Driving Circularity

Integrating Ecodesign for end-of-life Traction Motors in Electric Vehicles

MSc Industrial Ecology

Aditi Urs

Driving Circularity

Integrating Ecodesign for End-of-Life Traction Motors in Electric Vehicles

Master thesis submitted to Leiden University and Technical University of Delft in fulfilment of the requirements for the degree of Master of Science in Industrial Ecology.

by

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Aditi P Urs
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EXECUTIVE SUMMARY

The transition to electric vehicles (EVs) has become a central pillar of global decarbonization efforts, driven by the need to reduce greenhouse gas emissions and dependency on fossil fuels. However, this shift presents its own set of challenges, particularly concerning resource demand and waste generation. Critical raw materials (CRMs), such as neodymium (Nd), are essential for manufacturing Neodymium-Iron-Boron (NdFeB) magnets, which enable the energy efficiency and performance of EV traction motors. The global EV industry's reliance on these magnets is juxtaposed with finite CRM reserves and a supply chain heavily dependent on imports. In the EU, over 98% of NdFeB magnets are imported, predominantly from China, creating substantial risks tied to geopolitical factors, rising demand, and potential supply shortages. Beyond supply constraints, the auto industry's traditional reliance on single-use manufacturing exacerbates the challenge by promoting linear models of production, use, and disposal. Addressing these interconnected problems requires systemic changes that prioritize higher-order strategies within the circular economy (CE), including remanufacturing and innovative approaches to design, rather than solely relying on end-of-life recycling solutions.

This research investigates how integrating ecodesign principles into the lifecycle of traction motors can contribute to reducing CRM dependency and enhancing circularity. Ecodesign principles, which aim to incorporate environmental considerations from the earliest stages of product design, offer a pathway to address these challenges by enabling product-life extension, material recovery, and reduced environmental impacts. Recognizing traction motors as integrated systems, the study focuses on optimizing the recovery and reuse of NdFeB magnets through remanufacturing. Although recycling is a widely adopted recovery strategy, this research argues that remanufacturing holds greater potential for retaining material and functional value, aligning more closely with the top tiers of the CE's 9R hierarchy.

A mixed-method approach was used to address the research objectives, combining Material Flow Analysis (MFA), expert interviews, and a comprehensive literature review. MFA quantified the flow of Nd within the EU's EV ecosystem, revealing inefficiencies in current material recovery systems. For example, scenario analyses for 2030 showed that remanufacturing could reduce Nd losses by over 55 tons annually compared to recycling alone representing an approximate 15% improvement in resource retention for EV traction motors. However, this percentage remains conservative given the fragmented adoption of recovery systems. Expert interviews identified barriers at technical, organizational, and policy levels, highlighting systemic gaps in design practices, reverse logistics, and stakeholder collaboration. A detailed literature review contextualized these findings within the broader scope of CE strategies and emphasized the need to move beyond recycling to prioritize strategies like remanufacturing and, ultimately, "Refuse" (avoiding CRM use entirely).

The study's findings emphasize that integrating ecodesign principles into traction motor recovery requires systemic changes across the value chain. Upstream, design practices must incorporate features such as modularity, disassembly, and lifecycle tracking, enabling efficient recovery and reuse. These principles align with the proposed ecodesign strategy matrix, which includes actionable solutions like designing for fault diagnostics, multi-tier recovery, and regulatory compliance. For example, integrating digital tools for inventory and resource mapping could improve supply chain transparency and ensure that high-value materials are tracked and retained throughout their lifecycle. Downstream, gaps in reverse logistics infrastructure remain a significant bottleneck, particularly in

the collection and sorting of end-of-life (EoL) traction motors. Addressing these downstream inefficiencies requires collaboration among stakeholders, including OEMs, policymakers, recycling industries, and remanufacturers.

While remanufacturing provides a promising mid-term solution to CRM dependency, the study highlights the necessity of long-term strategies to transition beyond CRM reliance altogether. For instance, developing CRM free motor designs or substituting NdFeB magnets with alternative materials could mitigate supply chain risks and reduce environmental impacts, aligning with the "Refuse" strategy within the CE framework. However, moving up the R hierarchy requires addressing significant challenges, including the compact and integrated design of current traction motors, which complicates disassembly and recovery. Furthermore, organizational inertia and short-term economic priorities within the automotive industry hinder the adoption of circular strategies. The absence of shared responsibility for imported EVs further exacerbates these challenges, as many vehicles are excluded from coordinated EoL management frameworks.

By synthesizing insights from MFA, interviews, and literature, this research underscores the transformative potential of remanufacturing and ecodesign principles in advancing circularity for traction motors. The proposed strategies emphasize systemic innovation, policy reform, and interdisciplinary collaboration as critical enablers for reducing CRM dependency and fostering sustainable mobility. However, the findings also acknowledge that remanufacturing alone will not fully address CRM demand; instead, it must be integrated into a broader framework that prioritizes upstream innovations, such as avoiding CRM use altogether. This research contributes to the field of Industrial Ecology by providing a nuanced understanding of how technical, organizational, and policy interventions can collectively drive the transition to circular supply chains, offering a viable pathway for reducing environmental and resource-related risks in the EV sector.

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LIST OF ABBREVIATIONS

Abbreviation	Definition
CE	Circular Economy
BEV	Battery Electric Vehicle
CRMA	Critical Raw Material Act
CRMs	Critical Raw Materials
DfRem	Design for Remanufacturing
EU	European Union
EV	Electric Vehicle
EoL	End of Life
HREEs	Heavy Rare Earth Elements
LREEs	Light Rare Earth Elements
OEMs	Original Equipment Manufacturers
PHEV	Plug-in Hybrid Electric Vehicles
PLE	Product Life Extension
Nd	Neodymium
NdFeB	Neodymium Iron Boron
MFA	Material Flow Analysis

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1. Introduction

The growing emphasis on energy transition and resource efficiency has led to increased attention on moving from linear to circular economic models, particularly in industries reliant on CRMs. The EV sector, a cornerstone of global decarbonization efforts, is heavily dependent on CRMs like Nd, essential for producing NdFeB magnets commonly called neodymium magnets (Carrara et al., 2023). However, the EU's reliance on imports, particularly from China, for over 98% of its magnets needs poses significant supply chain risks and heightens the urgency to develop resilient, circular solutions (Gauß et al., 2021).

There is an emphasis on the adoption of circular strategies that prioritize waste reduction, resource efficiency, and sustainability (Hool et al., 2023). A pivotal aspect of achieving these goals is the integration of ecodesign principles, which promote designing products for longer lifespans, with no toxic materials and its impacts on the environment is considered (Carrara et al., 2023; Pigosso et al., 2013). These principles are closely aligned with the overarching goals of CE strategies, including the 9R framework, which follows a hierarchical structure. In this framework, Refuse (R1) is prioritized at the top, while Recover (R9) is positioned at the bottom with Recycle just above it (R8). There is a need to prioritize higher-order recovery strategies, such as remanufacturing or above, rather than relying solely on more fundamental strategies like recycling, to enhance circularity for CRM containing products. (Morseletto, 2020).

In this light, this thesis adopts an exploratory approach to examine how ecodesign principles can be incorporated to improve the circularity of traction motors used in passenger car EVs (herein after EVs). The study utilizes methodologies such as MFA to estimate Nd outflows of EVs reaching EoL and assess the potential of remanufacturing strategies to support product recovery and resource efficiency.

1.1 Research Context

1.1.2 Role of Nd in decarbonisation technologies

Nd plays a pivotal role in advancing decarbonisation technologies, particularly through its use in the production of rare-earth permanent magnets. Their applications extend to MRI machines, electric bikes, hard drives, and wind turbines, further highlighting their versatility and importance (Heim & Wal, 2023). These magnets have the remarkable ability to deliver magnetic flux into the air gap of a magnetic circuit without requiring continuous energy expenditure. This characteristic makes NdFeB magnets highly efficient in various applications, providing power-to-weight advantages (McCallum et al., 2014). In addition, NdFeB magnets can be used to as a new method of energy generation by using the magnetic field of a magnet and converting the magnetic energy into kinetic energy without using any kind of fuel and overcoming the energy generation problem such as building a wind turbine (Shewane et al., 2014).

Despite their critical role in decarbonisation, challenges arise due to the limited geographic distribution of Nd resources and the complexities involved in its extraction and processing. These factors contribute to supply risks and highlight the need for sustainable strategies to secure Nd availability, ensuring the EU's climate goals and CE ambitions remain achievable (Carrara et al., 2023).

1.1.1 Importance of traction motors in EVs

Traction motors are fundamental to the performance and functionality of EVs, serving as the primary component responsible for converting electrical energy into mechanical energy to propel the vehicle forward. These motors are engineered (as illustrated in the exploded view of a traction motor in Figure 1.1.) to deliver high efficiency, reliability, and optimal performance, meeting key requirements such as high torque density, superior power density, and effective thermal management (Nordelöf et al., 2018).

A core element enabling the functionality of traction motors is the NdFeB magnet, which depends on Nd, a CRM which provide its magnetic properties. These magnets generate the strong magnetic fields required for efficient operation (Weir et al., 2020). Their compact size and high energy density make them particularly well-suited for EV traction motors, supporting lightweight designs and extended driving ranges. The components involved within the permanent magnet is briefly shown in Figure 1.2.

As the global adoption of EVs continues to grow, the importance of traction motors, and their reliance on critical materials like NdFeB magnets, becomes increasingly apparent, emphasizing their role in enabling the transition to sustainable transportation systems (Gauß et al., 2021).

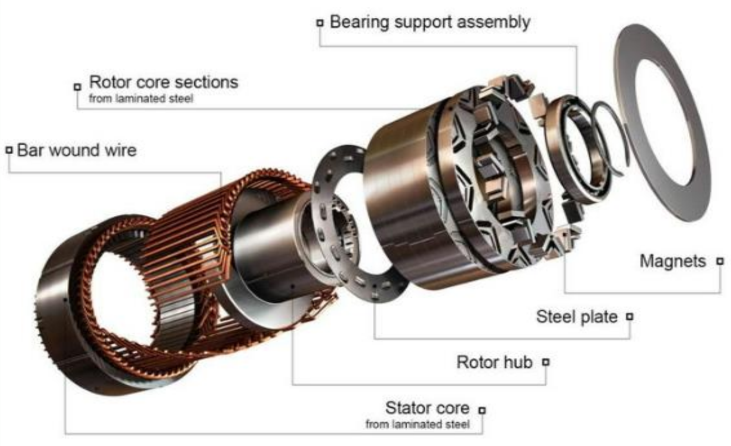

Figure 1.1 Exploded figure of EV traction motor and its components

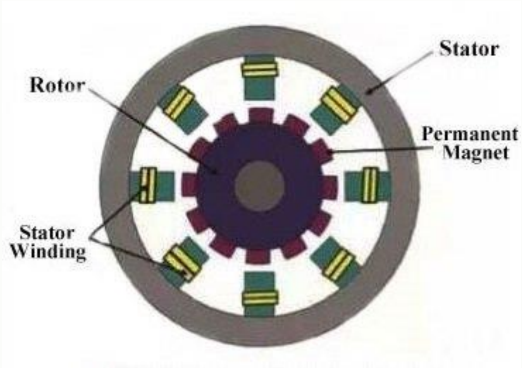

Figure 1.2 Permanent magnets placement in rotor casing

1.1.3 *Challenges related to CRM and their recovery from EVs*

Notably, approximately 95% of EVs rely on rare earth permanent magnet traction motors due to their superior energy efficiency, which directly impacts driving range. Rare earth elements (REEs) such as Nd, praseodymium (Pr), dysprosium (Dy), and terbium (Tb), critical for producing rare earth magnets, account for only 25% of total rare earth production volume. However, these elements represent a disproportionately high share, contributing to 80–90% of the total rare earth market value (Kramer et al., 2012; Gauß et al., 2021).

As the global drive toward achieving net-zero emissions gains momentum, the demand for critical materials is projected to exceed available supply, placing ongoing strain on the supply chains that underpin industries such as electric mobility. This rising demand is occurring in a context where current production levels and supply infrastructures are insufficient to meet future needs. While geopolitical factors may fluctuate, influencing material availability both positively and negatively, the consistent growth in demand driven by net-zero goals remains a major force shaping the future of CRM supply and market trends.

Currently, over 90% of rare earth magnets are produced in China, making the global supply chain highly concentrated and vulnerable to geopolitical tensions and rising domestic demand, particularly driven by China's expanding electric mobility sector (Rare Earth Elements, Permanent Magnets, and Motors, n.d.). This heavy reliance on a single-source supply poses a significant risk for European manufacturers, who face challenges related to supply security and price volatility (Gauß et al., 2021). Furthermore, the lack of transparency in supply chains, along with the absence of standardized certifications addressing environmental, social, and governance (ESG) impacts, further compounds these challenges (Ragonnaud & European Parliamentary Research Service, 2023). The European Commission recognizes the criticality of rare earths, ranking them among the most resource-sensitive materials and promoting research and innovation across the entire value chain. However, efforts to regain control over the rare earth industry face significant barriers due to the high costs and complexities associated with building new supply chains and refining technologies (Gauß et al., 2021. Adding to these challenges is the inefficiency of EoL management for products containing CRMs, including EV traction motors (Ragonnaud & European Parliamentary Research Service, 2023). Limited recycling infrastructure and technological constraints result in low recovery rates, leading to material/component losses, increased landfill burdens, and missed opportunities to reduce reliance on virgin material extraction.

Addressing these issues demands innovations in product design, strengthened policy frameworks to promote CRM recovery, and increased investment in advanced EoL management technologies.

1.2 Problem Statement

The rapid transition towards sustainable mobility, driven by the EU’s Green Deal and the global shift to electrification, has escalated the demand for EVs and, consequently, for REEs, particularly Nd. Nd is essential for producing high-performance NdFeB magnets, a key component in EV traction motors (Carrara et al., 2023). As the EU works towards climate neutrality, the demand for Nd in EVs is projected to rise significantly, creating serious concerns regarding the sustainability of the supply chain (Gauß et al., 2021). The criticality of Nd arises from the EU's overwhelming dependency on imports from countries like China, which currently dominates the supply chain for Nd and other REEs (Carrara et al., 2023). Which in response the EU has deemed Nd and certain REEs alike as critical raw materials. EU recognises the risks of supply disruptions, price volatility, and geopolitical uncertainties, which could hinder the EU's green transition and the automotive industry's competitiveness (Gauß et al., 2021). However, reducing reliance on China as a primary supplier of REEs does not automatically resolve the broader sustainability challenges linked to the production, use, and disposal of these materials. While diversifying supply sources can mitigate some geopolitical risks, it does not address the urgent need for sustainable practices throughout the entire lifecycle of these materials.

Despite the growing demand for NdFeB magnets, circularity within the EV sector remains a significant challenge. Recycling, a key strategy for recovering Nd from EoL products like EV traction motors, is still in its infancy, with less than 1% of NdFeB magnets being recycled in the EU (Carrara et al., 2023). As the EU pushes for climate neutrality, the focus must expand beyond supply chain vulnerabilities to include the environmental impacts associated with production, resource extraction, and the management of EoL products. Environmental, social, and governance (ESG) factors are central to this, not only for reducing supply chain risks but also for minimizing the environmental footprint of materials and ensuring ethical and sustainable lifecycle management. Achieving true circularity in the automotive sector requires a comprehensive, systematic approach to ecodesign. The complexity of promoting resource recovery and sustainable usage goes beyond minimizing waste; it involves creating frameworks that address challenges across the entire lifecycle of automotive components from material sourcing to EoL management. Without a systematic approach to ecodesign, the automotive industry will struggle to achieve the CRM resource efficiency and circularity required to meet the EU's green transition goals.

While reducing dependency on China is a critical step, it is equally important to tackle the environmental and ESG issues tied to the production, use, and disposal of CRMs like Nd. Ecodesign offers a holistic pathway to sustainability, promoting improved design, remanufacturing opportunities, and more effective recycling strategies. However, bridging the gap between theoretical ecodesign principles and practical application remains challenging due to factors like financial constraints, organizational inertia, and the complexity of multi-material compositions in automotive components (Fitzgerald, 2017; Kim & Yannou-Le Bris, 2021). This thesis aims to explore these ecodesign principles, develop strategies to enhance circularity, and promote sustainable resource use within the electric vehicle sector, ultimately contributing to a more sustainable and resilient automotive industry.

1.3 Scope of the Study

Given the pivotal role of passenger EVs in facilitating the green transition, the geographical focus of this study is set on the EU-27 member states. The research aims to develop a targeted approach for integrating ecodesign principles into the lifecycle management of traction motors, specifically for Battery Electric Vehicles (BEVs) and Plug-in Hybrid Electric Vehicles (PHEVs). This focus is justified by the fact that the combined sales of these two EV types currently represent a significant portion of the EV market, a trend expected to grow in the coming years.

The temporal scope of this study spans from July 2024 to mid-January 2025, with the thesis defence scheduled for the end of January 2025. The defined timeline provides sufficient opportunity to analyse and propose actionable strategies for embedding ecodesign principles into lifecycle management practices for traction motors. Given the broad scope of the research, this study centres on the strategic management of Nd used in NdFeB magnets, critical components in traction motors, rather than examining other applications of Nd or REEs. The primary objective of this research is to develop strategies for embedding ecodesign principles that enhance material recovery and extend the lifecycle of traction motors. The emphasis is placed on Nd utilized in NdFeB magnets and improving EoL management practices through strategies like remanufacturing. However, it is important to note that this research does not address the engineering or technical design optimization of traction motors. Instead, it adopts a strategic perspective, focusing on systemic challenges and providing practical insights for Original Equipment Manufacturers (OEMs) and third-party remanufacturers. The study's strategic focus addresses organizational, regulatory, and lifecycle management barriers to circularity. By concentrating on systemic issues and actionable strategies, this study comes in light of the EU's efforts to achieve sustainable mobility while offering further insights that can be applied across the EV industry.

1.4 Relevance of the Study

1.4.1 Relevance to the field of IE

This study contributes to the field of Industrial Ecology (IE) by addressing the critical need for sustainable resource management and CE practices in the rapidly growing EV sector. Industrial Ecology emphasizes the optimization of material and energy flows within industrial systems, aiming to reduce environmental impacts while enhancing resource efficiency (Industrial Ecology (MSc) - Leiden University, n.d.). By focusing on integrating ecodesign principles into the lifecycle management of traction motors, this research aligns with IE's core objectives of promoting closed-loop systems and material recovery strategies. The study also adopts a systems-thinking approach, addressing logistical, regulatory, and design challenges while leveraging insights from multiple disciplines to propose actionable strategies. As a result, it not only strengthens the theoretical foundations of IE but also offers practical insights to support circular transitions in the EV industry.

1.4.2 Societal Relevance

The societal relevance of this study lies in its potential to advance sustainable mobility solutions by addressing the challenges associated with the EoL management of EV components, particularly traction motors. With the continued rise in EV adoption, effective EOL strategies for handling these components are essential to mitigate environmental harm. Production of NdFeB magnets involves the extraction of REEs, a process that generates hazardous by-products, posing risks to both the environment and worker safety at mining sites (Langkau & Erdmann, 2020; Mancheri et al., 2018). In addition to this, the research highlights the economic opportunities that might follow-through due the development of new value chains in remanufacturing, thereby strengthening local industries and reducing dependency on imports. Moreover, the recovery and reuse of high-value components, such as traction motors, remain largely unexplored, presenting a compelling and complex problem within the field of IE. The study also aims to raise societal awareness regarding CE practices, encouraging stakeholders, including EV OEMs and third-party remanufacturers, to implement more sustainable and resource-efficient strategies.

1.5 Research Objectives

The primary objective of this research is to develop strategies for integrating ecodesign principles into the EoL management of traction motors, treating the traction motor as a whole product. Within this context, retaining and reusing the embedded NdFeB magnet is considered part of the remanufacturing process, reflecting a systemic approach to preserving high-value components within the motor. This perspective influences the framing of recovery strategies, as the magnet is not treated as a standalone product but as an integral component of the traction motor. As such, the research emphasizes designing for disassembly and modularity to facilitate the recovery and reuse of the magnet as part of the broader remanufacturing process. By adopting this approach, the study seeks to address the challenges and opportunities associated with applying ecodesign principles, particularly focusing on enabling remanufacturing processes as a viable alternative to recycling.

Leveraging insights from MFA, the research maps the flow of Nd, a critical raw material used in traction motors, to evaluate potential recovery pathways and inform sustainable design practices that align with this integrated product view. Through an examination of technical, economic, and organizational barriers, actionable strategies are proposed to optimize material recovery, extend the lifecycle of traction motors, and reduce reliance on virgin raw materials. By maintaining this holistic perspective on the traction motor, the research ensures that ecodesign strategies are appropriately tailored to maximize resource efficiency, preserve product value, and support the broader transition toward a CE within the EV manufacturing sector.

1.5.1 Research Questions

In order to explore the above-mentioned research objective, the following research question has been formulated:

> **"How can ecodesign principles be integrated to enhance the circularity of traction motors in EV at their end-of-life phase?**

To systematically explore this overarching question, it is broken down into three focused sub-questions. Each sub-question examines a different aspect of the integration process, helping to build a comprehensive circular strategy for recovery of traction motor.

The sub-questions guiding this research are:

1. *What are the key challenges and opportunities in implementing ecodesign principles for the recovery of traction motors?*
    - This sub-question aims to identify the main barriers and potential benefits associated with applying ecodesign strategies in the recovery processes of traction motors. It seeks to understand the technical, economic, and organizational challenges that manufacturers face and explores opportunities for improving product life-extension.
2. *What implications for ecodesign can be acquired from implementing MFA to neodymium in traction motors?*
    - This question focuses on how the application of MFA can provide insights into the lifecycle of CRM like Nd within traction motors. This gives an idea of the potential outflows of Nd along with traction motors which is estimated using scenario analysis. By mapping material flows, this analysis aims to understand the potential of remanufacturing over recycling.
3. *How can remanufacturing strategies be employed to integrate ecodesign principles and insights from MFA into enhance the circularity for traction motors?*
    - This sub-question explores the potential of remanufacturing as a strategy to incorporate both opportunities for ecodesign principles and insights from MFA. It examines how remanufacturing can optimize resource use, extend product lifecycle and create circular loops.

1.6 Thesis Outline

This thesis is organized into nine chapters, systematically addressing the research objectives and sub-questions to develop strategies for integrating ecodesign principles into the EoL management of traction motors in EVs. The structure provides a logical flow, combining conceptual insights with empirical findings to deliver a comprehensive framework. Chapter 1 introduces the research context, outlines the problem statement, and defines the scope of the study. It also highlights the academic and societal relevance, presents the research questions, and specifies the objectives and central concepts. Chapter 2 provides an in-depth background literature review, examining key topics such as REEs, NdFeB magnets, and their significance in EV technologies. It also evaluates supply-demand imbalances, existing CE frameworks, and established ecodesign strategies. Furthermore, the chapter identifies research gaps and underscores the necessity for systems thinking and life cycle approaches in the recovery of high-value materials. Chapter 3 outlines the research methodology, detailing the research design and methods employed, including systematic literature reviews, expert interviews, and MFA. The chapter also presents a research flow diagram, visually illustrating the key stages of the study, ensuring transparency in the processes used to analyse challenges, material flows, and remanufacturing opportunities.

Chapters 4, 5, and 6 focus on addressing the sub-questions, providing both theoretical insights and practical applications: Chapter 4 analyses the challenges and opportunities in implementing ecodesign principles for the recovery of traction motors, highlighting technical, economic, and regulatory barriers as well as areas of opportunity. Chapter 5 explores insights gained through MFA of Nd in traction motors, estimating potential outflows at EoL using scenario analysis. This chapter investigates how MFA supports strategic decision-making to enhance remanufacturing over conventional recycling. Chapter 6 examines the role of remanufacturing strategies in integrating ecodesign principles with MFA insights, demonstrating ways to optimize resource recovery, extend product lifecycles, and create circular supply chains.

Chapter 7 synthesizes the key findings of the research, offering a comprehensive discussion of the insights gained. It presents actionable steps to operationalize ecodesign principles and remanufacturing frameworks. Chapter 8 presents with conclusions and future research. Chapter 9 compiles the references, ensuring the research is well-grounded in existing literature, while providing avenues for further investigation. Chapter 10 contains the appendices, which include a systematic literature review summary, interview guides, MFA data assumptions, and EV market projections. These supporting materials ensure transparency and provide a resource base for future studies.

