Swedish Environmental
Research Institute

Sustainable European NdFeB Permanent Magnet Production

Synthesis Report of EU project RECO2MAG

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Summary

This report is a synthesis of five project deliverables in RECO2MAG (Novel grain boundaries engineered resource efficient Nd-Fe-B permanent magnets), a research project exploring a state-of-the-art production technology to produce sintered permanent magnets (PMs) from Rare Earth Elements (REEs). This synthesis report focuses on European NdFeB PM supply-chain, and market and sustainability. The project seeks to address the challenges of producing NdFeB PMs with reduced Dysprosium (Dy) content in Europe. This shift aligns with broader goals of enhancing sustainability and reducing reliance on REEs, particularly considering Europe's growing demand for REEs in green technologies.

The first chapter covers the technology, supply-chain, and European market aspects of NdFeB PMs

Currently, China dominates the NdFeB PM market, with only a handful of European actors active in the different parts of the supply chain. To compete with Chinese REE and REE PM prices, European actors can do several things, such as 1) focus on value offerings other than price, 2) improve material-use effectiveness and reduce REE content per magnet, and 3) be open for strategic collaborations.

Introducing circular economy into the lifecycle of NdFeB PMs can lower the amount of required primary material, but there are various challenges yet to be overcome. NdFeB magnets are often tightly integrated into motors, making them difficult to remove without causing damage or requiring extensive labor. If not properly separated, they can break into small pieces during disassembly, leading to contamination in other materials. Manual dismantling is also generally expensive and inefficient. To manage the disassembly issues at end-of-life (EOL), future electric motors could be designed with recycling in mind, making it easier to remove and recycle magnets. Also, automated recycling may be able to improve the costs over time. The EU is already creating legislative action to enhance the circular economy through recoverability of magnets by imposing regional benchmarks on recycled content and recovered EOL materials, as well as design requirements, through the critical raw material act (CRMA) and ELV-Regulation. Emerging recycling technologies can also further enable the EUs ability to create a REE circular economy.

The second chapter covers sustainability assessments of environmental, monetary, circular economy, and social aspects in state-of-the-art REE and NdFeB PM production

The scope of the assessments included producing state-of-the-art sintered NdFeB PMs for electric vehicles (EVs) at a European manufacturer, and assessing possible primary European Dy-production compared to Chinese Dy-production. Primary European Dy-production is likely to have higher environmental impacts than Chinese production in the short term due to lower ore concentration and Chinas already-established REE industry. The lower ore concentration requires more processing and resources, and higher energy consumption and chemical use. Thus, the environmental impacts of primary European-mined Dy would likely be greater per kilogram primary Dy.

The scope of the assessments also considered a lowering of Dy required (from 7 to 1 weight-percent) by the European NdFeB PM manufacturer through an improved milling technique. The lowered amount reduced the environmental impact categories from use of primary Dy by 20-80%, and lifecycle costs decrease by about 20% for production of NdFeB PMs.

To measure the circular economy performance, the European Commission's recommended method for measuring carbon footprint for products was evaluated (the product environmental footprint circular footprint formula, PEF CFF). The PEF CFF framework, while comprehensive, was found to be simplistic and inaccurate in its current state for detailed upstream and downstream supply chain analysis. Using the 3R/9R frameworks in conjunction with the PEF CFF could improve circularity by considering additional circular strategies. If the EU Commission added material datasets for REEs it would make the PEF CFF much more accurate than in its current state, where the datasets lack specificity for REE end-of-life (EOL) flows, and thus the insights that could be obtained through the PEF CFF.

Expanding REE mining in Europe requires addressing social issues such as health risks, gender inequality, and fair labor practices. Strict standards for working conditions, environmental practices, and community engagement are essential to ensure responsible mining and mitigate negative reputations associated with the sector. By addressing these challenges and leveraging emerging opportunities, Europe can enhance the sustainability of its NdFeB PM supply chain and support green technology adoption, while minimizing environmental and social impacts.

Table of contents

Summary 3

1 Introduction 6

1.1 Aim & Scope 7

2 Foundational Background: NdFeB Permanent Magnets and the European Supply Chain 8

2.1 The roles of Neodymium and Dysprosium 8

2.2 Processes and Organization for a European NdFeB Permanent Magnet Supply Chain 9

3 Assessing Sustainability: Environmental, Cost, Social, and Circularity Impacts 16

3.1 Sustainability Assessments 16

3.1.1 Objectives 16

3.1.2 About the Methods Used 17

3.2 Key Results 19

4 Conclusion 21

5 References 23

Appendices – System Boundaries 25

1 Introduction

This synthesis report is based on five individual technical reports (1) (2) (3) (4) (5) that IVL authored in the EIT Raw Materials project RECO2MAG[1] (Novel grain boundaries engineered resource efficient Nd-Fe-B permanent magnets (PMs)). This report aims to weave together key findings from the selected reports written as part of this research project to a broader audience, with a specific focus on their sustainability aspects in the EU Electric Vehicle (EV) industry.

The Green Transition requires NdFeB PMs for various crucial technologies. The magnets' functions vary between applications, but arguably their most important contribution are their energy conversion capabilities in key green technologies: converting mechanical-to-electrical energy in wind-turbines and converting electrical-to-mechanical energy in electric cars. As the European Union (EU) continues to shift carbon-intensive energy sources to renewables, the demand for these technologies increases. Consequently, it becomes of vital important to ensure a robust supply of the materials required in these green technologies, such as rare earth elements (REEs).

