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

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S Summary

This thesis investigated the potential for deploying magnet recycling technologies and their environmental consequences. These technologies are under development, aiming to provide a more sustainable alternative to magnets made from virgin rare earth elements (specifically neodymium-iron-boron (NdFeB) magnets). The market for rare earth magnets is experiencing great turmoil, with fluctuating prices and an exponentially growing demand driven by wind turbines and electric vehicles. As consumption increases, so do the waste volumes. Together with the limited mining capacity, this urges the development of a recycling system.

From an environmental perspective, the impact of magnet recycling depends on the availability of end-of-life (EoL) magnets, the efficiency of recovery and recycling technologies, and the effectiveness of the recycling system as a whole. The recycling processes have a low technology readiness level, therefore it is important to anticipate improvements in performance during their development. To study the trend of environmental impacts after introducing recycling on an industrial scale, a potential approach is to use environmental learning curves. However, a well-founded method is lacking for studying changes in environmental impact resulting from learning effects. We addressed these aspects of magnet recycling by investigating the following research questions.

1. What factors determine the success of recycling minor metals and their recycling systems?
2. What is the volume of NdFeB magnet waste in Europe? Which waste flows are most suitable for recycling?
3. What are the environmental impacts of industrial-scale recycling processes for NdFeB magnets?
4. How does technological learning affect environmental impacts, and how can life cycle analyses (LCA studies) address this effect?

Rare earth elements, used in magnets, are part of a larger group of minor metals that share several recycling challenges. To improve recycling rates, it is important to understand the bottlenecks and drivers in recycling value chains. Therefore, Chapter 2 analyzed existing recyclability frameworks and related recycling literature, revealing 113 factors that determine the success of recycling minor metals. These factors reflect a variety of perspectives, including economic, thermodynamic, and design perspectives. Together, they describe how product characteristics, recycling technologies, and societal conditions contribute to recyclability. These findings informed a novel recyclability assessment framework. The framework introduces a set of indicators, grouped by the stages of the recycling value chain, i.e. manufacturing, use & collection, preprocessing, metallurgical recovery and secondary marketing. Additionally, overarching factors are

addressed. Chapter 2 presented three case studies, in which the framework was applied to evaluate and compare the recyclability of minor metals in various products.

Chapter 3 quantified the amount of neodymium waste in European countries using material flow analysis, and assessed the recyclability of major EoL products using the framework from Chapter 2. In 2019, a waste flow of 2.8 kt neodymium was found, mainly consisting of NdFeB magnets. HDDs make up a large part of this waste flow, providing an attractive input for recyclers for several years. Other sources of secondary Nd, that are becoming increasingly significant, are the magnets used in industrial applications (pumps and robots) and in conventional cars. In the future, EoL electric vehicle motors and wind turbines may provide a source of neodymium with good recyclability. Given these dynamics of emerging magnet applications and waste flows, flexibility is required in waste collection and preprocessing. The recyclability assessment identified some bottlenecks in the recycling of EoL magnets. By addressing these, a robust recycling system can be established to handle the future growth in waste volumes. Future research could reduce uncertainty in the outcomes by mitigating reporting errors in production and trade data. Also, more detailed data on the market share of different magnet types would be beneficial.

