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Design of a permanent magnet direct recycling line: a comprehensive approach towards a circular economy

TESI DI LAUREA MAGISTRALE IN
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Abstract

In today's tech-driven world, sustainable practices are vital amidst increasing energy and resource demands. Linear economies, which follow a "take-make-dispose" model, are outdated. Circular Economy (CE) solutions, which emphasize resource efficiency and waste reduction, play an essential role. This thesis focuses on the direct recycling of permanent magnets extracted from end-of-life electric motors to support sustainable resource management within a circular economy framework. The findings show a gap in the literature regarding a systematic and detailed examination of the processes involved in the recycling of permanent magnets. To address this research challenge, a comprehensive review of circular economy principles and their application in the recovery industry was conducted, employing qualitative and quantitative methods, including literature reviews, patent landscape analysis, and exploration of corporate initiatives. The result is the effective integration of multiple alternatives, processes, stations, parameters, and tools within the direct recycling line to produce sintered and bonded permanent magnets. These processes encompass, among others, demagnetization and precise magnet extraction, where it was established that the use of inert surfaces is not necessary as long as the magnets have protective coatings; hydrogen decrepitation, where its use was justified by showing benefits in the final magnetic properties and economics, by requiring less milling and delivering a magnet powder in better condition; and the post-processing of magnetic powder, where strategies for the removal of unwanted materials such as degassing and hydrogenation disproportionation desorption and recombination (HDDR) were described. This study fills the gap by being a pioneer in the systematic identification and establishment of all the steps intrinsic to the execution of a recycling line. This integrated approach not only marks a significant accomplishment but also holds the potential for economic and environmental advantages by reducing energy consumption and carbon emissions mainly attributed to excluding the strip-casting step presented in virgin production.

Key-words: Circular economy, Recycling, Sustainable resource management, Permanent magnet, Rare-earth magnets.

Abstract in italiano

Nel mondo di oggi, guidato dalla tecnologia, le pratiche sostenibili sono vitali di fronte alla crescente domanda di energia e risorse. Le economie lineari, che seguono un modello "produci-consuma-butta", sono obsolete. Le soluzioni dell'Economia Circolare, che enfatizzano l'efficienza delle risorse, svolgono un ruolo essenziale. Questa tesi si concentra sul riciclo diretto di magneti permanenti estratti dai motori elettrici giunti alla fine della loro vita utile, al fine di sostenere la gestione sostenibile delle risorse. I risultati mostrano una lacuna nella letteratura riguardo a un'esame sistematico e dettagliato dei processi coinvolti nel riciclo dei magneti permanenti. Per affrontare questa sfida di ricerca, è stata condotta una revisione dei principi dell'economia circolare e nell'industria del recupero, utilizzando metodi qualitativi e quantitativi, tra cui revisioni bibliografiche, analisi del panorama dei brevetti ed esplorazione delle iniziative aziendali. Il risultato è stata l'efficace integrazione di alternative, processi, parametri e strumenti all'interno della linea di riciclo diretto per la produzione di magneti permanenti sinterizzati e bonded. Questi processi includono, tra gli altri, la demagnetizzazione e l'estrazione precisa del magnete, dove è stato stabilito che l'uso di superfici inerti non è necessario purché i magneti abbiano rivestimenti protettivi; la decrepitazione dell'idrogeno, il cui utilizzo è stato giustificato mostrando vantaggi nelle proprietà magnetiche finali ed economici, richiedendo meno fresatura e fornendo una polvere di magnete in migliori condizioni; e la post-lavorazione della polvere magnetica, dove sono state descritte strategie per la rimozione di materiali indesiderati come degassing e idrogenazione con disproporzionamento desorbimento e ricombinazione. Questo studio colma la lacuna essendo un pioniere nell'identificazione sistematica ed istituzione di passaggi intrinseci all'esecuzione di una linea. Questo approccio integrato offre potenziali vantaggi economici e ambientali, riducendo il consumo di energia e le emissioni di carbonio dovuto all'esclusione della pezzo fuso della striscia nella produzione vergine.

Parole chiave: Economia circolare, Riciclaggio, Gestione sostenibile delle risorse, Magnete permanente, Magneti di terre rare.

Contents

1 Introduction

1.1. Rare Earth Elements and electric motors

In today's technological landscape, the growth in demand for energy resources, food and raw materials has led to the crucial need to find sustainable practices and conserve resources. Linear economy is no longer feasible and therefore circular economy (CE) solutions are needed, where emphasis is placed on resource efficiency, recycling, and waste reduction [1].

The list of critical materials of the European Union has expanded over the years, and among the most critical materials are rare earth elements, which come mainly from a limited number of countries, causing concerns in the supply chain and suggesting the requirement of recycling. Among the most critical Rare Earth Elements (REEs) are terbium, dysprosium and neodymium and the EU countries are characterized as large importers of this class of elements, specifically of semi-products with the aim of manufacturing and exporting final products as part of their vision of being leaders in the manufacturing industry for REEs products [2], however, the demand for these materials is predicted to multiply rapidly in the coming years [3] and this underscores the importance of establishing strong research and development competence in circular economy for products containing REEs. So far, numerous studies indicate that the recovery of these elements and recycling methods seem to be profitable [4] and experts are focused on developing new techniques for all kinds of products. One of these products is permanent magnets found in a wide variety of applications such as hard disk drives, speakers, medical equipment, electric vehicles, digital technologies, and wind generators [5].

In the same way, the recycling of electric motors has great potential since not only can REEs be recovered within the permanent magnets, but other valuable materials can be recycled, such as cast iron, electrical steels, plain carbon steels, aluminium, and copper [6]. In addition, the EU directive on end-of-life vehicles has established recycling targets that involve recycling electric motors [7]. Specifically, the most interesting type of motors are permanent magnet synchronous motors (PMSMs) [8], which offer superior high-power density and energy efficiency compared to conventional electric motor types [9] from which the magnets represent about 20-40% of the BOM cost [10]. The market for this type of motor is expanding, as the technological world demands more and more high-performance motors [11].

1.2. REEs overview

Rare Earth Elements, which consist of 17 unique elements, are used in a wide range of products ranging from fluorescent lamps, batteries, and solar panels to magnets and fertilizers. They are applicable in a wide range of industrial applications such as photovoltaics, fuel cells, water treatment, and electronics [12]. Three of these 17 REEs are particularly important in the production of Rare Earth Magnets: neodymium, praseodymium, and dysprosium [4].

Rare Earth Magnets have a wide range of applications and first appeared on the market in the 1960s with the development of Samarium-Cobalt (SmCo) alloys. In comparison to Alnicos, Ferrites, and steel magnets, these alloys performed better. The introduction of permanent magnets based on the tetragonal compound Neodymium-Iron-Boron (NdFeB) in the early 1980s was a turning point moment. Exploration and advancement of NdFeB-based Rare Earth Magnets have gained traction, owing to its applications in electric vehicles, high-efficiency wind turbines, and high-performance electric motors. Finely tuned magnetic qualities such as increased product-maximum energy, coercivity, and remanence are required for these applications [4].

Nevertheless, this kind of magnets have some disadvantages. First, the extraction of REEs presents environmental problems, and on the other hand, reliance on NdFeB magnets offers considerable economic threats due to China's dominance in both rare earth mining (90% of global production) and magnet production (more than 80%) [13]. Instances such as China's decrease of export quotas and increase in export taxes have resulted in severe price increases and raised worries among industry actors in the European Union, Japan, and the USA [14].

This scenario emphasizes the importance of responsible Nd-Fe-B magnet manufacture, use, and recycling from end-of-life products as electric motors, as well as their incorporation into circular economy models, for long-term progress toward a green economy [14], [15].

Unfortunately, NdFeB magnet recycling is not yet being done on a large scale and the opportunity to recover such valuable materials is being lost. The magnets inside end-of-life products have the potential to be an important source of concentrated REEs and a systematic collection and separation of materials from waste streams, followed by economically feasible reprocessing are clearly necessary [14]. Proposals for the recovery of RREs within the framework of the Circular Economy must present a holistic approach to avoid the incorporation of circular solutions that might appear sustainable but inadvertently overlook the vital sustainability dimension. So, the solutions must contemplate the social, the environmental, and the economic impact [16].

1.3. Sources to supply the demand

Delving into the problem of supplying the exponential demand for NdFeB magnets, the conclusion is reached about the need to integrate the primary sources with the secondary sources. And while the ideal would be to rely entirely on secondary sources alone, REEs recovery cannot fully replace traditional alloy casting due to the lag produced by product lifecycles [17]–[19].

In this sense, it is also imperative to understand the material flow and stocks of REEs around the world. For this task, Material Flow Analysis (MFA) is the perfect tool, although the limited information about REE content and product heterogeneity complicate the process and numerous research have been conducted in order to quantify REE presence in waste materials such as Waste Electrical and Electronic Equipment (WEEE) [20].

Inside the EU-28, secondary production of REEs no rare earth elements are currently mined, including neodymium. However, the region has substantial reserves, mainly in Greenland and Sweden, that could potentially exceed current domestic neodymium demand. To solve this, the EU-28 must increase beneficiation and processing capabilities, discover new reserves, and improve extraction efficiency [21].

Experts stated that secondary neodymium sources in the EU-28 appear to be significant enough to meet a considerable share of domestic demand and minimize dependency on neodymium imports as raw materials or finished products. However, obstacles to neodymium recovery include product design, end-of-life collection, the future of low-carbon energy systems, changing recycling technologies, and economic viability [21].

Further investigation of neodymium content in products, including alterations in permanent magnet compositions and market penetration rates, is required to improve understanding of neodymium's socioeconomic metabolism. Secondary neodymium fluxes are particularly prevalent in industries such as factory automation and automotive, which rely largely on machinery, industrial robots, and automobiles. Collaboration between the public and private sectors to collect and disseminate this data is anticipated to reduce estimation uncertainty and drive resource efficiency measures throughout the neodymium value chain. To provide a comprehensive picture of the environmental aspects of neodymium supply and demand, future research should include secondary markets for neodymium-containing items as well as other effect categories such as global warming potential and cumulative energy demand [21].

Other studies on this subject include the analysis of the impact of the material cycle in four basic stages: production, fabrication and manufacture, usage, and waste management and recycling [22]. Traditional Nd-Fe-B magnet production, which is based on primary element mining, causes environmental damage: it produces approximately 8.5 kg of fluorine and 13 kg of dust per ton of rare earth produced; using concentrated sulfuric acid high-temperature calcination produces 9600 to 12,000 cubic meters of waste gas containing various compounds, acidic wastewater, and radioactive waste residues [23]. These results point out and emphasize the importance of an efficient recycling system and the need of controlling neodymium resources to assure long-term supply and offset the challenges faced by rising demand and restricted supply [24].

1.4. Objectives and research question

The primary goal of this thesis is to examine the feasibility, limitations, and potential benefits of direct recycling methods for permanent magnets, with a particular emphasis on NdFeB (neodymium iron boron) rare earth permanent magnets. This study is positioned within the context of the current state of the art in permanent magnet recycling. The study seeks to examine the economic viability and environmental impact of these recycling methods by thoroughly exploring and defining each process involved in several alternatives of direct permanent magnet recycling. Finally, through a comprehensive analysis, the research attempts to answer the research question: "How to effectively integrate a permanent magnet direct recycling line to support sustainable resource management within a circular economy framework?"

To solve this question, a set of different specific central research questions were stablished, and each of then seek to achieve one specific objective.

1. What is the current state of the art in permanent magnet recycling, particularly focusing on direct recycling methods, and what are the key findings, challenges, and gaps in the existing literature?
   Research objective: conduct a comprehensive assessment and evaluation of existing literature and advancements in the field of permanent magnet recycling, with a focus on the current state of direct recycling methods.

2. What are the distinct processes and techniques involved in different alternatives of direct permanent magnet recycling, and how do they contribute to the overall feasibility and sustainability of the recycling approach?
   Research objective: define and analyse each step and process involved in various direct permanent magnet recycling alternatives, such as disassembly, material separation, purification, and sintering and bonding techniques.

3. How does the economic feasibility of direct permanent magnet recycling compare to traditional manufacturing methods, taking into account various cost factors and potential economic benefits of recycling?
   Research objective: assess the economic feasibility of direct recycling methods in comparison to traditional manufacturing processes by considering costs associated with disassembly, material recovery, purification, and production of recycled magnets.

4. What is the comprehensive environmental impact of adopting direct recycling methods for NdFeB permanent magnets, and how does it compare to the environmental footprint associated with conventional production processes?
   Research objective: conduct a comprehensive life cycle assessment to quantify the environmental impact of direct recycling methods for NdFeB permanent magnets and comparing it to the environmental footprint of traditional manufacturing processes.

By addressing these research questions through a comprehensive approach, this study aims to provide insights into the effective integration of a permanent magnet direct recycling line within a circular economy framework, supporting sustainable resource management.

1.5. Scope

This thesis focuses on the critical domain of permanent magnet direct recycling, elucidating the complex processes involved in the direct recycling of permanent magnets, with a particular emphasis on NdFeB rare earth magnets. It is critical to emphasize that this study is primarily theoretical and analytical, with no practical experimentation or operational measurements used to determine the values presented in the literature. This study focuses solely on direct recycling methodologies, distinguishing itself from indirect techniques, which, while acknowledged and briefly discussed, fall outside the scope of comprehensive analysis.

This research goes beyond mere theoretical discussion, encompassing a thorough examination of the technical aspects governing the design of a direct recycling line for permanent magnets. The theoretical design presented in this thesis delves deeply into each distinct process that comprises the recycling trajectory, elucidating various routes and critical parameters that guide the efficacy and feasibility of the recycling processes. Notably, the theoretical design does not focus on a single aspect of the recycling process, but rather covers the entire spectrum of the recycling process, from the initial collection of discarded electric motors to the final delivery of recycled permanent magnets.

1.6. Significance and academic contributions

The research presented in this thesis contributes significantly to academic understanding of permanent magnet direct recycling, ushering in a new dimension of knowledge in the field of sustainable resource management. The comprehensive approach taken, which includes the meticulous determination of the entire recycling line for permanent magnets, is a hallmark of novelty. This distinct approach distinguishes this study from previous research efforts and positions it as a forerunner in an uncharted domain.

The thesis is distinguished by its thorough investigation of the multifaceted processes involved in permanent magnet direct recycling, with a focus on NdFeB rare earth magnets. This endeavour fills a significant research gap by being the first to systematically identify, expound on, and establish the necessary steps intrinsic to the functional establishment of a recycling line. This research goes beyond conventional recycling paradigms, catalysing innovative and holistic approaches to the direct recycling of permanent magnets.

As the global conversation shifts toward sustainability and circular economy principles, the significance of this thesis becomes even more apparent. Beyond advancing scientific understanding of direct recycling methodologies, it has practical implications for industries, policymakers, and stakeholders. The identification of critical parameters, the delineation of intricate stages, and the unravelling of operational nuances collectively provide decision-makers with an unprecedented resource for informed decision-making. This pool of knowledge paves the way for strategic resource allocation, keeps the momentum of sustainable practices going, and guides well-informed technological investments in the field of permanent magnet direct recycling.

It is worth noting that this study is theoretical and analytical in nature, with no practical experimentation or operational measurements to verify the values presented in the literature. While this constraint guides the scope of the research, it also lays the groundwork for future investigations. This thesis, as an important contribution to academic discourse, not only illuminates the theoretical design of a permanent magnet direct recycling but also attests to the potential of scholarly endeavours in driving transformative changes. In conclusion, this thesis provides a thorough examination of permanent magnet direct recycling, providing a profound insight into the orchestration of the recycling line. A pioneering achievement is set to revolutionize sustainable practices and mark the beginning of the circular economy, bringing lasting benefits to industries, economies, and the environment alike.

1.7. Thesis structure

This thesis is organized to provide a thorough and systematic examination of permanent magnet direct recycling, encompassing a variety of critical aspects to provide a comprehensive perspective on the subject. The sections that follow outline the organization and content of this research work:

Chapter 2: Theoretical background

This section provides the theoretical foundation for the subsequent investigation. It covers a wide range of topics about permanent magnets, including their composition, properties, and applications in modern technology. The circular economy framework is introduced as the overarching paradigm guiding sustainable resource management, while existing recycling processes are evaluated critically to determine their limitations and opportunities. Challenges in permanent magnet recycling are addressed, and current approaches are meticulously examined, highlighting gaps and shortcomings in the existing literature.

Chapter 3: Methodology

The third chapter delves into the research's methodological foundation. It elaborates on the research design used in structuring the study, detailing the rationale for the chosen approaches, data collection strategies, and data analysis methodologies. This section provides a clear roadmap for carrying out the various aspects of the study.

Chapter 4: Results

This section is the culmination of the theoretical and empirical investigation. It includes a thorough examination of the literature review, as well as key insights derived from scholarly discourse. A patent landscape analysis sheds light on the field's innovative advancements. Furthermore, the section includes the results of industry and project-based research, resulting in a range of findings that contribute to a broader understanding of direct recycling of permanent magnets.

Chapter 5: Discussion

This chapter undertakes a comprehensive review of each recycling station within the different alternative direct recycling routes. It provides a thorough, process-specific discussion of the technical complexities, challenges, and potential optimization strategies for each recycling station. It provides readers with a nuanced understanding of the practical aspects of implementing the proposed direct recycling processes.

Chapter 6: Economic analysis

This section conducts a comprehensive economic analysis, dissecting the financial aspects of direct recycling methods. It examines costs, investments, and long-term viability to determine the financial viability and sustainability of the proposed recycling methods.

Chapter 7: Environmental impact analysis

The final chapter evaluates the environmental implications of direct recycling methods in tandem with the economic analysis. It quantifies the environmental consequences of each approach, including energy consumption, emissions, resource utilization, and waste generation, to provide a comprehensive picture of the ecological footprint associated with each approach.

In essence, this thesis is designed to take the reader on a journey through the theoretical underpinnings, methodological framework, empirical results, and in-depth analyses that collectively contribute to a detailed understanding of permanent magnet direct recycling. This research seeks to inform researchers, industries, policymakers, and stakeholders alike through its systematic organization, fostering informed decision-making, sustainable practices, and progress in the domain of circular economy resource management.

2 Theoretical background

2.1. Introduction to the chapter

The essential elements that support the development of a thorough understanding of permanent magnet recycling within the context of the circular economy are explored in this chapter. This chapter's main goal is to explain the careful process used to answer the key research questions, illuminating the complexities of recycling and its implications for resource management.

The chapter's organization is as follows:

- Section 2.2 delves into the comprehensive synthesis, classification, and manufacturing processes of NdFeB permanent magnets. It explores their distinct characteristics involving techniques to enhance their properties. The subsections within this section delve into the intricate details of sintered and bonded magnets, presenting a thorough understanding of their production and mechanical properties.
- Section 2.3 addresses the integration of circular economy principles in the realm of permanent magnets and electric motors. It unfolds the various approaches, emphasizing the importance of sustainable management.
  Subsections 2.3.1 and 2.3.2 delve into embracing circular economy principles for permanent magnets and sustainable management approaches for permanent magnet synchronous motors, respectively.
  Subsection 2.3.3 explores the opportunities and limitations in the sustainable recovery and reuse of NdFeB magnets. This section underscores the pivotal role of circular economy strategies in ensuring resource efficiency and environmental responsibility.
- Section 2.4 delves into the crucial area of permanent magnets recycling. This section provides a comprehensive overview of the techniques, challenges, and potentials of recycling permanent magnets, considering both indirect and direct methods.
  Subsection 2.4.1 addresses the recycling perspective of end-of-life permanent magnets, shedding light on their potential and challenges.
  Subsection 2.4.2 explores recycling indirect strategies, specifically focusing on hydrometallurgical and pyrometallurgical approaches.
  Subsection 2.4.3 examines direct approaches, elucidating their significance in recycling techniques.

- Section 2.5 discusses the gaps present in the existing literature. It underscores areas that remain unexplored or insufficiently studied in the context of permanent magnet recycling.

In conclusion, this chapter provides a crucial background for the process of developing a solid understanding of permanent magnet recycling within the framework of the circular economy. The foundation for the ideas and findings that this study will produce is laid out in each of the succeeding sections, which explore particular aspects, approaches, and difficulties.

2.2. Permanent magnets manufacturing overview

NdFeB permanent magnets have distinguished themselves as the best available magnets since their introduction to the market in 1984. Their superior energy product highlights their effectiveness and applicability for lightweight mobile applications [25].

Permanent magnets are categorized as "hard" magnetic materials because they keep magnetization even after the magnetizing field is removed, regardless of their shape. The remanent magnetic flux density (Br) and resistance to demagnetization, expressed by the coercivity (Hc), are critical properties for magnetic applications. NdFeB is the best permanent magnet material because it has high remanent flux densities, good mechanical properties, and the ability to control temperature stability with extra element doping [23], [26].

They are normally composed of around 30% rare earth elements, primarily neodymium (Nd), though dysprosium (Dy), terbium (Tb), and praseodymium (Pr) can also be included [27].