Neodymium (Nd) and dysprosium (Dy) are key rare earth raw materials in permanent magnet (PMs) production, for the above-mentioned applications of electric vehicles (EVs) and wind-turbines. Although substitutes do exist, today's PM-production technologies will not produce magnets that can reach the same material properties of PMs produced with REEs (see Chapter 2.1). The rare earth raw material's uniqueness, coupled with the EU's increased demand of EV's and renewable electricity (through e.g. wind-turbines), means that these REEs are highly sought-after in the region. They have thus been classified as having a high Economic Importance (EI) by the EU Commission. Furthermore, today, the REEs are also almost entirely sourced in a single region: China. This creates a supply risk (SR) for the REEs, as sourcing from just a single region creates vulnerabilities in the supply chain. The high EI and SR for raw materials are what has led the EU to classify REEs as critical raw materials (CRM).

Research projects like RECO2MAG are aimed at managing pressing CRM supply risks to the EU economy by bringing together cross-functional expertise and

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[1] www.reco2mag.rgf.bg.ac.rs

industry to develop Europe's own sustainable raw material and critical component supply chains to reduce dependency on imports. This in turn is meant to increase energy security, economic stability, and environmental sustainability in the Green Transition. The varied expertise in material science, business & marketing, environmental management, and more, gives the RECO2MAG project a holistic overview of the potential of European manufacturing NdFeB PMs with European primary REEs.

1.1 Aim & Scope

IVL Swedish Environmental Research Institute (IVL) was responsible for the *work package (WP7) Sustainability assessment and comprehensive modelling for circular REEs PMs economy* and was also involved in *WP8 Go to Market Strategy*, so this report will synthesize the specific reports in which IVL authored for EIT Raw Materials[2]. Five separate report deliverables, each addressing distinct sustainability aspects, are what this synthesis report is based on:

- A Market Analysis[3],
- A Product Chain Organization (PCO)[4],
- A Life Cycle Assessment (LCA),
- A Life Cycle Costing (LCC) assessment, and
- A Circular Economy (CE) performance assessment[5].

The report will primarily consider primary state-of-the-art REE mining and NdFeB PM production, although some parts cover secondary REEs in a smaller scope.

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[2] RECO2MAG initially set out to use grain boundary diffusion (GBD) in the proposal, a technique which retains the benefits of Dy's heat-protecting abilities in PMs while minimizing the amount required per magnet produced. The technique works by concentrating Dy to the surface of the magnets, meaning less Dy-content is required overall for a similar desired effect. However, as the experimental parts of the projects developed, the focus shifted towards other techniques to minimize the Dy content of the PMs. One of these was to introduce a milling technique which lowered the Dy content required by making the particles in the bulk material smaller. The system analyses in this report will focus on the latter.

[3] Using Porter's Five Forces, PESTLE, and Business Model Canvas

[4] Consists of two elements: 1) drawing up a basic life cycle of the studied product, and 2) doing a study of the organizations and interactions along it.

[5] Used the Product Environmental Footprint (PEF) Circular Footprint Formula (CFF)

2 Foundational Background: NdFeB Permanent Magnets and the European Supply Chain

This chapter will cover general information about materials and the European supply chain for NdFeB permanent magnets (PMs).

2.1 The roles of Neodymium and Dysprosium

Neodymium (Nd) is a core component for NdFeB PMs, and Dysprosium (Dy) acts an alloying element. They serve different functions:

- **Neodymium** helps produce the magnetism and resistance to demagnetization that make NdFeB PMs the strongest permanent magnets available with today's current material technology.

- **Dysprosium** is used for its ability to increase the temperature at which the NdFeB PM is still able to produce its magnetism and increases the maximum temperature before it gets demagnetized (also known as the Curie temperature).

Both EV motors and wind turbines generators simultaneously require high-performance magnetism and heat resistance to function as designed, so both Nd and Dy are often used to this effect.

However, when it comes to cost and availability, there is a stark difference between the two REEs, as Dy is much rarer and more expensive than Nd and other REE alloying elements. The rarity is in large part due to the different concentrations that they are found in ores. Although different mines might have different concentrations of the two constituents, Dy is usually found in smaller quantities, which requires more processing (and produces more mining- and processing waste) to separate the same amount of metal from the mineral as with Nd. Thus, there is a driving force to minimize the Dy content in PMs as much as possible, both from an economic and supply perspective (and from a sustainability viewpoint, as this report will later uncover).

Exposing pure neodymium (Nd) and dysprosium (Dy), or the magnetic powders used to produce permanent magnets (PMs), to oxygen can lead to oxidation, thereby diminishing their magnetic performance in these materials.

2.2 Processes and Organization for a European NdFeB Permanent Magnet Supply Chain

Supply chains are complex, and the NdFeB PM supply chain is no different. The trend in increasing EV and renewable energy demand suggests that changes in the NdFeB PM supply chain will follow. The EU has used legislative measures to manage the material criticality of REEs through strategic implementation of legislature (e.g. through the Critical Raw Materials Act (CRMA)), and market actors are interested in expanding or changing existing supply chains. To understand EU actors their interplay in the existing supply chain, this section will discuss supply chain and market aspects of NdFeB PMs.

Figure 1 shows the stages usually required to produce NdFeB PM containing electric motors in EVs. All stages in this chain are dependent on the processes before and after, which illustrates the real world with actors that are responsible for one or more of these stages. For example, the locations of *Metal & Alloy Production* and *Sintered PM production* actors can affect the transportation required between them, which can affect the price of the sintered PMs made in the *Sintered PM production* step.