Chapter 4 investigated the environmental impacts of new technologies for recovering, recycling and remanufacturing NdFeB magnets. The focus was on the direct recycling of NdFeB alloys, which recovers the materials as powders rather than separating the individual elements. The anticipated performance of large-scale recycling was modeled, and compared to the production of primary magnets. This analysis applied ex-ante LCA, combining input from measurements of pilot processes, expert technology forecasts, thermodynamic modelling, and equipment data from manufacturers. The results show that at pilot scale, recovered NdFeB powders have lower impacts than primary powders for almost all impact categories, demonstrating the environmentally benefit of recovering NdFeB alloys. Magnets from anticipated large-scale recycling have over 80% lower impacts than primary magnets in most of the impact categories analyzed. We examined the effect of four technology developments: process changes, size scaling, internal recycling, and optimization. All four types contributed to improving the performance from pilot-scale to industrial scale. The final configuration was validated by comparing it with an industrial reference and theoretical optimum configuration. Effective changes include reducing material losses during sieving, and improving the energy efficiency through size scaling. Furthermore, four magnet manufacturing routes were investigated: sintering, extrusion, metal injection molding (MIM), and bonding. Each has a distinct environmental profile, but all can progress to similarly low levels of impact. Extrusion and MIM are less mature, which results in higher initial environmental impacts. Since each magnet type has unique properties, the choice among routes should be based mainly on the functional requirements. Future LCA studies may incorporate cleaner electricity production and developments in primary magnet supply chains.

Chapter 5 fundamentally explored the effects of learning on the environmental impacts of industrially deployed technologies. We reviewed the theoretical foundations and empirical evidence of technological learning. We identified various learning mechanisms, some of which only affect production costs. Previous studies have mainly demonstrated reductions in impacts related to energy use. A key observation is that the results may vary by impact category, and certain impacts may not decline at all. Next, we developed a procedure for assessing learning effects in ex-ante and prospective LCA. We argue that learning involves operational or organizational changes, which are motivated by incentives. Therefore, environmental impacts may follow a learning curve if the origins of impacts coincide with where the main incentives are directed. By providing step-by-step guidelines to evaluate environmental learning effects and learning rates, we allow future studies to model the impact trends during industrial technology development. Applying the procedure to magnet recycling, significant learning effects are expected. Furthermore, we highlighted the need for expanding the evidence base for the environmental effects of technological learning. This can be achieved by reinterpreting datasets of existing technologies to determine their learning rates.

In conclusion, the average environmental footprint of NdFeB magnets in Europe can be reduced by improving and deploying magnet recycling technology. Deployment is limited by the availability of waste magnets. Recycling could at most fulfill 45% of the NdFeB demand in 2019, and this maximum share may decrease in the future due to the longer lifespans of emerging magnet applications. Still, recycling has a large growth potential, as it is currently not widely practiced. The environmental benefits of recycling compared to primary production will initially be limited, but may increase significantly as the processes improve. Recycled magnets can ultimately achieve over 80% lower impacts for most impact categories, as revealed through ex-ante LCA. The analysis of learning effects indicated that the environmental impacts may decrease by about 20% for each doubling of the cumulative recycling output.

This research supports previous studies that demonstrate the contribution of NdFeB magnet recycling to sustainable development. Recycling reduces the pressure on the primary magnet supply chain and increases the availability of raw materials for producing low-emission technologies such as electric motors. Moreover, recycling technologies that are implemented on a large scale have lower environmental impacts than primary production processes. Recycling alone cannot satisfy the demand for NdFeB magnets. However, the combination of multiple recycling technologies with effective waste collection systems can contribute to a significantly more circular magnet industry. Emerging technologies for magnet recycling enable successful and sustainable recycling systems in the future. These systems can be realized with circular business models and guiding policies based on this research.

This research focused on magnet recycling in Europe, making the results less relevant for other world regions. Other countries may differ in the demand for magnet applications, the societal context of recycling systems and the electricity mix. Depending on the growth rate of magnet demand, the maximum share of recycled feedstock may be higher or lower. When comparing the environmental impact of primary and recycled magnets within a non-European country, the preferred alternative is likely to be the same as in this study. However, a comparison with the global average of primary magnets requires a separate analysis.

Some aspects require further attention by researchers and recyclers. These include digital solutions for tracking and detecting magnets in products, collaboration to align the stages of recycling, co-recovery of magnets and other materials, and methods for promoting behavior that supports recycling. Recyclers can use insights in the various EoL magnet types and differences among countries to develop recycling activities. These recyclers can gain essential experience by learning-by-doing in an industrial setting.