NdFeB magnets are classified in sintered and bonded magnets. Sintered magnets, sometimes referred to as nucleation-type magnets, dominate the market. During the manufacturing procedure of this magnets, a NdFeB starting alloy is made using a strip caster, which casts the alloy onto a rotating wheel that is swiftly cooled by water. This quick cooling produces an alloy with microscale NdFeB grains and a notably homogeneous microstructure. The material is then subjected to hydrogen decrepitation (HD) to pulverize it, followed by jet-milling to produce grain sizes that are typically between 3 and 5 micrometres [25].

A magnetic field is used to align the powdered material, which is subsequently compacted into a textured green compact and subjected to sintering. In order to improve the magnetic properties of the sintered structure, particularly coercivity, it is subsequently annealed. To achieve the finalized product, mechanical processes such as cutting to define the shape, and coating to protect the magnet susceptibility to both hydrogen and oxygen, are used in the final processing [25], [28].

Also, a grain boundary diffusion technique may be used where Dy and Tb are added. This method specifically strengthens the grain boundaries of the magnet by diffusing the heavy REEs [25]. These elements can be used to improve the properties of NdFeB magnets, specifically to increase magnetic characteristics or to broaden the operating temperature range. Notably, the most common of them, dysprosium increases resistance to demagnetization and ensures magnetic characteristics at high temperatures [29].

The second important category of NdFeB permanent magnets are nanocrystalline, polymer-bonded magnets. Usually, NdFeB alloy is quickly cooled through melt spinning to produce polycrystalline flakes with nanoscale grains; these flakes are then milled to achieve a standard particle size; finally, the flakes are combined with a polymer compound and either injected or pressed to produce a magnet. The main advantage of this technology is its ability to generate magnets with complex geometries without the need for considerable shaping. As a disadvantage, these magnets' energy densities are clearly much lower compared to those of sintered magnets because the permanent magnet material becomes diluted by the polymer's presence [25]. At the end of the process, cutting and coating are utilized to obtain the final product.

2.3. Circular economy integration

In the context of modern resource management, the idea of a circular economy represents a critical paradigm change. A circular economy focuses on the construction of closed loops where resources are continuously reused, remanufactured, and recycled as opposed to the conventional linear "take-make-dispose" paradigm. It imagines a regenerative system that promotes resilience and economic growth in addition to reducing waste and minimizing environmental impact. Within this framework, materials and products are made to be long-lasting, repairable, and eventually reintegrated into the manufacturing process. The circular economy encourages resource conservation, dissociates economic expansion from resource consumption, and supports objectives for sustainable development [30].

The importance of circular economy on permanent magnets is closely related to the global necessity of sustainable resource management. Permanent magnets are being used more and more in a variety of industries, from electronics and renewable energy to transportation, underscoring the crucial part they play in contemporary technologies. However, the widely used linear model of production and consumption for these magnets is challenged by several urgent issues, emphasizing the importance of adopting effective recycling techniques [6].

Rare earth elements, which are limited in supply and environmentally delicate to extract, make up most permanent magnets, which makes circular economy strategies the essential processes for recovering these priceless materials from end-of-life goods, easing the burden on limited resources, and minimizing the environmental harm caused by original extraction.

Circular economy reduces the need for new extraction, which lowers carbon emissions and lessens ecological disturbance. Circular economy strategies are focused on using less energy than conventional primary production techniques, resulting in a more environmentally friendly energy footprint and are focused on providing numerous economic benefits. The recovery strategies might also encourage a local supply of essential resources, lowering reliance on imports and minimizing price volatility. Finally, by extending the life of these magnets, waste generation is decreased, and responsible resource use is encouraged [6], [16], [30].

2.3.1. Sustainable motor management

Permanent magnets play a critical role in various modern applications, including electric vehicles, high-efficiency wind turbines, and high-performance electric motors. From these, electric motors are the foundation of contemporary industrial and technical progress, powering a wide range of essential functions in areas from renewable energy production to transportation and manufacturing [31]. And one of the most important motors are the permanent magnet synchronous motors (PMSMs), which offer superior power density and energy efficiency compared to conventional electric motor types. The magnetic flux in these motors is generated by permanent magnets, which eliminates copper losses caused by electrical excitation, and no slide contacts are needed to transfer current, resulting in low maintenance. However, as it was anticipated, PMSMs require rare earth magnets, such as neodymium (Nd) and dysprosium (Dy), which presents a disadvantage in terms of resource efficiency [9].

A methodology has been developed to choose the most environmentally friendly end-of-life option for electric and electronic equipment that fails before the end of its expected lifespan but only for small power motors [32].

Reuse, refurbishing, remanufacturing, and recycling are some of the strategies for managing electric motors that are introduced by the circular economy where remanufacturing efforts are expected to increase as hybrid and electric vehicles become more integrated into society [6]. The circular economy process starts with the collection of end-of-life motors, and then the specific process of reusing, repairing, or remanufacturing them begins [33]. The next step is to perform a preliminary examination of their physical status in order to find any electrical, mechanical, or combined faults. Due to a variety of reasons, including varying levels of wear and tear, component damage during use, missing parts, and product revisions, the disassembly procedure may not exactly match the original assembly sequence [6].

While certain components, like the rotor, require just partial removal to be reused, others, like the bearings and windings, require reconditioning. Identification of reusable components that need to be repaired or reconditioned is guided by thorough inspections and fault diagnostics. Cleaning and predictive analysis are performed on these components. Items that cannot be repaired must be properly disposed of. The degree of a worn-out or damaged component's degeneration determines whether it should be repaired or replaced. The stator and rotor are then put back together, followed by end-of-line tests and final product assembly [6].

2.3.2. Recovery and reuse of magnets

In general, there are three ways to recover used NdFeB magnets, direct reuse, permanent magnet alloy recycling, and elemental recycling involving total magnet dissolution and extraction of REEs oxides. The most environmentally and economically beneficial path would preferably involve direct reuse of the magnets. This technique is frequently not economically viable due to the specialized design needs of items, which are generally characterized by precise magnet parameters (such as shape, size, chemical composition, and magnetic characteristics) [34].

Magnet reuse appears more promising. To assess the potential of magnets for reliable functional recycling, evaluating their aging process is crucial. Research indicates that the magnets aren't damaged by operational stresses and mechanical defects are more likely to occur during disassembly or subsequent cleaning processes [35].

Directly reusing the magnets in their original function is generally feasible. After removal from the rotor, the magnets require cleaning, removing any adhesive residues, and must be free from damages. Reports reveals that while a used rotor might show signs of rust, the magnets themselves don't exhibit red or white rust (indicative of iron or rare-earth corrosion) after cleaning because the magnets are protected against corrosion through coatings, such as nickel, and the neodymium phase is stabilized by cobalt doping [35].

Nevertheless, to make magnets accessible for direct reuse in various applications, a certain degree of standardization is necessary. Attempts to standardize magnets were made in the nineties but didn't succeed due to varying specific customer demands. For gearbox-integrated motors which are highly integrated and fitted for each manufacturer, the magnets are optimized accordingly. However, manufacturers are moving towards a modular electric motor design. In the case of electric traction motors, the situation is more favourable, making standardization in terms of outer magnet dimensions potentially conceivable in the future [35].

Moreover, technological progress must be considered. In today's dynamic landscape, long-term standardization, particularly regarding magnet composition, is challenging and could delay progress. Overall, it can be concluded that magnet standardization is not feasible nowadays and may not necessarily be essential from cost and production perspectives. In the future, standardization of magnet dimensions or geometry seems possible, but not the standardization of magnetic quality (chemical composition and structure) [35].

In summary, direct reuse of used magnets isn't practical. This isn't due to inadequate performance of old magnets, as their performance remains consistent throughout their product life, but primarily due to the diversity of specifications concerning magnet geometry and performance profiles in secondary markets [35].

Consequently, the viability of using recycled Nd-Fe-B magnets is dependent on developing a business case that capitalizes on their potential cost savings, reduced resource dependence, and improved environmental friendliness.

While the magnetic characteristics of recycled magnets may lag slightly behind those of virgin material magnets, they nevertheless outperform other magnet alloys by several orders of magnitude. However, starting with a diverse range of chemical compositions and physical qualities makes the problem of creating recycled magnets with custom qualities as specified by designers and system engineers a big challenge. This problem can only be solved by improving de recycling strategies [34].

2.4. Permanent magnets recycling

End-of-life permanent magnets are predicted to become a primary REE resource by 2030, in line with the concepts of the circular economy. These magnets have a lifespan of 2-30 years and can be refurbished and reused, however at a lower performance than virgin material. Although industrial-scale implementation is sparse, research is focusing on indirect REE recovery from NdFeB magnets utilizing pyrometallurgical or hydrometallurgical processes [36].

The industrial sector faces an important difficulty due to a lack of exact understanding about the existing quantities of neodymium [37], but recent studies show that worldwide recycling potential in the following decades is constrained when compared to the demand for finished goods. Recycling was considered unlikely to profit from economies of scale because there is not enough waste produced. A sharp increase in demand and a delay in the time it takes for products to reach their end-of-life stage define this trend. However, after this lag time has passed and demand has steadied, recycling will truly become a significant driving force [38]. Therefore, it's crucial to explore all the alternatives that either minimize or eliminate the usage of REEs [39].

2.4.1. Indirect recycling strategies

Rare Earth Elements can be recovered using a variety of metallurgical techniques from used NdFeB magnet materials. These strategies include, among others, direct processes as hydrogen decrepitation or indirect as hydrometallurgical processes and the extraction of REEs from pyrometallurgical slag.

2.4.1.1. Hydrometallurgical route

Hydrometallurgical methods are indirect methods frequently employed in the recycling of rare earth permanent magnets. The initial phases of the hydrometallurgical technique involve leaching either magnets or scrap magnets to start the process. By using procedures like solvent extraction, ion exchange, or ionic liquid techniques, it is possible to isolate the different REE species [40]. The progression then requires the precipitation of either a specific REE salt or compound, or the targeted precipitation of mixed REEs from co-dissolved non-REE components. At some point, it becomes practical to convert the material into REE fluorides or oxides [41].

Selective dissolution, elevation of REE concentration, and separation of REE species from significant equivalents are the focus in the hydrometallurgical process. Making sure that all important metals are fully recovered at the same time is essential, and for that reason the creation of cutting-edge separation technologies is essential to handle these complexities.

Depending on how complex the scenario is, different dissolving procedures can be employed. For magnet scrap, dissolution can be carried out using total dissolution of the magnet, with or without roasting beforehand; sequential roasting followed by targeted leaching of the REEs; or selective transformation of REEs within solid magnets or magnet scraps directly into a novel solid phase. The solubility of REE salts at various temperatures or hydrothermal conditions can be used to guide another possible strategy, which entails converting the REEs in the magnet scrap into precipitated REE compound forms.

Several studies focused on this recycling process [42]–[55], and could be considered the most studied recycling strategy. Recent research seeks to improve the hydrometallurgical alternatives and has suggested new procedures, and a good part of them comprises solvent extraction methodologies [56]–[64].

Hydrometallurgical procedures are used because they are compatible with lower grade and complex streams containing a variety of impurities while producing high product purity [65]. At the end the results show recoveries of REE on more than 99% of purity [66], [67].

These techniques do, however, come with significant limitations. Before new magnets can be produced, several production steps are required. Additionally, a significant amount of chemicals is used in the process, which results in the production of a sizeable amount of wastewater and effluents [25], and hazardous compounds are used in gas phase extraction process [68], [69].

It should be noted that most of the studies focus on recycling permanent magnets that come from a sintered process, the main reason for this omission in the studies is because bonded magnets have a much lower REEs content than sintered magnets, which make recycling of this kind of magnets a subject of less interest. For this reason, in order to recycle an originally bonded magnet, a process must be followed that begins with the separation of the binders from the rest of the magnet. Most techniques involve indirect recycling strategies where the polymeric binders are dissolved using organic solvents, generally at high temperatures via solvolysis. The use of CO2-expanded water, on the other hand, has showed promise for a cleaner solvolysis technique for epoxy resins. Of all the polymer binders, PA6 and PA12 are considered to be well soluble in ionic liquids with coordinating anions, such as chloride, acetate, or dialkylphosphate [70]–[72].

2.4.1.2. Pyrometallurgical route

When water is restricted and waste generation must be controlled, pyrometallurgical approaches can be used [73]. The strategic phase transformation of REEs within the magnet is the main goal of high-temperature processes used on waste NdFeB magnets. The major non-REE components are effectively separated as an outcome of this conversion, which results in the formation of a new phase. Higher concentrations of the separated REEs are present in the subsequent phase, making them appropriate for the manufacture of RE metals through procedures like molten salt electrolysis or metallothermic reduction. The pyrometallurgical approaches for extraction that have been identified can be categorized as follows: roasting, liquid metal extraction, molten salt extraction, molten slag extraction, and electrochemical processing [74]–[78].

It's interesting to note that many of these pyrometallurgical techniques work best with magnet scrap that contains high concentrations. On the other hand, the less concentrated end-of-life magnet scrap could be processed with slag extraction procedure. However, it's crucial to remember that in these situations, later hydrometallurgical procedures like REE leaching are crucial [25].

On the other hand, high-temperature techniques are extremely sensitive to the oxidation state of REEs contained in magnetic waste [79], [80]. Optimizing these processes demands a thorough understanding of oxidation at high temperatures. This knowledge is critical for developing successful ways for recovering precious REEs such as Nd, Dy, and Pr from discarded permanent magnets.

The pyrometallurgical method has advantages such as no wastewater formation and a simpler process flow with few phases [81]. However, the pyrometallurgical liquid-phase processing entails certain drawbacks. Significant energy input is demanded by this approach, necessitate a large amount of energy and material purity, which is difficult to achieve with mixed trash feeds [68], [69]. Alternatively, within the realm of pyrometallurgical gas-phase processing, the utilization of extensive amounts of chlorine gas raises concerns due to its environmental implications [25], [82]. Finally, pyrometallurgy, which is commonly used in the processing of high-grade ores, has difficulties in the processing of low-grade ores [65].

2.4.2. Direct recycling strategies

Direct recycling, commonly referred to as closed-loop recycling, has several benefits that cut across the environmental, financial, and societal spectrums. The preservation of resources is one of the main advantages. Direct recycling helps to preserve ecological balance by recovering and reusing materials from end-of-life items, such as rare earth elements from permanent magnets [83].

Direct recycling greatly decreases the energy-intensive phases compared to primary production methods that require resource extraction, refining, and processing, lowering carbon emissions and reducing ecological impact. This strategy supports environmentally friendly behaviours and preservation of the environment. Direct recycling essentially provides a holistic answer that aligns with the objectives of resource conservation, energy efficiency, waste reduction, economic stability, and environmental responsibility. By adopting this strategy, society and industry make a huge step toward building a future that is more resilient and sustainable [62].

A closed-loop is produced by taking end-of-life electric motor stream, recycling NdFeB magnets, and integrating the final product inside the supply chain of the permanent magnets [23]. The extraction of REEs from these streams provides an additional source of metals in addition to traditional mining. However, it is critical to stress that, while recycling might reduce dependency on natural resource extraction, it cannot completely replace mining and primary metal production. This is owing to the complex interplay between raw material demand, the availability of recyclable sources, and the difficulties associated with processing specific end-of-life items to recover REEs [65].

Following material extraction, numerous potential direct routes for re-processing emerge. These pathways involve techniques such as powder resintering and HDDR processing [84] which will be explained in depth in later chapters.

These approaches are employed in the initial magnet production process and is necessary to adapt them to end-of-life permanent magnets. For instance, when dealing with recycled sintered NdFeB material, modifications are needed due to the elevated oxygen content. In recycled material, oxygen levels typically range from 2000 to 5000 ppm, significantly surpassing the oxygen content in primary cast NdFeB material, which typically falls between 300 and 400 ppm. Additionally, the end-of-life NdFeB magnets will contain a variety of magnet compositions, raising concerns about the consistency of magnetic performance that may be expected from magnets made of this material. Despite these possible disadvantages, direct recycling techniques often have less impact on the environment than indirect recycling because direct reprocessing needs less processing steps. As a result, it is expected that the price of producing magnets will also be decreased [25].

2.5. Gaps in the literature

In terms of resource preservation and sustainable material management, permanent magnet recycling is of utmost importance. However, the existing literature reveals numerous significant gaps that need for in-depth examination despite the growing acknowledgement of the necessity for efficient recycling systems. The main gaps in the body of existing knowledge are outlined in this section. Lack of thorough research into direct recycling methods for permanent magnets is one of the most obvious gaps in the literature. The literature shows a glaring gap in the thorough investigation of direct recycling procedures for permanent magnets, despite the fact that numerous indirect recycling methodologies have been investigated. This omission points to a major research deficit in the area.

The literature also reveals a lack of consensus on certain recycling procedures in the permanent magnet industry. There is a striking lack of agreement regarding the most effective and efficient approaches, even though numerous strategies have been presented for dismantling, separating, and recovering magnet materials. This gap gets wider by the divergent findings and suggestions from various research, which prevent the creation of uniform recycling processes. In-depth comparison studies that methodically assess and compare various procedures are required to close this gap, allowing the field to unite around widely accepted approaches.

Finally, within the permanent magnet direct recycling, another salient gap pertains to the lack of sufficient information regarding optimal process parameters and effective material handling techniques. However, because the complexities of process parameter optimization are not properly covered in the present literature, researchers and practitioners have little guidance in building effective recycling processes.

3 Methodology

3.1. Introduction to the chapter

This chapter delves into the extensive research and configuration of a permanent magnet direct recycling system in the context of the circular economy. The main objective of this chapter is to explain the meticulous process undertaken to address this fundamental research question.

In this regard, the following chapter clarifies the entire methodological path adopted to reach the conclusions that underpin this thesis. The research encompasses two fundamental phases. The initial phase presents the research effort, bifurcated into three key subdivisions: a comprehensive literature review, a patent landscape analysis, and an in-depth scrutiny of projects and companies related to the topic of study. This phase systematically discerns current methodologies in the field of circular economy, weighing their advantages and disadvantages. At the same time, it clarifies the current technological landscape and identifies the countries that are at the forefront of investment in the exploration and capitalization of permanent magnets. Overall, this phase provides a panoramic view of the status and evolutionary trajectory of permanent magnets in recent years.

The second phase embarks on the intricate task of configuring a direct permanent magnet recycling system. Here, the different recycling station alternatives are examined and evaluated, recommended parameters are proposed, and possible solutions are analysed.

The chapter is structured as follows:

- Section 3.2 presents the different research approaches and confronts them to conclude that a mixed method is the most appropriate in this study, since it is necessary to integrate quantitative and qualitative data to include the different dimensions of the subject.
- Section 3.3 presents the selection of a mixed-methodologies approach that stems from the multifaceted nature of this research requires a fusion of qualitative and quantitative insights. This chapter details a strategic combination of qualitative and quantitative exploration, encompassing projects, articles, and patents. This methodological confluence allows for a holistic exploration of the intricate dynamics and multiple dimensions of permanent magnet recycling.

- Section 3.4 describes the data collection process. It begins with an exposition of the keywords used for item retrieval and then moves on to a systematic explanation of the various filters used to refine the results, filtering out only the most relevant and pertinent items.

In summary, this chapter walks through the research undertaken to establish a configuration of a permanent magnet direct recycling system within the context of the circular economy. The following sections elaborate on the selected research approach, methodology selection, and data collection process, collectively forming the basis for the research conclusions.

3.2. Research method

To delve deeper into the research question, it is important to begin the research by establishing the methodology, and determining its qualitative, quantitative, or mixed approach. This fundamental choice requires a thorough understanding of both methodologies, delving into their characteristics and complexities.

3.2.1. Qualitative research

In the literature, qualitative research is distinguished by its investigation of phenomena's traits and qualities, which includes aspects such as context and varied views [85]. A more pragmatic definition emphasizes the use of language, rather than numerical data, for data collecting in qualitative research [86]. This sort of research comprises acquiring, analysing, and interpreting numerous non-numerical data types, such as language, in order to illuminate individuals' views and responses within their societal context [87].

The qualitative study seeks to rigorously examine the experiences of people affected by Social Reality in their natural environments. It takes an exploratory approach, attempting to understand the causality of occurrences or behaviours and unravel their unfolding in individual cases. It acts as a foundation for developing theories and hypotheses by utilizing qualitative data [88]. In-depth interviews, focus groups, case studies, and ethnography are some of the approaches used in qualitative research [87]. In essence, qualitative research entails an ongoing, iterative process of data collection and analysis [89]. Furthermore, as insights accumulate, the original research plan may necessitate adjustment and expansion [89].

In contrast to quantitative research's rigorous, sequential approach, qualitative research values flexibility, adaptability, and context responsiveness. According to research, the phases of sampling, data gathering, analysis, and interpretation are cyclical rather than rigidly linear.

Importantly, this approach fits the paradigm of qualitative research, characterized by its flexibility, openness, and contextual responsiveness. As Fossey et al. highlight in their 2002 study [89], qualitative research involves an iterative cycle in which sampling, data collection, analysis, and interpretation interact dynamically. This process reflects this iterative approach, continually refining search strategies and adapting the data set based on new insights.