Overall, the thesis structure is designed to progressively build a holistic understanding of how ecodesign strategies can be effectively applied to traction motor recovery, linking theoretical perspectives with empirical evidence. It delivers a multidisciplinary approach, addressing technical, economic, and policy dimensions while offering practical solutions for enhancing circularity and resource resilience within the EV industry.

2. Background Literature Review

This section establishes the necessary foundational knowledge for the thesis by reviewing key literature. It emphasizes the importance of CRMs, particularly NdFeB magnets, in enabling the functionality of traction motors in EVs. Additionally, the review delves into the supply-demand dynamics within the EU, highlighting the growing challenges of dependency on external sources and the urgency of supply chain resilience. This exploration lays the groundwork for understanding how ecodesign principles can be integrated into the lifecycle of traction motors, particularly through strategies like product life extension and product recovery.

The impacts of climate change are increasingly undeniable. To address this, the EU, under its Green Deal initiative, aims to achieve climate neutrality by 2050 (The European Green Deal, n.d.). This involves transitioning from fossil fuel-based energy systems to green technologies. However, this shift brings with it a substantial demand for specific materials. REEs are particularly vital for advancing green technologies (Ciacci et al., 2018). Figure 2.1 highlights the sectors and technologies that depend on CRMs for their successful implementation in highlight is Traction Motors. This demand is expected to grow as the EU expands the deployment of wind turbines and electrifies its transportation sector. Given the EU's heavy reliance on imports for these materials and the increasing demand, concerns have emerged regarding their long-term availability and the reliability of their supply for manufacturers (Habib, 2019). In response, the EU has identified CRMs as essential resources for critical applications in digitalization, defence, and energy transitions (Critical Raw Materials, n.d.). Figure 2.1 illustrates the various sectors and technologies reliant on these materials, in highlight is Traction Motors. (Carrara et al., 2023).

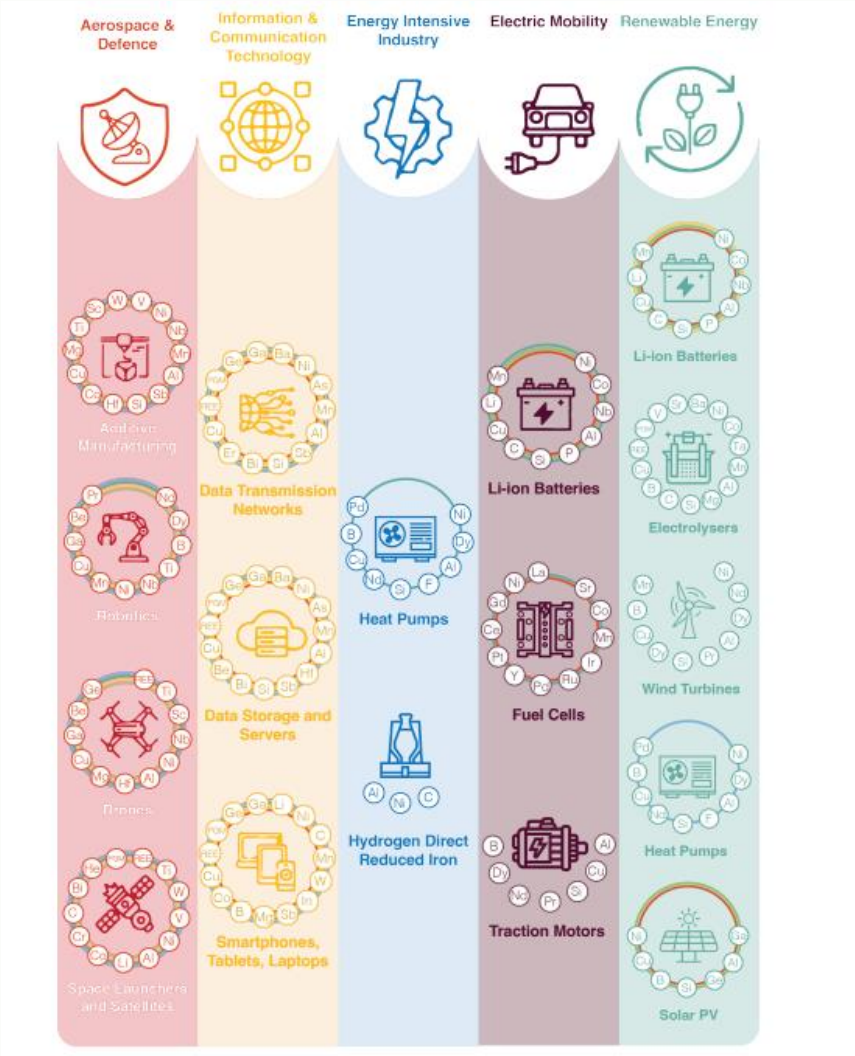

Figure 2.1 Sectors and technologies that depend on CRM. Source: (Carrara et al., 2023)

2.1 Rare Earth Elements

REEs include the 15 lanthanides, as well as scandium and yttrium (USGS, 2002). These elements are categorized into Light Rare Earth Elements (LREEs), ranging from lanthanum (La) to gadolinium (Gd), and Heavy Rare Earth Elements (HREEs), which span from terbium (Tb) to lutetium (Lu) (Panagopoulou, 2018). Although REEs are relatively abundant in the Earth's crust, their distribution in economically viable concentrations is uncommon (Rare Earth Elements, n.d.). Mining these elements is challenging because they naturally occur together and must be extracted collectively, requiring complex chemical separation processes. This extraction process is associated with significant environmental challenges. According to Mancheri et al. (2018), the production of 1 ton of Rare Earth Oxides (REOs) from ion-adsorption clays generates 1,000 tons of heavy-metal-contaminated wastewater and refining 1 ton of REO results in approximately 1.4 tons of radioactive waste. These economic, environmental, and social impacts highlight the critical need to develop secondary sources of REEs.

2.2 NdFeB Magnets

REEs are used in various applications, including catalysts, glass, ceramics, and more (Goodenough et al., 2018; Riaño & Binnemans, 2015). Among these, a significant portion of imported REEs is utilized in the production of rare earth permanent magnets as illustrated in Figure 2.2. The demand for Nd, a key component in these magnets, has grown substantially due to its role as the primary REE in these magnets (Yang et al., 2016). Nd magnets, typically consist of 25–30% neodymium, 60–70% iron (Fe), and about 1% boron (B) by weight. A standard NdFeB magnets used in EVs is presented in Figure 2.3. The earliest version of these magnets was first developed in 1984 by General Motors and Sumitomo Special Metals, providing a cost-effective alternative to samarium cobalt (SmCo) magnets, which were then the most advanced high-performance magnets (Heim & Wal, 2023; Widmer et al., 2015).

Initially, NdFeB magnets found applications in consumer electronics and hard drives. From 2004 onward, their usage expanded to include industrial applications such as robotics, pumps, and automotive systems. More recently, they have become vital in clean energy technologies, playing a crucial role in EVs and wind turbines (Van Nielen et al., 2023).

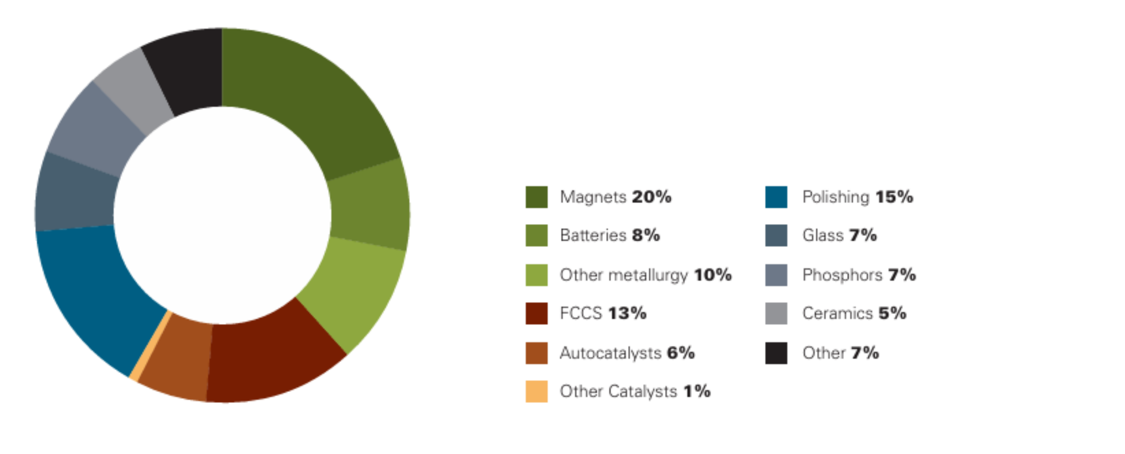

Figure 2.2: Breakdown of estimated rare earth consumption by sector in EU, 2012. Source : (Ahonen et al., 2015)

Figure 2.3: NdFeB magnet. Source : (Shewane et al., 2014).

2.3 NdFeB Magnets and EVs

In an EV, three primary components work together: the battery, the electric motor, and the controller. The electric motors, commonly referred to as traction motors, house NdFeB magnets within their stator and rotor assemblies. The placement in an EV is shown in Figure 2.4. These magnets play a crucial role in generating a strong magnetic field, which facilitates power conversion and propulsion, driving the vehicle forward (Ningbo Ketian Magnet CO., LTD., 2024). While the principle is straightforward, the challenge arises from meeting the growing demand for NdFeB magnets due to the rapid expansion of the global EV market. For instance, in 2023, approximately 14 million EVs were sold globally, a 35% increase from 2022. Most of these sales were concentrated in regions such as China, Europe, and the United States, where EVs have gained substantial market share (Global EV Outlook 2024).

NdFeB magnets are the preferred choice for EV traction motors for several reasons. First, their extremely strong magnetic field allows for the design of compact and lightweight motors compared to alternatives like ferrite or AlNiCo magnets (Heim & Wal, 2023). Second, they are highly efficient, as they do not require an external power source to induce a magnetic field in the rotor. Third, these magnets deliver high torque and are easily controllable (Chan & Cheng, 2012). Finally, no other magnets currently available can match their performance, making a full substitution with less CRMs unlikely in the near future (Carrara et al., 2023). In the Figure 2.5, we can confer that the substitutability of NdFeB magnets ranks pretty high and there is also loss of performance. Their compact designs and ability to provide the necessary performance demanded by the EV OEM's makes it indispensable.

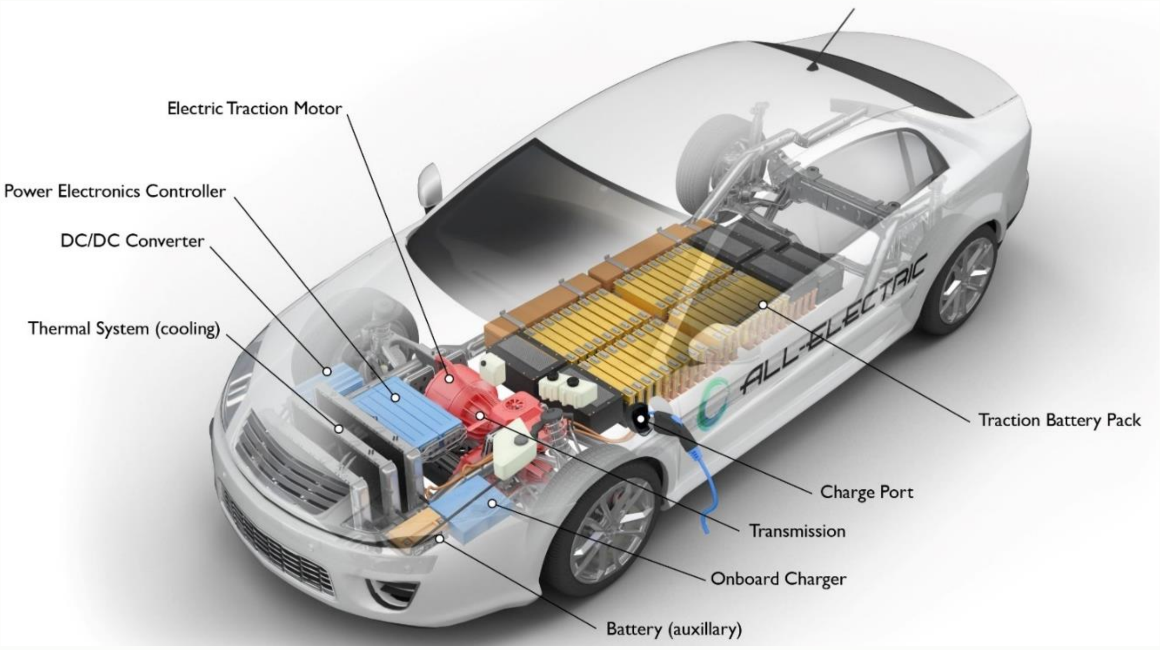

Figure 2.4: Placement of traction motor in an EV. Source (Google).

In future coming years, projections indicate that by 2025, nearly 90–100% of EVs will rely on NdFeB magnets. Additionally, each EV traction motor typically contains 1–2 kg of rare REEs with Nd as the primary component (Bailey et al., 2017). This presents a significant opportunity to recover these magnets, either for reuse or to extend their life cycle, contributing to greater sustainability in EV production.

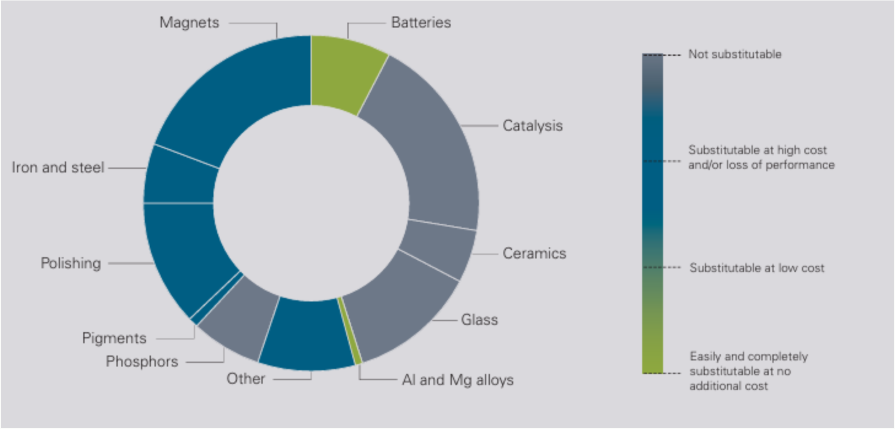

Figure 2.5: An overview of the current substitutability of rare earth elements by application. Source: (Ahonen et al., 2015).

2.4 Demand – Supply Disparity

This chapter highlights the critical role of Nd in supporting the EU's transition to green mobility, while addressing the challenges posed by the region's dependence on external sources for this essential material. The current supply chain for Nd, a key component in rare earth permanent magnet, is heavily concentrated with China producing approximately 122,200 tonnes, 94% of the global supply of 130,000 tonnes in 2019 (Gauß et al., 2021). Projections suggest that the EU's demand for Nd in green technologies could increase nearly sevenfold by 2030 and nine- to tenfold by 2050 (Carrara et al., 2023). However, multiple studies indicate that supply growth is unlikely to keep pace with this rising demand (Adamas Intelligence, 2021).

Specifically, for EVs, the demand for REEs where, Nd has the largest share in traction motors is expected to escalate from 5,000 tonnes in 2019 to approximately 70,000 tonnes annually by 2030 (Gauß et al., 2021). This is due to the rise in EV passenger car sales as shown in Figure 2.5. This rapid increase raises serious concerns, as the EU currently imports 98% of its permanent magnet supply (approximately 16,000 tonnes per year) from China (Carrara et al., 2023).

The EU's lack of domestic production across the rare earth value chain further exacerbates its vulnerability, as there is currently no primary rare earth mining within the region (Gielen & Lyons, 2022). Moreover, on the downstream, less than 1% of rare earth permanent magnet scrap is recycled in Europe, resulting in a missed opportunity to establish low-carbon secondary value chains. This supply chain dependency leaves EU manufacturers exposed to disruptions, price volatility, and speculative fluctuations, impacting material access and sustainability. The downstream effects are substantial, given that the EU27 mobility and automotive sector is projected to expand to €400 billion, supporting 6 million jobs by 2030 (Gauß et al., 2021). Failure to secure rare earth supplies could result in the relocation of electric traction motor production outside the EU, posing significant risks to economic stability, employment, and industrial competitiveness.

Addressing these challenges is essential to safeguard the EU's position in the global EV market and ensure the success of its climate goals. While recycling has been widely proposed as a partial solution, it alone may not meet future demands, highlighting the urgent need to develop secondary value chains, by moving up the R-ladder, in this case is remanufacturing. Establishing such systems not only enhances resource security but also strengthens the EU's industrial resilience, enabling a sustainable CE to support its green transition.

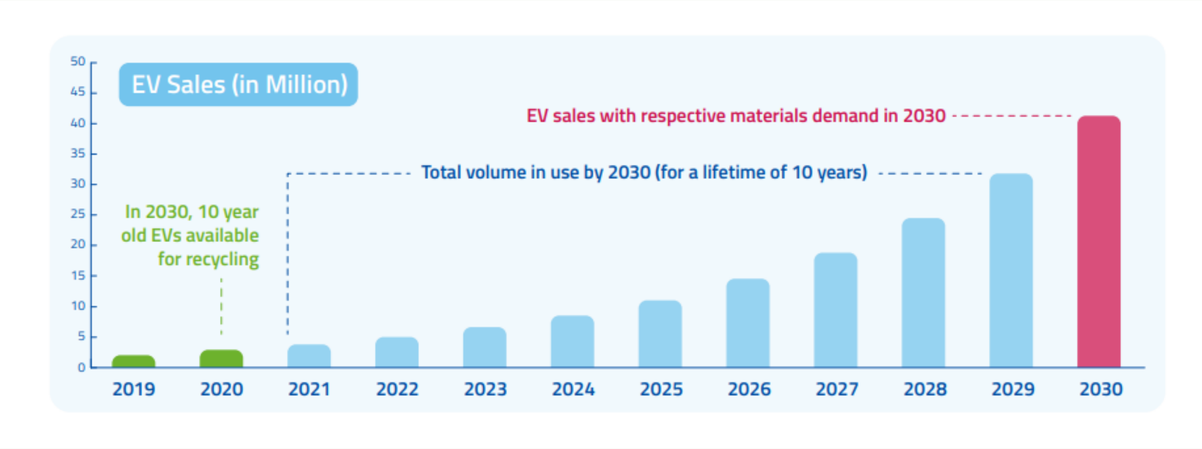

Figure 2.6: EV market demand is growing exponentially. Source: (Gauß et al., 2021).

2.5 Europe’s open strategic autonomy and Critical Raw Material Act

The EU has long acknowledged the critical need to secure a stable and sustainable supply of CRMs to support its strategic sectors, including renewable energy, digital technologies, aerospace, and defence. In response to these priorities, the Critical Raw Materials Act (CRMA), introduced in 2023, serves as a cornerstone regulatory framework aimed at addressing CRM supply risks while advancing sustainability and resilience within value chains. This chapter examines the CRMA as an integral component of the EU’s broader "Green Industrial Plan" and highlights its alignment with the "Net-Zero Industry Act" (NZIA)—both of which underscore Europe’s push for open strategic autonomy by emphasizing circularity and resource efficiency in CRM management (Hool et al., 2023).

The concept of open strategic autonomy reflects the EU’s effort to balance free trade principles with the imperative to reduce dependencies on external suppliers for critical resources. This policy approach has gained traction in light of geopolitical tensions and global supply chain disruptions, which have revealed vulnerabilities stemming from over-reliance on imports (Jakimów et al., 2024). By fostering greater self-reliance while remaining economically open, the EU aims to mitigate supply chain risks and strengthen its industrial resilience.

The CRMA directly addresses three major challenges confronting the EU’s CRM supply chain: inadequate risk anticipation, underutilization of domestic CRM resources, and unsustainable sourcing practices. To tackle these issues, the act establishes ambitious targets for domestic capacities by 2030, including meeting 10% of annual demand through extraction, 40% through processing, and 25% via recycling (Critical Raw Materials Act, n.d.). These benchmarks aim to diversify supply chains, reduce reliance on third-country suppliers, and bolster circularity through increased recovery and reuse of CRMs—especially in high-value applications like permanent magnets. The legislation also mandates regular stress tests for CRM supply chains, along with strategic stock reporting and supply chain audits for large enterprises operating in key sectors. To illustrate the thematic scope of the CRMA regulation proposal and its stakeholder impacts, Figure 2.6 provides a structured overview of the key regulatory areas and the affected stakeholders, including governments, industries, and research institutions (Hool et al., 2023).

While the CRMA represents a significant step forward in securing the EU’s resource independence and advancing its clean technology goals, several challenges remain. These include data gaps, potential hurdles in achieving the specified benchmarks, ensuring regulatory coherence across member states, and safeguarding the long-term economic feasibility of proposed measures.

These policies provide critical opportunities for this study to explore viable solutions to enhance circularity and resilience in the supply chain for high-value components like traction motors.

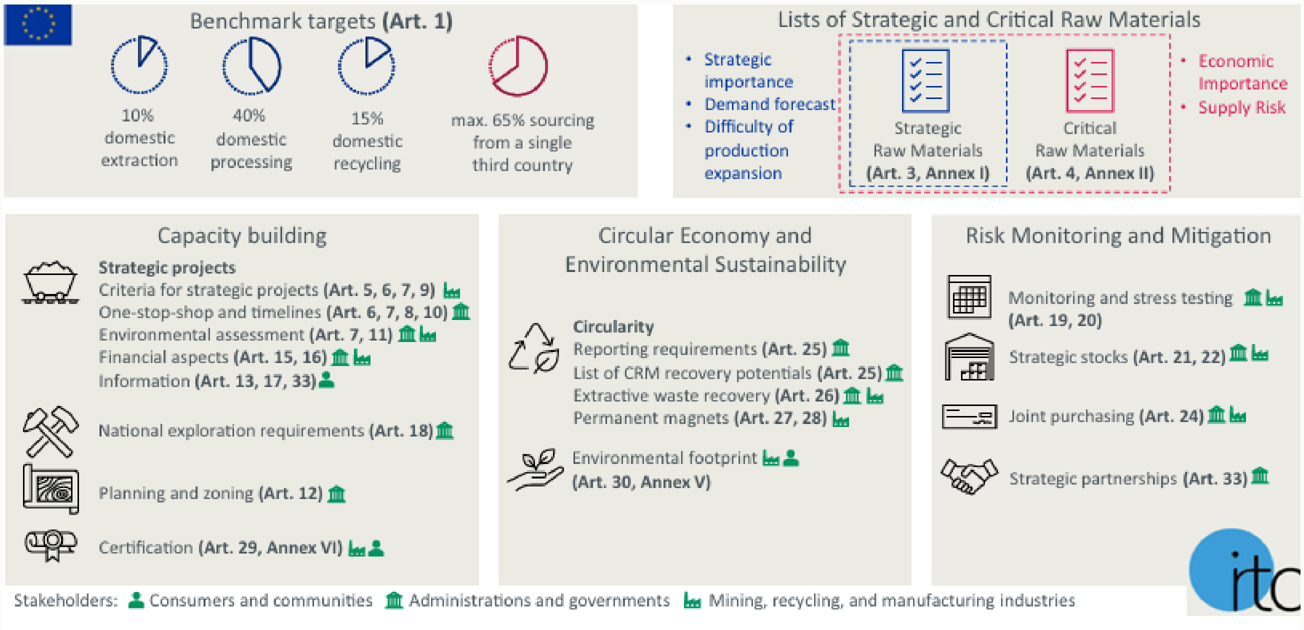

Figure 2.7: A thematic overview of the CRMA regulation proposal from March 16, 2023, and affected stakeholders. Source: (Hool et al., 2023).

2.6 Circular Economy and Ecodesign

2.6.1 Overview of CE principles and 9R strategies

Creating a secondary material flow to extend product's value chain has become a necessity. To facilitate this, moving from linear economy to CE has been one of the pillars in EU's Green Deal (European Council, 2023). The concept of a CE can be understood as an economic system in which the lifecycle of products, parts and materials is extended, and material consumption, waste, and losses are minimized (European Parliament, 2023; Morseletto, 2020). Furthermore, this means moving beyond the take-make-dispose model to closing material loops. CE is also associated to lower GHG gases, potency to avoid disruption in supply chains and environmental impacts.