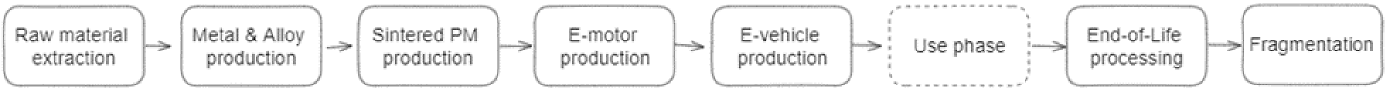

Figure 1 A simplified product chain structure for sintered NdFeB PMs for EVs.

The chain might look simple, but there are many variations of each step of the chain. For example: actors in each step, material composition differences (e.g. oxides vs. pure metal), differing material concentrations, or different techniques for *End-of-Life processing*. There is research and emerging processing and production technologies that also potentially add to the dynamic of the chain to various degrees.

Today, most of the stages prior to E-motor production are in China, with Chinese producers offering NdFeB PMs with market prices below their European counterparts. European PM producers in the current market (e.g., in Slovenia, Finland, Estonia, and Germany), or those looking at entering the EU market, are struggling to compete with the prices of Chinese products. Thus, the producers must look for ways outside of price to provide value.

The state of extracting and refining primary REEs in Europe

The *Raw material extraction* stage in Figure 1 is a combination of mining and production of primary rare earth oxides (REOs) from the ores. The subsequent REE metals production processes are done in the *Metals and Alloy production* step.

Europe has several REE deposits in Northern Europe, but there are currently no open mines that extract primary REEs (4) in the EU (REEs may still be found as a byproduct in mining tailings (mining waste)). One critical area of primary extraction is the issue of obtaining permits for mining; "The opening of a mine in Europe is estimated to take anywhere between 5-12 years, with LKAB expecting 10-15 years before mining can start in the recently discovered REE deposit near Kiruna, Sweden. This means that, in the nearer future, the growing market demand will likely cause the import of REE to increase" (4).

Permits play a crucial role in ensuring that construction and operations comply with regional and local regulations. It's widely recognized that mining activities have significant environmental impacts at the local level. However, these impacts are an important consideration as we work toward the green transition—a shift aimed at improving the environment globally by reducing carbon emissions. While this transition is essential for addressing climate change, it also highlights the need to carefully manage its localized effects, especially those within the EU member states. Sustainability systems analyses, such as those discussed in Chapter 3, are vital for ensuring that the EU can identify effective ways to minimize environmental impacts in new green mining projects.

After extraction, the ore is processed into REOs. In Europe, there is one existing plant (in Estonia) and another plant being constructed (in Norway), that produce REOs. REOs are generally stable, as opposed to REE metals which oxidize when oxygen is present. (4)

After REO production, the oxides are removed to produce REE metals. In 2019, a UK-based REE metal producer was reported as being the only REE metal producer outside of China or Japan. More recently, a plant in Estonia produces REE metals.

(4) The removal of oxygen from REO is also relevant here as some recycling techniques can provide REOs as feedstock to these factories.

These raw materials are then processed into intermediate products, which are subsequently used in the production of NdFeB magnets. Finally, the magnets enter the market as components in various applications such as electric vehicles (EVs), wind turbines, and consumer electronics. (4)

Strategic growth opportunities for NdFeB PM market

The market analysis identified three areas directed at NdFeB PM producers as market opportunities:

1. Focus on value offerings other than price,
2. Improved material-use effectiveness and reduced REE content per magnet,
3. Openness for strategic collaboration.

Area 1 is attributed to Chinese magnets having lower prices, due to existing large-scale industry and supply of REEs. It also has historically produced magnets with better magnetic properties. European producers can lead in this area by e.g., undisputable quality, timely deliveries, reduced carbon footprints and local supply in line with EU environmental standards.

Area 2 will likely require effective collaboration with actors in charge of the magnet End-of-Life to get effective access to the secondary materials, see the following section for more. Additionally, the use of low-energy-demand technologies will significantly impact production costs and pricing structures. (4)

Area 3 is a way (e.g., through strategic alliances) to deal with the fluctuating market for REEs and NdFeB PMs, potentially giving advantages such as ensuring technical compatibility with market leading products, expanding, and making the existing European supply chain more robust. (5) Geopolitical tensions and trade policies between major economies affects supply chain stability and drive market prices.

Research institutes can also collaborate with mining companies and producers to optimize the efficiency of REE usage and develop new technologies that minimize Chinese resource dependency. (4)

Magnet lifetime is hard to predict

Magnet-use lifetime is a determining factor in the amount of material that circulates. EV magnets are dependent on the lifetime of the EV itself. An estimate puts EV lifetimes at 9-13 years, although the lifetime of an EV is hard to predict as EVs are still a relatively young product, with respect to how long they last and the rate of technology development in recent years. Compared to vehicles running on diesel engines, EVs don’t have statistics to the same degree, because EVs haven’t been around for as long and the technology development means that EVs produced a decade ago are very different from EVs produced a couple of years ago. For this reason, it is still hard to set a baseline for lifetime. (5) However, it is likely that it will at least take about ten years or more for most EVs to end up at pre-treatment facilities for dismantling components like the electric motor. Thus, it is also (given that the magnets in the electric motor aren’t replaced in between), that EV NdFeB PMs sold in EVs today will be “locked in” for ten years or so.

