact categories. This extension aims to broaden the applicability of learning curves to a wider range of technologies.

1.7 Outline

Research questions 1–4 are addressed by the four ensuing chapters of this thesis. To gain insight into magnet recycling technologies and recycling systems at different levels, including opportunities for improvement, several complementary research methods are applied.

Chapter 2 addresses RQ 1 by conducting a literature review on factors that determine the recyclability of minor metals. The outcomes of the review are used to develop a framework for recyclability assessment, including indicators that enable quantitative comparisons.

Chapter 3 explores RQ 2 using a dynamic MFA approach to quantify the demand and waste flows of neodymium contained in magnets. This analysis provides insight into the composition of waste flows and their country of origin. A recyclability assessment provides additional information on the suitability of EoL products for recycling.

Chapter 4 delves into RQ 3 by determining the environmental imapacts of magnet recycling routes, for small-scale and for potential industrial-scale configurations. This chapter applies ex-ante LCA to identify hotspots of environmental impacts in the recycling chain, and compares recycled to primary magnets. Furthermore, the effect of techological progress is systematically assessed by grouping the different development mechanisms.

Chapter 5 addresses RQ 4, by presenting a method to account for learning effects in prospective LCA. This method builds on a review of organizational learning theories and evidence on environmental learning. These insights help to assess whether learning curves apply and to estimate the learning rate.

Chapter 6 synthesizes the main findings of Chapter 2–5. This final chapter answers the main research question by summarizing the environmental consequences of deploying large-scale NdFeB magnet recycling. It also provides a reflection on this research and its implications for the future.

Data availability

This thesis contains four appendices, corresponding to each of the main chapters and containing supplementary information and figures. Some supplementary data tables are unfit for printing. For these tables, the reader is referred to the Electronic Supplementary Information (ESI) on the webpage of the published article.

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