There are many ways to achieve CE in an industry setting. This is usually done by using the R-strategies, which academics and practitioners often refer to (Kirchherr et al., 2018; Morseletto, 2020). The 9R framework is an industry favourite. The 9R-Framework is sub divided into three different categories to distinguish different phases along the value chain Figure 2.7. The framework which includes categories and individual principles follow a hierarchy with recycling and energy recovery being the least-desired options (Hennings, 2023). Initial literature review suggests that currently, only recycling has been the most explored principle to recover CRMs present in NdFeB PM at EoL. However, recycling and energy recovery are known to produce significant emissions, low yield rates, has no fundamental influence on promoting more circular production and consumption patterns in general (Morseletto, 2020). This suggests that a new strategy, such as exploring higher levels of the R hierarchy like remanufacturing, is needed to recover these materials and ultimately achieve closed material loops.

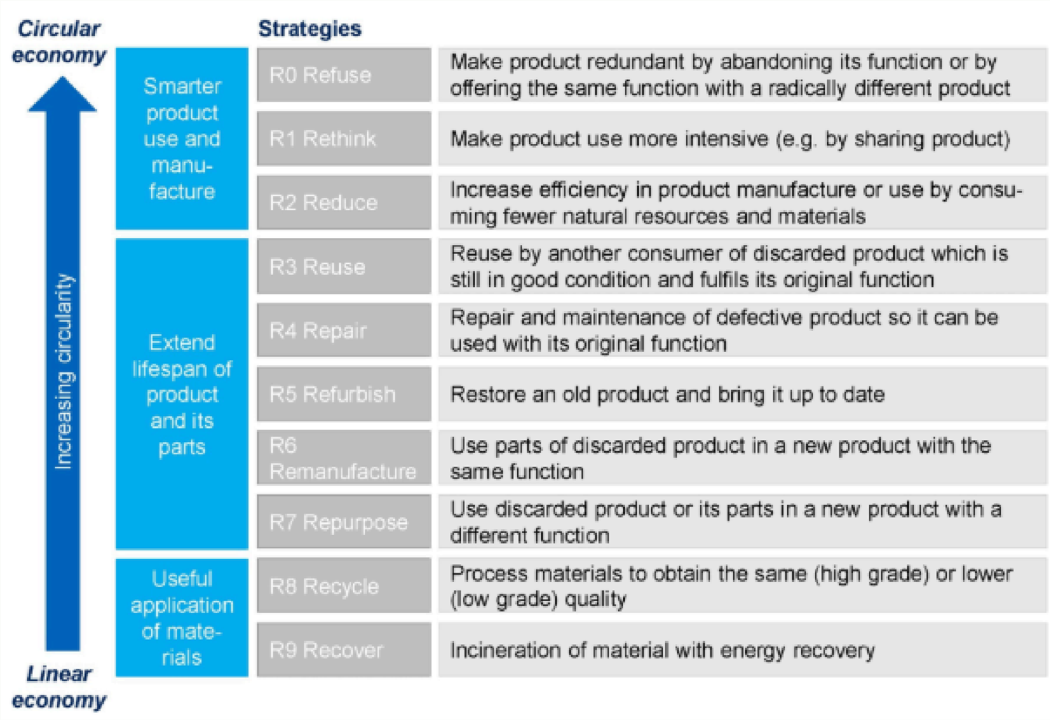

Figure 2.8: 9R- Framework of principles for a CE. Source: (Potting et al., 2017).

2.6.2 Defining Ecodesign and ecodesign approaches

Ecodesign, as defined by ISO 14006:2011, refers to incorporating environmental considerations into product design and development with the goal of minimizing negative environmental impacts throughout a product's lifecycle (ISO 14006:2011, n.d.). The standard outlines a six-stage framework for developing ecodesign projects: specifying product functions, identifying key environmental parameters, formulating environmental protection strategies, establishing environmental objectives and targets, defining product specifications, and crafting technical solutions. These steps aim to harmonize environmental objectives with stakeholder requirements during product development.

However, in practice, ecodesign often diverges from this standard. Pigosso et al. (2013) categorize ecodesign practices into two primary groups: management practices and operational practices. Management practices involve clearly defined goals for improving environmental performance, incorporating ecodesign tasks into daily routines, and setting environmental indicators and assessment methodologies. Operational practices include strategies such as reducing energy and material consumption, extending product and material lifespans, selecting low-impact resources and processes, optimizing product lifespans, and facilitating disassembly. For simplicity, this study focuses on the latter group, emphasizing strategies for product life extension and material recovery.

Numerous ecodesign methods have emerged to evaluate environmental impacts. Buamann et al. (2022) identified 150 ecodesign methods and tools under the umbrella of environmental product development (EPD). In the field of ecodesign, the terms "tools" and "methods" are often used interchangeably (Pigosso et al., 2009). This study regards ecodesign principles as a broad concept encompassing various tools and methods that address environmental concerns during product development. The choice of appropriate ecodesign principles depends on the specific stage of product development. This study prioritizes end-of-life ecodesign principles that focus on closing material loops and extending product lifespans.

In recent years, practitioners have shifted their perspective on ecodesign from being a checklist-based approach to a mindset and analytical process (Knight & Jenkins, 2008). Despite theoretical advancements, practical applications of ecodesign face significant challenges. Researchers advocate shifting the focus from tool development to integrating ecodesign principles into project management processes and broader organizational goals (Prendeville et al., 2016). However, the flexibility of ecodesign approaches, while enabling broad industry adoption, often leads to inconsistencies, especially when balancing product performance with environmental goals required from each industry. Fitzgerald (2017) highlights the need for company-specific guidelines and systematic integration into product development processes, as standalone, generic tools are frequently ineffective.

Although ecodesign aligns with CE objectives, its practical implementation is hindered by organizational inertia, financial constraints, and the complexity of creating closed-loop systems for products with intricate material compositions, such as EV components (Kim & Yannou-Le Bris, 2021). This gap underscores the necessity for industry-specific guidelines and standardized frameworks to facilitate actionable ecodesign implementation.

However, the regulatory landscape like the Ecodesign Directive, introduced in 2008, has primarily focused on energy efficiency during the use phase of products, with limited integration of resource efficiency requirements for specific product categories (Dalhammar, 2015; Bundgaard et al., 2015). From July 2024, the Ecodesign Directive will be replaced by the Ecodesign for Sustainable Products Regulation (ESPR), which broadens sustainability measures, including bans on destroying unsold products (Ecodesign for Sustainable Products Regulation, n.d.). However, like its predecessor, the ESPR predominantly emphasizes recycling, overlooking higher-order strategies such as remanufacturing and reuse. This narrow focus often leads industries to meet basic compliance standards without adopting systemic changes that ecodesign could facilitate, such as designing for durability and remanufacturing.

In summary, while ecodesign theory has expanded to include a range of strategies consistent with CE principles, practical implementation remains constrained by economic, regulatory, and organizational barriers.

2.6.3 Remanufacturing as an End-of-life strategy

The EoL stage, as defined in this study, occurs when a user discards a product, regardless of whether the product still retains functional value. This definition allows for the consideration of alternative strategies such as reuse or remanufacturing within the product's lifecycle. According to Rose (2001), EoL strategies encompass methods employed to recover value from discarded products. These methods include activities like the strategic collection and processing of used products after they are no longer in use. The primary recovery strategies include direct reuse, refurbishment (small repairs), recycling, remanufacturing of products or components, and the implementation of Product Service Systems (PSS) (Pigosso et al., 2009).

Among these strategies, direct reuse ranks highest in terms of environmental benefits. While direct reuse is ideal for items such as clothing or household goods, it fails to address the complexities of user requirements and product quality in advanced applications like traction motors.

PSS represents a paradigm shift from traditional product sales to service-oriented solutions that meet customer needs. This model emphasizes durability and supports reuse, remanufacturing, and recycling by allowing manufacturers to retain ownership of products while offering services like leasing, maintenance, and eventual recycling (Mont, 2002). While this approach aligns with environmental goals, its application in traction motors presents substantial challenges. Decentralized EV ownership and fragmented supply chains complicate the consistent return and EoL management of traction motors. Furthermore, the lack of infrastructure for reverse logistics and remanufacturing within the EV industry exacerbates these logistical difficulties. The automotive market’s focus on cost efficiency and performance further undermines the feasibility of PSS, given the additional costs and operational complexities it entails.

Recycling, often considered a last-resort strategy, focuses on material recovery when reuse or remanufacturing is impractical. Although recycling reduces products ending up in landfills and conserves resources, it often degrades the material's physical properties, making it less suitable for high-performance applications (Pigosso et al., 2009). Recycling traction motors presents further challenges, including high disassembly costs, energy-intensive processes, and diminished material quality. Unlike remanufacturing, recycling does not preserve the manufacturing value embedded in traction motors, limiting its environmental and economic benefits.

Remanufacturing emerges as a more sustainable EoL strategy, significantly reducing the dependence on primary raw materials and the energy needed to produce new products (Pigosso et al., 2009). It offers dual advantages by extending product lifespans and retaining the value-added during design and manufacturing. The remanufacturing process involves several stages: disassembly, testing, cleaning, repairing, inspecting components, updating, replacing parts, and reassembly (Seitz, 2006; Sundin & Bras, 2004). A generic remanufacturing process suggested by ERN is presented in Figure 2.8. To ensure relevance and efficiency, remanufactured products must meet current industry standards, avoiding the risks of technological obsolescence.

Successful remanufacturing relies on Design for Disassembly (DfD), which facilitates the dismantling, cleaning, repairing, and reassembly of products. While DfD plays a crucial role, the remanufacturing process faces obstacles, including the absence of advanced recovery technologies and systemic issues like weak decision-making frameworks and institutional barriers that impede the collection of goods for remanufacturing (Zwolinski et al., 2006).

In the automotive sector, research by Seitz (2006) highlights that OEMs often pursue remanufacturing to ensure a steady supply of affordable spare parts and fulfil warranty obligations, rather than as part of broader sustainability or profit-driven goals. This underscores the need for better alignment between corporate strategies and remanufacturing initiatives. Policies and technological innovations that address these systemic and technical challenges are essential to enhance remanufacturing. Closing material loops through effective remanufacturing practices could significantly contribute to the development of a circular and sustainable production model.

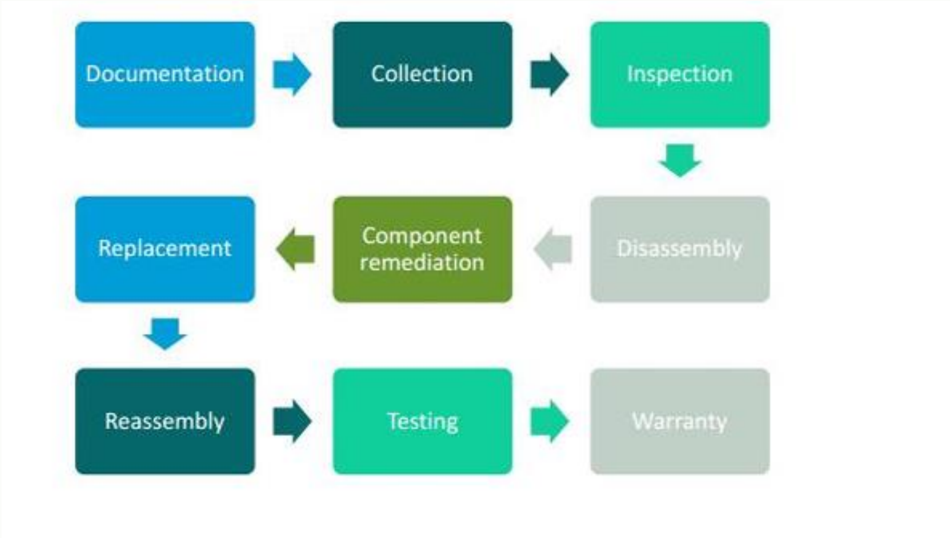

Figure 2.9: Generic remanufacturing process (Source: ERN 2016).

2.7 Research Gaps

The increasing focus on sustainability has spurred extensive research into ecodesign, particularly in industries that depend heavily on CRMs such as Nd. Despite progress in theoretical frameworks and policy measures, including initiatives like the CRMA, significant gaps persist in the practical implementation and optimization of these principles. This is especially evident in the manufacturing of traction motors for EVs.

- An initial review of the existing literature indicates that efforts to promote circularity in NdFeB magnets predominantly emphasize recycling. However, other strategies outlined in the R-ladder framework, such as reuse, repair, and remanufacturing, receive considerably less attention (Hennings, 2023). As a result, remanufacturing approaches remain underexplored within this context, suggesting an overlooked opportunity to reduce material dependency and enhance sustainability (Chowdhury et al., 2023).
- The challenges associated with adopting ecodesign principles vary significantly across different sectors. This variation underscores the necessity for targeted investigations to better understand sector-specific obstacles and identify tailored solutions that facilitate the effective integration of ecodesign principles (Paulson & Sundin, 2015; Dekoninck et al., 2016).
- Ecodesign has traditionally been associated with Life Cycle Assessment (LCA), where product functionality serves as the unit of analysis. However, this approach is not well-suited for the level of the system boundary considered in this study.
- Furthermore, there is an urgent need to develop sector-specific strategies that tailor ecodesign principles to meet the unique demands of each sector, in this case, the manufacturing of traction motors (Cordis, 2022).

In conclusion, while substantial progress has been made in advancing sustainability through ecodesign principles and CE strategies, several critical research gaps remain, particularly in the context of traction motor manufacturing for EVs. Current efforts predominantly focus on recycling NdFeB magnets, neglecting the potential of remanufacturing as a less resource-intensive and more sustainable approach. Furthermore, sector-specific challenges highlight the need for customized frameworks that integrate remanufacturing and MFA to enhance resource efficiency and product longevity for traction motors.

3. Methodology

3.1 Research Design

3.1.1 Mixed-method approach (qualitative and quantitative)

This research employs a mixed-method approach to address the primary research question, specifically examining how ecodesign principles can be integrated into the lifecycle of traction motors in EVs. The study takes an exploratory mixed-methods approach (Creswell, 2014), focusing particularly on remanufacturing as a strategy for recovering Nd present in NdFeB magnets. A convergent design is adopted, where both qualitative and quantitative data are gathered simultaneously, analysed separately, and subsequently integrated. This approach facilitated the integration of diverse data sources to address the technical, economic, and systemic challenges related to traction motor recovery and ecodesign.

The qualitative component aims to address the first sub-question, which seeks to identify both challenges and opportunities in implementing ecodesign for traction motors. This analysis is conducted through a systemic literature review and a series of expert interviews. Data from the literature and interviews are systematically compared, and any novel insights that emerge are presented. In the quantitative component, MFA is employed to assess the potential for recovering Nd from traction motors, enabling an understanding the impact of material recovery on ecodesign decisions. In this context MFA can provide a comprehensive understanding of Nd flows, identifying inefficiencies and opportunities for recovery at each lifecycle stage. In addition, it can reveal critical points of material loss and guide the integration of ecodesign principles tailored to traction motor recovery. To visualise this, scenario analysis is further used to explore the advantages of remanufacturing over traditional recycling. A baseline scenario with no circular strategy is modelled to compare. Through this comparison, remanufacturing is introduced as an alternative value chain, offering potential recovery of EV traction motors. Sub-question 3 focuses on addressing the gap between theory and practice. Desk research is conducted to understand how current industry practices align with business and regulatory standards, supporting remanufacturing as a suitable end-of-life strategy for traction motors. Following this, the applied research methods are presented, detailing the approach taken to address each sub-question.

3.2 Data Collection

This section details the specific methods employed to collect data to address the research sub-questions. To provide a clear overview of the methodological process, Figure 3.1 presents a research flow diagram outlining the sequence and interconnections of these approaches. This visual guide helps contextualize the methods used and their alignment with the study's objectives.

3.2.1 Sub-question 1: What are the key challenges and opportunities in implementing ecodesign principles for the recovery of traction motors?

- **Literature Review Methodology**

The literature review in this study follows a structured search strategy, utilizing databases such as Scopus and focusing on targeted keywords, including "ecodesign," "challenges" and "opportunities," to identify relevant and high-quality sources. To ensure rigor, selection criteria are applied to academic sources.

The initial search results for "ecodesign" produced a wide range of studies across multiple industries. To refine these results for relevance, AND/OR gates were employed when using the keywords "challenges" and "opportunities" to focus on challenges and opportunities for ecodesign. In few searches, keywords similar to "barriers" and "benefits" were utilized too. To ensure alignment with the study's objectives, three main criteria were established to select relevant journal papers: (1) concentration on the integration and challenges of ecodesign, (2) inclusion of practical applications and case studies, and (3) relevance to CRM recovery. Based on these criteria, eight key articles were selected, three of which were identified through a snowball sampling technique. Additionally, publication date and geographic representation were considered, with a particular emphasis on studies within the EU to enhance the regional relevance of the findings. The publications vary from 2002- 2017. Newer publications on ecodesign seemed to be missing due unknown reasons.

- **Semi-structured Expert Interviews**

In addition to the literature review, this study employs semi-structured expert interviews to gain in-depth insights from academics specializing in ecodesign. Experts were selected based on specific criteria, prioritizing those with a demonstrated research focus in ecodesign principles, CE practices, or remanufacturing. Preference was also given to individuals with experience bridging academic research and industry practice, particularly those who have transitioned from one domain to the other within the context of sustainable product design and ecodesign implementation. Potential interviewees were identified through collaborative brainstorming sessions with both research supervisors, ensuring alignment with the study's objectives.

Post expert identification, they were reached out using electronic mail to request their participation. Out of 6 experts contacted, response was received from 4 experts. A consent letter was signed before the interview. The interview process followed a structured approach to maximize the depth of insights gained. Each interview began with a brief introduction to the thesis topic, after which permission was sought from participants to record the discussion for transcription purposes. Interviewees were also asked to specify their preferred level of involvement in the study, including their choice of anonymity, in accordance with human research ethics guidelines. At the close of each interview, participants were invited to share any additional remarks, and they were thanked for their time and contributions.

The interviews, lasting between 30 and 45 minutes, aimed to capture detailed perspectives on the challenges and opportunities within ecodesign, specifically regarding its integration into value chains. The full set of interview questions is provided in *Appendix C*.

3.2.2 Sub-question 2: What implications for ecodesign can be acquired from implementing MFA to Nd in traction motors?

Sub-question 2 focuses on conducting an MFA to examine the flow of Nd within NdFeB magnets. This analysis entails collecting quantitative data on imports, exports, and production of these magnets, developing a model of Nd material flows, and performing scenario analysis to evaluate different recovery strategies. The MFA provides a comprehensive overview of resource flows, identifying key opportunities for integrating remanufacturing into the traction motor value chain.

- **MFA modelling approach**

MFA modelling approach in this study is defined by specific boundaries and parameters aimed at accurately capturing Nd flows within the European Union (EU27), hereafter referred to as the EU. The analysis focuses on the modelling year 2021, using data from the range 2018–2023 to provide a robust dataset for assessing trends and variations. The scope encompasses two types of EVs, which includes BEVs and PHEVs, to account for the varied applications of NdFeB magnets in EV traction motors. Additionally, the import of cars from China is incorporated to capture the significant Nd contributions from this key source. The lifecycle of magnet production is segmented into four distinct stages, which include mining, manufacturing, usage, and end-of-life phases within the EU; however, the initial stages of mining and manufacturing Nd containing components are outside the EU boundary. This approach enables a comprehensive view of Nd flows within the EU's value chain while acknowledging the globalized nature of raw material sourcing.

- **Scenario analysis for different recovery strategies**

This scenario analysis explores the potential of adopting higher R-order recovery strategies for Nd, focusing particularly on recycling and remanufacturing. The default scenario for 2021 reflects the current state of Nd recycling, serving as a baseline for evaluating alternative strategies. In the counterfactual scenarios, we project Nd recovery goals for 2030, modelling the effects of increased recycling rates and the integration of advanced remanufacturing techniques. These strategies are assessed against anticipated demand projections through 2030.

When comparing three models (current recycling, increased recycling, and remanufacturing), key focus areas include the volume of Nd in landfills, requirements for primary Nd production, proportion of secondary production, and Nd decommissioning directed toward waste management.

3.2.3 Sub-question 3: How can remanufacturing strategy be employed to integrate ecodesign principles and insights from MFA into enhance the circularity for traction motors?

- **Desk research**

Desk research forms the foundation for this sub question by gathering and analysing secondary data from various sources, including academic articles, industry reports, policy documents, and remanufacturing practices related to ecodesign. Through desk research, best practices in the integration of ecodesign and remanufacturing strategies will be identified, focusing on industries that have successfully applied these approaches to create circular chains. This provides a reference point for potential applications in the traction motor industry.

This methodological approach ensures a thorough analysis, leveraging both theoretical insights and practical examples to bridge gaps in the current understanding of integrating ecodesign, MFA, and remanufacturing strategies.

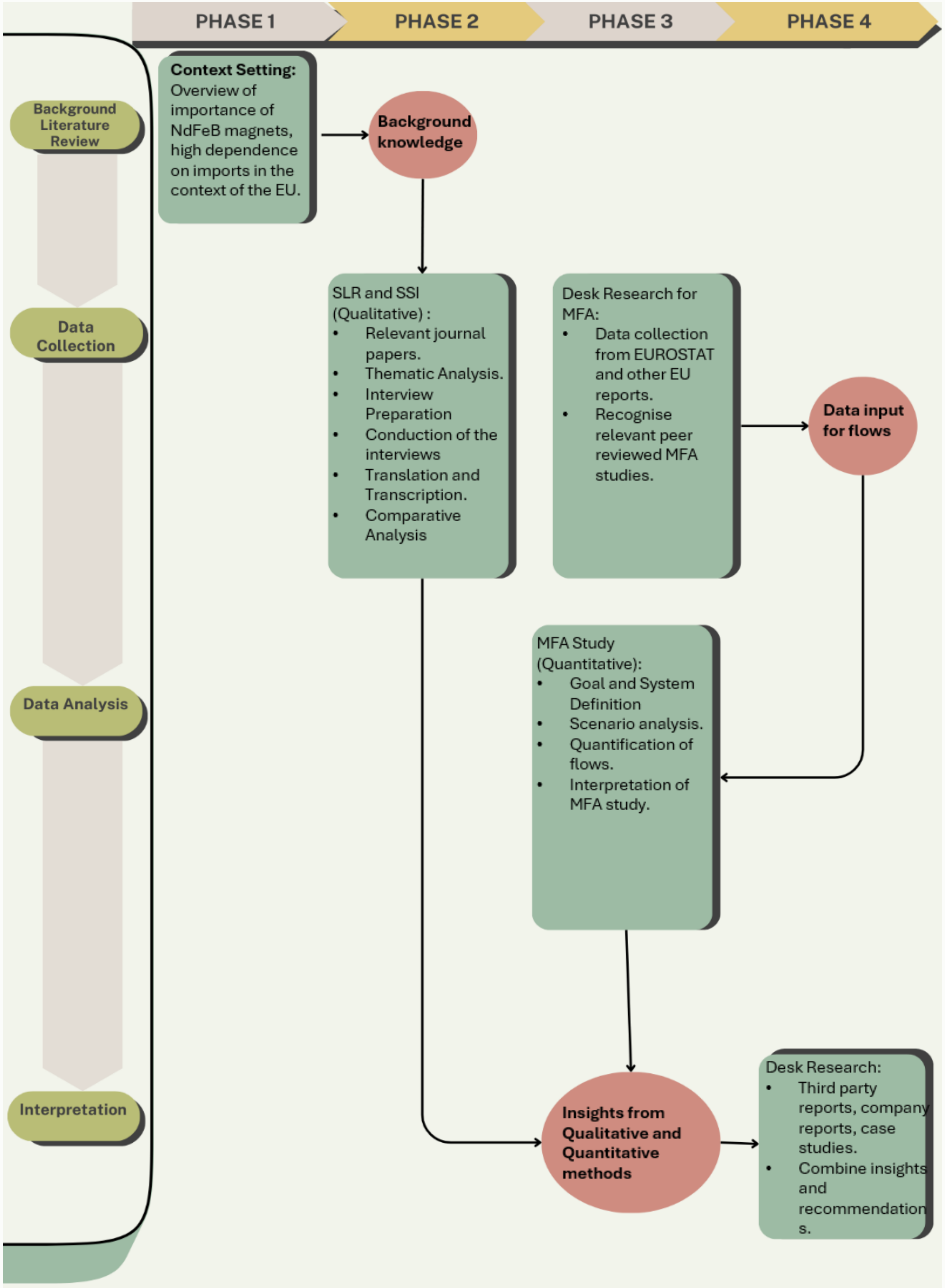

Figure 3.1 Research Flow Diagram. Source: (The author)

3.3 Data Processing and Analysis

3.3.1 Systemic Literature Review

The final step in the literature review process involved summarizing the identified journal articles and recognizing major themes. To maintain a structured and systematic approach, the key findings were categorized into two primary areas: challenges and opportunities. The synthesis of results highlighted recurring patterns and contrasts across themes, such as shared challenges, differing perspectives, or complementary insights from various journal papers. A detailed summary of the reviewed articles is included in Appendix A.