Circular economy measures can lower primary REE demand – Production waste

Introducing more circularity into the EU-centric REE supply chain is one way to lower the needed amounts of virgin (either inside or outside of the EU) or imported REE raw materials. As the EU has a high degree of legislative power with its member countries, it also has the potential to guide effective regional resource management in complex supply chains to a higher degree than with non-member countries. A couple of relevant laws passed and soon-to-be-passed as part of the Green Deal are the Critical Raw Materials Act (CRMA) and Regulation and the Proposal for a EOL vehicle Regulation (4). These two laws aim to directly improve the circularity of European PM raw materials in the European supply chains. Some ways this is done is through more detailed material declarations, benchmark minimum recycling and recycled content use in different parts of the supply chain, and improving & speeding up investments and infrastructure for processing critical raw materials, such as Nd and Dy. For example, one likely requirement is that automotive manufacturers are legally obliged to have the PMs labelled, which will facilitate PM recycling (4) by enabling dismantlers and recyclers to more effectively separate PMs by content.

The project identified some of the more common Circular Economy flows found in the NdFeB PM supply chain for EVs. Figure 2 illustrates these by expanding on Figure 1 prior.

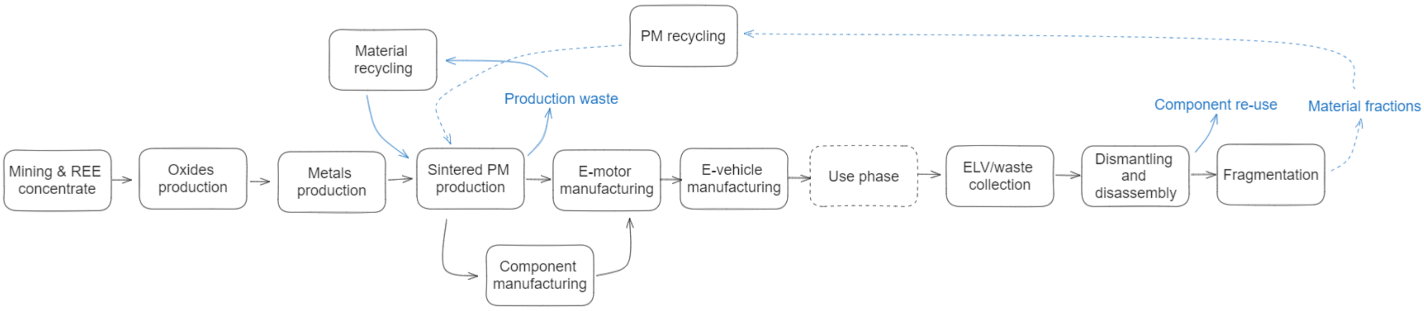

Figure 2 An extended version of the product chain structure for sintered permanent magnets in e-motor applications, including end-of-life treatment and potential circularity-enabling material flows in blue. ELV = end-of-life vehicle (4)

From left-to-right in Figure 2, *production waste material recycling*, is one of the circularity measures identified for NdFeB PMs in the EV supply chain or found in research as a circular economy option. Although not closely investigated in the RECO2MAG reports, production waste material recycling improves resource efficiency by collecting materials such as oxidized rare earth elements (REEs) or oxidized NdFeB powder for recycling. The geographical locations where scrap is generated in production and where it is recycled may differ.

Circular economy measures can lower primary REE demand – Separation

The separation of PMs from the electric vehicle and electric motor component is a critical step for its circular economy potential. Two other circularity measures highlighted in Figure 2 are *component re-use* from the dismantling and disassembly stage, and *material fractions* from the fragmentation stage. Before delving into the strategies, it is useful to have a general understanding of the waste management steps today.

End-of-life vehicles are collected for waste treatment. Studies show that many end-of-life vehicles (ELV) vanish from records in the EU (4), leading to a loss of potential recoverable components and materials.

Electric motors are disassembled from the end-of-life vehicles in pre-treatment as required in the current ELV Directive. The directive also demands that 95 percent of ELV mass is recirculated, whereof 85 percent through either recycling or reuse. The current directive doesn't specify which materials the limits pertain to, and furthermore, the directive's original intent was for internal combustion engine vehicles rather than electric vehicles with electric motors. (4) However, the ELV regulation proposal considers the electrification of the transportation industry in recent years and provides stricter limits on what materials must be recovered, including REEs in PMs. It also provides improved rules on design for easier dismantling, better instructions for dismantlers, and guides product design for easier removal of the magnets from the electric motors. (4)

For NdFeB PMs to be recycled or re-used, they must be dismantled from the electric motor. Key obstacles include the separation of magnets from motors, as they are often integrated in ways that make removal challenging and inefficient. Failure to remove the magnet from the electric motor means that the material is instead fragmented with the rest of the motor (iron fractions for internal combustion engines), resulting in the pulverized magnet material becoming dispersed across multiple fractions, making post-separation recovery impractical. Moreover, the pulverized magnets can act both as an impurity in iron fractions and a safety hazard for workers (4). Dismantling is also labor-intensive with today's designs and routines, which incurs large costs depending on the country that provides the labor (4). Automation, or semi-automation can possibly alleviate some of these costs in the long run, and future improvements in electric motor design that follow a possible new ELV Regulation (4) can potentially improve the resource recovery in this supply chain and improve circularity as a whole.

Circular economy measures can lower primary REE demand – Re-use and recycling

Magnet end-of-life recycling technologies are still an active area of research, and there are several options for recycling technology. Recycling of REEs today generally means recycling of oxidized and/or contaminated NdFeB powders with hydrometallurgical methods, i.e. using various solvents and other chemicals in several process stages to extract pure REE metal powder.