This continuous refinement is driven by the evolving nature of the data and a commitment to completeness. It recognizes the fluidity inherent in qualitative research, where constant adjustments and adaptations are made to ensure that the research remains responsive to new information.

3.2.2. Quantitative research

Quantitative research comprises the systematic collection and analysis of numerical data with the goal of providing a concise description, prediction, or control over factors of interest. According to McLeod [88], the basic purpose of quantitative research is to test causal links between variables, forecast outcomes, and extrapolate conclusions to larger populations.

Methodologies such as experiments are commonly used to collect data, with the primary goal of precisely quantifying the variables. However, as complementary sources, channels such as questionnaires or controlled observations can also produce qualitative data. Quantitative data is frequently gathered using instruments such as surveys, rating scales, or closed-ended questions that produce numerical values or categorical replies [88].

3.2.3. Mixed research

The intricate dynamics of a permanent magnet recycling process, for example, can be thoroughly and effectively investigated using a mixed research methodology that combines quantitative and qualitative methodologies. This method combines the best elements of the two methodologies, boosting the overall breadth and validity of research findings by fusing quantitative insights with contextual knowledge.

Using both quantitative and qualitative methodologies together allow for a deeper comprehension of the topic. While qualitative insights delve into the underlying causes and contextual details, quantitative data reveals statistical trends and patterns. Researchers can cross-validate data using a combination of approaches, which strengthens the validity and dependability of the findings. Richer interpretations may result from discrepancies or consistency between quantitative and qualitative data. By placing quantitative data in context, qualitative research provides depth. It offers information on the "why" behind certain trends or patterns and sheds light on their practical applications. Quantitative data can support or refute qualitative ideas, supporting a deeper investigation of research topics. Qualitative data can also be used to drive the formulation of qualitative hypotheses.

A combined research strategy is quite advantageous for a thorough investigation of the permanent magnet recycling process. The complexities of recycling include different contexts, as industrial, technological, economic, and environmental aspects. A more complete picture is developed by combining quantitative information on recycling effectiveness, material characteristics, and economic viability with qualitative insights into the motives, difficulties, and perspectives.

3.3. Defining methodology

When setting out on the mission to establish a specific recycling pathway for permanent magnets, the data collection process becomes a crucial moment characterized by the complexity of its layers. The compelling need to holistically understand the dynamics of permanent magnet recycling demands a seamless integration of qualitative and quantitative perspectives. The inherent complexity of the scope of the study drives the adoption of a mixed methods approach, which seamlessly interweaves the strengths of these methodologies. This fusion stems from the recognition that certain dimensions of exploration require qualitative insights, allowing for the exploration of the nuances of behaviours and perceptions in the field of permanent magnet recycling. At the same time, the requirement for quantitative precision stems from the complexities involved in dissecting the technical design, economic efficiency, and material attributes of these magnets.

In the pursuit of configuring a direct recycling line for permanent magnets, the data collection process is a critical phase that comprises three distinct stages (1) database research utilizing targeted keywords, (2) patent landscape analysis, and (3) industry research. Each stage plays an indispensable role in developing a comprehensive framework for direct recycling. By seamlessly intertwining qualitative exploration with quantitative rigor, this methodology not only unravels strategic and innovative avenues for direct recycling but also enables the development of a comprehensive framework for direct recycling.

The first stage is a comprehensive literature review, which provides an in-depth analysis of the relevant body of literature. A literature review's nature allows for methodological flexibility, allowing for the use of qualitative or quantitative frameworks depending on the topic of inquiry. This strategy can consolidate past research, build knowledge foundations, and promote the development of strong conclusions [90]. It begins to build a framework once data collection and gathering of relevant information is completed. This stage functions as a navigational tool to discover and understand the concepts regarding permanent magnets recycling, the different strategies that exist to perform it, and the advantages and disadvantages associated with each approach.

However, its importance goes further than mere exposure. This stage also identifies in depth the sequential steps that permanent magnets undergo to maintain their magnetic properties after undergoing a recycling process. In essence, this literature review allows exploring the strategic pathways as well as the processes, parameters, and technologies, equipping the research with the knowledge to make informed decisions and understand the dynamics of permanent magnet recycling.

Moving forward, the second stage of this data collection process involves a thorough patent landscape analysis. In this phase, it is delved into patent databases to meticulously examine the intellectual property landscape surrounding permanent magnet recycling. This analysis not only sheds light on the inventive pathways pursued by researchers, innovators, and industries but also offers insights into the global distribution of patent activity. By scrutinizing patents, it can be identified the countries with the most substantial patent contributions, discern the key applicants driving innovation, and discern patterns of collaboration or competition in the field. This comprehensive review of patents not only informs this research with the latest technological advancements and emerging strategies but also provides a holistic view of the global patent landscape. This inclusive understanding allows to make informed decisions and navigate the intricate web of permanent magnet recycling strategies, ensuring that the direct recycling line is optimized for both technological excellence and sustainable impact.

Concluding the data collection process, the third stage involves a fundamental and widespread exploration conducted through popular search engines. This basic search approach is integral to cast a wider net, encompassing a broader spectrum of information beyond scholarly databases. By employing this technique, it is aimed to uncover a comprehensive range of materials, which may include articles, reports, and discussions from a variety of sources. While this phase lacks the in-depth analysis of the literature review, it serves as an invaluable means to capture diverse insights, perspectives, and practical considerations. The outcomes of this stage contribute a multidimensional perspective that enriches the understanding of the challenges, trends, and innovative endeavours associated with permanent magnet recycling.

In essence, the combination of these three distinct stages forms a robust foundation for the data collection process. Each stage uniquely contributes to the understanding, ranging from a comprehensive overview to a detailed patent analysis and concluding with a broad search. This holistic approach contributes to a diverse range of insights, culminating in a comprehensive narrative that informs the configuration of an effective direct recycling line for permanent magnets.

3.4. Data collection

According to experts, there are two types of data-gathering procedures that can be used in research: primary data and secondary data [91]. Scholars define primary data as material obtained independently by the researcher through interviews or questionnaires Bryman and Bell [92]. Secondary data, on the other hand, refers to information that has previously been acquired by other scholars or organizations, such as books, documents, and articles. Secondary data was gathered and analysed for the purposes of this thesis.

3.4.1. Sample selection

Stage I: Database research using keywords

The first phase of the sample selection process involved the formulation of an initial search formula. This formula was developed to encompass keywords closely related to permanent magnets and served as the basis for subsequent data collection efforts.

To improve the accuracy of the formula, an iterative process of refinement was followed. This fine-tuning was instrumental in shaping the search parameters and obtaining a more relevant data set.

This research began in February 2023, a comprehensive review was conducted in the SciVerse Scopus online database. Using Boolean terms and advanced search techniques, a comprehensive scan of titles, keywords, and abstracts was conducted.

To further narrow the scope, it focused on specific academic areas, such as "Engineering", "Energy", "Environmental Science", "Chemical Engineering", "Materials Science" and "Chemistry". In addition, the search was limited to articles published in the English language to ensure consistency with the scope of this research.

With the following formula, a total of 500 results were found:

(TITLE-ABS-KEY ("reus*") OR TITLE-ABS-KEY ("recycl*") OR TITLE-ABS-KEY ("remanufactur*") OR TITLE-ABS-KEY ("circular economy")) AND (TITLE-ABS-KEY ("electric motors") OR TITLE-ABS-KEY ("permanent magnet*") OR TITLE-ABS-KEY ("electric* machin*")) AND PUBYEAR > 2005 AND PUBYEAR < 2024 AND PUBYEAR < 2025 AND (LIMIT-TO (DOCTYPE , "ar")) AND (LIMIT-TO (SUBJAREA , "ENGI") OR LIMIT-TO (SUBJAREA , "ENER") OR LIMIT-TO (SUBJAREA , "ENVI") OR LIMIT-TO (SUBJAREA , "MATE") OR LIMIT-TO (SUBJAREA , "CENG") OR LIMIT-TO (SUBJAREA , "CHEM")) AND (LIMIT-TO (LANGUAGE , "English"))

Subsequently, the abstracts of the published papers were subjected to meticulous evaluation to determine their suitability for inclusion in the final dataset. The main factor guiding the inclusion process was the relation between circular economy and electric motors. Articles on topics outside the scope of this research, such as recycling of other elements using magnetism, energy and power applications, and magnetic separation of plastics were deliberately omitted. In total, 341 publications were excluded based on these specific criteria.

After rigorous screening, 159 studies were selected that met the selection criteria. The entire exhaustive process is illustrated visually in Figure 1, which shows the successive steps of the final selection data set.

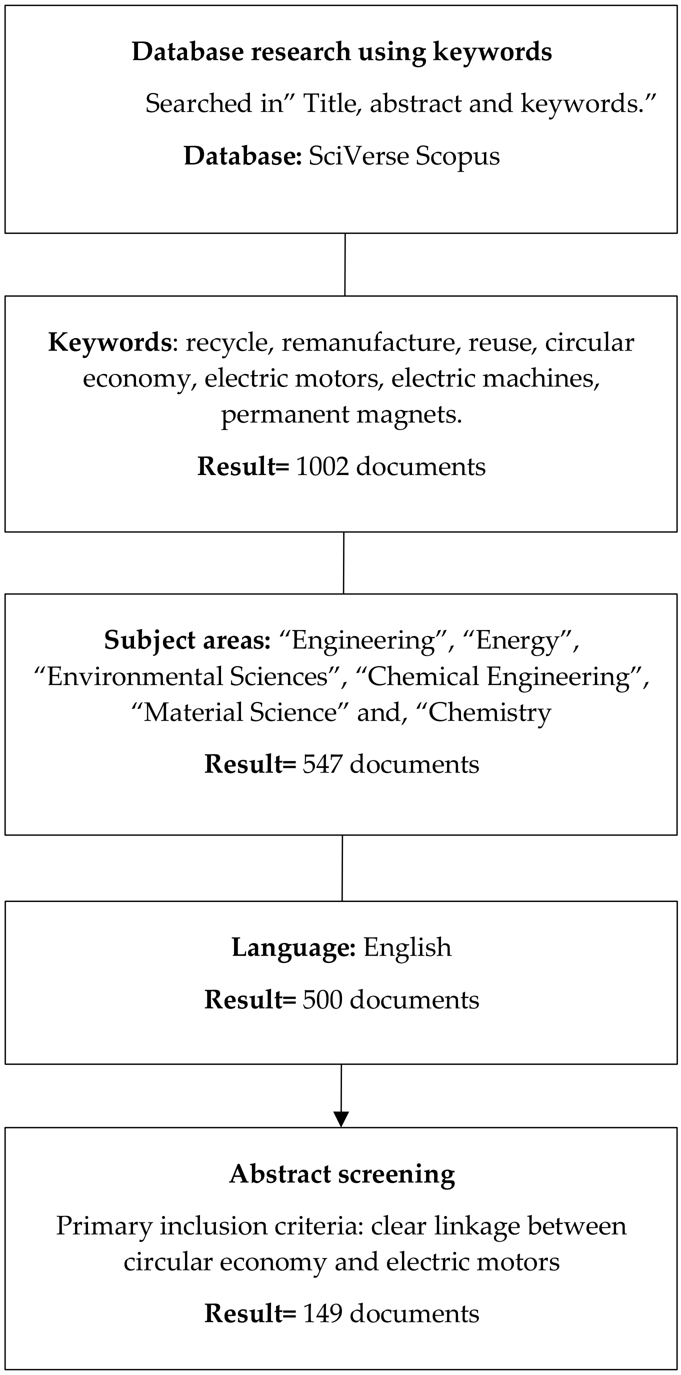

Figure 1. Filtering process for the article database research.

Stage II: Patent landscape analysis

The initial phase of the patent landscape analysis encompassed the formulation of an initial search formula, designed to encompass keywords closely linked to permanent magnets. This search formula served as the foundation for subsequent data collection efforts.

An iterative approach was then employed to refine the search formula. Through this method, non-specific terms unrelated to the research objectives, such as those pertaining to food, music, and plastic waste, were meticulously eliminated. This iterative refinement was essential in honing the search parameters and achieving a more pertinent and precise dataset.

The research initiative was inaugurated in February 2023, leveraging the capabilities of Google Patents to efficiently obtain a substantial volume of patent information. The keyword framework was designed to emphasize the realm of permanent magnets and was further tailored to target specific patent codes and fields of interest using "OR" as an Boolean operator in the researched formula.

The key patent codes and fields of interest included:

Y02W: Climate Change Mitigation Technologies in Information and Communication Technologies.

Y02P: Climate Change Mitigation Technologies in Processes or Apparatus.

H01F: Magnets; Inductances; Transformers.

B02C: Crushing, Pulverizing, or Disintegrating; Milling.

C22B: Extracting or Refining of Non-Ferrous Metal Compounds.

In a strategic effort to narrow the scope, the search was concentrated within distinct patent classifications, such as those related to "Engineering," "Materials Science," and other pertinent domains. Additionally, preference was given to patents published in the English language, ensuring alignment with the research's objectives.

The refined formula utilized for the search was:

("Permanent magnet" OR "Magnet" OR "Magnets") NEAR5 (Recycl$ OR Remanufactur$ OR Reus$)

Following the data extraction, an evaluation was conducted on the abstracts of the acquired patents. This evaluation aimed to determine the suitability of each patent for inclusion in the final dataset. The primary criterion for inclusion was the evident relationship between circular economy principles and permanent magnets, which constituted a pivotal theme of the analysis.

Patents that deviated from the research focus, such as those pertaining to subjects like waste disposal, non-relevant chemical processes, and greenhouse gas reduction, were intentionally excluded (exemplified by patent codes B03C, B01J, Y02E, B29B, B09B, B65D, B65F, B07B, B01D, B03B, C04B, C02F, B23Q, and C21B). This discerning curation process led to the exclusion of 4,729 patents, ultimately resulting in the compilation of a dataset of 2,329 patents that closely aligned with the selection criteria.

The comprehensive journey of patent screening and selection is visually represented in Figure 2, illustrating the sequential stages that culminated in the establishment of the definitive dataset. This exhaustive process, akin to the provided example, underscores the rigorous methodology employed to gather the most pertinent patents for the landscape analysis.

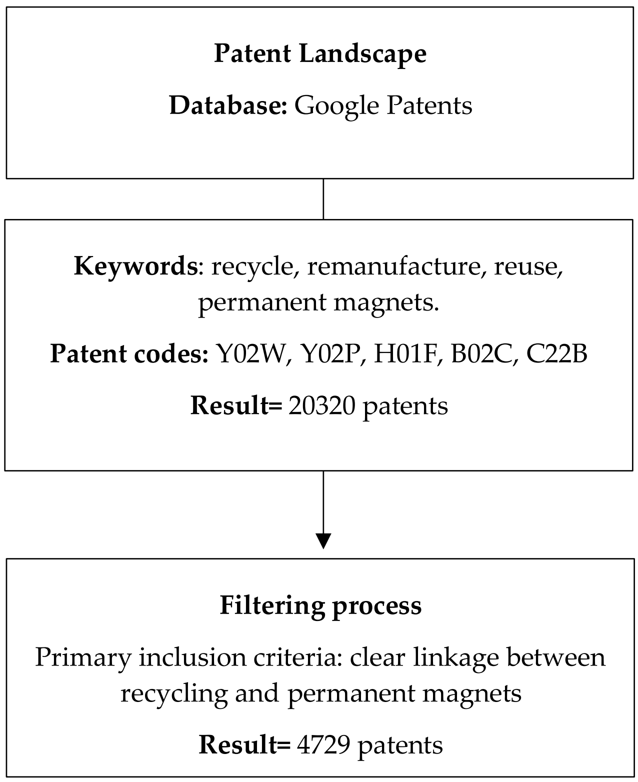

Figure 2. Filtering process for the patent analysis.

Stage III: Industry research

In February 2023, a basic search was conducted on Google to identify relevant companies and projects engaged in permanent magnet recycling. The search was guided by a concise formula that included key phrases such as "companies working on permanent magnet recycling," "permanent magnet recycling solution," and "recycling companies for earth rare magnets."

Upon executing the search, a total of 7 companies and 8 projects were identified as potentially relevant to the research objectives. Subsequently, a meticulous evaluation process was initiated to assess the suitability of each company or project for inclusion in the research thesis. The primary criterion for inclusion was the clear demonstration of involvement in recycling processes related to permanent magnets.

During this evaluation, a deeper review was conducted to ascertain the extent of each company's or project's direct recycling strategies for permanent magnets. Companies and projects that showcased explicit recycling methodologies were subjected to further analysis, with a particular focus on identifying and determining the viability of recycling stations. This resulted in a subgroup of 4 companies and 6 projects.

The systematic evaluation process allowed for the identification of companies and projects that aligned with the core research goal of understanding and evaluating direct recycling strategies for permanent magnets. This rigorous assessment ensured that only those entities with substantial recycling efforts and clear pathways for recycling were considered for more comprehensive analysis within the context of the thesis (Figure 3).

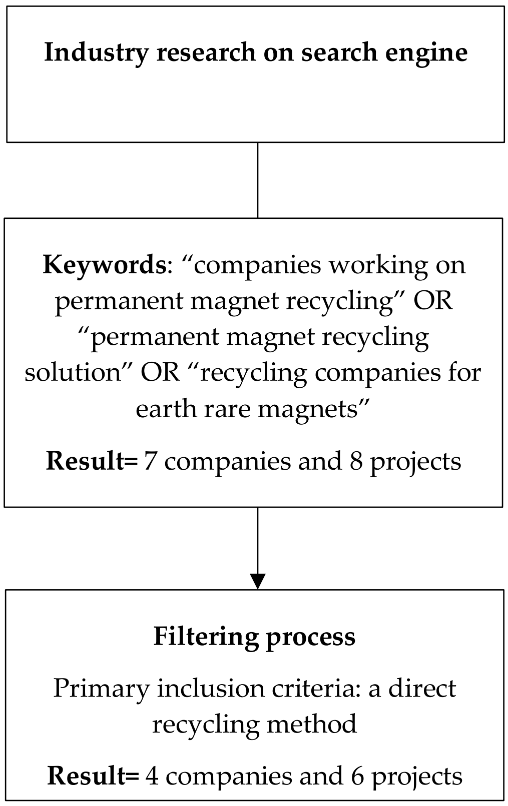

Figure 3. Filtering process for the industry research.

4 Results

4.1. Introduction to the chapter

The findings of a thorough investigation into the creation of a circular economy-compliant system for the direct recycling of permanent magnets are revealed in this chapter. This chapter's main goal is to describe the thorough process that was followed in order to address the main research question, taking into account both the complexity of the approach and the extent of the information acquired.

The research project was divided into two key stages, each with its own goals and contributions. The first phase is a threefold effort that includes a thorough analysis of the scientific literature, a thorough examination of the patent landscape, and a careful examination of relevant businesses and projects. Current approaches relevant to the circular economy field are assessed critically through this comprehensive lens, highlighting their benefits and drawbacks. The technological landscape is analysed concurrently, revealing countries leading permanent magnet research and application. Together, these aspects create a comprehensive picture of the development and status of permanent magnets.

The investigation digs into the complex web of setting up a direct recycling environment for permanent magnets as it moves into the following step. Finally, diverse recycling routes and tactics are carefully investigated within this environment.

The organization of this chapter takes form as follows:

- Section 4.2 provides an explanation of the conclusions reached after a thorough investigation of academic databases. Through a synthesis of academic literature, it reveals trends, insights, and gaps within the field of permanent magnet recycling.
- Section 4.3 provides information about the permanent magnet industry's technological landscape. This section illustrates trends, discoveries, and advancements gleaned from a thorough analysis of relevant patents.
- Section 4.4. explores the corporate and project environment and presents a complex variety of businesses and initiatives related to permanent magnet recycling. It reveals information on current tactics, innovation hot spots, and important projects.
- Section 4.5. carefully describes various recycling routes as the conclusion of the identification of permanent magnet recycling options.

4.2. Descriptive results of database research

The analysis of the descriptive results helps to understand in depth the key trends in the research world related to the strategies and concepts of circular energy applied to permanent magnets.

The descriptive results of this stage included two samples of journals:

1) **All journals**, results of the research formula
2) **Selected journals**, here the most relevant journals are included considering two criteria:
    - Belonging to Q1 or Q2 of SJR ranking.
    - Journals with at least three publications about permanent magnets in the Circular economy (CE) framework.

The subset of journals makes up about 23% of the total number of journals on the dataset but account for a large 53.4% of all papers in the group. This emphasizes their significant influence on the development of the permanent magnet recycling topic.

For all journals analysis, Table 1 shows the most cited articles within the sample. The articles in this collection mostly cover the years 2011 to 2015, this temporal concentration may imply that the research and publication activities connected to permanent magnet recycling and the recovery of rare earth elements peaked during this period. This can point to a developing interest or a turning point in the area at this moment.