To organize and present the findings effectively, the literature mapping approach outlined by Creswell (2014) was adopted. This method offers a systematic framework for analysing and categorizing the literature, facilitating the identification of key themes, interrelationships, and gaps. The map is organized around three overarching themes: Challenges in Implementation, Opportunities and Enablers for Implementation, and Future Research Directions. These themes are further divided into sub-themes, such as Technical and Practical Barriers, Organizational and Cultural Barriers, and Drivers for Adoption, as depicted in Figure 4.1.

This framework provides a clear visual representation of how the adoption of ecodesign principles aligns with broader circular economy objectives, including the transformation of business models. Furthermore, it illustrates the interconnectedness of themes, such as the role of ecodesign in extending product lifecycles and advancing circular economy strategies. By structuring the literature review in this manner, the study offers a comprehensive overview of existing research, identifies critical areas for future exploration, and underscores the importance of ecodesign in fostering sustainable manufacturing practices.

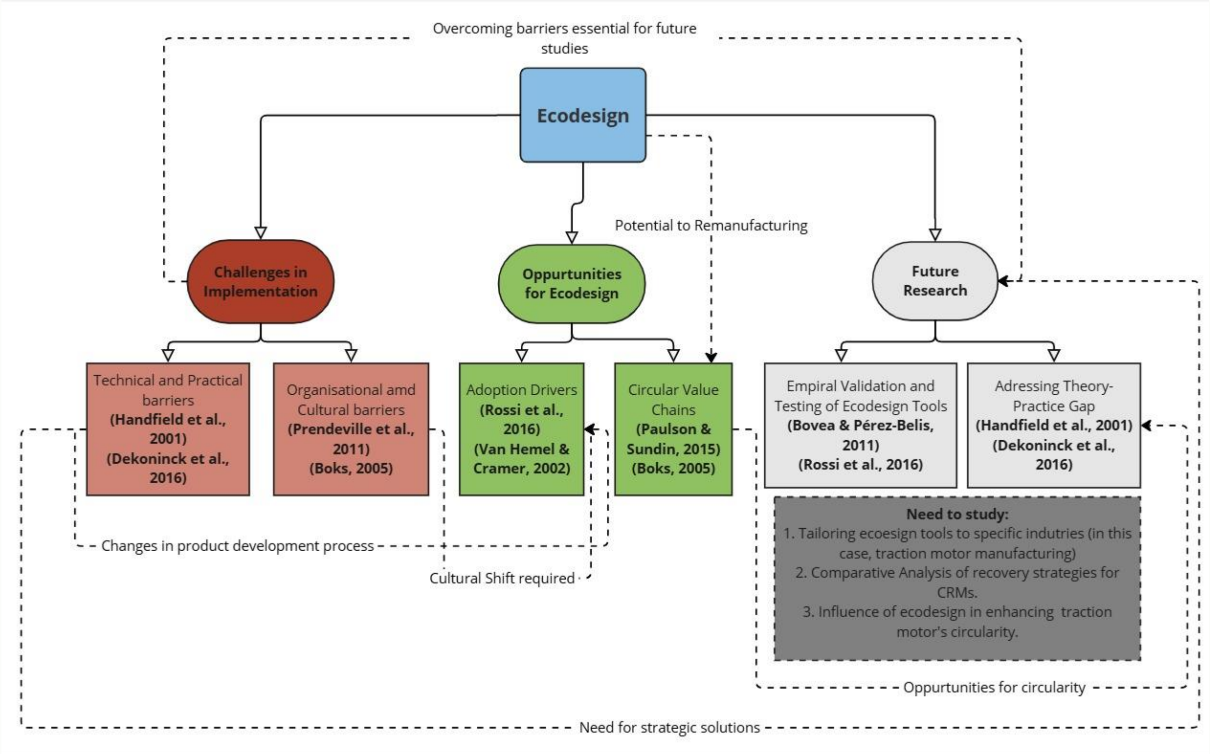

Figure 3.2 Thematic Literature Map of Ecodesign Challenges, Opportunities, and Future Research Directions (Source: the author).

3.3.2 Semi-structured expert interviews

The semi-structured interviews were transcribed, and the collected data were systematically organized into pre-defined categories. The two primary categories again were challenges and opportunities and further subdivided into detailed subcategories to allow for a more nuanced understanding of the insights gathered. These subcategories included topics such as the definition and flexibility of ecodesign principles, the current state of adoption and implementation, economic barriers, the influence of policy and regulatory frameworks, and prospects for remanufacturing, among others.

To ensure a comprehensive analysis, recurring themes, unique perspectives, and potential contradictions were also identified across the responses. The grouping process allowed for a clearer delineation of shared barriers and enablers, while also highlighting diverse viewpoints regarding the feasibility of ecodesign integration.

By using this systematic categorization, the processed data provided valuable insights into the barriers and drivers for ecodesign adoption, while also informing the development of tailored strategies. Further details regarding the categorization process and the results of the thematic analysis can be found in Appendix D. This approach not only ensured methodological rigor but also allowed for a holistic examination of the data, contributing to actionable recommendations.

3.3.3 MFA Methodology

After gathering the required data, it was categorized into three main groups: inflows (imports of Nd and NdFeB magnets, whether as standalone products or embedded in EVs), outflows (including exports, recycled materials, and material losses to landfills), and stocks (Nd retained within the EU EV fleet). The data processing involved mapping these resource flows using Excel spreadsheets and STAN software to identify potential pathways for recovery. A scenario analysis was conducted to compare the current practices with scenarios involving improved recycling and remanufacturing strategies. Due to data gaps, certain variables, such as recycling rates, were based on assumptions. However, the findings offer valuable insights into key opportunities for enhancing circularity in traction motors. Detailed results and flow diagrams generated from the MFA are presented in Chapter 5, providing a comprehensive understanding of the analysis and its implications.

4. Ecodesign Challenges and Opportunities in Traction Motors (Sub-question 1)

In this chapter, the findings from both the literature review and expert interviews will be presented to address sub-question 1 and offer new insights. The literature review findings informed the development of interview questions, helping to fill gaps identified in existing research. Insights that were not captured through the literature review were explored in depth through expert interviews. The results from these two sources are then analysed separately, compared, and synthesized.

4.1 Results from Systemic Literature Review

The literature establishes that ecodesign principles can play a pivotal role in shaping sustainable manufacturing, especially for high-value components like traction motors. However, there is limited research on how these principles directly contribute to CE goals within the specific context of EVs and critical components like NdFeB magnets. This synthesis focuses on challenges, opportunities, and critical areas requiring further study, as highlighted in the literature map Figure 4.1.

Challenges in Implementation

A common challenge highlighted across multiple studies is the technical and practical barriers to implementing ecodesign in industrial settings. Studies by Bovea & Pérez-Belis (2011), Handfield et al. (2001), and Dekoninck et al. (2016) identify that existing ecodesign tools are often complex, time-consuming, and not well-aligned with the needs of industries that demand high levels of efficiency, such as automotive manufacturing. These technical difficulties are particularly pronounced when trying to incorporate sustainability measures, such as material circularity, into product design without compromising on cost, functionality, and performance.

Furthermore, organizational and cultural barriers emerge as significant obstacles. Boks (2005) discusses how organizational inertia, lack of management commitment, and resistance to change limit the integration of ecodesign principles into conventional business models. Traditional manufacturing processes, which prioritize cost-effectiveness and speed-to-market, often clash with the more long-term perspective required for successful ecodesign adoption. The lack of clear responsibility for environmental issues, as noted in (Handfield et al., 2001), further exacerbates this issue by undermining efforts to drive ecological sustainability within organizations.

Opportunities and Enablers

Despite these challenges, there are several notable opportunities and enablers identified in the literature that could facilitate the adoption of ecodesign. Papers such as Prendeville et al. (2011) and Paulson & Sundin (2015) suggest that integrating ecode sign principles with CE strategies presents transformative potential, particularly in creating business models that focus on product lifecycle extension, remanufacturing, and closed-loop systems. These strategies not only align with sustainability goals but can also drive innovation, offering manufacturers a competitive edge in markets that are increasingly demanding sustainable products.

Regulatory drivers and growing consumer demand for environmentally friendly products, as identified in (Rossi et al., 2016) and (Van Hemel & Cramer, 2002), are also key enablers. Government incentives and market pressure can create the necessary push for companies to embrace ecodesign as a core component of their product development processes. This is particularly relevant for industries such as automotive manufacturing, where regulatory frameworks around CO2 emissions and material efficiency are evolving rapidly, influencing the demand for sustainable, circular solutions.

Future Research Directions

A significant gap in the current literature lies in the direct application of ecodesign principles to the circularity of CRMs, such as Nd, used in EV traction motors. While studies have explored general ecodesign tools and their application in various industries, there is limited research on how these principles can be specifically tailored to address the challenges associated with CRMs, which are key to the development of sustainable EV's.

Additionally, there is a need for research that investigates the intersection of ecodesign with business model innovation. The potential for new business models that prioritize product lifecycle extension, leasing models, and remanufacturing could drive the adoption of CE practices in industries. More research is needed to understand how ecodesign can be integrated into such business models, especially in the context of high-value components like EV traction motors and their reliance on critical materials like Nd.

Finally, research should further explore how organizational barriers can be overcome. As identified by (Boks, 2005), integrating ecodesign into an organization's culture and business processes requires tailored change management strategies, improved communication, and incentives for employees. Future studies could explore how to best foster this organizational change, particularly in large automotive manufacturers where entrenched practices and resistance to innovation may limit the integration of sustainability principles.

Based on the literature review summary and the literature mapping, it can be inferred that:

1. **Holistic Approach:** Ecodesign has maximum benefits when applied from the very beginning of the product development process. This involves considering the entire product lifecycle, from design to end-of-life, ensuring alignment with CE goals.
2. **Balancing Priorities:** A key challenge is balancing environmental requirements with traditional product requirements such as cost, safety, and functionality. For traction motors, this may involve optimizing energy efficiency without compromising performance or affordability.
3. **Phased Approach:** Given the complexity and high precision required in traction motor manufacturing, a phased implementation of ecodesign principles may be more pragmatic. This approach could begin by targeting specific components or processes (such as optimizing NdFeB magnet remanufacturing) before scaling to the entire production process. This gradual integration will help address technical complexities while enabling iterative improvements in sustainability.
4. **Tailored Ecodesign Tools:** Developing simplified, user-friendly ecodesign tools specific to traction motor manufacturing could enhance adoption. These tools should be integrated into existing design software and product development software used in motor design.
5. **Ecodesign Education:** Improving designers' and engineers' knowledge of environmental issues and ecodesign principles is crucial. For traction motors, this might involve training on sustainable materials, energy-efficient designs, and CE principles.

6. **Supply Chain Collaboration**: Ecodesign efforts can prompt improved communication and collaboration with suppliers on environmental issues. This is particularly relevant for traction motors, where component sourcing at EoL plays a significant role in overall sustainability.
7. **Cross-Functional Collaboration:** Effective ecodesign integration requires breaking down organizational silos and encouraging cross-functional collaboration between departments such as design, engineering, procurement, and sustainability. In the context of traction motor manufacturing, fostering communication between these teams will help ensure that sustainability considerations are integrated across all phases of product development, from conception to production.
8. **Leadership Support:** Strong commitment and support from top management are vital for the successful adoption of ecodesign principles in traction motor manufacturing. This support not only ensures the allocation of necessary resources but also helps overcome resistance to change within the organization.

In summary, the integration of ecodesign principles into the design and production of traction motors presents both challenges and opportunities. By adopting a phased approach, developing tailored tools, enhancing education and collaboration, and securing leadership support, manufacturers could effectively align product development with sustainability goals, contributing to the broader objectives of the CE.

4.2 Findings from Semi-Structured Expert Interviews

4.2.1 Results of Thematic analysis

This chapter presents the results from the thematic analysis of the insights gained from expert interviews, focusing on challenges and opportunities in integrating ecodesign principles within traction motor manufacturing to support circularity. By systematically identifying recurring themes, this analysis aims to provide a comprehensive understanding of the barriers faced and potential areas for growth and innovation in ecodesign.

Ecodesign, while broadly defined faces unique challenges when applying it to specific industries. Experts 1, 2 and 3 had their own understanding and views around ecodesign and meant different to each one, while the consideration of environmental impacts remained constant. For Expert 1, ecodesign meant material efficiency and ensuring circularity while for Expert 3, it meant reducing energy usage during the use-phase of a product. The adaptability of ecodesign enables its application across a wide range of industries, but it also presents challenges in the context of EV manufacturing.

When asked about the current state of recovering CRM containing product to extend their lifetime, experts highlighted technical and logistical challenges. Expert 1 highlighted, traction motors often have intricate design that make magnets extraction difficult. Expert 1 also mentioned, pinpointing the exact location of CRMs within complex assemblies as one of the challenges.

Experts (most) pointed out significant organizational resistance to integrating ecodesign principles, particularly in well-established companies accustomed to traditional linear production models. This resistance often stems from a lack of cross-functional collaboration and insufficient understanding of the long-term benefits of CE practices. The cultural shift needed to prioritize sustainability across all departments, from design to sales, remains a significant challenge.

While remanufacturing offers a promising avenue for extending the life of traction motors and recovering valuable materials like NdFeB magnets, several barriers hinder its widespread adoption. Currently, there's no compelling economic incentive for manufacturers to integrate remanufacturing into their business models. Implementing remanufacturing requires significant effort and resources to establish pilot programs and scale operations. Companies often prioritize quick returns on R&D investments, overlooking the long-term benefits of remanufacturing strategies. Expert 1 illustrated this with the example of professional refrigerators, where the design-for-remanufacturing is not included initially because companies aim to earn back their investments much sooner than the product's actual lifespan. This misalignment between short-term financial planning and long-term sustainability needs is a significant barrier to the adoption of CE practices. However, Expert 3 highlights that there are few technical barriers in adopting remanufacturing and mentioned that there is economic incentive in adopting this strategy. One interesting insight from the Same expert was that design for disassembly was not always critical for remanufacturing to be viable. Although they took the example of the aviation industry in this regard, this could be applicable to automotive industries as well.

On the policy side of things, the lack of clear guidelines on implementing CE principles in high-tech manufacturing was identified as a barrier. The need for more targeted policies that explicitly support ecodesign in product lifecycle planning was emphasized as a crucial area for future development. Expert 2 highlighted combination of policies can be highly beneficial in making industries go circular.

Despite these challenges, several opportunities can be inferred for better integrating ecodesign principles in traction motor recovery. All the experts agreed that incorporating ecodesign and remanufacturing considerations from the initial concept phase can significantly impact the product's lifecycle management. All the experts suggested it's possible to design traction motors to undergo multiple remanufacturing cycles without compromising performance or quality. This means companies willing to invest in ecodesign and circularity could gain a competitive edge. The growing availability of ecodesign tools when tailored to traction motor manufacturing presents an opportunity for improved implementation. Tools that integrate with life-cycle thinking like LCA could provide valuable insights into resource efficiency, helping companies optimize their designs for circularity without compromising on performance.

In addition, the regulatory environment plays a crucial role in shaping the adoption of ecodesign principles in traction motor recovery. When asked if current regulations favour recycling over other higher R-order strategies, experts had interesting things to say. Expert 2 argued the lack of strong lobbying for remanufacturing has resulted in fewer policies supporting this recovery strategy compared to recycling. Furthermore, Expert 3 argued due to simplicity in recycling technologies and already established recycling technology, recycling is valued despite remanufacturing's higher potential value.

Most experts agreed the CRMA, while it's too early to assess its full impact, such regulations are shaping the framework for economic strategies in the industry. Additionally, the internal motives of the companies are essential in fully realising the full potential of CRMA.

4.3 Comparative Analysis: Literature Review vs Semi-structured Expert Interviews

This comparative analysis aims to bring about the contrasts and contradictions between literature review and expert interview. The analysis presented follows no order of priority. The analysis also deduces this information to interpret what that could mean to tractor motor manufacturing and EV industries.

1. Scope and Focus of Ecodesign

Literature Review: Presents a broad, holistic view of ecodesign, encompassing various stages of product lifecycle and multiple environmental considerations.

Expert Interviews: Highlight more targeted approaches, with a particular emphasis on energy consumption during the product's operational phase. The interviews also affirm that the greatest environmental benefits are achieved when ecodesign is implemented at the early stages of product development, particularly in the case of traction motors.

Interpretation: This contrast indicates that while academic literature supports a broad, holistic approach to ecodesign, industry practitioners tend to focus on specific aspects that align with the unique environmental impact profile of their sector. In the case of traction motors, energy consumption during operation stands out as a pivotal factor, likely taking precedence over other lifecycle stages in real-world applications.

2. Ecodesign Flexibility

Literature Review: Generally, advocates for flexible, adaptable ecodesign approaches that can be applied across various products and industries.

Expert Interviews: Experts agree that ecodesign principles are flexible but note that their interpretation varies across the industry. For some, ecodesign focuses on material efficiency and circularity, while for others, reducing energy use during the product's operational phase is paramount. This reflects the diverse priorities and environmental impacts associated with different stages of the product lifecycle.

Interpretation: Both the literature and expert interviews highlight ecodesign's flexibility. However, the expert interviews reveal a more sector-specific focus, with traction motor manufacturers prioritizing operational energy efficiency, whereas the literature advocates for a more holistic approach covering all lifecycle stages.

3. Technical Barriers

Literature Review: Tends to focus on general technical challenges in ecodesign implementation, such as tool complexity and integration with existing processes.

Expert Interviews: Experts echoed these concerns, with Expert 1 emphasizing the complexity of traction motor design, which makes magnet extraction and the location of CRM difficult. These challenges hinder the recovery of materials, especially in intricate assemblies.

Interpretation: Both sources acknowledge the technical challenges associated with integrating ecodesign, however there is a contrast which highlights the gap between generalized academic knowledge and industry-specific practical challenges. For traction motor ecodesign, addressing these specific technical barriers may be more crucial than implementing generic ecodesign tools.

4. Economic Considerations

Literature Review: The literature discusses the economic trade-offs associated with ecodesign, noting that while CE practices may have long-term benefits, they often face short-term economic challenges.

Expert Interviews: Experts also highlight the lack of economic incentives for remanufacturing, particularly in the short term. Expert 1 illustrated how companies often prioritize quick returns on R&D investments, making it difficult to justify the long-term investments required for remanufacturing and ecodesign. However, Expert 3 argues that remanufacturing can offer economic incentives, provided it is carefully managed.

Interpretation: Both sources recognize the economic challenges associated with ecodesign, especially the tension between short-term financial pressures and long-term sustainability goals. The expert interviews add nuance by offering specific examples, such as the refrigeration industry, where short-term economic considerations hinder the adoption of remanufacturing strategies.

5. Organizational Factors

Literature Review: Organizational resistance to ecodesign is a key theme in the literature, particularly in well-established companies with entrenched linear production models. The need for a cultural shift toward sustainability and the importance of cross-functional collaboration are highlighted.

Expert Interviews: Experts pointed to significant organizational resistance, particularly in companies that are used to traditional, linear production models. The lack of cross-functional collaboration and understanding of the long-term benefits of sustainable practices were identified as key barriers to the adoption of ecodesign principles.

Interpretation: Both the literature and expert interviews underscore the importance of organizational factors in the successful integration of ecodesign. The expert interviews provide more direct insights into the internal challenges companies face, including the need for cultural change and better interdepartmental cooperation.

6. Role of Legislation and External Drivers

Literature Review: The literature stresses the importance of clear policies and regulations in promoting ecodesign and CE practices. It emphasizes the need for targeted regulations that incentivize sustainable product development and lifecycle management.

Expert Interviews: Provides a more complex view, noting that while external drivers are important, internal factors like innovation opportunities and cost reduction can be stronger motivators.

Interpretation: This nuanced contradiction indicates that the drivers for ecodesign adoption may be more diverse and complex than often portrayed in academic literature. For traction motor manufacturers, identifying and leveraging the most effective combination of internal and external drivers could be key to successful ecodesign implementation.

7. Remanufacturing Perspectives

Literature Review: Generally, presents remanufacturing as a key strategy for CE, focusing on its potential benefits and implementation challenges.

Expert Interviews: Experts highlight that remanufacturing offers significant potential but is hindered by the lack of clear economic incentives and the difficulty of integrating it into business models. Expert 3, however, argues that remanufacturing can be economically viable, particularly in industries where technical barriers are low. They also suggest that design for disassembly is not always a critical requirement for successful remanufacturing, citing examples from the aviation industry.

Interpretation: Both the literature and expert interviews acknowledge the promise of remanufacturing but also note significant barriers. The expert interviews provide more specific examples, such as the aviation industry, where remanufacturing can succeed without requiring extensive design changes.

This comparative analysis reveals both alignment and divergence between the insights from the literature review and expert interviews. While both sources highlight the challenges and opportunities in implementing ecodesign principles, the expert interviews provide more sector-specific insights and examples, particularly related to traction motors. These findings underline the complexity of applying ecodesign in practice and emphasize the need for tailored solutions to overcome technical, economic, organizational, and regulatory barriers.

5. Material Flow Analysis of NdFeB Magnets in Traction Motors (Sub-question 2)

5.1 Overview of Material Flow Analysis

The global Nd demand for EV's is estimated to increase from 5,000 tonnes in 2019 to 40,000-70,000 tonnes in 2030. EU's market share in the EV industry is bound to be 40 – 45% in 2030. This shows considerable material demand and consumption. To understand the flow of Nd in traction motors, MFA methodology is employed in this study. MFA is a methodology grounded in the principle of mass conservation, enabling the quantification of material flows and stocks within a defined spatial and temporal boundary (Brunner & Rechberger, 2003) and one of the core methodologies in IE research field.

Globally, several studies have utilized MFA to map Nd flows. For instance, Nansai et al. (2014) analysed material flows of various rare earth elements, including Nd, while Liu et al. (2022) examined global Nd flows, incorporating regional trade balances. Within the EU context, notable contributions to understanding Nd flows include studies by Guyonnet et al. (2015) which charted historical Nd flows, and Ciacci et al. (2018), which modelled flows up to 2016. Van Nielen et al. (2023) focused on the necessity for recycling systems to handle Nd-containing products reaching EoL. Future projections of Nd flows, particularly the anticipated large-scale waste flows from EV motors, were explored by Reimer et al. (2018) However, these studies often report diverging results due to differences in their scope, temporal boundaries, and product selection. This MFA builds upon these foundational studies by emphasizing the role of remanufacturing as a strategy to promote circularity and reduce dependency on primary Nd imports.

This study applies MFA to track Nd usage in traction motors for EVs. The primary objective is to identify potential higher order recovery strategy in comparison to traditional recycling processes. Specifically, remanufacturing of traction motors is assessed to evaluate its potential for reducing the primary consumption of Nd imports. The model adopts a bottom-up approach by quantifying the Nd content per vehicle and scaling it to broader Nd import flows, making it a demand-driven model.

5.2 Methodological Approach

5.2.1 System Boundary

The system boundary for this study encompasses the EU27 region (excluding the UK) to analyse the Nd flows related to EVs. All forms of Nd entering or exiting this region are accounted for as imports and exports, respectively. The modelling year is set to 2021, a critical period for assessing post-COVID-19 supply chain disruptions and the impact of newly implemented EU policies aimed at advancing green technologies. By focusing on 2021, the study provides insights into baseline conditions for EV adoption and Nd flows in the context of evolving policy and market dynamics. This analysis specifically considers Battery Electric Vehicles (BEVs) and Plug-in Hybrid Electric Vehicles (PHEVs), given their significant reliance on Nd-based PM in traction motors.