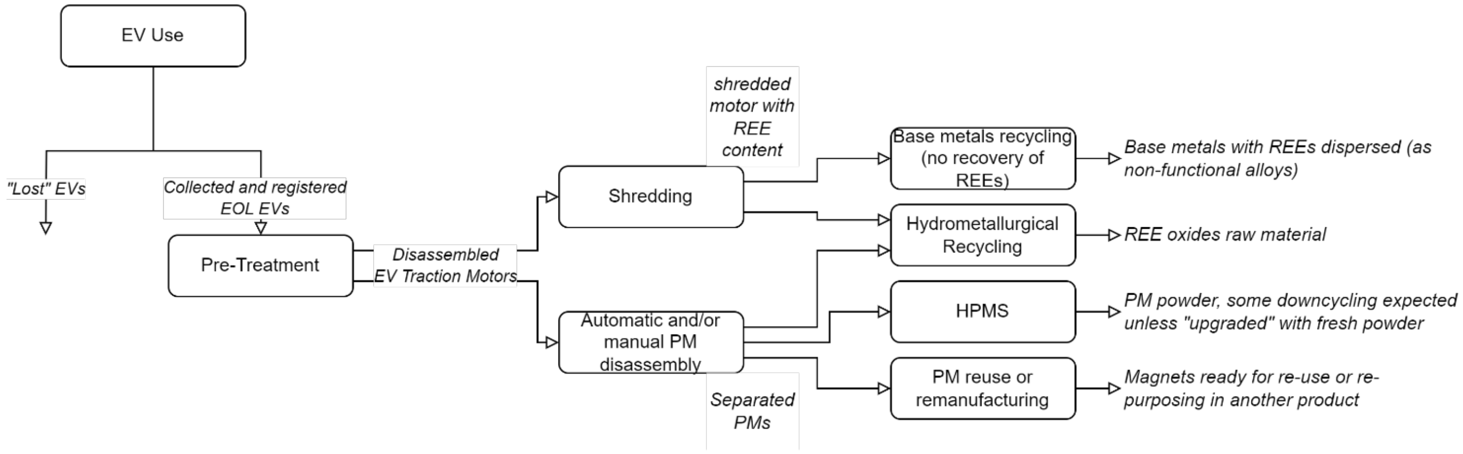

Figure 3: Some possible recycling pathways for NdFeB PMs. HPMS = hydrogen processing of magnetic scrap. (3)

Figure 3 shows some pathways that include both some more common (hydrometallurgy) and more research-stage (HPMS) types of recycling. In Europe, REE recycling is currently very limited, with few actors actively engaged in the process. REEMAG is a U.S.-based company that is part of the European-based organization REIA (Rare Earth Industry Organization), and has a patented, carbon-free process to recycle end-of-life neodymium-iron-boron (NdFeB) permanent magnets into their original powders for reuse in electric vehicles (EVs), wind turbines, and other applications. Another company, REF Minerals in Latvia, has established infrastructure for recycling secondary raw materials but does not currently focus on REE oxides. (4)

Short-term opportunities exist for expanding the scope of established recycling companies to include REEs, as existing infrastructure could reduce entry barriers. However, challenges remain, such as achieving economies of scale and addressing the need for improved disassembly and fragmentation processes. These depend on either new infrastructure or design-for-disassembly approaches, with the most efficient solutions likely requiring a combination of both. (4)

Additionally, uncertainties regarding the content and quality of PMs pose significant hurdles. Ensuring full control over recycled materials would require traceability of magnets back to their origin, which is complicated by the complexity of automotive supply chains. While improved traceability could be facilitated through consolidation of original equipment manufacturer (OEM) supply chains and internalization by EV producers, the reality of frequent part reuse, export, and loss of product records makes universal traceability unlikely in the near term. (4) Traceability through required manufacturer declarations from the proposal for an ELV Regulation has potential to improve recycling processes, but it will be many years for those magnets to arrive at a recycling plant.

3 Assessing Sustainability: Environmental, Cost, Social, and Circularity Impacts

Measuring the lifetime environmental-, cost-, social-, and circularity performances of NdFeB magnets is crucial to identify systemic inefficiencies and improving the sustainability of PMs throughout the lifecycle of the product. This chapter synthesizes results from a life cycle assessment (LCA), a life cycle costing (LCC) assessment, and a circular economy (CE) performance assessment and highlights sustainability challenges and opportunities of NdFeB PM production in Europe based on the RECO2MAG project. LCA, LCC, and CE performances are measured using quantitative methods, while social aspects are covered qualitatively.

There are many sources available for those wanting to learn more about LCA, LCC, and circular economy metrics and social aspects. Instead of repeating the information from those sources here, some references are provided in the footnotes for those interested in learning more. With that in mind, this chapter is written so that the key results (section 3.2) and conclusions (section 3.3) can be understood by anyone, but the section about the sustainability assessments (section 3.1) likely require some more specific sustainability knowledge and experience.

3.1 Sustainability Assessments

LCAs, LCC assessments, CE performance assessments, and social aspects were part of the RECO2MAG project.

3.1.1 Objectives

In a nutshell, the sustainability assessments' objectives were to answer the following research questions:

1. How would environmental impacts of hypothetical European-based Dy-production differ from current Chinese Dy-production?

2. How would the environmental impacts of a new milling process for sintered NdFeB PM-production differ from current PM-production (i.e. a reduction of Dy-content from 7 to 1 percent)?

3. What are the differences in lifetime costs of producing sintered NdFeB PM using the new milling process (1 percent Dy) versus the current milling process (7 percent Dy)?

4. Can the PEF CFF be used to measure circularity in current and possible future scenarios, and improve sintered NdFeB PM circularity?