The articles appear in a variety of journals, with a focus on "Green Chemistry," "Environmental Science and Technology," and "Hydrometallurgy." The choice of these journals would suggest that the research is multidisciplinary in character, incorporating environmental, chemical, and metallurgical factors in the hunt for sustainable recycling methods. The titles and subjects of these articles reveal several recurring themes. The topics of hydrometallurgy, life cycle analysis and urban mining highlight the emphasis on environmentally responsible and sustainable techniques for recovering rare earth elements from end-of-life items.

Regarding the distribution of the research focus (circular economy in general, recycling, remanufacturing or reusing) a clear trend can be observed in Figure 4. Recycling appears to be the approach that has been the subject of the greatest investigation, with 113 studies. This suggests that many sustainability and environmental research initiatives are likely to centre on recycling.

In Figure 5, "Material crisis" appears to be a topic of considerable interest and concern within the context of the circular economy, as seen by the nine papers that are specifically devoted to it. This means that academics and researchers may be concentrating on investigating problems with resource depletion, scarcity, and sourcing concerns that affect the viability of circular economic models.

Specifically, in the recycling strategy, “Recovery Method” has been the subject of 82 studies (Figure 6), making it clear that it is the recycling field's most investigated and explored subtopic. Recovery methods relate to the methods and procedures used to extract valuable materials from waste streams, highlighting the need of innovative recycling approaches and real-world solutions.

Figure 7 presents the distribution on research interest in remanufacturing subtopics with remanufacturing “product” being the most studied. And finally, Figure 8 shows “Direct reuse” subtopic as the most popular among reusing research.

For the analysis of selected journals, in Figure 9 it can be seen a quadrant chart that tries to determine the relationship of the journals, their prestige, and their interest in the subject. The number of papers published (x-axis) and the Journal Rank Indicator (y-axis), which indicates the impact, influence, or prestige of the journal, are used to create the figure. A certain range of publications and the journal position are represented by each quadrant.

Journal Rank Indicators are a metric for evaluating the quality, significance, and reputation of scholarly journals in a certain field of study. These indicators aid in the understanding of a journal's importance in terms of its influence, credibility, and value of the research it publishes. In this case, the metric used called SJR, was created by Scopus and is based on the notion that not all citations are equally valuable. It considers the citation journal's reputation. A higher SJR rating denotes the journal's better visibility and relevance within its field.

As shown in the upper right quadrant, the only journals with a Q1 ranking that have published more than five articles on this subject are “Green Chemistry”, “Environmental Science and Technology”, and “ACS Sustainable Chemistry and Engineering”. Several journals stand out in the upper left quadrant even though they are in Q1 but have not published many articles.

In the lower right quadrant, “Journal of Sustainable Metallurgy”, stands out as the journal with the most papers published in all the dataset, however, it is ranked as Q2, so its relevance is not as high as that of the previous journals.

In Figure 10, it can be noted the evolution of the number of total papers published by the selected journals compared to the number of papers published related to permanent magnets in the context of the circular economy. The dataset depicts a timeline from 2006 through 2022, a period in which the publishing scene witnessed significant changes.

Table 1. Most cited articles in the sample

Author	Title	Year	Journal	Cited by
Massari S.; Ruberti M.	Rare earth elements as critical raw materials: Focus on international markets and future strategies	2013	Resources Policy	539
Vander Hoogerstraete T.; Wellens S.; Verachtert K.; Binnemans K.	Removal of transition metals from rare earths by solvent extraction with an undiluted phosphonium ionic liquid: Separations relevant to rare-earth magnet recycling	2013	Green Chemistry	276
Rademaker J.H.; Kleijn R.; Yang Y.	Recycling as a strategy against rare earth element criticality: A systemic evaluation of the potential yield of NdFeB magnet recycling	2013	Environmental Science and Technology	211
Tunsu C.; Petranikova M.; Gergorić M.; Ekberg C.; Retegan T.	Reclaiming rare earth elements from end-of-life products: A review of the perspectives for urban mining using hydrometallurgical unit operations	2015	Hydrometallurgy	192
Gutowski T.G.; Sahni S.; Boustani A.; Graves S.C.	Remanufacturing and energy savings	2011	Environmental Science and Technology	179
Sprecher B.; Xiao Y.; Walton A.; Speight J.; Harris R.; Kleijn R.; Visser G.; Kramer G.J.	Life cycle inventory of the production of rare earths and the subsequent production of NdFeB rare earth permanent magnets	2014	Environmental Science and Technology	179
Vander Hoogerstraete T.; Binnemans K.	Highly efficient separation of rare earths from nickel and cobalt by solvent extraction with the ionic liquid trihexyl(tetradecyl)phosphonium nitrate: A process relevant to the recycling of rare earths from permanent magnets and nickel metal hydride batteries	2014	Green Chemistry	175
Riaño S.; Binnemans K.	Extraction and separation of neodymium and dysprosium from used NdFeB magnets: An application of ionic liquids in solvent extraction towards the recycling of magnets	2015	Green Chemistry	160
Du X.; Graedel T.E.	Global rare earth in-use stocks in NdFeB permanent magnets	2011	Journal of Industrial Ecology	150
Roosen J.; Spooren J.; Binnemans K.	Adsorption performance of functionalized chitosan-silica hybrid materials toward rare earths	2014	Journal of Materials Chemistry A	148

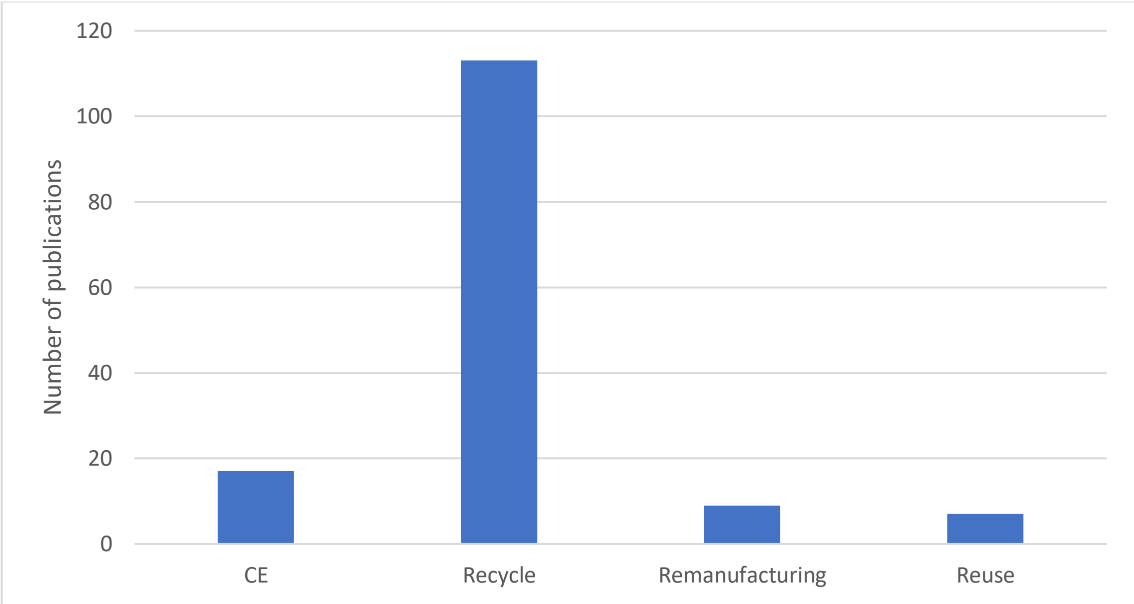

Figure 4. Distribution on research focus by general approach or specific circular economy strategy.

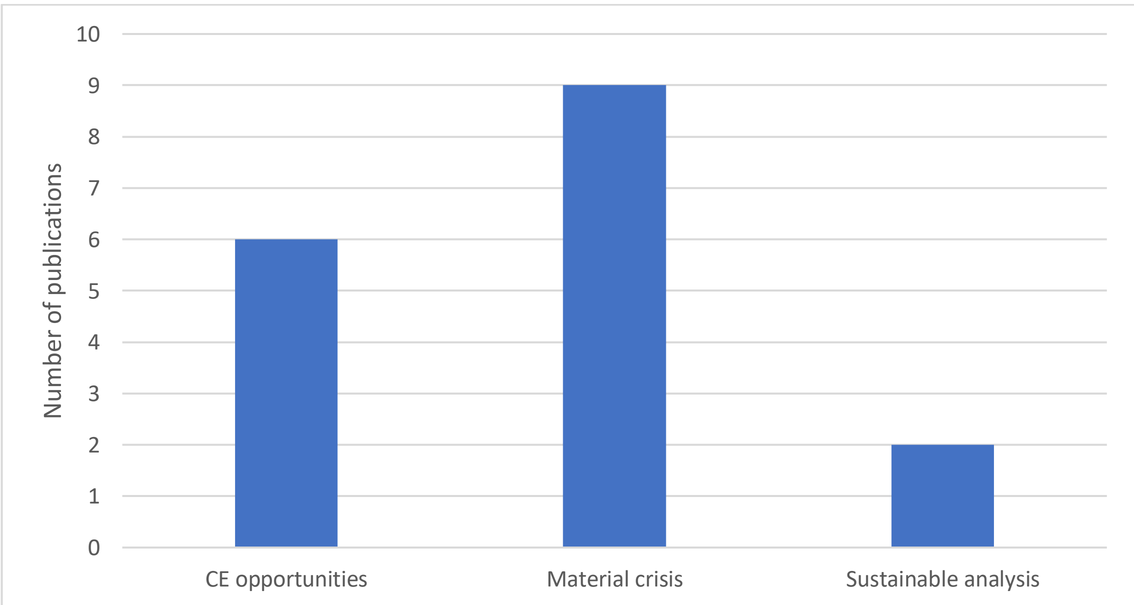

Figure 5. Distribution on research focus of papers in general circular economy strategies.

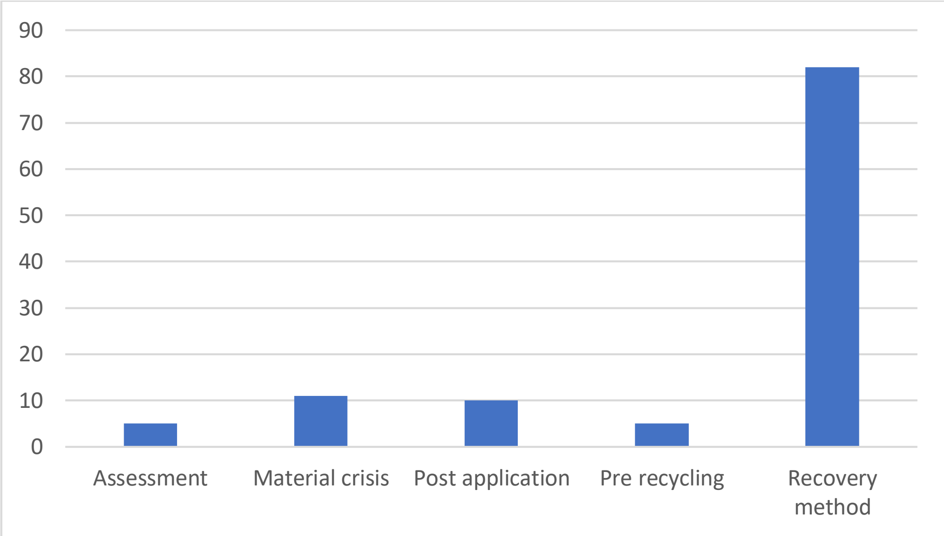

Figure 6. Distribution on research focus of papers in recycling.

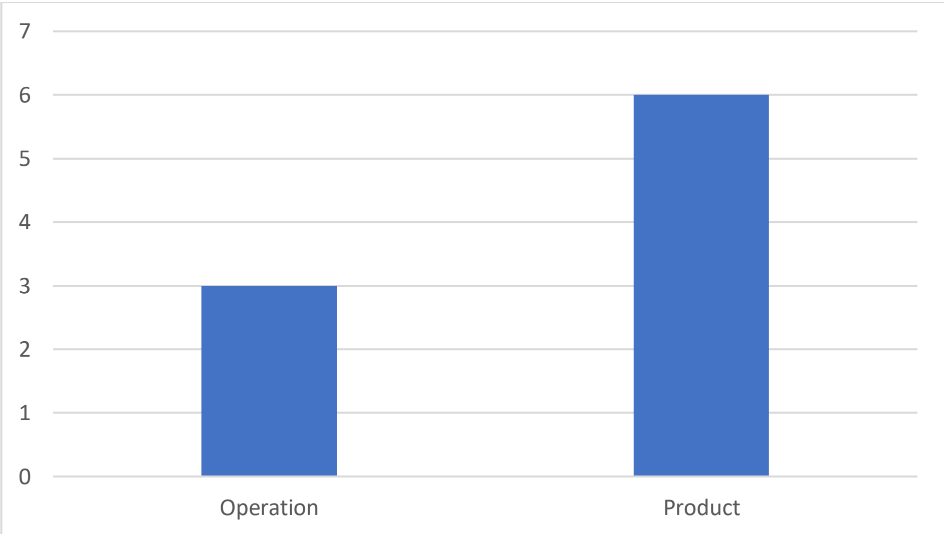

Figure 7. Distribution on research focus of papers in remanufacturing.

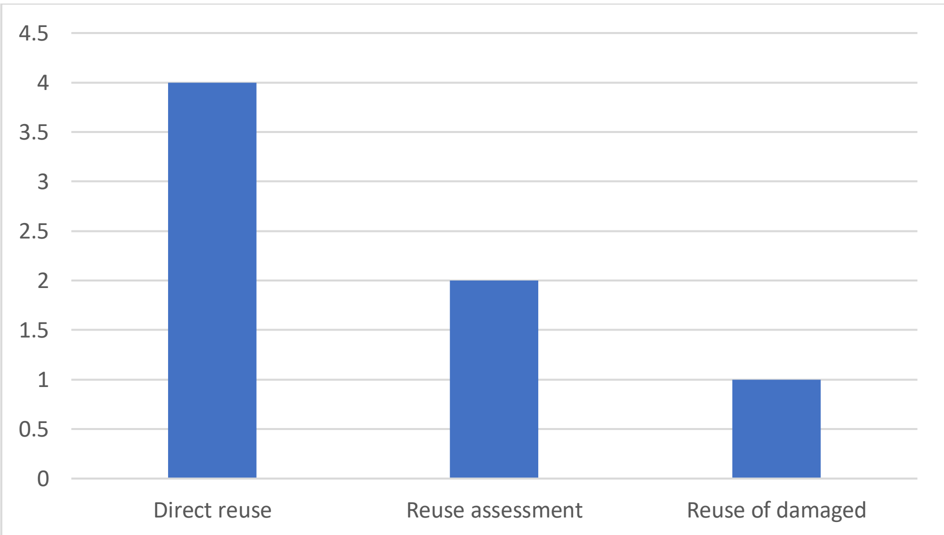

Figure 8. Distribution on research focus of papers in reusing.

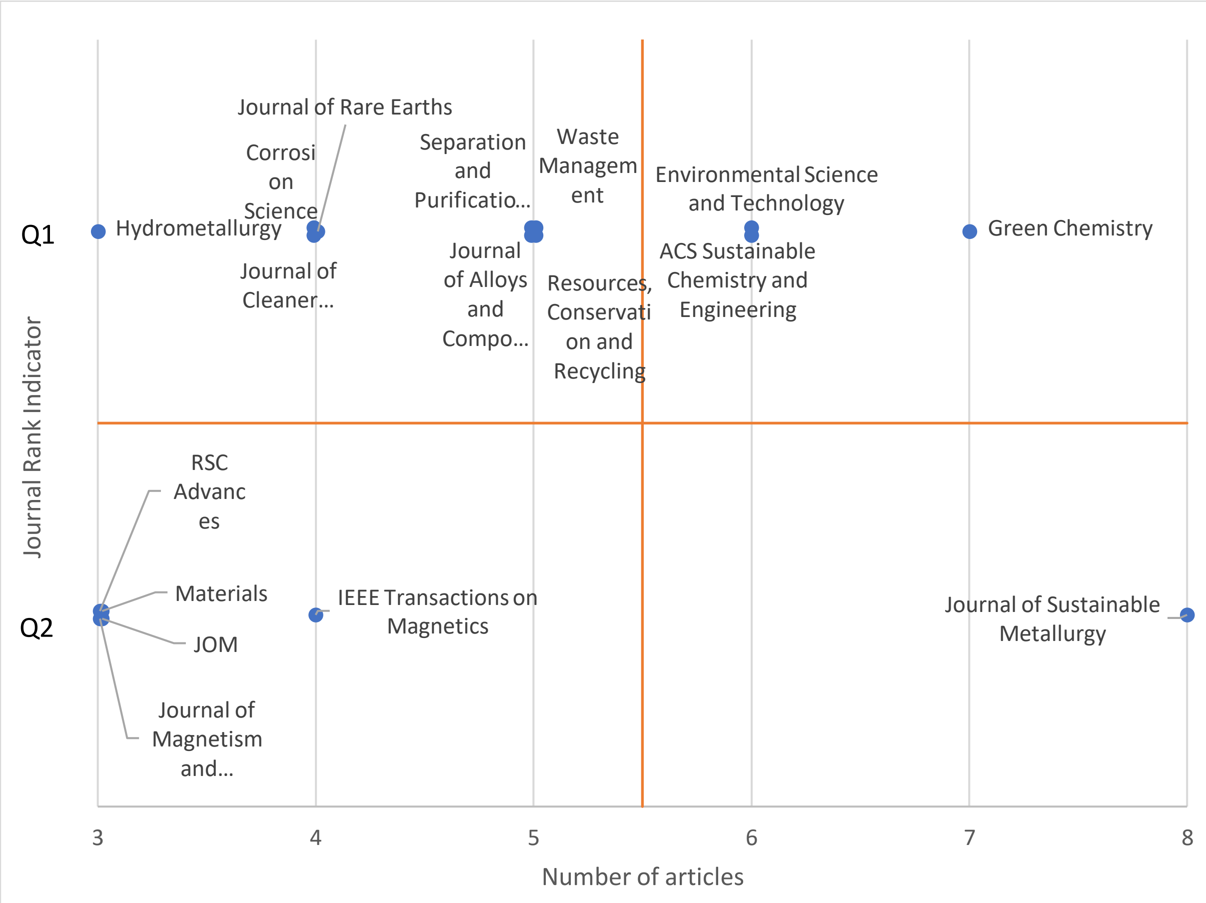

Figure 9. Journals per ranking and number of articles.

The initial years, from 2006 to 2011, had a very low number of papers on permanent magnet recycling, with periodic interest peaks in 2008 and 2011. Then, there was a noticeable increase in research output from 2012 to 2016 as an apparent result of rising scholarly interest in the subject. There was a striking increase in research activity and in the number of articles published in the years 2014 and 2015. This time frame may indicate a crucial turning point for the subject, with increased focus and potential innovations in permanent magnet recycling techniques. And despite a minor decline in research production in 2016, it remained generally steady from 2017 to 2020, indicating a persistent interest in the subject. In comparison to the years before, the data for 2021 and 2022 indicate a small fall in research output. However, this could be ascribed to a few things, such as changes in financing priorities, developments in technology, or shifting academic environments.

In Figure 11 it can be observed the growth rate of publications concerning permanent magnets and the rate of general publications. From this, it can be inferred that the growth has increased in both cases, however, the growth of permanent magnets has been higher in percentage terms, increasing almost 5 times in the last ten years.

Although the values are not abysmal, it is possible to identify a trend towards research on this under-researched topic.

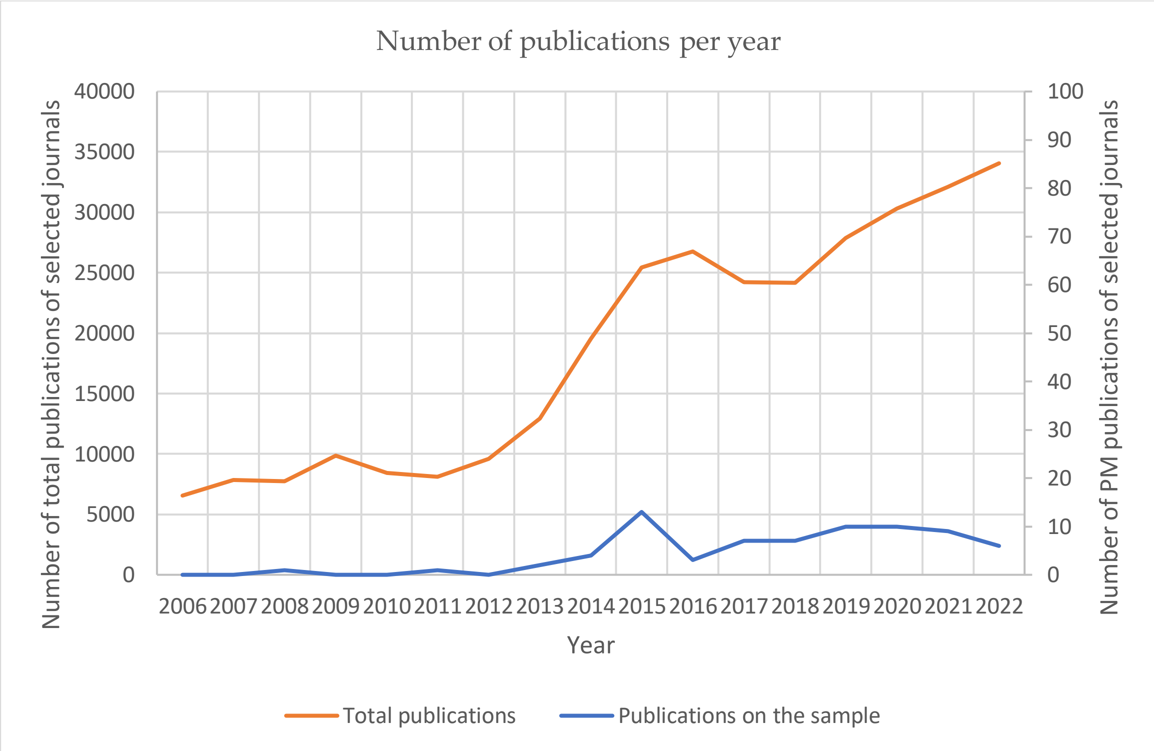

Figure 10. Number of total publications per year vs number of publications on the sample per year (another scale) from selected journals.