The primary objective is to compare the efficacy of remanufacturing traction motors against recycling strategies by projecting scenarios into 2030. This helps identify pathways for optimizing Nd recovery, reducing dependency on primary imports, and enhancing material circularity.

5.2.2 System Definition

The system defined for this study excludes upstream mining and refining processes of Nd since these activities do not occur within the EU. The analysis begins at the fabrication stage, where Nd alloys imported are subsequently used in magnet production (about 80%), integrated within the larger process of manufacturing traction motors for EVs.

Once manufactured, EVs enter the use phase, contributing to in-use stocks. Following the end of their lifecycle, these vehicles proceed to waste management systems. At this stage, the traction motors may either enter circular processes, such as remanufacturing or recycling, or be discarded as waste. The system captures material flows across all life-cycle stages within these boundaries—fabrication, manufacturing, use, and waste management, to evaluate their impact on Nd recovery and circularity efforts. A base model is presented in Figure 5.1.

This framework allows for a comprehensive understanding of how remanufacturing compares with recycling in terms of material conservation, providing insights for optimizing strategies to achieve circular material flows by 2030.

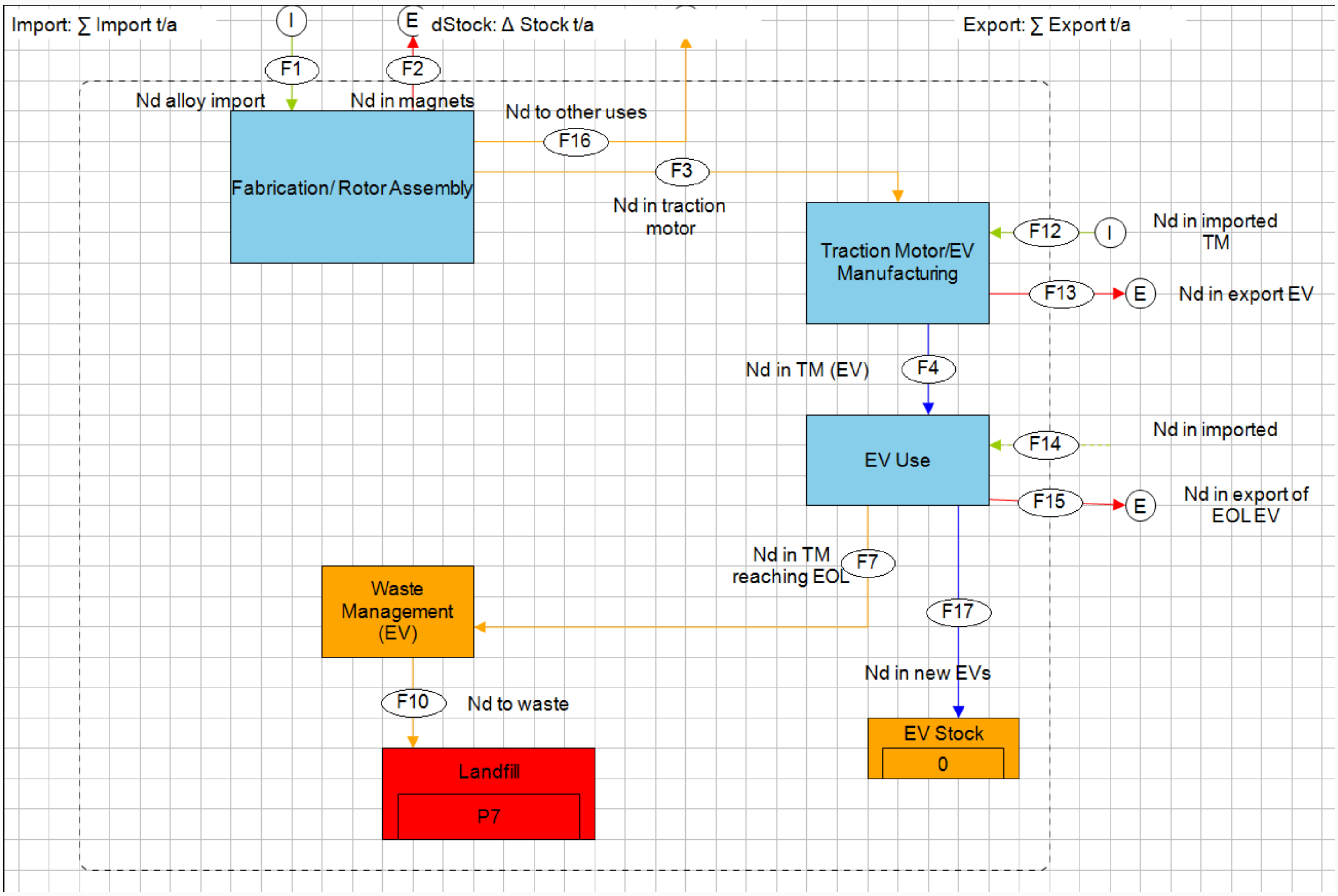

Figure 5.1 Base model for MFA of Nd in EV traction motors in the EU. Source: (The author)

5.2.3 Subsystem and Processes

The qualitative base model presented in Figure 5.1 and the system is divided into sub-systems and processes as shown in Table 5-1.

Table 5-1: Processes included within the system boundary.

Process number	Process name
	Subsystem: Component manufacture and assembly
P1	Fabrication/ Rotor Assembly
	Subsystem: Traction Motor assembly
P2	Traction Motor/ EV manufacturing
	Subsystem: Use
P3	EV Use
P4	EV stock
	Subsystem: EOL processing
P5	Waste Management (EV)
	Subsystem: EOL destination
P6	Landfill

5.2.4 Scenario, Data Collection and Assumptions

This chapter outlines the scenarios, data collection methods, and assumptions used to analyse the potential impacts of integrating R strategies, including recycling and remanufacturing, on the supply and demand dynamics of Nd. The scenarios presented—2021 Baseline (Scenario 1), 2030 Increased Recycling (Scenario 2), and 2030 Integration of Remanufacturing (Scenario 3) are developed to evaluate the feasibility and effectiveness of alternative recovery pathways for NdFeB magnets used in traction motors. The analysis aims to highlight the role of secondary sources and circular practices in reducing dependence on primary imports

Scenario 2021- Baseline

Table 5-2: Data requirement and identified Data Source for Scenario 2021- Baseline

Data Requirement	Data Source
Import of REE+	Eurostat
PM Import Data	(Gauß et al., 2021)
Nd content in PM	(Van Nielen et al., 2023)
Trade Statistics on EV sales (export)	Eurostat
Current EV stock	(RMIS - Raw Materials in Vehicles, n.d.)

Assumptions

- All domestic NdFeB magnet production within the EU is presumed to fulfil internal demand. Given the EU's heavy reliance on imported NdFeB magnets, it is likely that domestic production would be prioritized for regional use.
- Currently, no recycling process is happening in the EU.

Scenario 2030- Increased Recycling

Table 5-3: Data requirement and identified Data Source for Scenario 2030- Increased Recycling.

Data Requirement	Data Source
Import of REE+	Eurostat
PM Demand Projections	(Gauß et al., 2021)
Nd content in PM	(Van Nielen et al., 2023)
Trade Statistics on EV sales (export)	Eurostat
Current EV stock	(RMIS - Raw Materials in Vehicles, n.d.)
EV Fleet projections to 2030	International Energy Agency (IEA)

Assumptions

- The lifespan of the EV's is considered to be 10 years.
- The Nd content per EV is assumed to remain unchanged between 2021 and 2030.
- The import of REE+ is intentionally kept constant to understand the potential of secondary sources of Nd.
- It is assumed that reuse of EV traction motors is technically infeasible without any intervention. The heterogeneity of Nd-containing components requires their decommissioning before recycling.
- A 50% recycling rate is assumed for traction motors, reflecting the gradual establishment of facilities capable of achieving higher recycling efficiencies. This is supported by projections from (Reimer et al., 2018).

Scenario 2030- Integration of Remanufacturing

Table 5-4: Data requirement and identified Data Source for Scenario 2030- Integration of Remanufacturing.

Data Requirement	Data Source
Import of REE+	Eurostat
PM Demand Projections	(Gauß et al., 2021)
Nd content in PM	(Van Nielen et al., 2023)
Trade Statistics on EV sales (export)	Eurostat
Current EV stock	(RMIS - Raw Materials in Vehicles, n.d.)
EV Fleet projections to 2030	International Energy Agency (IEA)

Assumptions

- It is assumed that 40% of NdFeB magnets from EoL EVs will be recovered and remanufactured by 2030.
- In the remanufacturing process, there is 20% material loss and primary raw material is required for bringing the product to quality standards.

5.3 Quantification

The data requirements for this study are addressed through comprehensive data collection processes, as detailed in Appendix E. A detailed breakdown of flows is provided in Table 5-5, with calculations primarily based on secondary data. When necessary, mass balance approaches are applied to ensure consistency and accuracy.

To quantify flows, a combination of top-down and bottom-up approaches is employed. The top-down approach uses macro-level data at the regional scale, while the bottom-up approach estimates flow at the application level and scales them based on the number of EVs entering and exiting the system. These estimates are modelled using STAN software to track material flows effectively.

A flow-driven model is adopted to capture the dynamic nature of the system, enabling the estimation of EV stock inflows and outflows over time. For Scenario 2 and Scenario 3, the model integrates imports of PM and Nd content in EVs to ensure data consistency and homogeneity. The quantification of flows follows an iterative process, involving multiple rounds of data collection, validation, and model adjustments. This iterative approach ensures reliability and reflects evolving trends in material use and recovery technologies.

Table 5-5: Overview of quantified flows, which includes the approach used for quantifying, data uncertainty and the source for each flow.

Flow number	Flow Name	Approach for Quantification	Data Uncertainty	Data Source
Scenario 2021- Baseline				
F1	Nd alloy import	Top-down	High	Secondary
F2	Nd in magnets	Unknown	Unknown	
F3	Nd in traction motor	Mass balance	-	Calculated
F4	Nd in TM (EV)	Bottom-up	High	Secondary
F5	Nd in imported TM	Bottom-up	Low	Secondary
F6	Nd in export EV	Bottom-up	High	Secondary
F7	Nd in TM reaching EOL	Bottom-up Mass balance	Low	Secondary
F9	Nd to waste	Mass balance	-	Calculated
F11	Recovered Nd from TM	Not applicable	-	
F12	Nd to waste	Not applicable	-	
F13	Nd in TM to recycling	Not applicable	-	
F14	Nd in imported EVs	Bottom-up	Medium	Secondary
F15	Nd in export of EOL EV	Unknown	Unknown	
F16	Nd to other uses	Mass balance	High	Secondary
F17	Nd in new EVs	Mass balance	-	Calculated
Scenario 2030: Increased Recycling				
F1	Nd alloy import	Top-down	High	Secondary
F2	Nd in magnets	Unknown	Unknown	
F3	Nd in traction motor	Mass balance	-	Calculated
F4	Outflow of EV cars to use	Mass balance	-	Calculated
F7	Nd in TM reaching EOL	Bottom-up Mass balance	Low	Secondary
F8	Nd in TM to recycling	Mass balance	-	Calculated
F9	Nd to waste	Mass balance	-	Calculated

F10	Nd to waste	Mass balance	-	Calculated
F12	Nd in imported in PM and EVs	Bottom-up	High	Secondary
F13	Nd in export EV	Bottom-up	High	Secondary
F14	Recycled Nd	Mass balance	-	Calculated
F15	Nd in export of EOL EV	Unknown	Unknown	
F16	Nd to other uses	Mass balance	-	Calculated
F17	Nd in new EVs	Mass balance	-	Calculated
Scenario 2030: Integrated Remanufacturing				
F7 (1)	Nd in TM reaching EOL	Bottom-up	Low	Secondary
F9 (1)	Nd to waste	Mass balance	-	Calculated
F13	Nd in PM and EV Import	Bottom-up	High	Secondary
F14	Nd in exported EV	Bottom-up	High	Secondary
F15	Traction Motor to Reman- OEM	Mass balance	-	Calculated
F17	Nd in new EVs	Mass balance	-	Calculated
F18	Outflow of EV cars to use	Mass balance	-	Calculated
F19	Nd to Traction Motor	Mass balance	-	Calculated
F20	Nd in EV Traction Motor Export	Bottom-up	High -	Secondary
F21	Nd to waste	Mass balance		Calculated
F22	Traction Motor to Reman- SC	Mass balance	-	Calculated
F23	Reman Traction Motor- OEM	Mass balance	-	Calculated
F24	Reman Traction Motor- SC	Mass balance	-	Calculated
F25	Nd alloys	Top-down	High	Secondary
F26	Nd in magnets	Unknown	Unknown	
F27	Nd to other applications	Mass balance	-	Calculated
F28	Nd to waste	Mass balance	-	Calculated

5.4 Data Uncertainty

The uncertainties of the flows are classified into low, medium and high as followed in (S, 2023).

Flows F1 (Scenarios 1 and 2) and F25 (Scenario 3), which represent Nd alloy imports, exhibit high uncertainty due to variations in the forms and applications of these alloys. Only one dataset was used despite multiple datasets being available. Similarly, post-import flows (F16 in Scenarios 1 and 2 and F27 in Scenario 3) show high uncertainty due to inconsistencies in the literature regarding Nd alloy allocation to intended applications. Flows F6, F13, and F14 (Scenario 1) face high uncertainty as exports, expressed in monetary terms, were converted into car numbers based on average unit prices for BEVs and PHEVs and finally the Nd content. These prices are subject to market fluctuations and might vary in export numbers. Additionally, Flows F12 (Scenario 1) and F13 (Scenario 3) are influenced by projections of EV penetration by 2030, which vary widely across sources.

Flow F14 (scenario 1), representing EV imports, exhibits medium uncertainty due to the aggregation of data from multiple sources, despite accurate estimates of Nd content.

Flow F7 (Scenario 1,2 and 3) has low uncertainty, benefiting from a flow-driven model used for its estimation. Further details can be found in Appendix G.

5.5 MFA Results

This section presents the results derived from the MFA conducted for the three scenarios—2021 Baseline, 2030 Increased Recycling, and 2030 Integration of Remanufacturing.

5.5.1 Scenario Comparison

Scenario 2021

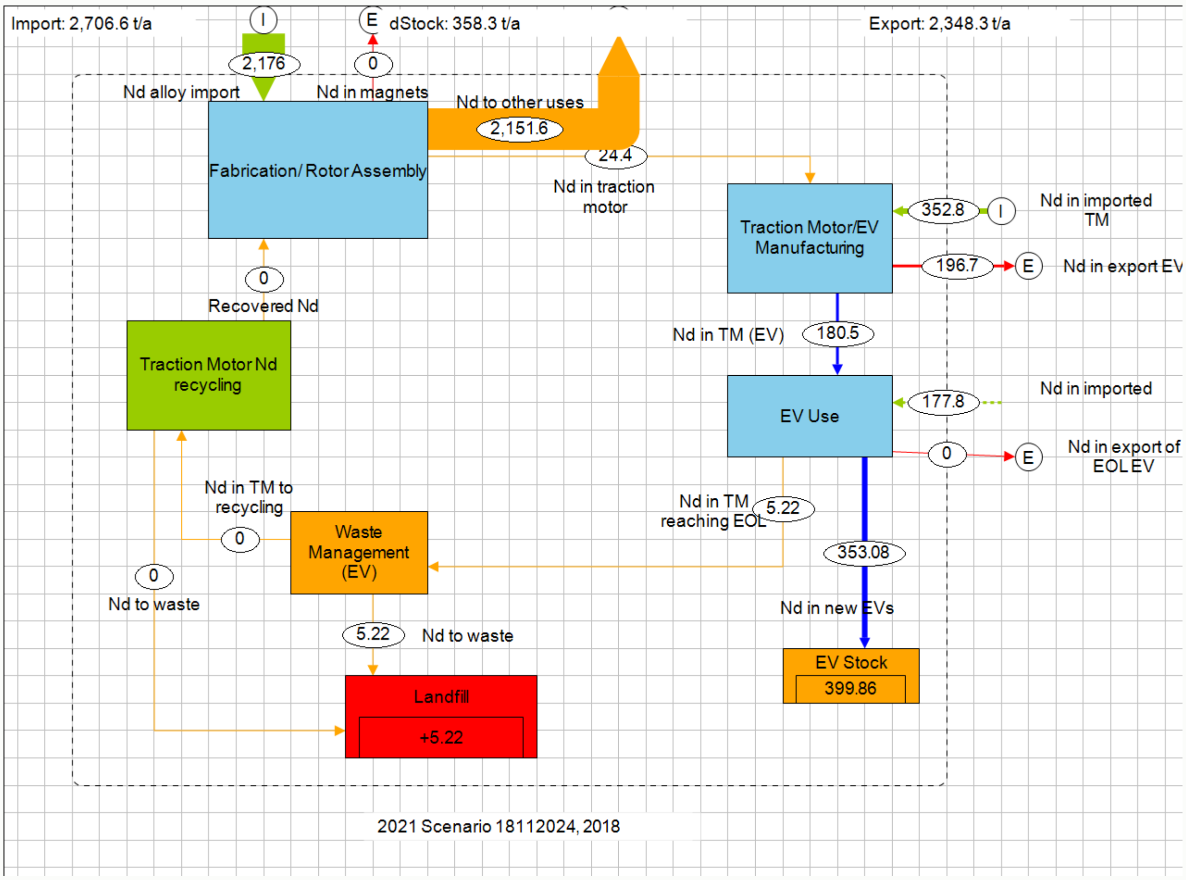

Figure 5.2 MFA of Scenario 2021

The MFA for Nd in 2021 (Figure 5.2) highlights the flow of Nd within the EU. The total Nd input into the system, largely driven by imports, is 2,706.6 tons, with 2,176 tons entering as Nd alloys. From the broader 17,000 tonnes of REE+ imports, 20% is attributed to Pr+Nd, with Nd comprising an estimated 80% of this share. However, only a fraction (>4%), 24.4 tons, is directly utilized in domestic manufacturing of traction motors for EVs, while a vast majority, 2,151.6 tons, is allocated to other applications. Additionally, 352.8 tons of Nd enter the system embedded in imported PM, illustrating the reliance on foreign production.

For EV manufacturing and use, 353.08 tons of Nd are introduced into the EU EV stock through new vehicles, underscoring Nd's vital role in advancing green mobility. Conversely, a significant portion, 196.7 tons, is exported embedded in EVs, contributing to notable outflows. The growing domestic EV stock retains 1,682.3 tons of Nd, reflecting a steady expansion in EV adoption and signalling a potential reservoir for future recovery.

Furthermore, practically non-existent, 5.22 tons of Nd from EoL traction motors were sent to landfills in 2021, representing a critical loss of valuable material. The imbalance between inputs and outputs results in an accumulation of Nd stocks within the EU, highlighting the region's growing dependence on imports and missed opportunities for circularity.

Scenario 2030: Increased Recycling

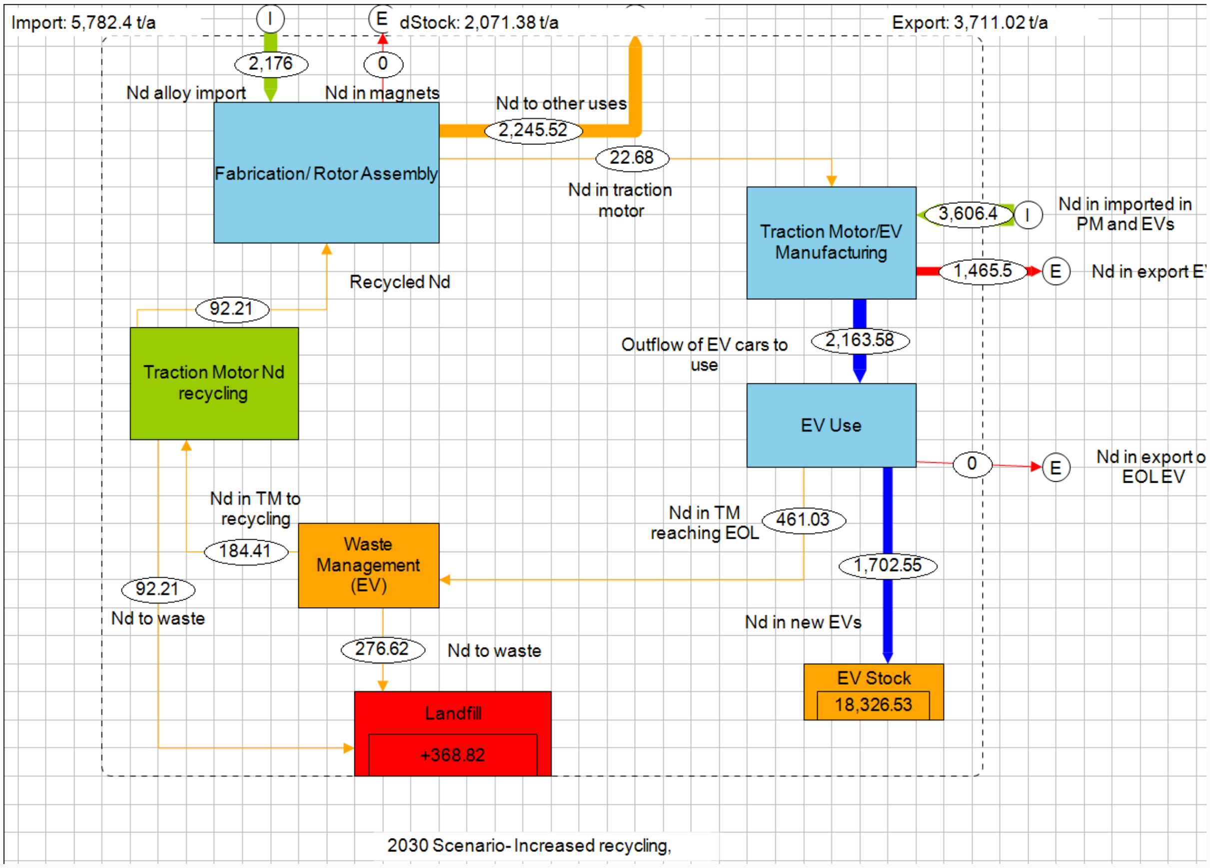

Figure 5.3 MFA of Scenario 2030- Increased recycling

In analysing the 2030 scenario with enhanced recycling efforts (Figure 5.3), the REE+ import volume has been intentionally maintained at the 2021 levels. This modelling choice stems from three key factors: first, the EU's domestic production of PM remains limited to approximately 1,000 tons annually, with a striking 96% of these magnets being imported. Second, from the imported Nd alloys only a fraction of it is sent to be utilized by EV cars, where a majority of Nd magnets are imported to meet its functionality. Thirdly, projecting REE import volumes for 2030 is highly uncertain due to market fluctuations and geopolitical complexities. Maintaining constant import levels allows for a clearer assessment of secondary material flows generated through recycling initiatives.

This scenario reflects a substantial increase in Nd demand driven by projections for EV sales. Imports of Nd are aggregated across PM and EVs, maintaining the 2021 share for Nd alloys used in EV manufacturing. The results demonstrate the sector's dynamic growth, with 3,606.4 tons of Nd entering the system through imported PM and EVs, while 1,465.5 tons of Nd are exported in manufactured EVs. Recycling processes show adequate progress, recovering 184.41 tons of Nd from EoL traction motors. However, inefficiencies persist, as 368.82 tons of Nd are still lost to landfills despite improved recovery mechanisms.

The accumulated Nd stock in EVs across the EU rises sharply to 18,326.53 tons by 2030, driven by consistent growth in EV adoption and an annual inflow of 1,702.55 tons of Nd into newly manufactured EVs. This substantial increase in stock underlines the sector's growing material footprint and the critical role of secondary flows in meeting future demand.

While this scenario highlights meaningful advancements in recycling, reducing dependency on imports and mitigating waste streams, the continuing losses to landfills indicate the need for further innovation in recycling technologies and policy frameworks.