5. What are the social aspects of European REE mining?

Functional Units

The functional units were chosen such that they can be used to create useful comparisons between the manufacturing processes and supply chains in the research questions. They were specifically:

- Environmental impacts of 1 kg of Dy produced in Europe (for LCA) and

- Environmental impacts/costs of 1 kg of NdFeB PM produced by the European NdFeB sintered PM producer. (for LCA, LCC, and CE assessment).

The PMs used in comparisons were of equal capability with respect to their applications in EVs.

3.1.2 About the Methods Used

Data was provided by a European manufacturer of NdFeB PMs that produces NdFeB PMs for EVs. See the Appendix for system boundary diagrams.

LCA method

The LCAs followed common ISO-standards[6,7] , assessing the common environmental impacts of global warming potential (GWP 100 years), acidification potential (AP), eutrophication potential (EP, both freshwater and marine). They also assessed ecotoxicity potential, human toxicity potential (HTP), ozone depletion potential (ODO), photochemical ozone formation, abiotic depletion potential (ADP) and water deprivation potential (WDP).

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[6] ISO 14040:2006 Environmental management Life cycle assessment Principles and framework.

[7] ISO 14044:2006 Environmental management Life cycle assessment Requirements and guidelines.

The LCAs included transports and waste management, as well as all relevant processes within the system boundaries visualized in Figure 4 and Figure 5 in the Appendix.

Various sources were used, including scientific publications (6) (7) (8) (9) and LCA databases (10) (11).

LCC method

The LCCs used general factory lifetime calculation methods for: investment costs, operational costs, purchase of raw materials & energy, and externalities. Maintenance and replacement costs were not included. Externalities were calculated with the Environmental Prioritization Strategies (EPS)[8] method, which finds equivalents for costs associated with emissions and use of natural resources, which the manufacturer does not pay for.

CE performance assessment method

The circularity assessment used the European Commission's recommended methods for calculating environmental footprint for products[9] (PEF), and specifically the circular footprint formula (CFF), which has standard values for recycled content and recycled material at EOL for various materials. The assessment also included a possible future scenario, showing how the Critical Raw Material Act might impact circularity for producers with the recycled content and EOL recycling target benchmarks. The system boundaries include the extraction of raw materials for dysprosium production, the manufacturing processes of NdFeB magnets, and the end-of-life treatment, encompassing recycling and disposal processes.

Social aspects of European mining method

A qualitative social impact analysis was used to consider regional and local challenges when and if more EU REE mining projects would open.

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[8] https://www.lifecyclecenter.se/wp-content/uploads/2015_05-The-EPS-2015d-impact-assessment-method.pdf
[9] https://environment.ec.europa.eu/publications/recommendation-use-environmental-footprint-methods_en

3.2 Key Results

Reducing Dy-content in EV NdFeB PM production from 7 to 1 percent lowers environmental impact categories down by 20-80 percent, and total lifecycle costs by about 20 percent

The environmental impact categories that benefited the most were ozone depletion (in the ozone-layer) & ozone creation, eutrophication (too many nutrients in water), global warming potential (gases released that increase global warming), acidified bodies of water, and depletion of limited resources. The monetary costs for purchase of raw materials & energy were almost halved when using less Dy.

Rare Earth Elements production creates a much relative heavier burden on the environment and resource depletion than the monetary cost paid for by NdFeB PM-producers

The burden on the environment (externalities, see Chapter 3.1.2) was calculated to be around 100 times larger for the environment and resource depletion than for the NdFeB PM manufacturer itself. In other words, the monetary costs paid by the producer of NdFeB PMs is about one hundredth of the relative costs that are "paid" by the environment and resource depletion. Using less dysprosium did not affect the ratio to a meaningful degree.

Dy Production in Europe will likely have higher environmental impacts than respective Chinese-produced Dy, at least in the short term

In the LCA, the European Dy production produced 72 percent more CO_2-equivalents by weight of Dy. The higher environmental impact of Dy production in Europe compared to Chinese Dy production can be attributed to several key factors:

- Lower Ore Concentration: European ores have lower concentrations of rare earth elements (REEs), necessitating the processing of larger quantities to extract the same amount of Dy.

- Energy Use and Chemical Extraction: The additional processing required for lower-grade ores results in higher energy consumption and greater use of chemicals, which contribute to environmental degradation.

In contrast, Chinese production benefits from higher-grade ore deposits and more established industrial processes, reducing both resource intensity and environmental impact.

Access to data and data quality on REE-materials and processes is generally insufficient and lacks transparency.

There was a limited selection of unique, recent, and/or detailed data from publicly available literature and scientific publications.

The datasets from the European commission did not have anything on REEs at the time, meaning that much less accurate and granular data was chosen to represent the various types of REE EOL-flows in the CE assessment (PEF CFF).

The European Commission’s recommended method (PEF CFF) for calculating environmental footprint is insufficient to guide a producer’s circular economy strategies effectively

Although the PEF CFF framework (the chosen CE performance assessment method) includes the entire cradle-to-cradle product lifetime processes, and distributes carbon-emission impacts between the stages, it is still a relatively simplistic method to describe even a single PM-producer’s upstream and downstream supply chains. Part of the reason is that it only considers *recycled content* and *EOL recycled materials*, and doesn’t consider other methods of introducing circularity, such as remanufacturing, extending the product lifetime, or downcycling. Another relatively simple way to understand a product’s circularity is using the 3R or 9R framework, which break down product EOL-pathways by methods, possibly giving additional ways to increase circularity.