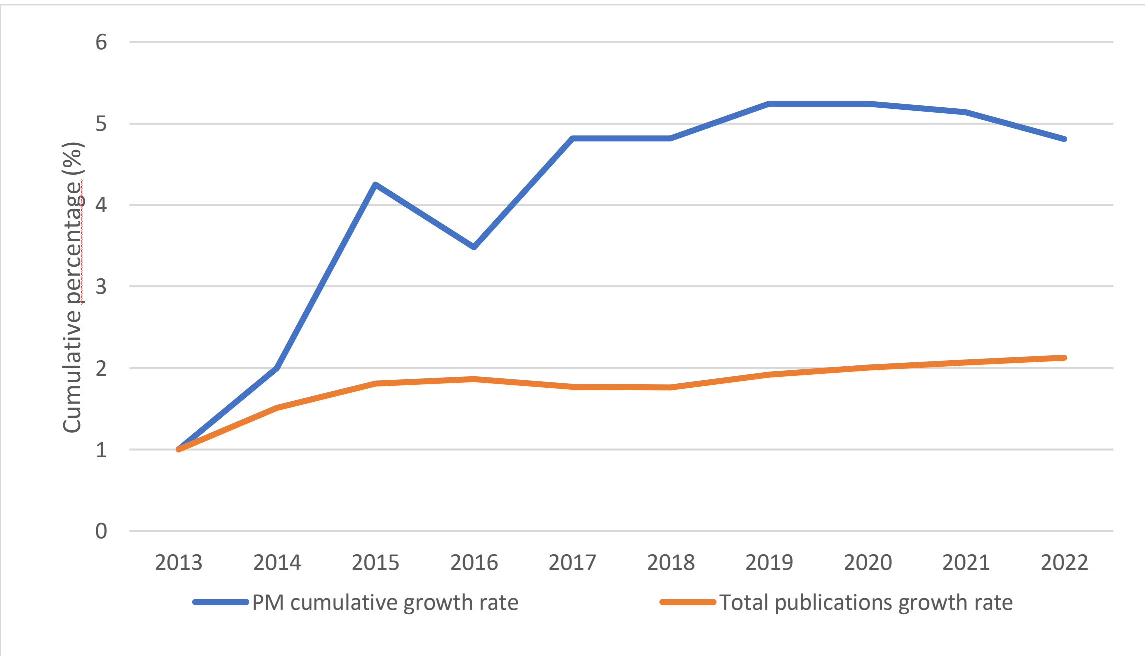

Figure 11. Cumulative growth rate of publications of selected journals (permanent magnets in the CE framework vs total publications).

4.3. Descriptive results of patent analysis

This analysis intends to shed light on how permanent magnet recycling patents are distributed among various nations and patent offices. The information comprises of the total number of published patents for each nation or patent office related to permanent magnet in the context of circular economy.

Figure 12 positions China far ahead, which shows that its industrial and research sectors place a lot of emphasis on permanent magnet recycling. The fact that Japan is in second place suggests that it has a track record of technological advancement in the recycling and magnets fields. The United States comes in third, demonstrating a substantial interest in the subject, probably because of its highly developed technological environment.

The presence of China, Japan, and South Korea in the top patent-producing nations reflects the area's emphasis on manufacturing, technology, and innovation in the fields of magnets and recycling in Asia.

Nevertheless, Figure 13 shows the distribution of patents among numerous nations, such as Australia, Canada, Brazil, and Russia, demonstrating a widespread understanding of the significance of environmentally friendly approaches to magnet recycling.

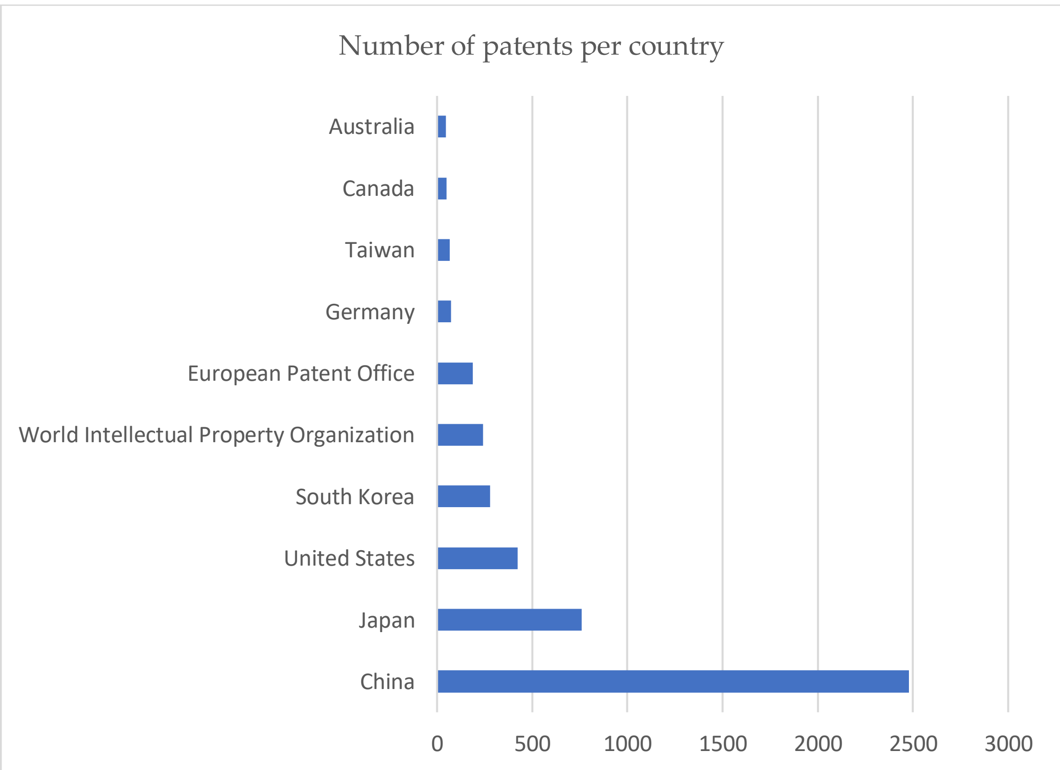

Figure 12. Patent distribution in the top 10 countries.

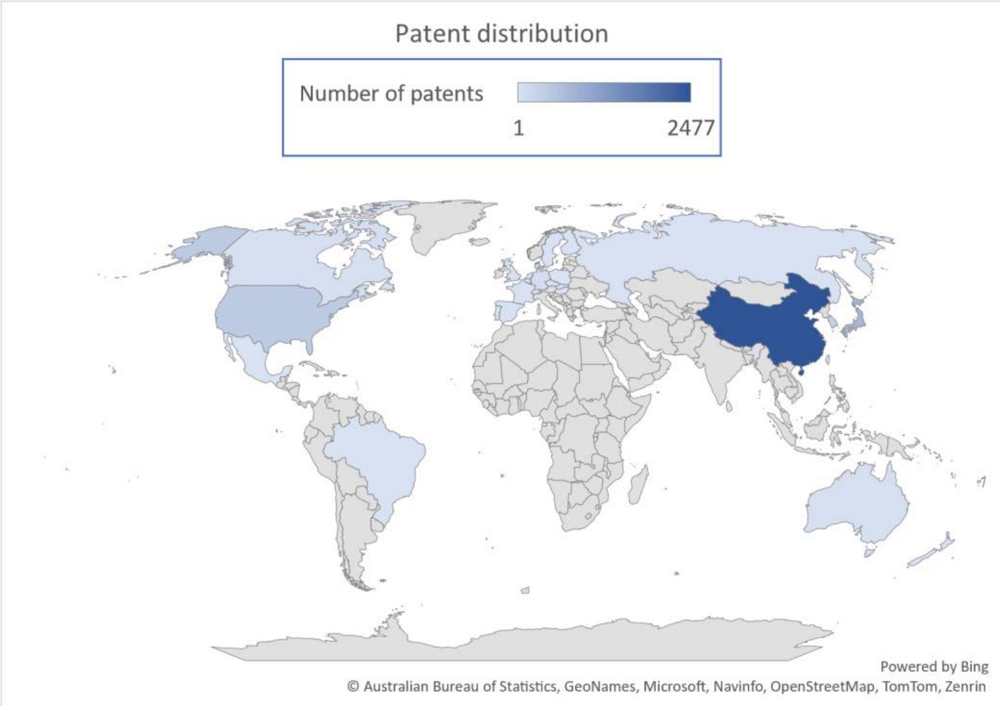

Figure 13. Patent distribution around all countries.

Finding the most pertinent patent holders is another crucial step, and the dataset includes many patents for numerous companies that are actively working in this area.

Japanese companies, including Hitachi Metals, Ltd., Shin-Etsu Chemical Co., Ltd., and Mitsubishi Materials Corporation, are prominent players in the field of permanent magnet recycling. Collectively, they hold a significant number of patents, underscoring Japan's leadership in this area (Figure 14).

The list of significant patent owners includes entities in nations other than Japan, including China (Beijing University of Technology, Jiangxi University of Science and Technology, University of Science and Technology Beijing and Xinfeng County Baotou Steel Xinli Rare Earth) and UK (The University of Birmingham and Seren Technologies). This indicates that recycling permanent magnets is a diverse and global commitment.

The presence of an academic institution and a company the UK implies that academics and business in this country are working to advance research and innovation in permanent magnet recycling.

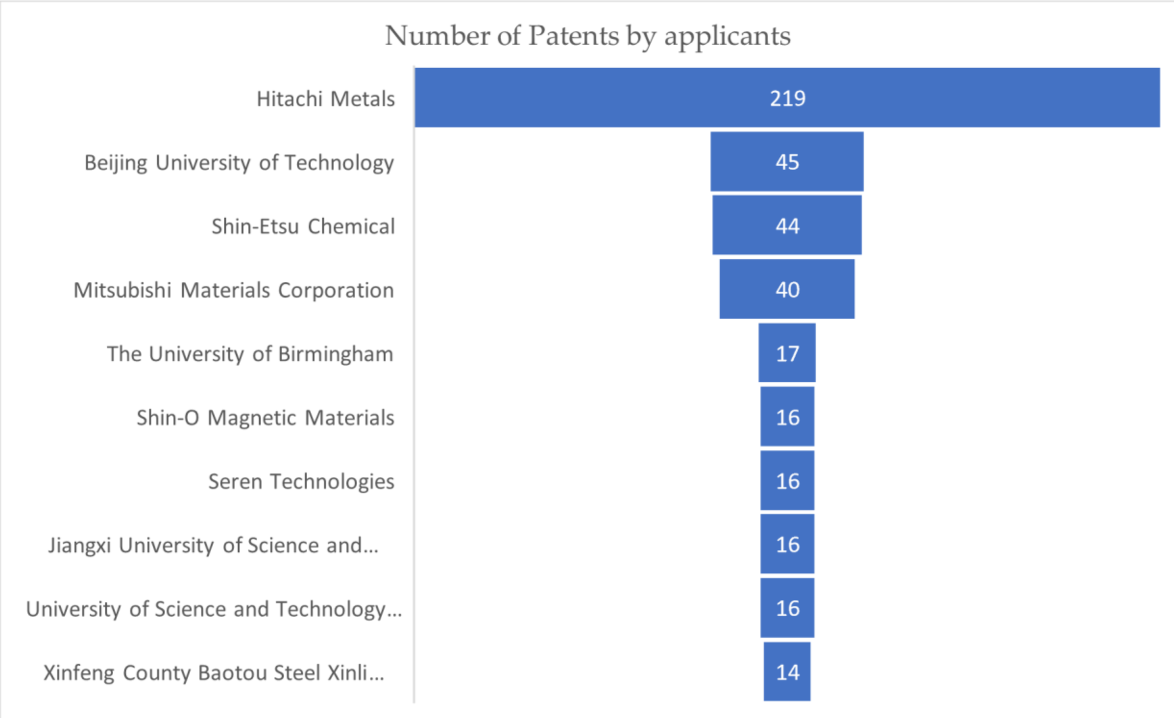

Figure 14. Top 10 patent holders.

Furthermore, in Figure 15, the evolution of the number of patents all over the world, the evolution of number of patents of China and, the evolution of number of patents in Europe are presented. It is evident from the data that China has significantly contributed to the rise in permanent magnet recycling patents and that has consistently submitted more patents than any other country throughout the years.

The number of patents issued in this industry by China has been steadily increasing, and the growth rate has accelerated recently. China is a prominent player in the world of patents, so it is evident that the worldwide growth in this area is being driven by China's expansion.

According to the data, it is reasonable also to conclude that the patent growth in the permanent magnet recycling area in the rest of the word has not followed the China's trend. In addition, it is important to note that the European contribution has been almost constant over the years and no growth has been seen.

In addition, the total number of patents in Europe, adding up all years (379) and is barely higher than the number of patents in China during 2023 (365) which is quite alarming and indicative of the large lag in terms of patents and research concerning permanent magnets in the context of the circular economy. This is a global concern due to the high concentration of patent information and breakthroughs in just one country.

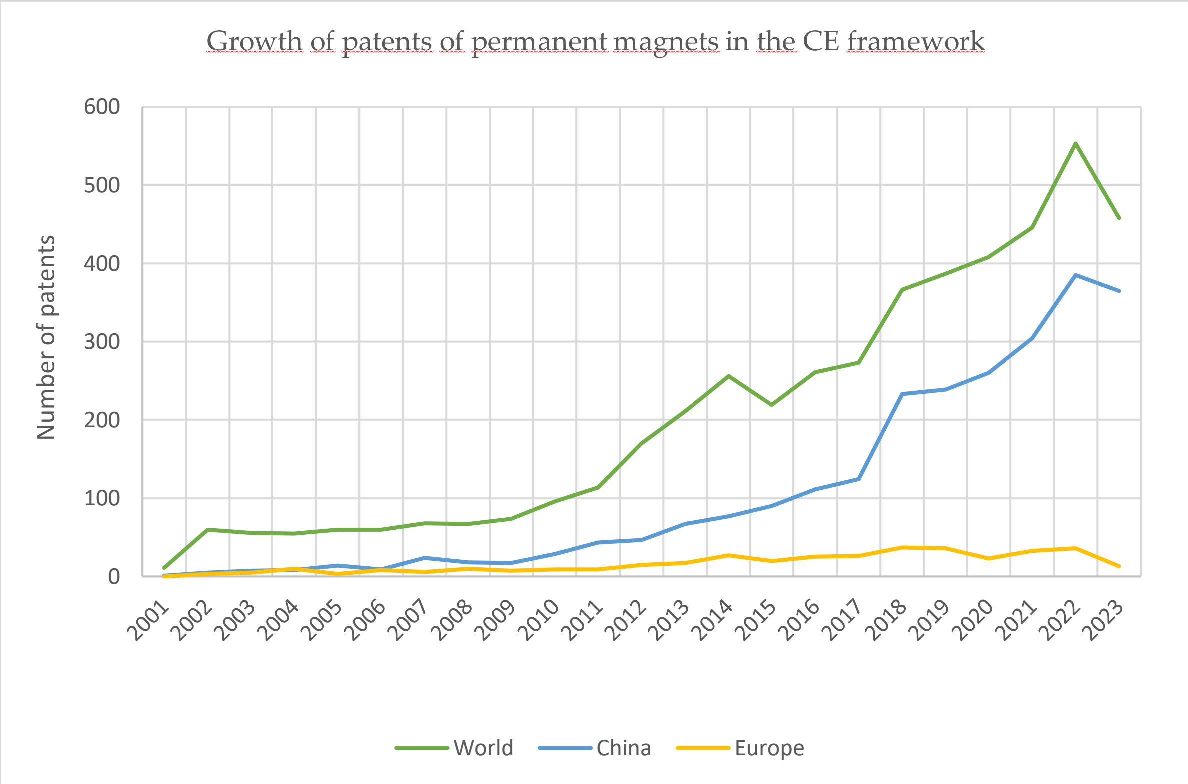

Figure 15. Patents evolution. World, China, and Europe.

4.4. Descriptive results of industry research

Several notable initiatives focusing on the recycling of rare earth magnets have been initiated in Europe starting from 2010. These include prominent projects like MORE [35], REMANENCE [93], EREAN [94], RECVAL [95], REProMAG [96], REE4UE[97], SUSMAGPRO [83] and VALOMAG [98] (Table 2). The high number of projects suggests that in the last years, European Union has increased economic and academic efforts for achieve a sustainable management of permanent magnets.

Most of these projects (MORE, REMANENCE, RECVAL, SUSMAGPRO and VALOMAG) were extensive research with the aim of determine the best ecological and economical solutions between direct and indirect recycling alternatives, including the development of concepts and technologies of components and material for the recycling process. From these, SUSMAGPRO [83] could be highlighted because its practical approach conformed by four pilot pants with the objective of produce more than 100 tons per year of magnet powder. The plants are runed by STENA Recycling (Sweden), University of Birmingham (United Kingdom), Magneti Ljubljana (Slovenia) and MIMplus Technologies (Germany).

Some other projects centre on indirect recycling strategies as EREAN, which developed an effective method for the separation of REE mixtures using pyro/hydrometallurgical [94]; and REE4UE, which validated and demonstrated in two industrially relevant Pilots an innovative Rare Earth Alloys (REA) production route from permanent magnets [97].

On the other hand, on the direct recycling line, REProMag focused on creating and validating a novel for Rare Earth magnets that enables the economically advantageous production of net-shape magnetic components with complicated structures and geometries [96].

Table 2. European projects on permanent magnets recycling.

European projects in the field		
Title	**Time period**	**Recycling method**
MORE: Motor Recycling	2011-2014	Direct and indirect recycling
REMANENCE: (Rare Earth Magnet Recovery for Environmental and Resource Protection)	2013-2016	Direct and indirect recycling
The FP7 EREAN project: (European Rare Earth (Magnet) Recycling Network)	2013-2017	Indirect recycling: pyro/hydrometallurgical process
RECVAL HPM: innovative RE-use and reCycling VALue Chain for High-Power Magnets	2014-2017	Direct and indirect recycling
REProMag: Resource Efficient Production Route for Rare Earth Magnets	2015-2017	Direct recycling
REE4UE Project : rare earth recycling for Europe	2015-2019	Indirect recycling: hydrometallurgical process
SUSMAGPRO: Sustainable Recovery, Reprocessing and Reuse of Rare Earth Magnets in a European Circular Economy	2019-2023	Direct and indirect recycling
VALOMAG: VALOrisation of MAGnets	2020-2022	Direct and indirect recycling

Continuing with the results of the investigation, seven companies that are dedicated to the recycling of permanent magnets were identified (Table 3). This information allows to offer a look at the recycling processes used at a commercial level and at the place of origin of said companies, which reveals market dynamics, emerging players and potential countries of interest.

The selected companies vary in the recycling process they use, some are dedicated to using direct approaches and others to indirect approaches, so it cannot be established that there is a dominant recycling process par excellence in the market. On the other hand, it can be noted that most of these companies are in Europe and another two come from the United States. Additionally, it could be concluded that the majority of the companies presented below have a small size in terms of employees, and in terms of permanent magnets produced per year considering that the demand of rare earth permanent magnets per year is more than 100,000 tons [99].

Table 3. Companies on permanent magnet recycling.

Companies in the field

Logo	**Name**	**Location**	**Number of employees**	**Rare earths powder production**	**Recycling method**
	REEcycle (2014)	Houston, Texas, United States	2-10		Indirect recycling: hydrometallurgical process
	NOVEON (2014)	San Marcos, Texas, United States	51-200	2000 tons/year	Direct recycling
	GEOMEGA (2008)	Boucherville, Québec, Canada	11-50	1642 tons/year	Indirect recycling: hydrometallurgical process
	Heraeus Remloy (2022)	Frankfurt, Germany			Indirect recycling: pyrometallurgical process
	MagREEsource (2020)	Grenoble, France	11-50	50 tons/year	Direct recycling
	REEfine Technologies (2019)	Lyon, France	2-10		Direct recycling
	HyProMag (2018)	Birmingham, United Kingdom	2-10	50 tons/year	Direct recycling

5 Discussion: design of a recycling line

5.1. Introduction to the chapter

This chapter explores circular economy-based recycling strategies specifically suited for sintered and bonded permanent magnets production while navigating the complex world of sustainable design. The main goal is to clarify the systematic techniques used to unravel the challenges involved in this endeavour, revealing a thorough roadmap that details the various steps and procedures required for effective recycling.