Scenario 2030: Integrated Remanufacturing

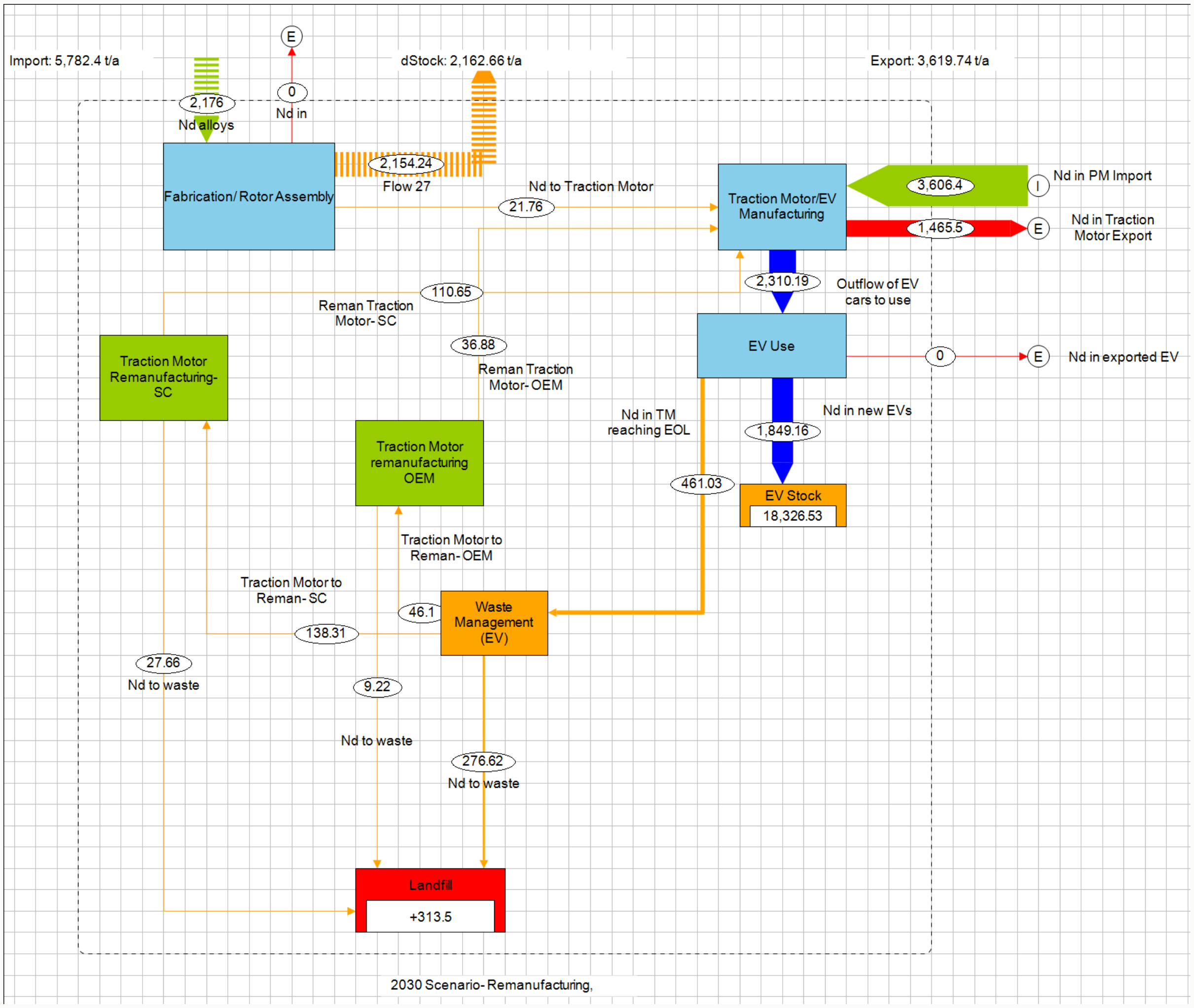

Figure 5.4: MFA of Scenario 2030- Integrated Remanufacturing.

The 2030 scenario with integrated remanufacturing (Figure 5.4) highlights significant advancements in material efficiency and circularity for Nd in EV systems. The total Nd imports remain consistent with 2021 levels at 5,782.4 tons. Of this, 2,176 tons arrive as Nd alloys, while 3,606.4 tons are embedded in imported PM and EVs. A notable aspect of this scenario is the potential of remanufacturing processes, which reduce Nd losses and landfill contributions compared to other scenarios.

Key improvements include the remanufacture of traction motors by both OEMs and secondary channels (SCs), resulting in the recovery and reintegration of 110.65 tons of Nd by SCs and an additional 36.88 tons by OEMs embedded at component level. Even with effective integration of these processes, still 313.5 tons of Nd are lost to landfills although which is 55.32 tons marked reduction compared to the recycling scenario. This remanufacturing approach successfully diverts 184.41 tons of Nd from waste management streams, emphasizing the efficacy of circular strategies in minimizing waste and maximizing resource reuse.

The stock of Nd in EVs continues to grow, reaching 18,326.53 tons, with 1,849.16 tons entering through new EVs. This stock accumulation underscores the increasing importance of end-of-life recovery systems to sustain Nd availability. Furthermore, exports of Nd in traction motors and EVs total 3,619.74 tons, indicating strong participation in global supply chains.

This scenario demonstrates a plausible pathway toward achieving greater sustainability through integrated remanufacturing enhancing resource efficiency. However, the remaining landfill losses highlight the need for further investment in recovery technologies.

6. Remanufacturing Integration as Ecodesign in traction motors (Sub question- 3)

This section makes presents the results of the desk research. In addition, the section calls upon the synthesized insights derived from sub questions 1 and 2 to establish a matrix that aligns ecodesign principles with specific stages of the remanufacturing process and presented with integration strategies.

According to Nasr & Thurston (2006), design for remanufacturing can be considered at two levels: the product strategy level and the detailed product and engineering level. As already mentioned in section 2.6.2, the below ecodesign principles suggested will focus on the former which includes operations, reverse logistics concerns and recovery of traction motors which is largely overlooked in design considerations (Prendeville et al., 2016).

Remanufacturing has been a well-established practice across various industrial sectors, particularly those producing capital-intensive products with longer lifespans, this includes industries like aerospace, automotive, EEE, heavy duty and off-road equipment, marine equipment and many more (Parker et al., 2015). In Europe, remanufacturing activities in the automotive sector date back to 1955 (Bobba et al., 2021). Initially focused on mechanical and hydraulic components, these efforts have since expanded to encompass mechatronic and electronic systems. Although numerous automotive parts are currently viable for remanufacturing, traction motors remain largely overlooked, likely due to the relatively recent introduction of EVs and the limited number reaching EOL. However, this trend signals an impending surge in EOL EVs, presenting an opportunity to proactively develop remanufacturing strategies for the coming years.

Recognizing this potential, the European Remanufacturing Network (ERN) was established in 2015 to promote industrial adoption of remanufacturing practices and enhance the competitiveness of remanufactured products (Ismail, 2016). Recent studies have emphasized the market potential, benefits, and growth opportunities associated with remanufacturing, with the ERN projecting that the value of Europe's remanufacturing sector could reach €100 billion by 2030. However, beyond monetary feasibility, critical design considerations such as ease of disassembly, product traceability, and technological advancements significantly influence economic viability (ERN-market study). While research on Design for X approaches has gained traction, there remains a pressing need to integrate life-cycle perspectives, particularly at the end-of-life (EOL) stage, into the design process to fully realize the benefits of remanufacturing.

In the following paragraphs, we will go through what hinders in the recovery of these traction motors in a practical setting. A study by Sundin and Dunbäck (2013) identify key reverse logistics challenges, notably the lack of control over the quantity, quality, and timing of returned cores. These variables, shaped by product lifecycles, consumer disposal behaviours, and market dynamics, create stochastic patterns that complicate production planning and inventory management. Such unpredictability often leads to either surplus cores or shortages that fail to meet demand. Additionally, quality inconsistencies, caused by varied usage, disassembly, and transport conditions pose significant hurdles. For instance, some components may sustain damage that is not visible until the remanufacturing process, increasing scrap rates and costs. Furthermore, balancing supply with demand remains difficult due to fluctuating market requirements, technical advancements, and limited forecasting accuracy, leading to potential inventory buildup or service failures. The lack of standardized product acquisition processes and the reliance on diverse supplier types, such as end-users, OEMs, scrap yards, and brokers, further add complexity to reverse logistics. Waugh et al. (2021) underscore the importance of emergence of new stakeholders, such as Tier 1 suppliers and remanufacturers, to optimize the value chain. Early collaboration with OEMs can enhance access to EOL products and foster robust remanufacturing programs.

Design challenges in reverse logistics are further exemplified by van Dam and Bakker's (2024) study on surcharge (deposit) systems. These systems, designed to ensure consistent core supply, involve workshops or garages paying an additional fee when purchasing remanufactured parts, with the right to return used parts. However, this process spans multiple trade levels, creating financial risks and potential inter-stakeholder tensions. Cores are subject to both technical and surcharge-related evaluations, leading to potential rejections at various stages and financial losses for suppliers. Despite potential benefits of digital platforms for optimizing these systems, resistance to change highlights the importance of "soft factors" such as trust, transparency, and traceability alongside technological and legislative measures. The intricacy of these systems, deeply rooted in the automotive aftermarket, may also limit their adaptability to other industries.

After core acquisition, new challenges emerge in aligning remanufacturing strategies with long-term product use. Extending product life cycles may reduce revenue streams under linear business models, where frequent replacements drive profits. Product-service business models, such as leasing rather than selling materials, offer a solution by shifting revenue streams from ownership to usage (Ellen MacArthur Foundation, 2013). However, implementing such models requires companies to transform internal motives and operational processes which was also highlighted in the expert interviews.

In this context, European EV manufacturers (hereinafter referred to as OEMs) face systemic transitions, including redesigning business models and integrating remanufacturing strategies (Gunasekara et al., 2021; Kurilova-Palisaitiene et al., 2024). Insights from ecodesign principles reveal overlapping and contrasting impacts on traction motor value chains, emphasizing the interplay between circular design strategies and remanufacturing practices. These multifaceted challenges and opportunities, summarized in Table 6-1, highlight the importance of holistic approaches in overcoming barriers to sustainable remanufacturing.

Table 6-1: Complementary set of challenges for ecodesign and remanufacturing (Source: Author)

Challenges	Explanation	Source
Design for remanufacturing	– Traction motors typically lack design considerations for remanufacturing during the initial product development phase. – PM in traction motors consist of a heterogeneous mix of materials, posing challenges for recovery and reuse.	(Goodall et al., 2014), SLR Expert Interviews
Recovery of Used EV/ traction motor	– Absence of reverse logistics systems to facilitate the recovery and handling of EV components at end-of-life. – Unclear allocation of responsibility among stakeholders for managing EVs after reaching end-of-life. – Uncertainty about the quality of used traction motors.	(Jensen et al., 2019) (Bobba et al., 2021) (Sundin & Dunbäck, 2013) MFA
Lack of certification of remanufactured	– European policies predominantly emphasize recycling, with limited focus on promoting remanufacturing, repair, and reuse initiatives. – Lack of access to spare parts long after EV production has ceased.	(Bobba et al., 2021) (Arnold et al., 2021) (Waugh et al., 2021)
OEM's internal motives	– The success of remanufacturing integration is largely influenced by a company's internal motivations and strategic priorities. – Unrealised potential of remanufacturing.	Expert Interviews (IRP, 2018)
Access to information and tools	– Limited knowledge sharing among stakeholders hinders the development of a comprehensive information base.	Rematec, Expert Interviews (Parker et al., 2015)

	– Restricted access to critical data due to OEMs' reluctance to share product knowledge with potential competitors.	
Skill and technology development	– Remanufacturing demands the development of new skills, leading to a need for a specialized workforce. – The EV industry requires standardized remanufacturing processes and components to address variability and ensure consistency.	(IRP, 2018) Expert Interviews
Remanufacturing metrics	– Absence of CE metrics that effectively incorporate remanufacturing strategies.	Expert Interviews MFA

In addition to these challenges, numerous studies concur that remanufacturing offers mutual benefits for both manufacturers and consumers. Consumers benefit from lower costs, while remanufacturers, in this case the EV OEMs, gain advantages through reduced consumption of raw materials and energy (Sundin & Dunbäck, 2013; Arnold et al., 2021). Moreover, the viability of remanufacturing is closely tied to its economic benefits and potential for job creation (Arnold et al., 2021). Typically, the production cost of remanufactured products is estimated to be 40–60% lower than that of newly manufactured products. Implementing remanufacturing strategies also establishes a novel value chain for traction motors, fostering employment opportunities. The compiled set of opportunities is shown in Table 6-2.

Table 6-2: Complementary set of opportunities for ecodesign and remanufacturing (Source: Author)

Opportunities	Explanation	Sources
Economic Incentives	– Companies need to shift focus from short-term profitability to prioritizing long-term sustainability and resilience.	Expert Interviews
Import Dependency of Raw Materials	– The high import dependence on PM has emphasized the importance of retaining these components within the EU.	(Waugh et al., 2021) MFA
Supply chain Disruptions	– Supply chain disruptions present an opportunity to localize production,	(Jensen et al., 2019)

	diversify sourcing strategies, and enhance supply chain resilience	
New Business Models	– Updating existing business models to incorporate remanufacturing can create new revenue streams for companies.	(Jensen et al., 2019) Expert Interviews
New Directives and Regulations	– Policies such as the Ecodesign Directive, CRMA, and Ecodesign for Sustainable Products Regulation (ESPR) emphasize the development of more durable and sustainable products.	(Arnold et al., 2021)

6.1 Ecodesign Integration

Ecodesign strategies serve as practical guidelines for embedding sustainability principles into new product development (NPD) processes by addressing specific stages of the product life cycle (Prendeville et al., 2016). Unlike formal ecodesign tools, which many companies struggle to adopt and internalize, ecodesign strategies offer a more accessible approach to integrating sustainable design practices. Examples of such strategies include DfRem, function integration, light-weighting or right-weighting, and material substitution (Prendeville & Bocken, 2016). Several studies (Prendeville & Bocken, 2016; Yang et al., 2015; Charter & Gray, 2008; Sundin et al., 2008) emphasize the importance of operational strategies to support remanufacturing processes. Key approaches, such as Design for Reverse Logistics, Design for Disassembly and Reassembly, and Design for Technology Integration, have been widely acknowledged as enablers for remanufacturing.

However, this study builds upon existing research by refining and expanding strategies for integrating ecodesign principles into remanufacturing processes, with a specific focus on traction motors. Insights gathered from sub-questions 1 and 2, along with an in-depth analysis of relevant case studies acquired during desk research, have led to critical observations and improvements. An ecodesign principle – integration strategy matrix has been built which capture the challenges and opportunities presented above.

Currently, the EU lacks established remanufacturing processes specifically tailored for traction motors. As a result, there is no dedicated take-back or reverse logistics system in place to support the recovery and remanufacturing of these components. Instead, traction motors predominantly end up in steel recycling waste streams, leading to the loss of valuable materials, such as CRMs, and limiting opportunities for resource circularity.

To address this gap, the development of a comprehensive remanufacturing framework is essential, necessitating systemic transformations across multiple levels of the value chain. One critical challenge is the high proportion of imported EVs, whose EOL management does not currently fall under the responsibility of EU-based OEMs. Ensuring proper EOL management for these vehicles would require extended producer responsibility (EPR), compelling OEMs to take accountability for imported EVs once they reach the end of their operational life. In addition to regulatory adjustments, there is a pressing need to establish third-party organizations that can facilitate the recovery, and remanufacturing of traction motors. Currently, the absence of such infrastructure severely restricts the feasibility of transitioning to a CE for traction motors. Establishing remanufacturing hubs and collaborative networks between OEMs and independent remanufacturers could significantly enhance recovery efforts.

Furthermore, insights from expert interviews highlight that locating and retrieving high-value components like traction motors at the EOL stage can often be challenging. These components may have lifespans that differ from the products they are embedded in, resulting in either underutilization or premature disposal. For instance, a traction motor may outlast the vehicle it is installed in, making it crucial to track and isolate reusable parts before they are scrapped.

In summary, transitioning to an integrated remanufacturing system for traction motors in the EU requires:

- Policy reforms to enforce EPR obligations for imported EVs.
- Infrastructure development to support reverse logistics and remanufacturing hubs.
- Advanced tracking technologies to monitor component lifecycles and optimize recovery efforts.
- Collaboration with third-party organizations to expand recovery capacity.

Building upon these insights, this study proposes a matrix of ecodesign principles designed to overcome the identified barriers and enhance remanufacturing capabilities. While many of these strategies align with existing literature, this research expands upon them by incorporating observations from expert interviews and real-world challenges specific to traction motors.

Table 6--3: Matrix of Ecodesign Principles and Their Application in Remanufacturing Process to Enhance Circularity in Traction Motors. Source: (The author).

Ecodesign Principle	Application in Remanufacturing Process	Integration Strategy
Design for Multi-Tier Recovery	Recovery and EoL Management	• Recognizes that not all traction motor components are suitable for remanufacturing and integrates reuse, remanufacturing, and recycling into a hierarchical recovery system.
Design for Inventory and Resource Mapping	Supply-Chain Management	• Maintain digital logs of material usage, product composition, and recovery status to optimize resource allocation. • Develop regional resource databases to match recovered materials with remanufacturing facilities. • Use material passports to track material usage and forecast recovery potential.
Design for Fault Recognition	Inspection and Diagnostics	• Integrate diagnostic sensors; develop standardized testing protocols. • Create a fault database to optimise product efficiency.
Design for Remanufacturing Loops	Product-Life Extension	• Design replaceable wear-and-tear components, such as bearings and seals, to preserve structural integrity during remanufacturing. • Incorporate markings or tags to track remanufacturing history and usage cycles, facilitating effective lifecycle management.
Design for Compliance with Regulations	Quality Assurance and Testing	• Incorporate regulations into design specs; develop compliance testing procedures; implement compliance tracking systems

In summary,

- **Design for Multi-Tier Recovery** acknowledges that not all components of traction motors are equally suited for remanufacturing and establishes a hierarchical recovery system. It prioritizes reuse for components that retain their functionality, remanufacturing for those that can be restored to a near-new state, and recycling for materials that can no longer serve their original purpose. This ensures a streamlined approach to EoL management.
- **Design for Inventory and Resource Mapping** to improve supply-chain transparency and efficiency, this principle promotes the use of digital logs that document material usage, product composition, and the

recovery status of traction motors and their components. It encourages the development of regional resource databases that facilitate the matching of recovered materials with nearby remanufacturing facilities, reducing transportation costs and delays. Additionally, material passports are recommended to provide detailed information on material specifications, recovery potential, and traceability throughout the product lifecycle.

- **Design for Fault Recognition** involves designing products with features that allow easy detection, diagnosis, and isolation of faults or failures. For traction motors, integrating fault recognition systems, such as sensors and diagnostic software, can streamline the remanufacturing process by identifying defective components without the need for extensive disassembly. This reduces inspection time, facilitates targeted repairs, and improves overall efficiency. Fault recognition also supports predictive maintenance, enabling early interventions that extend the product's life span and enhance its remanufacturability.
- **Design for Remanufacturing Loops** focuses on extending the functional lifespan of traction motors by making them easier to remanufacture. It advocates designing components such as bearings, seals, and connectors to be easily replaceable, which helps preserve the motor's structural integrity. It also includes markings, tags, or embedded digital IDs to track the remanufacturing history and usage cycles of each motor, enabling better lifecycle management. These features ensure motors can undergo multiple remanufacturing cycles efficiently.
- **Design for Compliance with Regulations** emphasises compliance with environmental and safety regulations is a fundamental aspect of sustainable product design. For traction motors, this involves adhering to EU directives on waste management, hazardous substances, and end-of-life vehicle (ELV) handling. Incorporating compliance measures during the design phase ensures that remanufactured products meet regulatory standards, avoiding legal and environmental liabilities. It also facilitates smooth certification processes and market acceptance of remanufactured traction motors.

This section has synthesized insights from the literature review and case studies to construct a matrix that aligns ecodesign principles with the stages of the remanufacturing process. It highlights key observations derived from sub-questions 1 and 2 and tailors the approach specific to traction motors. The section outlines critical gaps, including the absence of existing remanufacturing systems for traction motors in the EU, the lack of take-back systems, and the necessity for systemic changes to support remanufacturing practices. Additionally, it stresses the importance of establishing third-party recovery networks and OEM accountability for imported EVs reaching EOL.

While this analysis does not aim to be exhaustive, it provides a foundational framework for integrating ecodesign strategies into remanufacturing processes. Key strategies such as Design for Reverse Logistics, Design for Disassembly and Reassembly, and Design for Technology Integration are revisited, with new observations added to enhance existing guidelines. This framework underscores the need for systems thinking and holistic product life cycle management approaches to enable effective remanufacturing. Moreover, it highlights the potential for leveraging creative and strategic design methods to unlock broader business opportunities within the emerging remanufacturing landscape for traction motors.

7. Discussion

The findings presented in this study highlights the benefits of integrating ecodesign principles into the lifecycle of traction motors to enhance circularity and product recovery. By extending the focus beyond recycling, this study explored remanufacturing strategy as a complementary approach, recognizing its unique advantages in retaining product value and reducing environmental impacts. By addressing key gaps in the existing literature, including the absence of remanufacturing infrastructure and systemic reverse logistics frameworks, this study emphasizes the opportunities for building circular supply chains for critical materials like Nd.

The research through its research design revealed several critical factors influencing the integration of ecodesign principles in high-impact industries. In addition, traction motor recovery is influenced by several interconnected factors, including technical, economic, and systemic challenges. Furthermore, one of the main barriers identified is the organizational inertia within the companies which might be true for automotive industry included, has traditionally focused on performance and cost optimization rather than end-of-life consideration. The absence of immediate financial incentives further complicates adoption, as the benefits of ecodesign strategies tend to accumulate over the long term rather than directly impacting short-term profitability. Despite these challenges, the increasing regulatory pressure on resource efficiency and the supply–chain management create a favourable environment for the adoption of ecodesign principles within industries.

Keeping the theoretical and practical challenges in mind, this research advances the practical application of ecodesign by emphasizing principles such as Design for Multi-tier Recovery, Inventory and Resource Mapping, Fault Recognition, Remanufacturing Loops, and Compliance with Regulations. Each principle has been adapted to meet the unique challenges and opportunities for traction motor recovery. For instance, to address the heterogeneous composition of NdFeB magnets and their limitations for remanufacturing, the study proposes a hierarchical approach to optimize higher "R" order strategies through Multi-tier Recovery. Unlike previous studies, which often lack specificity for high-value and complex products like traction motors, these principles aim to enhance broader design concepts like DfRem and modularity.

Despite several studies suggesting solutions for improving reverse logistics, such as deposit systems as previously mentioned in Chapter 6, little progress has been achieved. Hence this study tries to point out the potential and the role of digital tools in facilitating resource/ product recovery. This would in-turn enhance supply- chain transparency, providing insights for possible future optimization. Additionally, while existing studies (e.g., Sundin et al., 2008) advocate for modularity, this study expands on the concept through the Design for Remanufacturing Loops principle. By incorporating mechanisms like digital tags and usage-cycle tracking, it enables scalable remanufacturing processes for industries reliant on high-value components. This innovation aligns with the need for scalability in remanufacturing processes, particularly in industries with high-value components. The research also challenges the prevailing emphasis on recycling in existing studies and policies, promoting remanufacturing as a superior recovery strategy for traction motors and aligning with the CE's "R" hierarchy.

The analysis highlights that current recycling rates for traction motors are relatively low, exposing critical gaps in recovery systems that must be addressed to reduce material and product losses. Moreover, the export of a substantial portion of EVs complicates closed-loop recovery strategies, emphasizing the need for coordinated international efforts to improve circularity- an area requiring further exploring in future studies. Although remanufacturing emerges as a promising approach, particularly for preserving product value, its application to traction motors is still nascent and lacks supporting infrastructure within the EU. This absence highlights the importance of targeted investments in facilities, technologies, and reverse logistics to establish effective remanufacturing systems. Additionally, the adoption of circular strategies, including remanufacturing, may require adjustments to existing business models, promoting service-based approaches or leasing systems to enhance product traceability and recovery. The successful implementation of these strategies also depends on fostering collaboration among diverse stakeholders, including OEMs, recycling industries, policymakers, and third-party recovery systems, to ensure seamless integration along the value chain.