Social issues will likely increase in the EU without the enforcement of strict standards

Addressing negative reputations in mining regions (China and Europe) requires transparency, effective communication between companies and communities, and building trust. European regulations must enforce strict standards on working conditions, environmental practices, and community inclusion to ensure responsible mining. Success in expanding REE mining hinges on addressing health risks, gender inequality, and social security, ensuring fair wages and safe conditions for all workers. Continuous audits and clear regulations are essential to maintain compliance with social and environmental standards.

4 Conclusion

A holistic understanding of sustainable production of European NdFeB PMs requires various perspectives, which this synthesis report from the RECO2MAG project provides. The first chapter covered the general information about materials and the complex European supply chain, and its actors, for NdFeB permanent magnets (PMs). The second chapter presented systemic inefficiencies and potential sustainability improvements of PMs throughout the lifecycle of the product, from environmental-, cost-, social-, and circularity assessments.

The market today is clearly leaning heavily towards the purchase and use of Chinese REE and NdFeB PM production for EVs and other green technologies. Altough Europe has some select actors in different parts of the supply chain, it is clear that much still needs to be done in virtually all parts of the supply chain for a sustainable supply of PMs for the green transition and to reduce reliance on external markets. The lack of local extraction and processing of REEs means that Europe will continue to be dependent on foreign sources of REEs in coming years. However, the REE deposits in Northern Europe, and legislative action such as the CRMA provides hope that Europe will streamline the construction of infrastructure to mine domestic critical raw materials for NdFeB PMs, while having control over the local environmental and social aspects. The relative low price of REE materials from Chinese actors is a market challenge for domestic producers to produce local REE PMs while providing competitive prices. Focusing on providing value in other ways will be necessary for a competitive edge, and will hinge on collaboration between market actors, and local & regional legislature to ensure that the potential value has real impacts. At the end of life for PMs, various challenges exist to increase REE circularity as a means to lower primary demand and decrease the negative environmental impacts of the burgeoning REE material demand for clean technologies, as well as the reliance on foreign REEs. Aside from the current lack of European REE recycling infrastructure, a major hurdle for REE recycling (or remanufacturing) is the technical difficulty and associated personell cost of dismantling REE PMs from electric motors. The new ELV-Regulation will very likely increase REE recovery rates through improved electric motor designs and benchmark limits for recycling REEs, but the major impacts of the regulation will likely take years as newly designed and produced EV motors with REE PMs will take time to “return” to car dismantlers. However, it is still a major and necessary step towards unlocking the circular potential of REEs and increasing the sustainability of Eurpean REE PM supply chain in the long term.

Adding the perspectives of the environmental-, cost-, social-, and circularity assessments directed at Dy- and REE-PM producers give further nuance to the above conclusions. The sustainability assessments showed that decreasing primary dysprosium content in EV NdFeB magnets from 7% to 1% reduces environmental impacts by 20-80% across key categories and lowers lifecycle costs by about 20%. It is clear from this that design improvements of the PMs have major potential in lowering the environmental burden and PM production costs, while still being able to maintain the desired properties for EV applications. As Dysprosium is still required for its ability to raise the maximum operating temperature of EV NdFeB PMs, this was great news. Looking more closely at potentially mining Dy domestically, it was found that the lower ore concentrations in European REE deposits as compared to Chinese mines would lead to several relative negative cascading impacts, such as increased energy use and greater chemical extraction requirements. The resulting higher environmental impacts of European primary Dy in comparison to Chinese primary Dy will thus be important to consider in the developing European REE market. Additionally the social local impacts of mining are many and will require various measure, such as transparent communication and building trust with the local population, to ensure that the locals are not exessively impacted from the local effects of mining for Europe’s green transition. Finally with regards to circularity, the current lack of data to effectively use the EU Commission’s recommended PEF CFF method for calculating circularity highlights a gap in current methodologies for calculating circularity. When new datasets and methodology specifications are published a clearer understanding of the main factors that affect circularity will likely be easier to determine. However, until then, common sustainability principles such as the waste hierarchy, 3R/9R framework, etc. are still valid and should be implemented as much as possible to ensure that the REE products are being utilized to their maximum potential.

Addressing these challenges and taking advantage of the opportunities covered in this report can take Europe one step in the way of creating a resilient supply chain for NdFeB magnets in Europe, all while minimizing environmental and social impacts while fostering innovation and competitiveness in low-carbon technologies.

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Appendices – System Boundaries

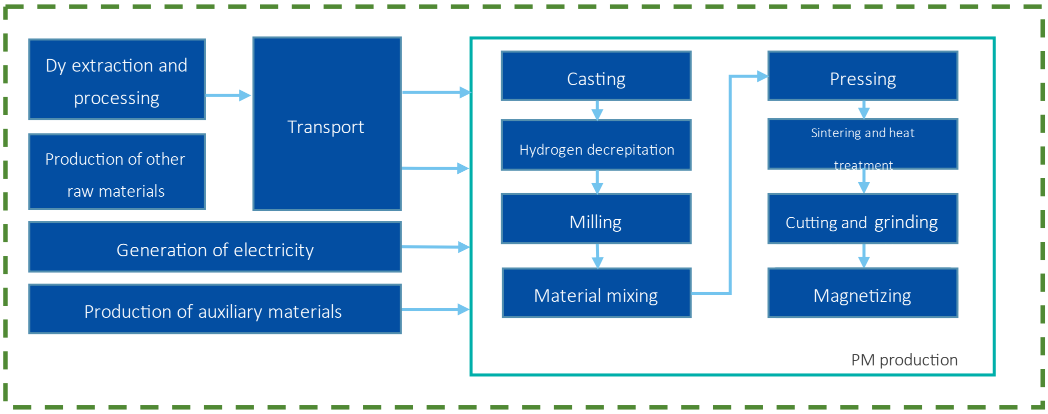

Figure 4: LCA and LCC assessment system boundaries for NdFeB PM production. (1)