The chapter comprises the following sections:

- Section 5.2 states the different routes and steps to follow for each of them based on the information extracted from articles, patents, projects and companies.
- Section 5.3 starts with the electric motor assessment section laying the groundwork for the succeeding steps of disassembly and magnet extraction.
- Section 5.4 explores the methodical dismantling of electric motors to recover valuable components.
- Section 5.5 discuss demagnetization and magnet extraction, two vital processes that are required to demagnetize magnets and remove their magnetic fields in order to prepare them for future processing.
- Section 5.6 explains the coating cleanse stage takes centre stage, as it delves into procedures and methods intended to scrape off coatings and to remove adhesives residuals for improved recyclability.
- Section 5.7 highlight the crucial stage of characterization, the analytical assessment of materials and serves as the basis for wise decision-making throughout the recycling process.
- Section 5.8 shows hydrogen decrepitation, the first pulverization step, which allows to convert the magnet in a coarse powder.
- Section 5.9 centres on milling and highlights the mechanical complexities of transforming materials into a suitable form for further processing.
- Section 5.10 focus on the removing of unwanted gases that can obstruct the following through degassing.
- Section 5.11 introduces Hydrogenation, Disproportionation, Desorption Recombination (HDDR), highlighting its function in material transformation.
- Section 5.12 presents the sintering route's concluding stages, including aligning, pressing, sintering, grain boundary diffusion, and annealing.

- Section 5.13 outlines the sequence of procedures necessary to produce recycled magnets using the bonding route, including mixing, 3D printing, aligning, and hot pressing.
- Section 5.14 reviews the final phases, which also include machining, coating, magnetizing, and a detailed analysis of performance traits.

This chapter essentially acts as a comprehensive manual for designing recycling routes, with each subsection advancing the understanding of the complicated web of sintered and bonded permanent magnet recycling within the broader framework of sustainable materials management.

5.2. Identification of routes

The recycling routes and associated stations for permanent magnets can be clarified in light of an extensive review of relevant literature, a thorough examination of the patent landscape, and a fundamental study into successful projects and companies currently operating. This methodical approach makes it possible to clearly define the sequential processes necessary for the effective recycling of permanent magnets.

Fist, the type of permanent magnet under consideration for the recycling process will determine the steps of the procedure. Permanent magnets can be divided into bonded and sintered groups. These diverse groups demand specialized processing methods for making recycling bonded and sintered permanent magnet from end-of-life sintered or bonded permanent magnets. EOL bonded permanent magnets would require a non-direct recycling separation and EOL sintered permanent magnets could start the direct recycling process immediately. The recycling process is described in Figure 16 and will be analysed in depth in the following sections of this chapter.

The first steps include collection, careful disassembly, detailed condition assessment, efficient demagnetization, and magnet extraction. The coating must be cleaned in the crucial procedure that follows to allow precise characterisation. Then, hydrogen decrepitation and milling are important phases that lay the groundwork for later operations. Before this pulverization stage is imperative to perform a rigorous cleaning process if the magnets of origin are bonded magnets.

Additional steps are necessary to produce a sintered permanent magnet. Degassing, aligning, and pressing are done precisely by following the standard procedures. The consolidation of the magnet's structural integrity depends on the processes of sintering and annealing.

The production of bonded permanent magnets, in the same way, necessitates the pursuit of specific steps. A Hydrogenation, Disproportionation, Desorption, Recombination (HDDR) process is started after conforming to the shared framework. The crucial steps of mixing, aligning, and hot pressing come next.

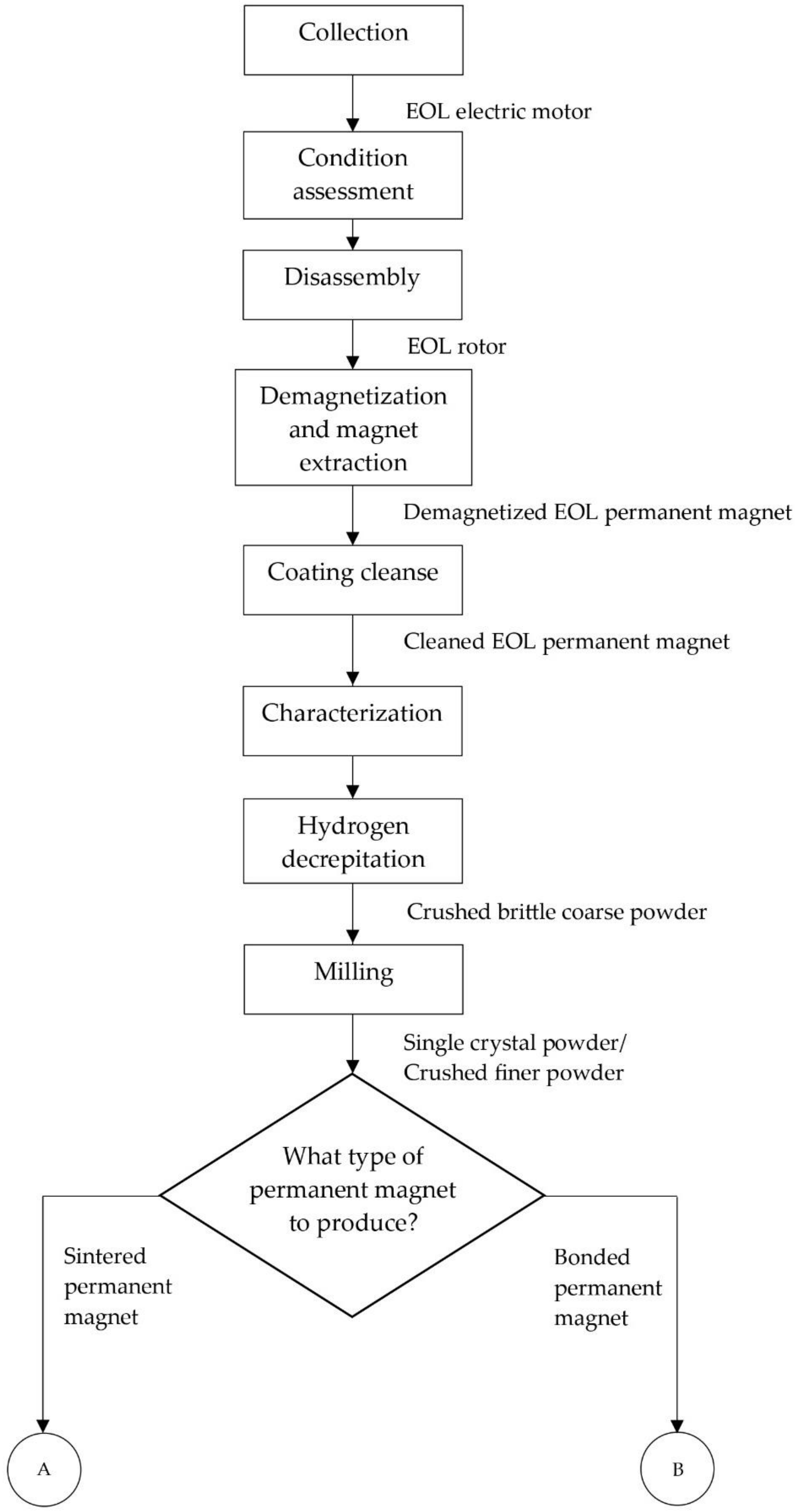

Figure 16a. Direct recycling line.

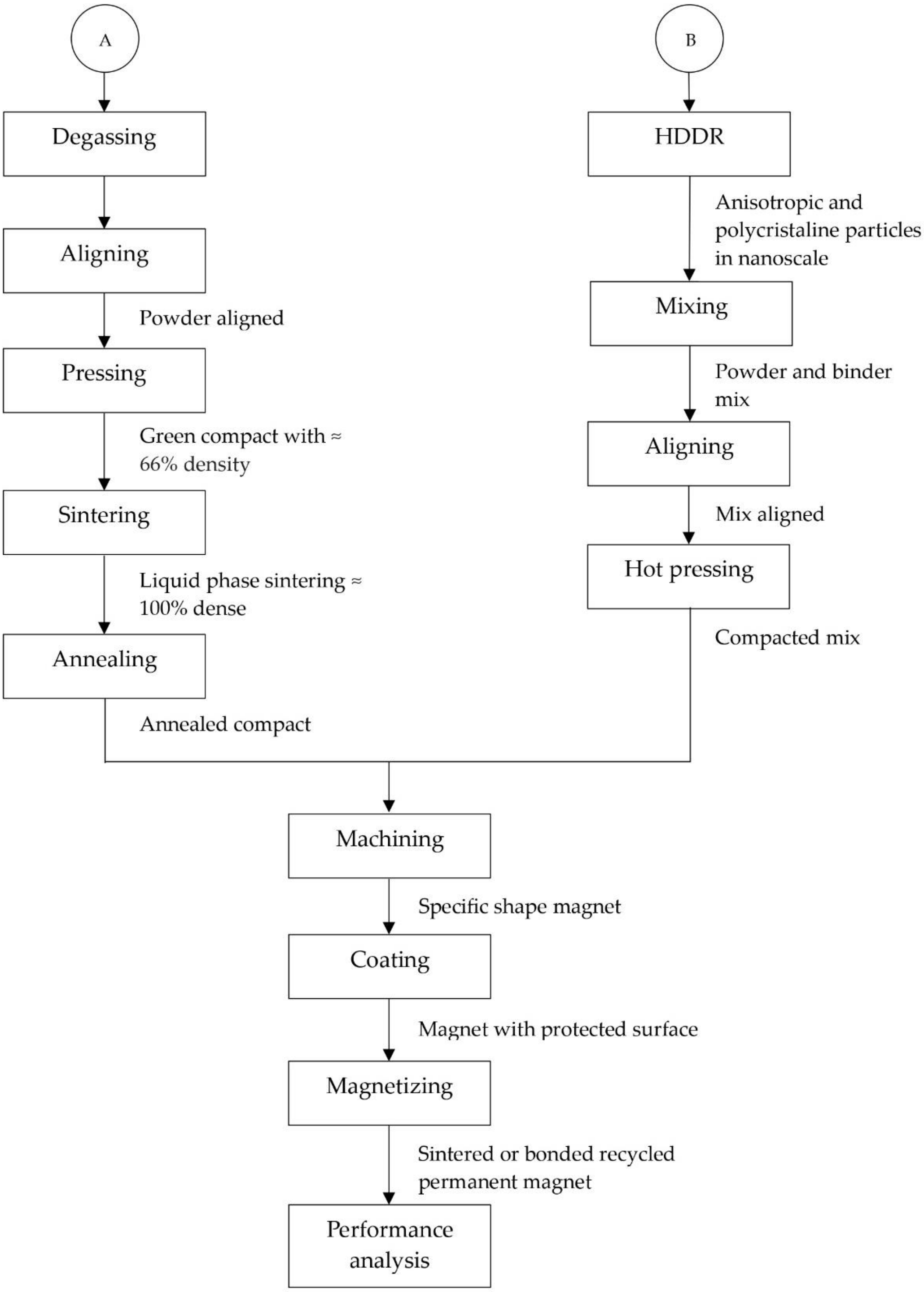

Figure 16b. Direct recycling line.

The final processes of in each route include machining, coating, and magnetization. Additionally, a crucial performance analysis is necessary at the conclusion of both recycling pathways. To determine the recycled magnets' functionality and suitability for the applications they are intended for, careful evaluation is essential. This final stage emphasizes how important it is to make sure that the recycling process restores the magnet's physical form while still maintaining its fundamental qualities.

For permanent magnets, identifying recycling routes and defining related stations essentially entails a laborious journey through numerous steps. Depending on the initial magnet type, these steps pave the way for the sustainable recycling of permanent magnets, aiding in the preservation of the environment and the effective use of limited resources.

All steps will be described in detail in the following subchapters. The activity of collecting motors at the end of their useful life for the subsequent recycling process of permanent magnets is the true initial stage of the complete strategy to support sustainable resource management within a circular economy framework. However, the integration of this process within the recycling strategy is part of a logistical coupling that must be carried out in conjunction with different companies that have the capacity to provide motor magnets at the end of their useful life.

5.3. Electric motor condition assessment

After end-of-life electric motors are collected, an analysis procedure is necessary to verify the apparent condition of the motor and the permanent magnets inside the motors. In order to evaluate an electric motor's key characteristics, a methodical set of tasks is involved in the assessment process.

Its overall condition is determined through general examinations, which also look for any obvious abnormalities, the evaluation then moves on to more precise measurements, such as checking for electrical connection continuity and measuring current in amperes with a digital multimeter. Additionally, the integrity of the motor's insulation is ensured by measuring the insulation resistance in ohms using a megohmmeter.

An evaluation of the motors permanent magnets is done in addition. To find any deviation from the expected values, the magnetic flux density is rigorously compared to specifications using cutting-edge instruments like a magnetometer or gaussmeter. Additionally, a thorough inspection is carried out to spot any potential physical harm or corrosion on the permanent magnets, elements that could greatly affect their ability to be recycled and general performance. Both the electric motor and the permanent magnets are subjected to a thorough examination allowing for well-informed decisions to be made throughout the construction of the recycling path.

These assessments are done mainly manually but recently, numerous digital technologies associated with Industry 4.0 (I4.0) have emerged, with a focus on utilizing the Internet of Things (IoT), Virtual Reality (VR), and Augmented Reality (AR) to enhance the effectiveness of the assessment process [100].

5.4. Disassembly of electric motor

After the electric motor is assessed, the disassembly process follows. There are only a few research on the disassembly or the selective extraction of parts for reuse or recycling, and additionally these studies frequently fail to take into account the whole recycling chain of permanent magnets [101].

The typical process stages that the disassembly system should encompass are handling of product, clamping of products, disconnection and extraction of product and component condition [102]. But, due to the magnetic field of permanent magnets, the extraction of the rotor is more difficult, and even if the handling and clamping could be done with a press, the extraction process is still a difficult task.

In any case, nowadays, manual labour is currently used to disassemble big conventional electric motors and generators for remanufacturing or raw material recovery and the main steps comprehend the rotor and stator separation [101]. This separation should be carried out with extremely careful.

Also, considering the inefficient that could be manual disassembly and the elevated labour cost in some countries, researchers has trying to switch to alternate methods that can be at least partially automated [101]. But convert this manual process presents big automation challenges. This problem results from the wide range of motor variations and the inherent difficulties in determining the state and specifications of the components in the returned goods [6], [103], [104].

However, some research already presents method for automated loosening using a collaborative robot and plans integrating machine vision to increase efficacy overall [105]. This means that although disassembly process is mostly manual, there have been some advancements that surely will contribute to the optimization of the recycling process.

Finally, researchers suggest that in order to make disassembly process easier the concept of "design for recycling," in which products are purposely engineered with recycling in mind, should be implemented [17], [68].

5.5. Demagnetization and extraction

Demagnetization and permanent magnet extraction are two processes that should be analysed at the same time [106]; the reason for this is that the extraction of permanent magnets could be done before or after the demagnetization process. Each of the two alternatives have challenges, but what is clear is that these two processes are two of the most critical for the whole recycling line. A well-developed demagnetization and an excellent permanent magnet extraction contribute to the recovery of the magnet in its better conditions.

Demagnetization of the material is a vital necessity for any recycling technique for both safety and operational considerations. Surprisingly, the research on recycling processes frequently provides insufficient understanding into this critical step. Frequently, simply a mention of submitting the material to elevated temperatures, maybe using a nonmagnetic furnace, with the goal of exceeding the Curie temperature is made. Another method is degaussing, which includes the introduction of a powerful magnetic field that oscillates at increasingly decreasing amplitudes [107].

The most used method is the heating over Curie temperatures in an inert gas chamber or a furnace, and NdFeB permanent magnets typically possess a Curie temperature of 312°C, which can range from 300°C to 350°C based on the rare earth composition, after this temperature, the magnetism is loss [108].

When the magnets extraction come first and then demagnetization, the challenge lies in the difficulty of extract the magnets while keeping their magnetic field. Some studies propose methods for automating magnet extraction for both interior permanent magnets (IPM) and surface mounted permanent magnets (SPM) type of rotors [101]. Considering the magnetized state all components in direct contact with the magnets must be made of non-magnetic materials. For the IPM type of rotor, the rotor segments must be separated, and the magnets are pressed out, one at a time to avoid reciprocal attraction, to a conveyor belt where could be demagnetized [25]. On the contrary, for SPM type of rotor, the bandages must be removed after softening adhesive glue (below the Curie temperature). Magnets are then sheared off with a non-magnetic wedge, sorted by polarity and individually stacked with plastic spacers to be demagnetized [101].

On the other hand, demagnetizing the magnets before the extraction brings the advantage of being able to handle the magnets with less caution. Furthermore, researchers have confirmed that the heating process not only can demagnetize the magnet but also can degrade the adhesive holding the magnets in place. However, for SPM a problem appeared since the demagnetization temperature is about 350 °C while the glue dissolved around 200 °C. As a result, magnets may unexpectedly separate due to residual magnetism, putting the magnet and heating unit at risk of damage. There was hence a need for a temperature-resistant solution. MORE project proposed the employment of a heat-resistant metal sleeve over the rotor which the objective of retain the magnets and avoid heir free movement [35], [109].

Nonetheless, when demagnetization is carried out through heat treatment in an ambient air environment, NdFeB magnets are prone to oxidation. Research indicates that the oxidation process initiates at approximately 300°C [80]. This effect suggests having a precise temperature regulation during the demagnetization process to prevent magnet oxidation during the process, but most important it's the atmosphere of the process, because implement a non-oxidizing setting with inert gases like Ar, N_2, or He, the oxidation is totally prevented. Among these gases, Ar have the better effect because its unreactive property, but considering its elevated cost, is preferable to use N_2. Argon is many times more expensive than nitrogen, and nitrogen being 88 times more abundant than argon means that the energy to produce a pound of nitrogen is 88 times less than the energy to produce a pound of argon [110].

Despite this, researchers have carried out the heat treatment in different atmospheres including air to study the real oxidation behaviour of the magnets and the limits of using air considering that most magnets have a protective surface coating to avert corrosion, commonly a plating layer of Ni/Cu/Ni [108]. The results indicate that under regular air, there were no clear indications of oxidation at 300 ◦C (surface analysis shoes 99% Ni and 1% O), at 350 ◦C the oxidation reaction started to be visible (Cu at 2.08% and O at 1.77%), and by 400 ◦C the surface acquired a brass-like hue (11.08% Cu and 4.39% O). Conversely, in a nitrogen-rich environment, no discoloration was apparent between 300 °C (O at 0.21%) and 350 ◦C (O at 0.42%) and only a modification in the shine of the NdFeBM plating layer was noticeable at 400 ◦C [108].

The study also pointed out that effectively that oxidation affects the magnets demagnetized at air and the nitrogen atmosphere achieve the suppression of oxidation. However, the study also shows that at this high temperature the oxidation is only superficial, and the oxygen only reacts with the coating layer. Further studies also shows that even if the temperature is increased to 700 °C, the examination of microstructures revealed that the surface exhibited CuO as the primary oxide product, succeeded by phases of combined NiO-Cu2O but the NdFeB magnet composition is not affected [111].

In this case, as long as the magnets have a protective coating, and a subsequent coating removal process is implemented, demagnetization in air could be performed. It should be noted that the use of the hydrogen atmosphere is still a quite reasonable option, which avoids the risks of oxidation and should be used whenever the magnets do not have a protective layer or this has been partially or totally degraded during operation.

After demagnetization, the magnets can be removed one by one and placed in a container for transport to the next stage.

5.6. Coating and residuals cleaning process

As was said before, magnets are often electrochemically coated with metallic coatings to protect against corrosion in applications and electronics. For this aim, several metals such as nickel, copper, aluminium, and zinc, as well as their combinations such as multilayered coatings, are used. The most recent commercial NdFeB magnets have a protective Ni/Cu/Ni coating to improve corrosion resistance in humid settings and high-temperature applications [81]. The approaches to remove these coatings are basically divided into hydrometallurgy and mechanical abrasion.

Most of the studies use hydrometallurgy, favoured since it is more affordable and less labour-intensive, in which sulfuric or hydrochloric acids dissolve the alloy, followed by the precipitation of rare earths as salts via oxalic acid or soda. Nevertheless, traditional hydrometallurgy methods cause the loss of precious core metals, generate enormous waste, and raise environmental issues. For this reason, organic solvents, and molten metals such as silver or magnesium can be used for rare-earth extraction [28]. Other researchers have developed a method for selectively removing nickel-copper-nickel coatings using an organic solvent and an elemental bromine solution based on research that shown dissolution capacity of bromine in metals like uranium, thorium, zirconium, titanium, iron, chromium, and nickel when used in organic solvents like ethyl acetate or methanol.