7.1 Implications for Ecodesign from MFA

The MFA results reveal critical insights into the flow of Nd in traction motors and highlight significant opportunities and challenges for integrating ecodesign principles into the EV sector.

Firstly, the comparison across scenarios highlights the pivotal role of remanufacturing and recycling in creating a circular lifecycle for CRM Nd. The 2021 baseline scenario highlights the absence of EoL resource and product recovery strategies, with all Nd from decommissioned traction motors being sent to landfills. In contrast, the 2030 scenarios demonstrate that adopting either recycling or remanufacturing can mitigate landfill losses. Notably, the integration of remanufacturing strategies results in a slight better reduction of Nd losses compared to recycling-only approaches. The recovery of 147.53 tons of Nd via remanufacturing indicates moving beyond recycling to prioritize remanufacturing and aligning with the "R" hierarchy, offers a pathway to extend the lifespan of materials and components while retaining their embedded value. This could also mean that combined R strategies could offer higher efficiency in resource recovery as well.

However, implementing these strategies within the dominant industrial regime presents significant challenges. For instance, reverse logistics for the recovery of traction motors remains underdeveloped. In the model, the recollection rate of Nd in EOL EV is estimated at only 40%, underscoring the unrealized potential for recovering traction motors as EV stocks continue to rise. Addressing these inefficiencies requires a systemic approach to reverse logistics, requiring concerted efforts among manufacturers, policymakers, and recycling industries to establish robust recovery frameworks.

These insights bear important implications for ecodesign practices. While traditional ecodesign principles emphasize early-stage product design integration to maximize environmental benefits, the findings highlight that there are environmental benefits in integrating ecodesign principles at the EoL stage as well.

Additionally, the growing stock of Nd in EVs by 2030 presents a significant opportunity for material recovery, yet its realization hinges on overcoming institutional, logistical, and technological barriers. The adoption of ecodesign principles tailored for circularity at EoL stages can serve as a catalyst for addressing these barriers, ultimately enabling a more resilient and sustainable supply chain for CRMs like Nd.

7.2 Remanufacturing: Is just not enough

The study identifies remanufacturing as a largely untapped strategy within the EV automotive industry, particularly for traction motors. While remanufacturing has demonstrated substantial success for other products, its application to traction motors is limited due to several challenges and unrealised benefits. These include the absence of design features that enable easy disassembly, inspection, and reuse, as well as the lack of reverse logistics infrastructure to support recovery processes. Furthermore, the fragmented responsibility among OEMs, particularly for imported EVs, and the absence of dedicated third-party recovery systems exacerbate these barriers.

Despite these challenges, the findings highlight the significant economic and environmental advantages of remanufacturing. By retaining the embedded value of high-performance components and reducing reliance on primary resources, remanufacturing not only minimizes material extraction but also reduces energy consumption and associated emissions. Additionally, the process promotes job creation and stimulates the development of new value chains, reinforcing regional industrial resilience and competitiveness.

The findings suggest that remanufacturing holds promise in addressing various aspects of sustainability concurrently. It facilitates the economic recovery of essential materials such as Nd, which is projected to experience supply-demand challenges in the coming years. While not yet explicitly included in existing policy frameworks, remanufacturing has the potential to support future compliance initiatives focused on circularity and resource efficiency. Additionally, it resonates with growing consumer demand for sustainable products, enabling manufacturers to position environmental responsibility as a key factor in gaining a competitive edge.

However, realizing these benefits requires systemic transformations. Modular product designs must become standard to ensure ease of disassembly, while traceability systems need to be developed to track materials throughout their lifecycle. Investments in remanufacturing facilities and reverse logistics networks are also critical to operationalizing recovery processes at scale. Policymakers must complement these efforts by providing incentives, standardized guidelines, and financial support to drive adoption. In conclusion, remanufacturing represents a missing link in achieving circularity for traction motors. Its integration into the broader lifecycle management of EV automobile components requires a multi-stakeholder approach at various levels of the supply-chain, combining technological innovation and policy alignment, to enable a sustainable transition for the EV sector.

7.3 Limitations

7.3.1 Limitations of thesis process methodology

While this research adopted multiple methods, including systemic literature review, semi-structured interviews and desk research, several limitations were identified that could influence the findings. The thesis predominantly focused on the term "ecodesign," as framed by the available literature and policy frameworks, particularly the EU’s Ecodesign Directive. However, emerging terms such as "design for circularity" or "circular design" have gained traction in recent years, reflecting newer developments in the field. These terms often emphasize broader systemic approaches to achieving circular economy goals, including business model innovation and lifecycle thinking. Had these terms been included in the literature review, the analysis may have identified more recent advancements in design methodologies, such as the integration of digital tools for tracking lifecycle impacts or innovative strategies for avoiding CRMs altogether. For instance, "circular design" often aligns with strategies that go beyond traditional ecodesign principles, advocating for system-level redesigns and more collaborative approaches among stakeholders. Incorporating "design for circularity" into the literature review might also have highlighted more advanced case studies or pilot initiatives that address the limitations of older ecodesign strategies. For example, while modularity and remanufacturing have been discussed extensively, circular design could emphasize the use of predictive maintenance systems or business models that integrate leasing and product-as-a-service concepts to further enhance circularity. These omissions suggest that future research should expand its scope to include these emerging terms and frameworks to capture the full spectrum of strategies applicable to traction motor recovery. Additionally, out of the six experts initially contacted for interviews, only three responded, limiting the diversity of perspectives gathered. Furthermore, the insights provided by these experts varied significantly, despite addressing similar questions, which posed challenges in synthesizing a unified perspective on the implementation of ecodesign principles. Originally, the research plan aimed to include interviews with industry stakeholders, such as traction motor manufacturers, to enrich the analysis, particularly for sub-question 3 related to remanufacturing strategies. However, due to time constraints, this approach was replaced with desk research. While desk research provided valuable insights, it may lack the depth and practical nuances that could have been captured through industry-focused interviews. Consequently, the reliance on secondary data may have limited the ability to capture real-world challenges, particularly regarding the operational feasibility of remanufacturing processes within the industry. Additionally, the data used in the MFA was sourced primarily from secondary datasets, which may introduce uncertainties in projections, especially regarding future EV adoption rates and export of EVs. These limitations highlight the need for further studies that incorporate primary data collection and pilot projects to validate the proposed strategies under practical conditions.

Overall, these limitations underline the need for further research that combines primary data collection, stakeholder engagement, and updated conceptual frameworks to advance the integration of ecodesign principles within the context of circular economy strategies.

7.3.2 Limitations of the MFA Study

1. MFA heavily depends on detailed and accurate data, which is often incomplete or outdated. For instance, in assessing historical Nd flows in passenger cars, discrepancies between datasets and variations in data aggregation can introduce significant uncertainties.

2. To address the complexity of material flow systems, this MFA study incorporates assumptions such as steady REE import levels. While this assumption make modelling feasible, they may not accurately capture real-world dynamics or account for variability.

3. The methodology does not fully incorporate potential future technological innovations, such as the emergence of alternative magnet technologies, improved motor designs with reduced Nd content, or advancements in recovery techniques that could significantly impact material flows.

4. Scenario analyses, particularly those for 2030, rely on forecasts for EV sales, recycling rates, and remanufacturing adoption. These projections are inherently uncertain and could be disrupted by market shifts, policy changes, or unexpected technological developments.

5. While MFA quantifies material flows, it does not directly evaluate environmental or economic impacts. For example, the model tracks Nd losses to landfills but does not assess the associated ecological consequences or the economic feasibility of recovery strategies.

6. The MFA methodology does not explicitly account for the perspectives of key stakeholders such as policymakers, manufacturers, or consumers. This omission poses a challenge, especially in the case of Scenario 2030: Integrated Remanufacturing. The lack of established take-back policies for traction motors necessitates assumptions about the establishment of a sub-contractor (third-party) system for motor recovery. Consequently, the exclusion of stakeholder input may undermine the practical applicability and real-world relevance of the model's results.

7. Over-reliance on specific reports or datasets can introduce biases into the analysis. For example, applying uniform recycling rates across scenarios might ignore regional differences in recycling infrastructure and policy effectiveness, reducing the reliability of results.

7.3.2 Limitations of the proposed ecodesign principles

The proposed ecodesign strategies present although might seem promising for improving circularity in traction motors, several limitations need to be acknowledged. One key limitation is that these design principles are largely conceptual, and a several practical challenges remain. For example, redesigning traction motors to align with the proposed ecodesign principles presents significant hurdles. These strategies primarily focus on integrating ecodesign into operational strategies but often overlook the technical modifications required, which could introduce limitations in performance and complicate compliance with standards for remanufactured traction motors. Given its highly integrated and compact structure incorporating such changes would mean substantial adjustments to traditional design and production processes. These changes could impact manufacturing costs and scalability, especially for systems that were not originally designed with circularity in mind.

Another limitation is the dependency on external factors, such as the development of reverse logistics infrastructure and advancements in recycling and remanufacturing technologies. The lack of well-established collection and sorting systems can impede the efficient implementation of reverse logistics, leading to inconsistencies in material recovery rates.

Economic feasibility also poses a constraint, as the cost-effectiveness of remanufacturing strategies depends on achieving economies of scale, which may be difficult in the initial stages of implementation. The fragmented nature of the EV supply chain, combined with variations in regional recycling capacities, further complicates efforts to establish harmonized processes for recovering traction motors across borders.

8. Conclusions and Recommendations

The accelerating transition to EVs has amplified the demand for CRMs such as Nd, a key component of NdFeB magnets in EV traction motors. With this rising demand, the supply cannot keep up. Hence new strategies are required to address the sustainability issues that come up with this rising demand. This thesis sought to address these challenges by exploring how ecodesign can be integrated into the life-cycle management of traction motors. The overarching research objective was to investigate actionable strategies to enhance circularity and resource efficiency in traction motors while navigating technical economic and systemic barriers. This chapter consolidates the key findings of the study, presenting conclusions drawn from the research objectives and sub-questions.

The chapter also explores future research directions, emphasizing areas where further investigation can contribute to bridging existing gaps. These recommendations aim to advance the practical application of ecodesign principles.

The study has address three key sub-questions, each contributing to a comprehensive understanding of the issues at hand and potential solutions.

> ***Sub-question 1: 'What are the key challenges and opportunities in implementing ecodesign principles for the recovery of traction motors?'***

The first sub question aimed to identify the key challenges associated with integrating ecodesign principles in high-impact industries particularly for traction motors. The findings revealed that while the potential of ecodesign for advancing circularity is well-documented, its practical implementation faces significant barriers. These includes complex and compact design of traction motors, which hinders disassembly and remanufacturing efforts, and the lack of alignment between existing ecodesign tools and industry needs. Moreover, organizational inertia, coupled with a focus on cost and performance optimization without EoL considerations poses significant barriers to adopting sustainable design practices. These challenges reflect broader systemic issues within the automotive industry, where short-term financial imperatives often overshadow long-term sustainability goals. However, opportunities and enablers exist for ecodesign implementation. Regulatory pressures such as CRMA and upcoming frameworks like ESPR are creating favourable policy environment for circular strategies. Additionally, the potential of cost saving through material/ product recovery offer strong incentives for industries to adopt ecodesign principles. A phased approach and cross-functional collaboration can enhance adoption rates, aligning industrial practices with CE goals.

> ***Sub-question 2: 'What implications for ecodesign can be acquired from implementing MFA to neodymium in traction motors?'***

Material Flow Analysis reveals that current EoL practices for NdFeB magnets in traction motors result in substantial material losses, with limited recovery efforts. Enhanced recovery strategies, in this case remanufacturing, could offer a promising alternative to traditional recycling but is still not enough to establish a robust secondary value chain. Insights from MFA also highlight the growing stockpile of Nd in EVs, presenting a critical opportunity for secondary material sourcing.

> ***Sub-question 3: 'How can remanufacturing strategies be employed to integrate ecodesign principles and insights from MFA into enhance the circularity for traction motors?'***

Remanufacturing emerges as a pivotal strategy to integrate ecodesign principles into traction motor recovery. By focusing on the reuse of high-value components like magnets, remanufacturing minimizes the need for virgin material extraction and reduces waste. However, the lack of established reverse logistics systems and supporting infrastructure remains a barrier. Collaborative approaches, including partnerships between OEMs and third-party remanufacturers, can address these gaps, enabling a viable remanufacturing ecosystem.

Main Research Question: "How can ecodesign principles be integrated to enhance the circularity of traction motors in EV at their end-of-life phase?

The findings highlight that integrating ecodesign principles into traction motor recovery is a complex challenge requiring systemic changes across technical, organizational, and policy levels. These systemic changes encompass both upstream and downstream processes throughout the lifecycle of traction motors. On the upstream side, this involves embedding ecodesign principles at the initial stages of product development, where maximum benefits can be achieved. Key strategies include designing for disassembly, modularity, and remanufacturing, all of which ensure effective EoL recovery. However, this study emphasizes that achieving true environmental benefits requires prioritizing strategies higher up the R hierarchy, taking remanufacturing as an example while advocating for an even broader scope.

Implementing these systemic changes requires a robust supporting ecosystem comprising efficient reverse logistics, appropriate policy incentives, and stakeholder collaboration. Downstream processes, such as the collection, sorting, and tracking of EoL traction motors, are essential for optimizing recovery efforts. Currently, gaps in reverse logistics infrastructure hinder the recovery of high-value components like NdFeB magnets, which limits the circularity of these systems.

While remanufacturing offers an effective mid-term solution for retaining the material and functional value embedded in NdFeB magnets, the findings underscore the importance of pursuing long-term strategies to reduce or eliminate reliance on CRMs entirely. This could involve substituting NdFeB magnets with alternative materials or innovating motor designs that eliminate the need for CRMs altogether, aligning with the "Refuse" principle (R1). Such shifts would significantly mitigate supply chain vulnerabilities and environmental impacts.

However, moving toward higher-order strategies on the R hierarchy presents its own set of challenges. Addressing the CRM challenge requires a multi-faceted approach that extends beyond recycling. While remanufacturing is a crucial strategy for value retention, it must be incorporated into a broader framework that includes reducing CRM dependence, innovating motor designs, and fostering systemic collaboration among OEMs, policymakers, recycling industries, and researchers. A lifecycle perspective is essential, focusing not only on optimizing recovery but also on rethinking the necessity of CRM-intensive designs.

Through an integration of insights from both interviews and the literature, this study underscores the potential for circularity in traction motors by driving systemic innovation, policy reform, and interdisciplinary collaboration. The findings emphasize the importance of reducing CRM reliance while advancing sustainable recovery strategies such as remanufacturing as a transitional solution. This approach is closely aligned with the broader objectives of the CE and sets a framework for redefining resource use in CRM-dependent industries.

8.1 Recommendations for future research

Future research should prioritize advancing diagnostic systems tailored specifically for traction motors, focusing on technologies like embedded sensors and AI-driven predictive maintenance tools. These tools can significantly enhance fault detection, streamline remanufacturing processes, and facilitate the identification of reusable components, ultimately extending the lifecycles of traction motors. Stakeholders such as OEMs and technology providers are key players in this area. OEMs can integrate these systems into product designs, while technology providers can collaborate on developing innovative solutions that address the unique challenges of traction motor recovery. Exploration of hybrid recovery models that combine recycling, remanufacturing, and direct reuse is critical to optimizing resource recovery and addressing the varying lifespans of traction motor components. These models should be developed in partnership with policymakers, recycling industries, and OEMs to align with sustainability goals and regulatory frameworks. Policymakers, in particular, can play a pivotal role by setting clear guidelines that encourage the adoption of such models, while recycling industries can focus on implementing these strategies at scale. Collaboration between these stakeholders will ensure resource recovery efforts are both efficient and environmentally sound. Targeted policy-driven incentives also require further investigation, particularly regarding the role of EPR and harmonized regulatory frameworks in accelerating the adoption of ecodesign principles. Policymakers and regulatory bodies should engage with industry stakeholders to design incentives that balance economic viability with sustainability goals. These could include subsidies for implementing remanufacturing technologies, tax breaks for circular practices, or penalties for failing to meet EoL management standards. Additionally, international collaboration may be necessary to create harmonized policies that address cross-border trade of EoL products and recovered materials.

Another key area of focus is integrating ecodesign principles across the entire lifecycle of traction motors, from raw material sourcing to EoL recovery. This includes designing for modularity and adaptability to accommodate evolving recovery technologies and reduce dependency on CRMs. Stakeholders such as material scientists, design engineers, and sustainability consultants have crucial roles to play in this integration. Collaboration between research institutions and OEMs can lead to innovative design solutions that are practical, scalable, and environmentally beneficial. Moreover, industry associations can act as facilitators by disseminating best practices and promoting knowledge sharing across sectors.

Finally, the scalability and operational feasibility of regional remanufacturing hubs tailored to traction motors must be examined to address infrastructure gaps. This includes identifying optimal locations based on proximity to EoL collection points, analysing technical specifications required for handling high-value components like NdFeB magnets, and establishing collaborative frameworks that involve OEMs, recycling industries, and local governments. Local governments can provide logistical and financial support, while OEMs and remanufacturers can share technical expertise and infrastructure investments. Researchers can contribute by developing models to assess economic and environmental impacts, ensuring these hubs align with CE principles.

These research directions not only address the technical and systemic challenges of traction motor recovery but also align with the interests and capacities of relevant stakeholder groups. By fostering collaboration among policymakers, OEMs, technology providers, and recycling industries, these recommendations aim to create a robust ecosystem that advances CE goals, promotes innovation, and ensures the sustainable management of CRMs in the EV sector.

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10. Appendices

Appendix A: Summary of Systemic Literature Review (Sub question – 1)

Citation	Objective	Methodology	Key Findings		Revelance
			Challenges	Oppurtunities	
(Bovea & Pérez-Belis, 2011)	Review and classify tools that have been developed to evaluate the environmental requirements of products and to facilitate their integration into the product design process	1. Comprehensive literature review of existing ecodesign tools. 2. Classification of tools into 6 criteria 3. Categorized the tools based on their aim and level of difficulty. 4. Created a taxonomy of ecodesign tools to help designers select the most suitable tool for their specific needs.	1. Integrating environmental requirements with other traditional product requirements (cost, safety, functionality, etc.) remains complex. 2. Different tools are suitable for different stages of the design process, making tool selection crucial. 3. The level of difficulty and resources required vary significantly among tools.	1. Tools that combine environmental assessment with multi-criteria approaches can help balance environmental requirements against other traditional requirements.	This paper provides a valuable framework for selecting ecodesign tools, which could guide the development of a systematic approach to integrating environmental requirements into traction motor manufacturing. Its taxonomy of tools can aid in choosing the best tools for balancing environmental and traditional requirements in circular business models.

	(Handfield et al., 2001)	Explore the gap between ecodesign theory and practice.	Literature Review, Case study, Interviews	1. **Lack of integration:** Environmental considerations are often treated as separate from core design processes, leading to a disconnect between environmental goals and product development. **2. Limited knowledge:** Many designers lack sufficient understanding of environmental impacts and how to address them effectively in their work. **3. Conflicting priorities:** Environmental goals often compete with other design objectives such as cost, performance, and time-to-market. **4. Organizational barriers:** Lack of clear responsibility for environmental issues and poor communication between departments hinder integration efforts. **5. Insufficient tools:** Existing ecodesign tools are often too complex or not well-suited to the practical needs of designers.	**1. Early integration:** Incorporating environmental concerns at the earliest stages of design can lead to more effective and innovative solutions. **2. Cross-functional teams:** Bringing together experts from different departments can foster better integration of environmental considerations. **3. Simplified tools:** Developing more user-friendly and practical ecodesign tools tailored to specific industries or product types. **4. Training and education:** Improving designers' knowledge of environmental issues and ecodesign principles can enhance integration efforts. **5. Leadership support:** Strong commitment from top management can drive the integration of environmental concerns throughout the organization.	Highlights key barriers in applying ecodesign principles in manufacturing, like lack of integration and conflicting priorities, which are directly relevant to the challenges in traction motor production. The findings support a strategic approach to closing the theory-practice gap in ecodesign implementation.	

(Prendeville et al., 2011)	Assess ecodesign tool usage in an SME.	Case Study with a single SME manufacturing company, Interviews	**1.Limited resources:** The SME faced constraints in terms of time, personnel, and financial resources to dedicate to ecodesign initiatives. **2. Lack of expertise:** There was a general lack of in-house environmental expertise, making it difficult to interpret and apply ecodesign principles effectively. **3. Tool complexity:** Many existing ecodesign tools were found to be too complex or time-consuming for practical use in an SME setting. **4. Integration with existing processes:** Incorporating ecodesign tools into established design processes proved challenging without disrupting workflow. **5. Market pressures:** The company struggled to balance environmental considerations with market demands for low-cost products.	**1. Cost savings:** Ecodesign practices revealed potential for material and energy efficiency improvements, leading to cost reductions. **2. Innovation potential:** The ecodesign process stimulated creative thinking, potentially leading to product innovations. **3. Market differentiation:** Implementing ecodesign practices offered opportunities for product differentiation in a competitive market. **4. Employee engagement:** Involving employees in ecodesign initiatives increased overall environmental awareness and motivation within the company. **5. Supply chain collaboration:** Ecodesign efforts prompted improved communication and collaboration with suppliers on environmental issues.	Highlights key barriers in applying ecodesign principles in manufacturing, like lack of integration and conflicting priorities, which are directly relevant to the challenges in traction motor production. The findings support a strategic approach to closing the theory-practice gap in ecodesign implementation.

(Dekoninck et al., 2016)	1. To identify and categorize the implementation challenges faced by practitioners in manufacturing companies when implementing ecodesign. 2. To develop and consolidate a comprehensive framework that defines these challenges for ecodesign implementation in companies	Extensive literature review, Development of an initial framework based on the literature review findings, Case studies with nine manufacturing companies, Refinement and consolidation of the final framework based on the case study findings	The study identified challenges in **five main** categories: 1.Strategy 2.Tools 3.Collaboration 4.Management 5.Knowledge • Management challenges were the most frequently mentioned by the companies sampled. • Tools-related challenges were not as prominent as might have been expected given the ongoing focus on tool development in the field.	While the paper focuses primarily on challenges, some opportunities for ecodesign integration can be inferred: 1. Improving management practices and support for ecodesign initiatives. 2. Developing more practical and user-friendly ecodesign tools. 3. Enhancing collaboration within companies and across supply chains. 4. Increasing knowledge and expertise in ecodesign principles and practices.	Identifies practical challenges, such as resource constraints and tool complexity, which could also impact traction motor manufacturing. The insights on cost savings and innovation potential from ecodesign align with the goals of building a sustainable and circular business model.
(Rossi et al., 2016)	1. To perform a new literature review of the principal ecodesign methods and tools published over the last 20 years 2. To understand the main obstacles that limit the actual and effective implementation of ecodesign methods and tools in industrial companies 3. To explore possible	Comprehension Literature Study	1. Lack of resources (time, budget, personnel) for ecodesign implementation 2. Limited environmental knowledge and expertise among design teams 3. Difficulty integrating ecodesign tools into existing product development processes 4. Complexity of many ecodesign tools, making them impractical for industrial use 5. Organizational resistance to change and lack of management support 6. Market uncertainties regarding eco-friendly products	1. Development of simplified, user-friendly ecodesign tools tailored to specific industries 2. Integration of ecodesign principles into existing CAD and product development software 3. Improved training and education on ecodesign for design teams 4. Creation of structured frameworks to support ecodesign implementation in companies 5. Promotion of life cycle thinking and user-centered design for sustainability 6. Collaboration across supply chains to address environmental impacts holistically	Offers an overview of ecodesign obstacles and strategies over the years, which can inform best practices and barriers for incorporating these principles into motor manufacturing. The focus on user-friendly tools and cross-departmental collaboration is particularly applicable to the complexities of traction motor production.

	strategies to overcome these barriers				
(Van Hemel & Cramer, 2002)	1. To learn which factors stimulate SMEs towards greening their products through ecodesign 2. To identify which factors hamper SMEs in implementing ecodesign 3. To analyze which ecodesign solutions proved most successful for SMEs	Empirical study of 77 Dutch SMEs that participated in the Ecodesign Project of the Dutch Innovation Centre Network	1. Lack of clear environmental benefit for some options 2. Options not perceived as company's responsibility 3. Lack of alternative solutions for some improvements 4. Technical, financial and organizational barriers	1. Internal stimuli like innovation opportunities, increased product quality, and market potential were stronger drivers than external stimuli 2. Customer demands, government legislation, and industry initiatives were the most influential external stimuli 3. The most successful ecodesign solutions were those supported by multiple strong internal and external stimuli	Though focused on SMEs, this study's insights on internal and external drivers for ecodesign adoption can be extrapolated to encourage traction motor manufacturers to embrace sustainable practices. Emphasizing both regulatory and market pressures aligns with motivating ecodesign for circularity.