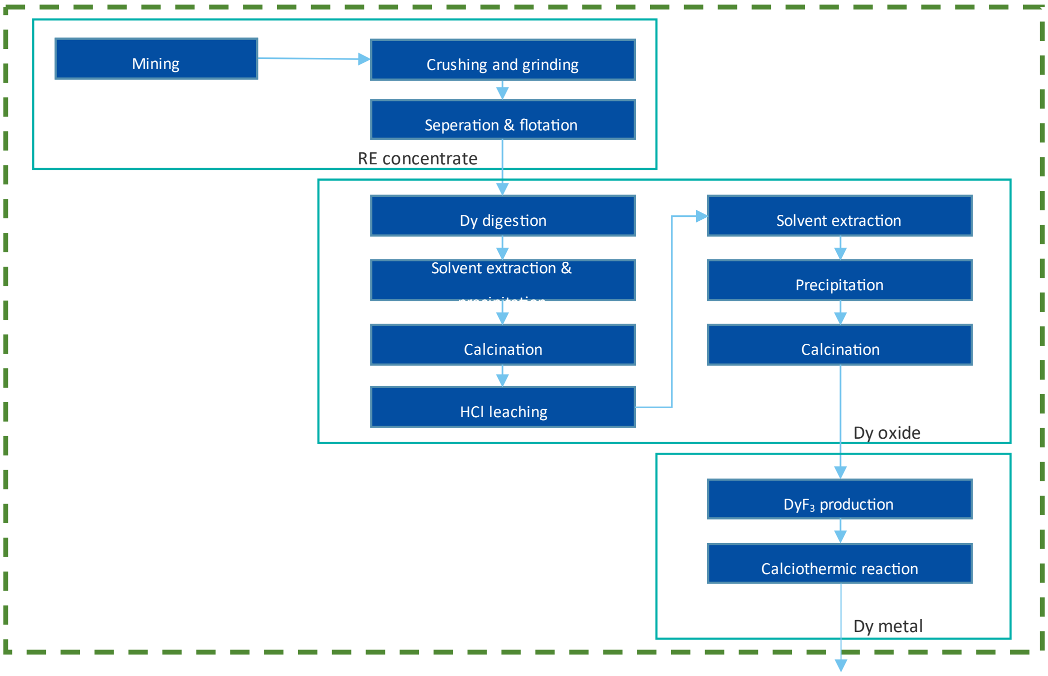

Figure 5: LCA system boundaries for Dy-production. (1)

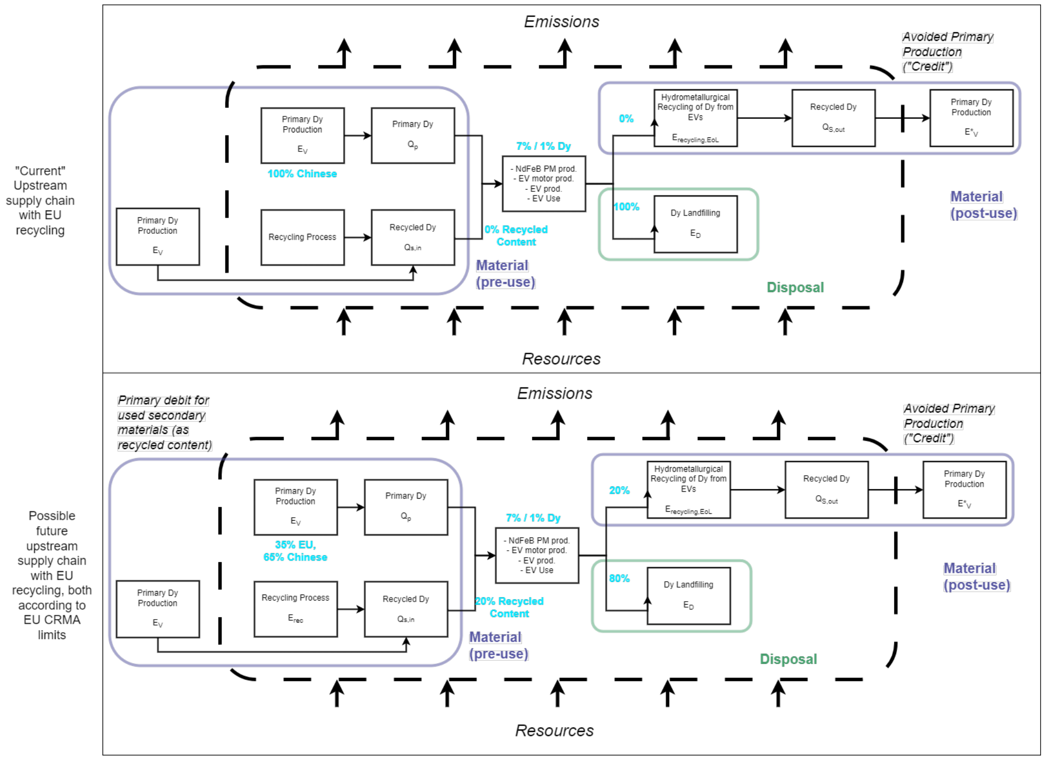

Figure 6: CE assessment CFF system boundaries for 100% Chinese production (above), and 90%/10% Chinese/European production (below). (3)

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