Their results highlight that nickel-copper-nickel coatings can be successfully removed within 1 hour using solutions containing 1 vol% bromine in EtOH without harming the magnet cores [112].

On the other hand, magnets may have adhesive residue from the demagnetization process, and to effectively eliminate any remnants without affecting the magnet substance it is necessary a delicate cleaning approach, a vibratory finishing process utilizing silicon carbide (SiC) as the abrasive agent is proposed by some researchers. This method not only would work to eliminate adhesive but also could eliminate the coating of the magnet giving as a result a completely clean magnet. Nonetheless, this approach requires a determined shape of the magnets, because if the magnet has a complex surface without flat faces and has groove or notches, the adhesive residues could accumulate [35], [101].

In conclusion, both approaches work correctly, and the selection depends on the magnet shape and the presence of adhesive residuals.

5.7. Characterization

Characterization process is part of the recycling line, and its importance lies in the possibility of asses the quality of the magnet. Although is recommended to perform this analysis in different steps, right after the cleaning process it is the perfect position to check the state of the magnet without the presence of coatings or adhesives.

Each step in the process of characterizing a permanent magnet provides information about its composition and physical characteristics. Techniques like Inductively Coupled Plasma-Atomic Emission Spectroscopy (ICP-AES) and Inductively Coupled Plasma-Optical Emission Spectroscopy (ICP-OES) are used to conduct chemical analysis. These techniques carefully ascertain the elemental composition, revealing the fundamental parts and the amount of REEs of the magnet [113].

Microscopy analysis using Scanning Electron Microscopy (SEM) is used in addition to the chemical analysis. Using this high-resolution imaging method, the microstructure of the magnet is intricately seen, exposing surface topography, crystal shape, and probable defects [113].

For identifying the crystalline phases, the magnet an X-ray Diffraction (XRD) analysis is used. This method examines the ensuing diffraction patterns, helping to provide a thorough understanding of the magnet's structure [113].

Finally, an oxygen analyser is also used in the characterisation process. This tool is essential for measuring the oxygen level of the magnet material. The careful measurement of oxygen levels is important since it has an impact on the magnet's performance and magnetic characteristics [113].

In essence, this consolidation of techniques, from chemical analysis to microscopy and phase determination, supported by sophisticated instruments like XRD and the Oxygen Analyzer, collectively paints a detailed portrait of the permanent magnet's composition, structure, and intrinsic attributes. This comprehensive characterization is instrumental in guiding subsequent steps in the recycling route, ensuring the strategic management of these valuable resources.

5.8. Hydrogen decrepitation

The first step to pulverize the permanent magnets is hydrogen decrepitation (HD) which is used to produce coarse powder and is preferable over only using milling because HD creates a very friable powder, which improves the subsequent particle size reduction, reducing production cost by 25% [114]. Furthermore, researchers have delved into the prospect of processing solid sintered magnets without the need for hydrogen but in the most favourable scenario observed in these studies, the recycled magnet displayed an alarming 18.5% reduction in intrinsic coercivity [115].

The hydrogen decrepitation process is based on the variation in reactivity between the matrix of $Nd_2Fe_{14}B$ grains and the Nd-rich phase when exposed to hydrogen gas [116]. The entire structure of the magnet collapses and turns into powder because of neodymium hydride production in the Nd-rich phase and induced expansion [117].

The grain border experiences a volume change that is three times greater than the grain volume change, causing a strain that deteriorates the magnets [118]. A trans-granular break in a single $Nd_2Fe_{14}B$ grain shows the hydrogenation product's brittleness. When dealing with HD powders based on working within an inert atmosphere becomes necessary due to these powders' known reactivity [119].

After hydrogenation, the HD process produces particles with a size range of 6–600 µm at a temperature of 25–400 °C [114]. The particle and grain size distribution of the powder is one of the key aspects of HD. The ultimate magnetic characteristics are directly impacted by the oxygen concentration of the particles, which is related to the significance of particle size distribution [114]. Heightened oxygen concentrations contribute to the degradation of magnetic properties, primarily due to the formation of neodymium oxide at the grain boundaries. The rise in oxygen content is linked to the reduction in powder particle size. When the particle size is between 5 and 10 micrometres, the oxygen concentration rises to 2700 parts per million (ppm). However, as the particle size rises, the oxygen content rapidly decreases. And this tendency noticeably slows once particle size reaches about 150 micrometres. As a result, it is feasible to produce powders with larger particle sizes, increased coercivity, and little oxygen concentration by carefully controlling the HD process. Notably, particles smaller than 75 µm have the lowest intrinsic coercivity value [117], [120].

On the other hand, even particles that are too large (>450 µm) can cause a decrease in magnetic properties. The improved crystallographic alignment seen in the medium-sized particles (150-450 µm) is what accounts for their higher magnetic properties when compared to those of particles in the big size range [121].

Given the concern that the magnetic properties are not adequate, it is necessary to explain that the final properties of the recycled magnets will improve with the following processes that are part of the recycling line.

Subsequently, the powder still has not its maximum potential and should be post processed. Several research have look for the next steps in order to recycling the powder into permanent magnets. The conventional and better routes are (1) milling, degassing to eliminate hydrogen, alignment/pressing, sintering, and annealing, called the sintering route, and (2) hydrogenation, disproportionation, desorption, recombination (HDDR) processing, mixing and pressing, called bonding route [119].

Another important consideration is the variance of the magnetic properties because the recycling process should be able to produce permanent magnets with not only good but similar magnetic performance. A group of researchers in the REMANENCE [93], conducted investigations achieved a high energy product in the resulting magnets while maintaining a remarkably narrow variability of merely ±5 kJ/m3, which is a consistency level typical in primary magnet production [25].

Finally, it should be noted that if the coating layer of the magnets was not correctly removed, the coating materials would combine with the powder in this step, and it would reduce the magnetic properties of the magnet. For that reason, the coating material must be extracted. If the layer was made only by Ni, it is transformed into flake-shaped particles with a wide size range (between 150 micrometres and 3 millimetres); but if the layer composition was Ni-Cu-Ni, it would transform in coiled sheets shape with a length of roughly 1 centimetre [84]. This separation of the protective covering requires sieving, and the amount of nickel is eventually reduced by this screening process to a concentration of 400 ppm [122]. This result increases the criticality in the previous coating cleaning process.

5.9. Milling

It should be pointed out that the grinding and milling process of the Nd-magnet alloy constitutes over 10% of the complete recycling expenses [128]. Additionally, the possibility of introducing impurities into the fine powder product due to the presence of grinding media and the materials used for lining in the milling apparatus (such as jet mills or ball mills) should not be underestimated. For these reasons and some others mentioned in the hydrogen decrepitation section, milling is not the only method to pulverize the permanent magnets. Nevertheless, is still necessary to further decrease the grain size within the coarse powder. And regardless of the objective of the recycling process, whether it is to obtain a sintered or a bonded magnet, it is recommended to carry out a milling process [129].

For sintered permanent magnets the powder is milled further to attain a size of roughly 5 μm, resulting in single crystals (typically using a jet mill). These crystals have a preferred magnetization direction, allowing them to be aligned within a magnetic field [130] which improves the magnetic properties of the powder.

For bonded magnets is not necessary to mill until single crystal, powders are sieved at 75–250 μm [113]. Instead, it is used to distribute the elements more evenly within the powder.

Due to oxygen content, during recycling, if good magnetic properties are to be maintained or even increase the powder particles can be sized down only up to ≥100 μm [131].

5.10. Degassing

The degassing procedure for a permanent magnet is a method to extract the hydrogen and is often used in the recycling production of sintered permanent magnet and involves a critical process that facilitates the removal of trapped gases from the material. A well-controlled thermal treatment process is used to accomplish this. The procedure requires heating the magnet powder either in a vacuum or an environment with inert gas. The hydrogen molecules trapped in the matrix of the material begin a process of desorption and diffusion as the temperature rises. As a result, the hydrogen gas trapped inside the individual powder particles gradually releases and escapes. A thermal treatment is used to produce the best degassing; it is normally carried out at temperatures higher than 700°C. By effectively removing gases through this precisely calibrated method, the permanent magnet's structural integrity and magnetic characteristics are improved making it suitable for further manufacturing procedures [120].

5.11. HDDR

In the pursuit of recycling rare earth permanent magnets, extensive research efforts have been dedicated to refining the recycling process. One powerful alternative seems to be the HDDR process, one approach that has proven to be successful [123], [124]. This process not only improve the magnetic properties of the powder, but it also decreases the grain size to about 0.3 mm by making use of the ability of materials like NdFeB to efficiently absorb and release hydrogen at high temperatures.

At temperatures between 700 and 950 °C, the addition of hydrogen causes $Nd_2Fe_{14}B$ to dissociate into its component parts, NdH_2, Fe_2B, and predominantly α-Fe. Disproportionation (Equation 1) is the reaction that results by adding hydrogen to the system in a furnace and after a decrease in pressure, it causes the previous reaction to reverse, which results in the release of hydrogen. Hydrogen is then released when the pressure is brought to a vacuum, which triggers recombination (Equation 2) and the start of new $Nd_2Fe_{14}B$ grain nucleation. This process proceeds until the Nd-rich phase and ultrafine $Nd_2Fe_{14}B$ grains are dispersed across the entire structure [125], [126].

The equation describing the HDDR reaction is as follows:

Disproportionation: $$Nd_2Fe_{14}B + 2xH_2 \rightarrow 2NdH_{2x} + {}_{12}Fe + Fe_2B \quad (1)$$

Recombination: $$2NdH_{2x} + {}_{12}Fe + Fe_2B \rightarrow Nd_2Fe_{14}B + 2xH_2 \quad (2)$$

The creation of a thin, continuous Nd-rich phase that encloses each $Nd_2Fe_{14}B$ grain during the HDDR process causes the isolation of the grains, which results in a reduction in grain size. This mechanism aids in the improvement of coercivity (Hcj), which ultimately leads to the magnets achieving a greater maximum energy product (BH)max.

The HDDR process can be implemented through two approaches. The first, known as conventional HDDR (C-HDDR or HDDR), involves using the initial hydrogen pressure as the operational pressure. Once disproportionation is complete, the reactor is evacuated to initiate recombination. Alternatively, dynamic HDDR (d-HDDR) takes a distinct route. It begins by subjecting the reactor to a vacuum, which gradually rises to the operational pressure before attaining the required temperature. Following full disproportionation, the reactor is emptied and replenished with argon gas. This allows for controlled recombination to prevent excessive supercooling. In both methods, the temperature begins at room temperature and undergoes controlled heating to reach the final set value. This temperature can be held steady or adjusted as needed during the process [125], [127]. According to published literature, Figure 17 shows a schematic illustration of the HDDR process in relation to temperature, and pressure where C-HDDR pressure is represented in the straight line and d-HDDR pressure is represented with the dotted line [114].

With the HDDR process resin bonded magnets are produced, and although they do not have the precise magnetic characteristics of sintered magnets, they have a higher energy density than ferrite materials. In addition, they outperform sintered magnets in terms of mechanical and chemical stability, as well as shape flexibility. Resin bonded magnets made from recycled materials may be less expensive than those made from raw resources. This improves the coercivity of resin-bonded magnets made from this powder. Best magnetic properties can be generated by regulating hydrogen pressure during disproportionation and recombination, boosting remanence in resin bound magnets due to easy alignment by a magnetic field [128].

The recovery rate of ultimate magnetic characteristics, which takes precedence over process efficiency, is a considerable difficulty in this recycling endeavour. It depends on deciding elements like pressure, temperature, oxygen concentration, starting chemical composition, and additions to achieve suitable magnetic characteristics after recycling.

In the HDDR process the ultimate magnetic properties of NdFeB magnets exhibit a decrease when pressure exceeds 1 bar (100 kPa). Heightened pressure accelerates the entire process, reduces surface activation time, and slightly boosts absorbed hydrogen, culminating in complete decrepitation or disproportionation and an increase in oxidation. The influence of elevated pressure on the particle size of the hydrated powder is intricate, causing a decrease at lower temperatures and an increase at higher temperatures. The interaction between temperature and pressure, which each directly influences the other, and the hydrogenation process are intimately related. As a result, specific temperature ranges for ideal working pressures can be found, and vice versa. Maintaining the operating temperature below 900 °C is advised in the context of the HDDR process [114].

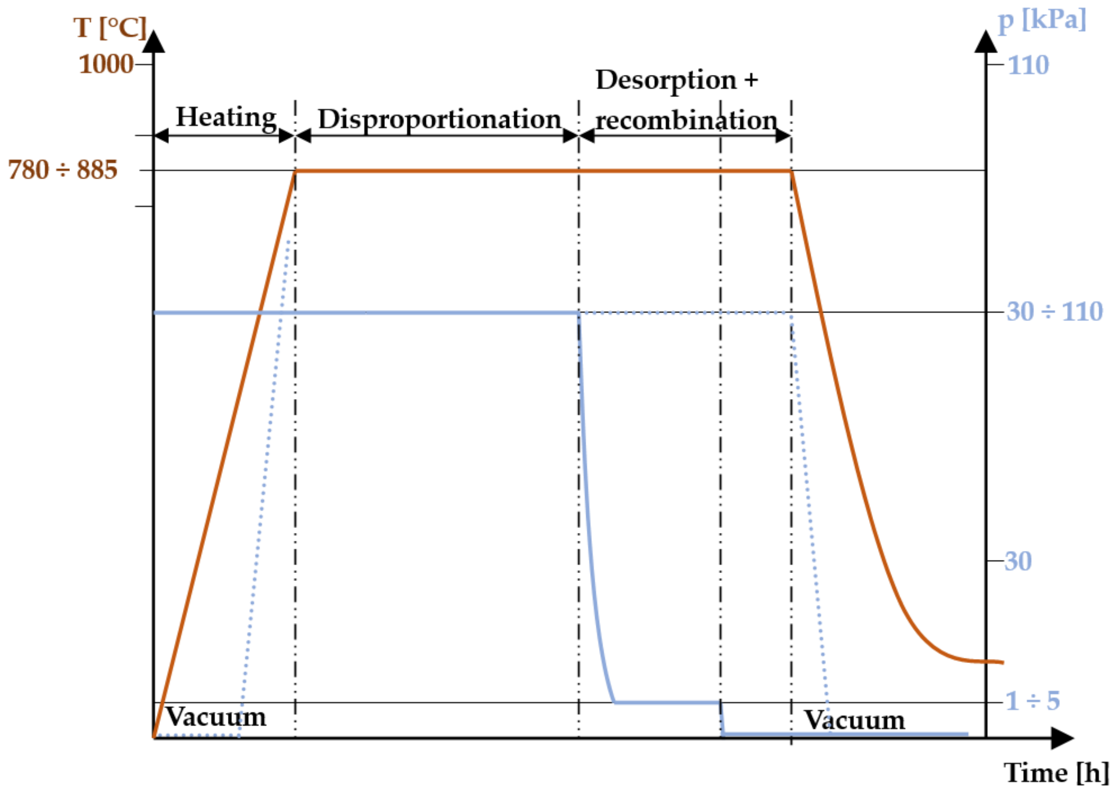

Figure 17. Schematic representation of the HDDR process in terms of temperature, and pressure.

After permanent magnet powders have undergone Hydrogenation Disproportionation Desorption Recombination (HDDR) treatment, there are important steps that must be taken to further refine their properties. Before these important steps, some analysis should be taken in order to check the properties of the new powder. Some of the analysis that can be of great help are a detailed analysis of the HDDR powder's microstructure using emission scanning electron microscopy (SEM) for obtaining information about particle distribution and arrangement; Field-Emission Scanning Electron Microscopy (FE-SEM) and an Energy Dispersive Spectrometer (EDS) to conduct a thorough examination of the element composition. Transmission electron microscopy (TEM) and high-resolution transmission electron microscopy (HRTEM) to examine the grain boundary microstructure of the HDDR powders in more detail. All these techniques enable the visualization of the powder's internal structure unravelling intricate details about grain boundaries and crystal lattice arrangements [113].

5.12. Sintering route

After the powder have an adequate grain size, the specific steps of the sintering route are carried out. Sintering magnet powder involves a well-planned series of stages, each of which helps to turn the original magnet powder into a strong, high-density magnet structure. The powder is initially carefully aligned, usually it is positioned inside a coil and exposed to a pulsed magnetic field with a 2 to 3 Tesla range. The aligning process objective is allowing the crystals to align in their preferred magnetization direction [130].

The powder is then transferred to a hydraulic chamber and is subjected to an isostatic pressure to create a green compact with a density of around 66%. The groundwork for densification during the sintering phase is laid during this interim step, and some researchers recommend a 60 MPa pressure inside this chamber [25].

The actual sintering process takes place in a vacuum atmosphere that is normally kept at 10^{-3} Pascal pressure. The sintering temperature is between 1080°C and 1120°C, and the sintering time is between 1 and 3 hours. These parameters result in a structure that is extremely dense—nearly 100% dense [25], [132].

Additionally, Spark Plasma Sintering (SPS), which involves pressing the powder and sintering concurrently, can be used. This method uses 100 MPa of pressure and 750°C hot pressing [133].

Following the core sintering phases, annealing steps take centre stage. The annealing process occurs within the temperature range of 750°C to 900°C, spanning a duration of 8 hours. This thermal treatment allows for the relaxation of internal stresses and the optimization of the magnet's microstructure [134].

5.12.1. Spark Plasma Sintering

Even if HDDR powders are mostly used to produce bonded permanent magnets, research has shown their compatibility with sintering process [133].

Rapid compaction techniques like hot deformation or spark plasma sintering (SPS) can be used to retain the HDDR powder's microstructure integrity without significantly affecting its magnetic characteristics. However, the difficulty resides in HDDR powder's vulnerability to oxidation, because the decreased coercivity and remanence in finer-sized HDDR powder.

Utilizing spark plasma sintering, non-milled HDDR powder is fully densified to achieve coercivity values comparable to newly produced commercial grade HDDR powder. It is remarkable that fine HDDR powder (<100 μm) performs poorly in SPS reprocessing and falls short of the characteristics of coarser HDDR powder (>100 μm). The coercivity (>1000 kA/m) and complete densification produced by optimal SPS treatment of coarser fractions (200 μm) are identical to those of the coarse recycled HDDR powder. According to one study, the threshold for HDDR powder reprocessing without sacrificing magnetic characteristics is suggested to be a particle size of more than 100 μm [131], [133].

5.12.2. Grain boundary diffusion

Another strategy to increase the coercivity of NdFeB magnets is applying grain boundary modification (GBM) to sintered magnet materials, which includes grain-boundary diffusion (GBD) and grain-boundary structuring (GBS). These techniques are now used during the recycling of sintered NdFeB magnets and do not appreciably change the basic structure of the magnet [133]. They allow for exact tuning of magnet characteristics to suit a wide range of end-user applications. GBM can be created by carefully injecting chemicals or mixed ingredients, as well as using hydrogen [132].

Prior to reprocessing with Spark Plasma Sintering (SPS), the additions could be integrated in the powder. Studies have analysed the diffusion of different ingredients, and DyF_3 is one of the most promised. DyF_3 in a tiny addition of 1 wt.% combined with the recycled HDDR resulted in a 17.5% increase in coercivity (HCi). Coercivity values reached approximately 1400 kA/m with DyF_3 concentrations up to 2 wt.%, showing a significant 69.5% improvement over the initial recycled HDDR powder [135].

Similarly, DyH_3 nanoparticles were used in one research to recycle waste sintered NdFeB permanent magnets. The coercivity of the recycled magnet gradually improved as the amount of DyH_3 nanoparticles ascended. In comparison to the initial waste sintering magnet, the best recycled magnet comprised 1.0 wt.% DyH_3 nanoparticles and exhibited properties of 101.7% jHc, 95.4% Br, and 88.58% (BH)max [132].

On the other hand, small amounts of NdHx nanoparticles were mixed with the HD powders in concentrations ranging from 0 to 10% by weight demonstrating that it is a promising way to recycle waste sintered NdFeB magnets [136], [137]. These neodymium hydride additions successfully made up for the neodymium loss which contributed to keeping the amount of Nd-rich material essentially constant [138].

Finally, it can be said that GBF offers an interesting alternative to process the magnet powder. All the results on the topic points its potential: the levels of oxygen and carbon contamination in the recycled magnet seems comparable to those in conventional magnets [139], the GBD resulted in improvement of the coercivity of the HDDR NdFeB systems [140] and some projects have started tests of recycling techniques on a larger scale and have found good results demonstrating a complete restoration of the initial properties of the scrap magnets. This remarkable outcome of high-coercivity sintered magnets (>2000 kA/m) is that the process is suitable for motor applications [17].

5.12.3. Press-less process

Another sintered recycled magnet process called Press-Less Process (PLP) have emerged in the last years. The method consists in the incrementation of the coercivity of the magnets by packing the initial powder to roughly half the bulk density of the magnet before sintering the finely powdered magnetic alloy inside a graphite mold. Additionally, this procedure enables the exclusion of a pressing machine, resulting in cost savings, in contrast to the more established process that entails pressing the green sample prior to sintering [141].