(Paulson & Sundin, 2015)	1.To identify current challenges and trends within eco-design 2. To disclose important eco-design related research gaps	Literature Review, Categorization of challenges and trends into four levels: system and success, strategy, action, and tools	1. Lack of tools built for achieving goals on a system and success level 2. Difficulty in understanding and influencing end-user behaviors 3. Integrating social and economic issues with eco-design 4. Confusion about the scope of eco-design compared to similar approaches 5. Creating effective legislation for system-level improvements 6. Overcoming barriers when implementing eco-design 7. Lack of expert knowledge and resources for implementation 8. Limited eco-design practice in companies 9. Insufficient environmental requirements in product specifications 10. Tools not fitting the purpose well enough	1. Developing tools that address system and success level goals 2. Improving understanding of end-user behavior in eco-design 3. Integrating all three dimensions of sustainability in product development 4. Clarifying the scope and goals of eco-design 5. Creating policies that affect the entire value chain 6. Developing implementation strategies to overcome barriers 7. Increasing expert knowledge and resource allocation for eco-design 8. Expanding eco-design practice across more companies 9. Incorporating environmental requirements into product specifications 10. Improving ecodesign tools to better fit industry needs	Highlights critical gaps and areas for growth in ecodesign tools and practices, relevant to advancing ecodesign in traction motor manufacturing. This paper's findings on integrating sustainability dimensions and legislative support align with the thesis' circular business model objectives.
(Boks, 2005)	To identify and analyze non-technical, organizational, and human factors that influence the success of ecodesign integration	Literature Review, Interviews, Case study	1. Organizational culture and resistance to change 2. Lack of cooperation between departments 3. Insufficient management commitment and support 4. Communication issues between different stakeholders 5. Limited environmental knowledge and expertise among employees 6. Difficulty in aligning ecodesign with existing business processes	1. Developing tailored change management strategies for ecodesign implementation 2. Improving internal communication and collaboration mechanisms 3. Enhancing environmental education and training programs for employees 4. Creating incentives and rewards for successful ecodesign initiatives 5. Integrating ecodesign considerations into existing decision-making processes 6. Leveraging champions and early	Identifies organizational and human factors that could influence the success of ecodesign in traction motor production. It emphasizes the need for internal alignment, effective communication, and leadership support—all crucial for implementing a circular model in this industry.

					adopters to promote ecodesign within the organization	

Table A.1: Summary of selected journal papers, where key findings are categorised into challenges and opportunities (by the author).

Appendix B: Consent Letter Form

You are being invited to participate in a research study titled 'Driving Circularity: Integrating Ecodesign in Recovery of Traction Motor in Electric Vehicles'. This study is being done by Aditi Urs from the TU under the supervision of Dr.David Peck

The purpose of this research study is exploring the integration of ecodesign principles into enhancing circularity in traction motors life-cycle and will take you approximately 35-40 minutes to complete. The data will be used for completion of master thesis. We will be asking you to discuss challenges in ecodesign or sharing insights on recovery strategies

As with any online activity the risk of a breach is always possible. To the best of our ability your answers in this study will remain confidential. We will minimize any risks anonymizing responses, securely storing data in password protected cloud services, and not collecting IP addresses or personally identifiable information (PII).

Your participation in this study is entirely voluntary and you can withdraw at any time. You are free to omit any questions.

By proceeding with this study, you agree to participate under the outlined conditions.

PLEASE TICK THE APPROPRIATE BOXES	Yes	No
A: GENERAL AGREEMENT – RESEARCH GOALS, PARTICPANT TASKS AND VOLUNTARY PARTICIPATION		

PLEASE TICK THE APPROPRIATE BOXES	Yes	No
1. I consent voluntarily to be a participant in this study and understand that I can refuse to answer questions, and I can withdraw from the study at any time, without having to give a reason.	☐	☐
2. I understand that taking part in the study involves: • *Recording Method: Information will be captured via video recording, which will later be transcribed into text.* • *Transcription and Data Storage: Video recordings will be transcribed, and once transcriptions are complete, the recordings will be securely deleted to maintain data minimization and privacy standards.* • *Data Minimization: Only essential personal identifiers will be collected, and any identifying information will be anonymized during transcription.*	☐	☐
B: POTENTIAL RISKS OF PARTICIPATING (INCLUDING DATA PROTECTION)		
3. I understand that taking part in the study involves the following risk, • *The possibility of unintentional disclosure of personal or professional information.* • *As the study may involve online data collection, there is a risk of data breaches or unauthorized access to the information shared by participants.* I understand that these will be mitigated by, • *Personal identifiable information (PII) will be removed or anonymized to ensure that individual responses cannot be traced back to specific participants.* • *Data access will be restricted to the research team involved in this study, and any open data sharing will only involve de-identified datasets.*	☐	☐

PLEASE TICK THE APPROPRIATE BOXES	Yes	No
4. I understand that taking part in the study also involves collecting specific personally identifiable information (PII) such as names, job titles, and company affiliations as well as associated personally identifiable research data (PIRD) including direct quotes and insights shared during the interviews, with the potential risk of my identity being revealed.	☐	☐
5. I understand that the following steps will be taken to minimise the threat of a data breach, and protect my identity in the event of such a breach, • *All PII will be anonymized in any published results, with only generalized or aggregated data being presented to protect participant confidentiality.* • *Access to raw data (such as audio recordings and interview transcripts) will be strictly restricted to authorized research personnel only, ensuring that sensitive information remains confidential throughout the study.*	☐	☐
C: RESEARCH PUBLICATION, DISSEMINATION AND APPLICATION		
6. I understand that after the research study the de-identified information I provide will be used for, • *The findings will be included in the researcher's master's thesis and may also be published in peer-reviewed journals and conference proceedings to contribute to the body of knowledge on circular business models and ecodesign principles in traction motor manufacturing.* • *Insights gained from the research may support the development of ecodesign guidelines for traction motor manufacturers and help refine existing policies, such as the Critical Raw Materials Act (CRMA), to better promote sustainable practices in the automotive industry.*	☐	☐

PLEASE TICK THE APPROPRIATE BOXES	Yes	No
• *The anonymized findings may be shared with academic and industry collaborators, and possibly featured on the TU Delft website, for educational purposes and to support ongoing research in sustainable manufacturing.*		
7. I agree that my responses, views or other input can be quoted anonymously in research outputs	☐	☐
D: (LONGTERM) DATA STORAGE, ACCESS AND REUSE		
8. I give permission for the de-identified interview transcripts and aggregated data that I provide to be archived in TU Delft repository so it can be used for future research and learning.	☐	☐
9. I understand that access to this repository is restricted to academic researchers and students in related fields, with no commercial use permitted.	☐	☐

Appendix C: Interview Questions

Expert 1: Nina Boorsma

Expert 2: Benjamin Sprecher

Expert 3: Tim Hoff

Objectives of the Interview:

The overall objective of this expert interview is to gather in-depth insights from professionals across various fields, specifically those with expertise in ecodesign, remanufacturing, CE strategies, and sustainable product design. The purpose is to explore and understand the challenges, barriers, and opportunities related to integrating ecodesign principles and CE practices across industries, with a focus on material recovery, remanufacturing, and regulatory influences.

Interview Protocol:

1. Introduction (5 mins)
    - Explain the interview's purpose, emphasizing that the focus will be on the integration of ecodesign principles, challenges in remanufacturing, and how current EU regulations affect these processes.
    - Reassure the expert that their responses will remain confidential and anonymized (if necessary).
    - Get verbal consent to record the interview if applicable.
2. Main Discussion (35-40 mins) The main body of the interview will focus on three key themes: ecodesign, circularity challenges, and policy influence.

Introduction:

- Could you briefly introduce yourself and describe your work related to ecodesign, CE, and sustainability?

Questions on Challenges:

Ecodesign:

1. How would you personally define Ecodesign?
2. Does the broad and generic nature of ecodesign principles create obstacles to their practical application, or could this flexibility be considered an advantage?

Current state

3. Have you identified specific bottlenecks or inefficiencies in supply chains for material recovery of CRMs?
4. How do these inefficiencies compare across different sectors?
5. Do designers face difficulties in balancing product performance and resource efficiency when applying ecodesign principles?

Remanufacturing barriers

6. What are the main technical barriers to successfully implementing remanufacturing processes in various industries?
7. How does the timing of remanufacturing impact the benefits of remanufactured products, particularly in terms of technology obsceneness?
8. What are the key trade-offs between end-of-life strategies like remanufacturing and recycling, and how do industries choose between them?

Economic barriers

9. What are the main economic barriers preventing manufacturers from fully adopting ecodesign principles?

Systemic barriers:

10. How can industries resistance to change, overcome to accelerate the adoption of ecodesign principles?

Questions on Opportunities:

Integrating Ecodesign

1. From your experience, at which stages of the product lifecycle—design, production, or end-of-life—do you think ecodesign can have the most significant impact on improving circularity?
2. Can products in general be designed to go through multiple remanufacturing cycles without compromising performance or quality?
3. What are the key synergies between the CE goals and ecodesign that manufacturers could leverage?
4. The concept of 'design for disassembly' has been increasingly discussed as a strategy for circularity. How well do you think this concept is being integrated into EU industries?

Regulatory and Policy Influence

5. How do you see EU regulations, like Ecodesign for Sustainable Product Regulation and Critical Raw Materials Act (CRMA), influencing the adoption of ecodesign principles and circularity principles?
6. Do you believe current EU policies place too much emphasis on recycling over other strategies like remanufacturing? If so, why?

Future for Remanufacturing

7. How do you see the concept of 'design for remanufacturing' evolving over the next decade, especially for high-performance products?
8. What strategies could be employed to make remanufacturing more attractive to manufacturers, particularly those who have not traditionally engaged with CE practices?

Closing

9. Is there anything else you would like to add that you consider relevant to this discussion?
10. Who else would you recommend I discuss this topic with to gain further insights?

Appendix D: Summary of Expert Interviews

Please refer PDF file submitted as supplementary document.

Appendix E: Scenario Data and Assumptions

E.1 Scenario 2021

Table E.1: Scenario 2021 flows and calculations

Process	Name	Flow	Value	T	Assumption/Calculation	Reference
Fabrication	Nd metals import	F1	17000	2176	20% for (Pr+nd); 80% allocated to Nd from (Pr+Nd); 80% allocated to magnet production	(Eurostat, 2024)
	Nd in magnets	F2	0%	0%	Assumption	
	Nd in magnets for other uses	F16		2151.6	F3-F1;	
	Nd in magnets for EV	F3		24.4	4% of total Nd alloy import to EV	(Rizos et al., 2022) (Gielen & Lyons, 2022))
Manufacturing	Nd imports of magnets for TM/EV	F12	18000	352.8	Total PM import and out of which 7% goes to EV	(Gauß et al., 2021).
	Nd in export magnets for TM/Ev	F13	501785.7143	196.7	Number of cars extracted from export of cars in euros	(Eurostat, 2022) See below table
	Nd in traction motor	F4		180.4712		
EV Use	Nd in imported EVs	F14	453571.4	177.8		
	Nd in export of EOL EVs	F15	0	0	Assumption	
	Nd in net new cars	F17		337.8812		

	Nd in EOL EV	F7		20.39	Calculated using flow driven model (excel)	
Waste management EV	Nd in waste	F10	100%	20.39	Assumption	
	Nd to recycling	F8	0	0%	Assumption	
Recycling	Nd in waste	F9	0	0	Assumption	
	Nd recycled	F11	0	0	Assumption	

E.2 Assumptions for F13:

Table E.2: Export and import of EV to EU in 2021. Values converted from billions to car units.

	Import	Export	Import of Nd containing EV cars	Export of Nd containing EV cars	Reference
BEV sales in billion euros	11.4	12.3			
PHEV sales in billion euros	5.9	6.8			
Average unit price of a BEV in euros	40,000	40,000	285000	307500	
Average unit price of a PHEV in euros	35,000	35,000	168571	194286	
Total			453571.4286	501785.7143	

E.3 Additional Variables:

Table E.3: Nd content estimation in BEV and PHEV

Type of EV	Magnet Mass	Nd Fraction	Nd content (kg)	Reference
BEV	1131	0.1964	0.2221284	van Nielen et al. 2023
PHEV	1801	0.1964	0.3537164	van Nielen et al. 2023

E.4 Scenario 2030: Increased Recycling

Table E.4: Scenario 2030 flows and calculation- Recycling

Process	**Name**	**Flow**	**Value**	**T**	**Assumption/Calculation**	**Reference**
Fabrication	Nd metals import	F1	17000	2176	20% for (Pr+nd); 80% allocated to Nd from (Pr+Nd); 80% allocated to magnet production	(Eurostat, 2024); (LGI et al., 2018)
	Nd in magnets	F2	0%	0%	Assumption	
	Nd in magnets for other uses	F16		2245.52	F3-F1;	
	Nd in magnets for EV	F3		22.68	4% of total Nd alloy import to EV	(Gielen & Lyons, 2022)
Manufacturing	Nd imports of magnets and EVs	F12	18000	3606.4	Calculated using flow driven model (excel)	
	Nd in export magnets for TM/Ev	F13	501785.7143	1465.529203	Number of cars extracted from export of cars in euros	(Eurostat, 2022)
	Outflow of Ev cars to use	F4		2163.58		
EV Use	Nd in export of EOL EVs	F15	0	0	Assumption	
	Nd in net new cars	F17		1702.55		
	Nd in TM reaching EOL	F7		431.03	Calculated using flow driven model (excel)	
Waste management EV	Nd in waste	F10		276.62	Assumption: Collection rate of 40%	(Reimer et al., 2018)
	Nd to recycling	F8		184.41	Assumption: 40% to recycling	(Reimer et al., 2018)
Recycling	Nd in waste	F9		92.21	Assumption: Recycling efficiency of 50%	
	Nd recycled	F14		92.21	Assumption	

E.5 Scenario 2030: Integrated Remanufacturing

Table E.5: Scenario 2030 flows and calculation- Integrated Remanufacturing

Process	Name	Flow	Value	T	Assumption/Calculation	Reference
Fabrication	Nd metals import	F25	17000	2176	20% for (Pr+nd); 80% allocated to Nd from (Pr+Nd); 80% allocated to magnet production	(Eurostat, 2024); (LGI et al., 2018)
	Nd in magnets	F26	0%	0%	Assumption	
	Nd in magnets for other uses	F27		2151.6	F3-F1;	
	Nd in magnets for EV	F19		21.76	4% of total Nd alloy import to EV	
Manufacturing	Nd imports of magnets and EVs	F13	18000	3606.4	Calculated using flow driven model (excel)	Excel file
	Nd in export magnets for TM/Ev	F20	501785.7143	1465.529203	Number of cars extracted from export of cars in euros	Excel File
EV Use	Nd in EV cars for use	F18		2310.19		
	Nd in export of EOL EVs	F14	0	0	Assumption	
	Nd in net new cars	F17		1849.16		
	Nd in EOL EV	F7(1)		461.03	Calculated using flow driven model (excel)	

Waste management EV	Nd in waste	F28		276.62	Assumption: Collection rate of 40%	
	TM to reman-OEM	F15		46.1	F28-F22	
	TM to reman- SC	F22		138.31	Assumption: In the recovered Nd, majority (about 75%) is to SC.	
Traction Motor Remanufacturing-OEM	Nd in waste	F21		9.22	Assumption: 20% material loss in remanufacturing process	
	Remanned TM-OEM	F14		36.88		
Traction Motor Remanufacturing-SC	Nd in waste	F9(1)		27.66	Assumption: 20% material loss in remanufacturing process	
	Remanned TM-SC	F24		110.65		

Appendix F: EV car sales from 2013 – 2023, and projections for 2030.

Table F.1: BEV and PHEV vehicles from 2011-2023 in EU (Source: (RMIS - Raw Materials in Vehicles, n.d.)). *Data for 2025 and 2030 (in bold) are projections.*

Year	BEV Sales (number)	PHEV Sales (number)	Total (number)	Nd content (tonnes)
2011	12957	361	13318	5.220656
2012	33305	9185	42490	16.65608
2013	42083	24164	66247	25.96882
2014	67813	30713	98526	38.62219
2015	101743	92953	194696	76.32083
2016	108616	121870	230486	90.35051
2017	144146	166311	310457	121.6991
2018	220369	182707	403076	158.0058
2019	360219	199701	559920	219.4886
2020	745789	619129	1364918	535.0479
2021	602497	530719	1133216	444.2207
2022	705221	636800	1342021	526.0722
2023	881415	804126	1685541	660.7321
2024	**Data Gaps**	**Data Gaps**	**Data Gaps**	940.8

2025	3300000	1500000	**4800000**	1881.6
2026	**Data Gaps**	**Data Gaps**	**Data Gaps**	2156
2027	**Data Gaps**	**Data Gaps**	**Data Gaps**	2469.6
2028	**Data Gaps**	**Data Gaps**	**Data Gaps**	2822.4
2029	**Data Gaps**	**Data Gaps**	**Data Gaps**	3214.4
2030	6800000	2400000	**9200000**	**3606.4**

Projected Nd demand from NdfeB magnets used in BEV and PHEV passenger cars from 2011-2030. Expressed in tonnes.

To fill in the above data gaps, CAGR method was employed.

Step 1: The formula for calculating CAGR is:
CAGR= $(Vf/Vi)^{1/n} - 1$

Where,

- *Vf*: Final Value (e.g., sales in 2030)
- Vi: Initial Value (e.g., sales in 2023)
- n*:* Number of years between Vi and Vf

Using the formula:
CAGR=$(9.2 / 1.6)^{1/7} – 1$

CAGR≈0.2812or28.12%

Step 2: Project Growth for Each Year
Using the CAGR value, sales for each year can be projected using the formula:
$Vt = Vi×(1+CAGR)^n$

Projections:

- **2024 (n=1)**:

V2024=1.6×(1+0.2812)1=2.05

- **2026 (n=3)**:

V2026=1.6×(1+0.2812)3=3.37

- **2027 (n=4)**:

$V_{2027}=1.6\times(1+0.2812)^4=4.32$

- **2028 (n=5)**:

$V_{2028}=1.6\times(1+0.2812)^5=5.54$

- **2029 (n=6)**:

$V_{2029}=1.6\times(1+0.2812)^6=7.10$

Appendix G: Flow-Driven Model

G.1 Inflow values of Nd in EV in tonnes from 2011-2030

The survival curve is plotted using the combined sales of BEV and PHEV from 2011 to 2030. The inflow value is obtained using the numbers given in Table F.1. The lifespan of EVs is considered to be 10 years.

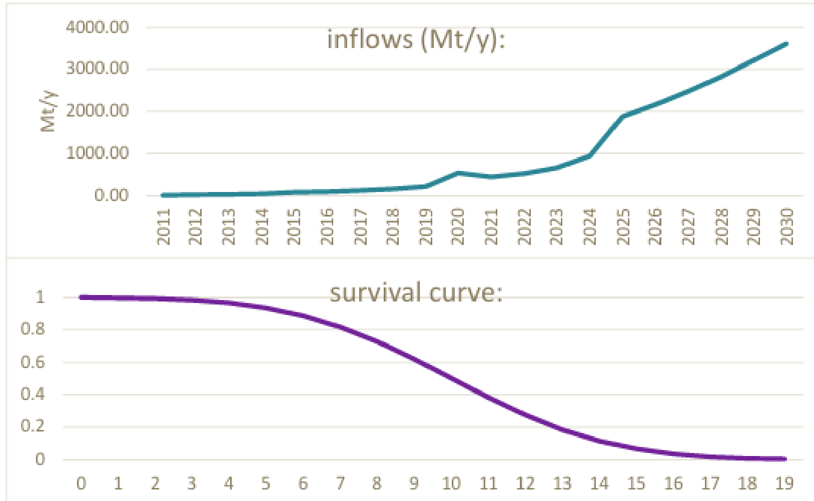
Figure G.1: Graphical representation in the rise of inflows (top) and decline in lifespan of EV (bottom)

Data inputs (and their units)

Normal distribution survival curve parameters:

μ (mean, years)	σ (standard deviation)
10	3.333333 ->

time (years)	inflows (Mt/y):
2011	5.22
2012	16.66
2013	25.97
2014	38.62
2015	76.32
2016	90.35
2017	121.70
2018	158.01
2019	219.49
2020	535.05
2021	444.22
2022	526.07
2023	660.73
2024	940.80
2025	1881.60
2026	2156.00
2027	2469.60
2028	2822.40
2029	3214.40
2030	3606.40



age (years)	survival curve:
0	0.999
1	0.997
2	0.992
3	0.982
4	0.964
5	0.933
6	0.885
7	0.816
8	0.726
9	0.618
10	0.500
11	0.382
12	0.274
13	0.184
14	0.115
15	0.067
16	0.036
17	0.018
18	0.008
19	0.003

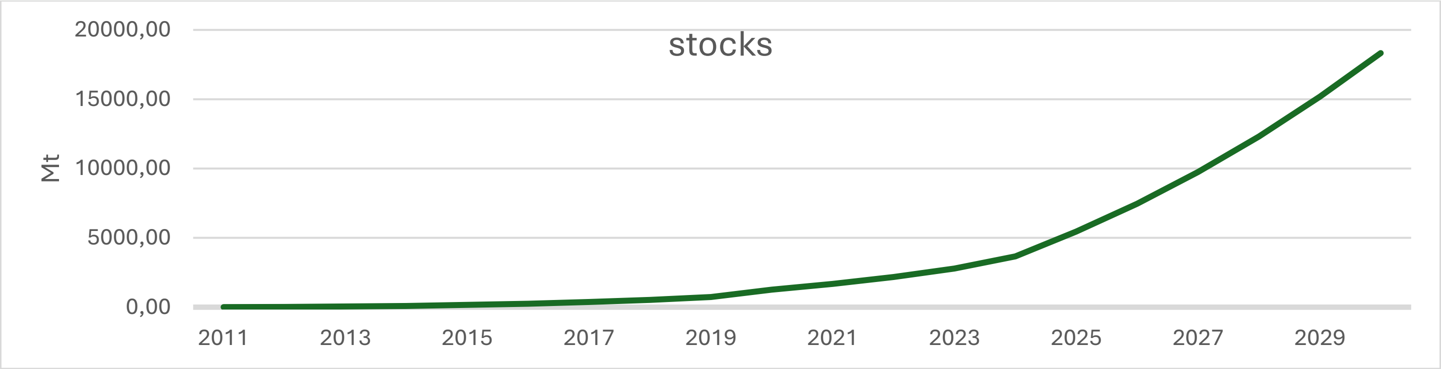
G.2 Outflow values and Stock accumulations of Nd in EV in tonnes from 2011-2030

Table G.1: Outflow values and Stock accumulations of Nd in EV in tonnes from 2011-2030

Year	*Outflow (Mt/y)*	*Nas (Mt/y)*	*Stock (Mt)*
2011	0.01	5.21	5.21
2012	0.03	16.62	21.84

2013	0.10	25.87	47.71
2014	0.24	38.39	86.10
2015	0.56	75.76	161.85
2016	1.18	89.17	251.02
2017	2.33	119.37	370.40
2018	4.30	153.71	524.10
2019	7.52	211.96	736.07
2020	12.82	522.23	1258.30
2021	20.39	423.83	1682.13
2022	31.40	494.67	2176.80
2023	46.87	613.86	2790.66
2024	68.18	872.62	3663.28
2025	97.72	1783.88	5447.16
2026	136.85	2019.15	7466.31
2027	188.73	2280.87	9747.18
2028	256.92	2565.48	12312.66
2029	345.89	2868.51	15181.16
2030	461.03	3145.37	18326.53

Figure G.2: Graphical representation of Nd stock accumulation in tonnes


stocks
Mt
20000,00
15000,00
10000,00
5000,00
0,00
2011
2013
2015
2017
2019
2021
2023
2025
2027
2029