5.13. Bonding route

Magnet powder is bonded using a series of carefully planned stages designed to combine mixing, magnetic treatment, and consolidation to form a cohesive structure. In order to aid the ensuing bonding process, the magnet powder must first be well combined with binders [113].

When the powder and binder mixture is ready, it is put inside a coil and exposed to a pulsed magnetic field with a 2 to 3 Tesla range. A homogenous and well-bonded final product can only be obtained by preconditioning the mixture with this magnetic treatment and carefully aligning the particles [113].

Consolidation of the treated HDDR powder marks the end of the bonding process. A hot-pressing process is used to achieve this consolidation. At a pressure of 182 MPa and a temperature of 670°C, the treated mixture is hot-pressed. A magnet with improved cohesiveness and integrity is created as a result of the heat and pressure combination [113].

5.13.1. Additive manufacturing (AM)

Often known as 3D printing, is a new technique that propels bonded magnet production forward. This technology is based on the principle of building objects layer by layer utilizing computer-aided design (CAD) models, providing a quick and cost-effective way to develop goods with complicated geometries, sophisticated material qualities, and multifunctionality [71]. AM technology has acquired great traction for the production of net-shaped permanent magnets. Researchers have demonstrated the use of ink-based 3D printing technology to fabricate composite Nd-Fe-B bonded magnets and the cost-effectiveness of ink-based 3D printing technique [142].

An important part of this Additive manufacturing of permanent magnets if the alignment process. It has been approaches to post-printing alignment using variable magnetic fields and approaches of in-situ alignment, which ensures magnetic easy axis alignment during the 3D printing process. The alignment process starts with the magnet particles traverse the extruder in a magnetic field zone. As it enters the nozzle, the polymer matrix that holds the randomly oriented magnet particles melts. As a result, the mobility of magnet particles increases, allowing the applied magnetic field to rotate the particles in the direction of the field source as the molten polymer flows through it [142].

The final recycled permanent magnets exhibit performance intermediate between ferrites and sintered NdFeB magnets, which means which means that while they may not have the best performance of the best magnets on the market, they can be used in many applications, including sensors and electric drive technologies. Remarkably, the outcomes unveiled that the coercivity, remanence, and maximum energy product experienced only minute fluctuations, being ±1 kA/m, ±2 mT, and 0.34 kJ/m3 respectively and this level of consistency resembles the level of magnets derived from primary sources [25].

5.14. Final steps and post processing

The last stages of the magnet production process comprise several crucial procedures, each of which affects the magnet's ultimate shape and performance. The magnet material is precisely machined to achieve precise forms or dimensions after being converted through sintering or bonding, ensuring a tailored fit for specified applications [113].

The surface of the magnet is then coated in order to add a protective covering. The magnet is protected against corrosion and has its overall durability increased, making it resistant to external variables thanks to this coating's dual function [113].

The magnetization process is a critical step in the manufacture of magnets. In order to do this, a strong external magnetic field must be applied to the magnet. This field is frequently produced by coils, permanent magnets, or pulse magnetization processes. The material's desired magnetic characteristics are encouraged by the external field strength, which frequently approaches 6 Tesla [113].

Precise measurements are made to verify the magnet's performance. Utilizing devices like magnetometers or physical object measuring systems (PPMS), the strength of the magnetic field and the behavior of hysteresis are measured. Coercivity, expressed in Oersteds (Oe) or Amperes per meter (A/m), and remanence, expressed in Teslas (T) or Gauss (G), are two of the most important magnetic properties examined. These tests provide information on the magnet's magnetic field and magnetization retention capacity [113], [143].

6 Economic analysis

6.1. Introduction to the chapter

Direct recycling methods with a major focus on resource conservation and environmental sustainability have developed as promising ways to recover REEs from permanent magnets. However, the viability of these recycling strategies must be assessed from an economic perspective to check their deployment viability at an industrial scale [144].

This economic analysis aims to assess the economic viability of direct permanent magnet recycling techniques as a means of REE recovery. The objective is to determine whether these methods offer a favourable cost-benefit ratio and are financially sustainable. It is imperative to stress that this analysis, while valuable, does not offer a comprehensive exploration of the full range of economic considerations. Rather, it is a first foray into the quantification of specific aspects and a first approximation of their magnitudes. The intention is not to cover all economic dimensions exhaustively, but to lay the groundwork for a fuller understanding of the economic implications associated with the adoption of direct permanent magnet recycling techniques and the recovery of rare earth elements (REE).

Assessing the economic viability of direct recycling systems is indeed a complex task with inherent limitations. To provide clarity, it is imperative to explicitly identify the boundaries and limitations:

Limitations:

- Limited access to thorough data and standardized pricing: this restriction relates to the difficulty in accessing detailed consistent and structured data about the Rare Earth Elements (REEs) market. The precision of economic estimates can be impacted by inconsistent or inadequate data.
- Inherent uncertainties when assessing emerging sectors, such as the recycling of REEs from permanent magnets: the economic environment for this industry is still relatively new and is changing quickly. This innate uncertainty results from elements like shifting technological landscapes and shifting market dynamics.
- Complex factors impacting the price changes of REEs: a variety of factors, including alterations to global supply and demand, geopolitical conflicts, and advancements in extraction and recycling technologies, can affect REEs prices.

These elements can cause large fluctuations in prices and make economic analysis more difficult.

- Variations in costs for the equipment, installation, instrumentation, engineering, construction, maintenance, and tools used in recycling: the cost of recycling REEs can vary greatly depending on several variables, including the equipment selected, the recycling process, and the tools used. As a result, the economic analysis includes rough numbers in the form of ranges derived from available secondary data.
- Environmental restrictions: as environmental regulations change; the financial viability of recycling techniques may be greatly impacted. Regulation changes may need expensive modifications to recycling procedures.
- Market competition: increasing competition from alternative recycling processes or materials may have an impact on market dynamics and, as a result, the prospects for the REE recycling industry's financial health.

Hypotheses:

- Equipment saturation assumed: this hypothesis assumes that the equipment used in the recycling process operates at full capacity without any downtime or underutilization. While this simplification allows for a more straightforward analysis, it may not accurately reflect real-world operational scenarios.
- No obsolescence risk considered: this hypothesis assumes that the magnets and associated technologies used in recycling will not become obsolete during the analysis period. Technological advancements can lead to equipment obsolescence, impacting the economic viability of recycling methods.
- Certainty of market demand considered: this hypothesis considers market demand for REEs as stable and predictable during the analysis. However, in practice, market demand can fluctuate due to various factors, including changes in consumer preferences, economic cycles, and global events.
- Steady technological advancements: assuming a steady pace of technological advancements in the recycling process without accounting for the possibility of disruptive breakthroughs can affect the accuracy of economic projections.
- Consistent government policies: the hypothesis that government policies related to REE recycling will remain unchanged may not account for shifts in political priorities, trade policies, or environmental regulations that can influence the economic landscape.
- Stable labour costs: assuming stable labour costs without considering potential changes in labour regulations, wage fluctuations, or skill shortages that can impact operating expenses.

The chapter is structured as follows:

- Section 6.2 presents the economic foundations behind the analysis and establishes the concepts necessary to understand the feasibility of the project.

- Section 6.3 shows the costs of the machinery and the formulas used to predict the respective OPEX and CAPEX costs.
- Section 6.4 concludes the economic analysis by showing the results and comparing costs to verify profitability.

6.2. Economic theory

To assess the economic viability of direct recycling methods for permanent magnets, a solid theoretical framework must be established and comprise important analytical ideas. The main concepts of "Yearly Production Cost," "Capital Expenditure" (CAPEX), and "Operating Expenditure" (OPEX), which taken together serve as the foundation for determining the economic sustainability of the recycling process, are introduced and explained in this section.

The Yearly Production Cost represents the financial outlay associated with the recycling process on an annual basis. It is calculated by summing two essential components: CAPEX over amortization period and OPEX as is show in Equation (3). This statistic is essential for assessing the economic viability of the process since it offers a thorough perspective on the financial commitments necessary to maintain the recycling operation.

$$Yearly\ production\ costs = \frac{CAPEX}{Amortization\ period} + OPEX \quad (3)$$

The initial investment needed to set up a recycling plant and buy the required tools and infrastructure is known as CAPEX. It includes several expenses, such as the cost of equipment necessary for the recycling process, installation and setup costs, the cost of additional instruments needed for operations, engineering costs related to design and planning, and finally the price of building the actual facility. A sizeable portion of the total investment is made up of CAPEX [145].

OPEX includes all ongoing costs related to running the recycling process. These costs are necessary to keep the recycling facility functional and to guarantee a constant and effective operation. OPEX consists of a variety of components, including the cost of labour for workers involved in the recycling process, rental costs for equipment and real estate, equipment maintenance costs to ensure optimal performance, electricity consumption costs, and the consumption of materials required for the recycling process [145].

A critical aspect of the economic analysis involves comparing the calculated Yearly Production Cost with the approximate cost of a permanent magnet. This comparison is essential in determining whether the recycling process is economically viable.

Another important metric for consideration is the determination of the payback period—the number of years necessary to recover the investment. This metric provides insight into the time required for the recycling process to start generating returns and plays a pivotal role in assessing the long-term financial viability of the techniques. To compute this value, an analysis on all cost and possible earnings must be carried out over the amortization period of the project.

6.3. Economic data

Table 4. Equipment costs. Extracted from Alibaba (2023).

Final recycled type of magnet	Stages and equipment	Costs range (Euros)	
Sintered	Sintering (Furnace)	50,000 €	100,000 €
Sintered	Pulverization (Jet mill and HD)	28,000 €	122,000 €
Bonded	Hot-Pressing	25,000 €	75,000 €
Sintered	Pressing	20,000 €	99,000 €
Bonded	Pulverization (HD and HDDR)	12,000 €	38,000 €
Bonded/Sintered	Disassembly (Press, bridge crane)	6,800 €	23,000 €
Bonded/Sintered	Demagnetization (Furnace)	4,500 €	15,000 €
Bonded	Aligning and magnetizing (Pulse magnetizer)	3,000 €	15,000 €
Sintered	Degassing (Furnace tube)	2,000 €	9,000 €
Bonded/Sintered	Coating cleanse (Sandblasting equipmet)	1,000 €	3,000 €

Table 4 shows the cost ranges for the most economically significative equipment.

6.3.1. CAPEX costs

In order to estimate CAPEX, established literature is consulted to determine the cost components. A range of prices taken from Alibaba, pertinent studies, and industry reports are used to estimate the cost of purchasing machinery. These ranges and all the percentage ranges that follow consider price variations and market turbulence.

Additionally, according to research the installation cost—an important part of the CAPEX costs—is anticipated to be between 10% and 30% of the overall machinery cost. Instrumentation costs typically falling between 8% and 12% of the total equipment costs (excluding installation expenses), engineering costs, encompassing design, planning, and project coordination, are anticipated to range from 8% to 12% of the total direct costs of the plant. Similarly, construction costs, incorporating physical facility development, are projected to represent from 18% to 22% of the total direct costs [144].

6.3.2. OPEX costs

The assessment of OPEX delves into the ongoing costs associated with the operation of the recycling process.

Between 3% and 5% of the total cost of the equipment, excluding installation costs, is projected to be spent on maintenance, a crucial component of OPEX. An extensive analysis of the recycling process is used to calculate the amount of electricity used. The project is anticipated to produce 50 tons of permanent magnets annually, working 330 days per year in two shifts of 8 hours each. The estimated amount of electricity used considers the energy needs of the machinery used in each distinct process. The labour cost assumes that 4 employees, each making 2200 EUR per month, will be involved. This cost captures the compensation for skilled workers involved in the recycling process.

6.4. Results

The economic analysis of the direct recycling techniques for permanent magnets reveals valuable insights into the potential viability of these methods in the context of recovering rare earth elements (REEs). The results of the analysis are presented below, shedding light on the estimated costs, and comparing them to market prices.

For bonded magnets, OPEX is estimated to range from 314,727 to 786,364 euros, and CAPEX for bonded magnets ranges from 525,672 to 1,656,372 euros.

Considering the market price of approximately 55.23 EUR per kilogram for bonded magnets [146] the calculated production costs for kg (from 7 to 17.93 EUR) remain notably lower. This indicates an apparent favourable economic proposition where the cost of producing bonded magnets by direct recycling techniques is economically viable.

Similarly, for sintered magnets, the OPEX is estimated to range from 368,921to 961,916 euros. While CAPEX for sintered magnets ranges from 650,916 to 2,156,810 euros. With the market price of sintered magnets is around 86.76 EUR per kilogram [146], the calculated production costs (from 8.25 to 22.11 EUR) remain below this threshold. This underlines that it seems to be economically feasible to adopt direct recycling techniques to produce sintered magnets.

Considering a tax rate of 27.9%, the investment recovery period is notably promising. The investment can be effectively recovered within a range of 3 to 5 years, considering the variability in magnet prices. This analysis suggests a relatively quick return on investment, which raises the recycling techniques' appeal from a financial standpoint.

A recurring pattern can be seen when comparing the market prices for both bonded and sintered magnets with the estimated production costs. In both situations, the cost of production using the recycling techniques is significantly less than the standard cost of the market. The production costs of the direct recycling techniques are below the market prices, which suggests that they have the potential for economic growth. This alignment denotes a promising outlook for the economy and implies that implementing these recycling techniques could result in significant cost savings while also promoting sustainable resource management.

Notably, the costs estimations of a plant that produce recycled sintered and bonded permanent magnets up to 4.8 million of euros, are consistent with the production costs observed in projects such as the facility operated by the University of Birmingham in collaboration with the SUSMAGPRO project (5.01 million of euros) [147]. The congruence between these findings and those of such established initiatives underscores the robustness of the economic assessment and contributes to the credibility of the economic feasibility conclusions drawn from the analysis.

In conclusion, this economic analysis indicates that, based on the rough calculations, the concept of a circular economy applied to magnets appears to hold promise. However, it is essential to emphasize the need for more precise calculations and extensive investigations to fully validate its viability, paving the way for sustainable resource management and technological advancement in the future.

7 Environmental impact analysis

7.1. Introduction to the chapter

Due to the growing awareness of the limited character of natural resources and the pressing need to combat climate change, concerns regarding the environmental impact of industrial processes have received a lot of attention recently. In this context, assessing environmental effects has become a crucial step in making decisions about the development of new technologies and products. In this section, it will be compared the environmental advantages of recycling NdFeB magnets to the traditional method of producing virgin magnets. The analysis is based on Life Cycle Assessments (LCA) carried out by several researchers, which sheds light on how both processes affect the environment [148]–[152]. Most LCA in this field seek to present a thorough comparison between the production of virgin NdFeB magnets and the recycling of end-of-life magnets. The analysis considers the environmental and energy impacts associated with each process. And usually, they use a cradle-to-gate methodology, assessing the environmental effects of each stage of the production process up until the magnets are ready for use.

- Section 7.2 recounts the current process to produce permanent magnets analysed in several life cycle research.
- Section 7.3 explore all the benefits of recycling process comparing to the virgin production.

7.2. Virgin production

New REE resource production is costly and time-consuming, taking 12–13 years from exploration to production. While faster, open-pit REE mining severely harms the environment by producing large amounts of waste like sulfur dioxide, sulfuric acid, hydrofluoric acid, and dust. Notably, more than 10,000 m3 of waste, acidic water, and radioactive slag rocks are produced for every ton of these metals extracted [29]. In this way, the production of virgin NdFeB magnets involves a complex series of steps, each contributing to the overall environmental footprint (Figure 18) [148]:

- Mining and beneficiation: mining is used to remove rare earth elements from the crust of the earth. Drilling, blasting, crushing, and grinding are typically used in this process to produce concentrates with a 61% rare earth oxide (REO) content.

- Acid roasting and leaching: acid roasting is used to transform the REO concentrate into the water-soluble $RE_2(SO_4)_3$. A leaching procedure is then used to increase the rare earth content, producing 92% $RECl_3$.
- Solvent extraction and electrolysis: solvent extraction is used to separate different REOs from one another. Finally, to create pure neodymium metals, neodymium oxide (Nd_2O_3) is dissolved in molten salt based on fluorides.
- NdFeB Production: strip casting, which involves melting together components like iron, boron, aluminum, copper, cobalt, and rare earths, is the first step in the manufacture of NdFeB magnets. The resulting NdFeB alloy flakes go through several processing steps, including hydrogen decomposition, jet milling, alignment, pressing, vacuum sintering, grinding, and slicing.
- Coating and Magnetizing: the magnets are electroplated, magnetized, and tested to make sure they have the desired magnetic properties.

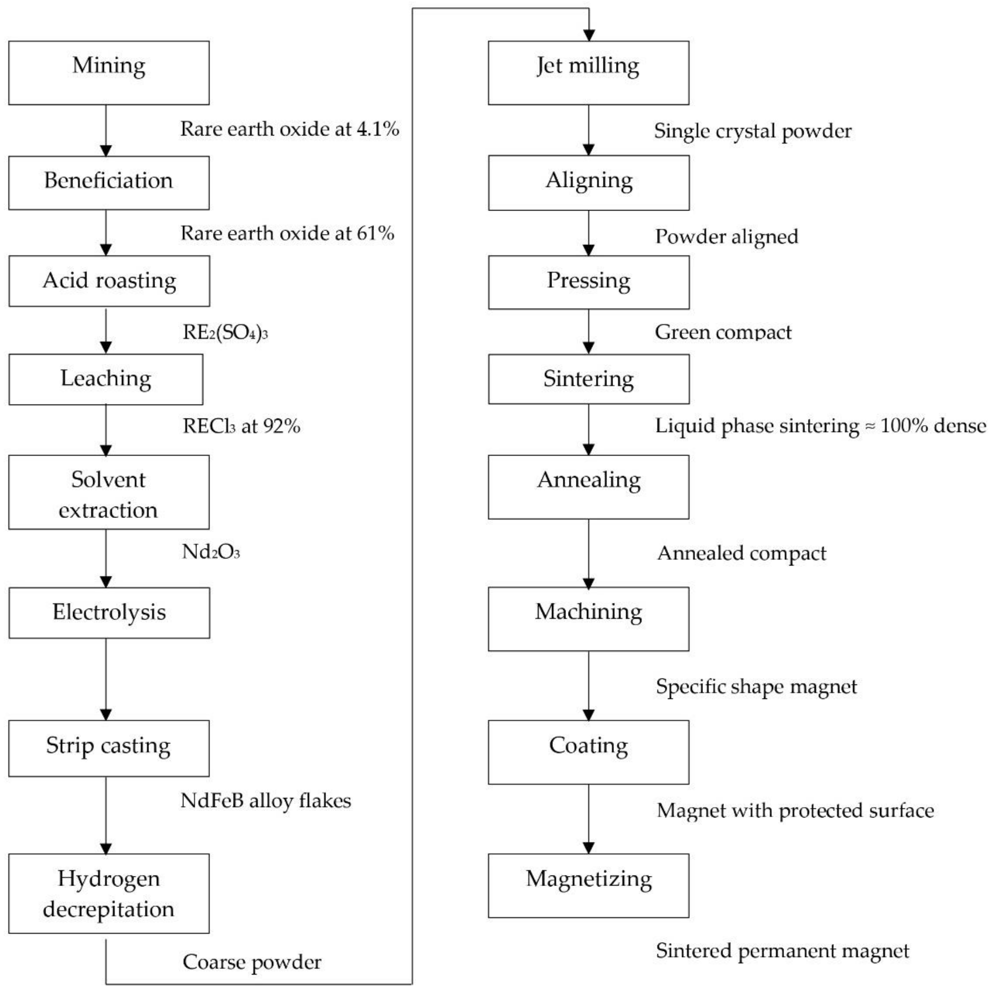

Figure 18. Permanent magnet virgin production.

7.3. Virgin against recycling production

As was described in this thesis, the recycling process comprehends several steps divided by different routes. In this analysis the sintered recycling process is compared to the virgin production. Both methods of producing functional magnets share steps in common, including alignment, pressing, sintering, annealing, machining, coating, and magnetizing. But in the beginning, there is a crucial distinction: In contrast to magnet recycling, which primarily focuses on the collection of end-of-life magnets, their cleaning, and the application of novel techniques like degassing, and grain boundary modification to transform them into functional magnets, virgin magnet production involves resource-intensive steps like mining, beneficiation, acid roasting, leaching, solvent extraction, and electrolysis to obtain rare earth elements and create the magnet alloy. The primary cause of the significant difference in environmental impact between the two approaches is this fundamental divergence at the beginning of the processes.

According to life-cycle assessments (LCA) of alternative waste treatment methods, recycling REEs may be more environmentally friendly than primary production [144], [153]. Studies focused on the energy consumption of the recycling method have been conducted by some academics. When compared to the conventional approach, the analysis revealed a significant 46% reduction in energy usage when using the recycling process. The decrease is mainly attributed to the exclusion of the strip-casting phase, which is a crucial step in forming the magnetically hard phase that serves as the substrate for (Nd, Pr, Dy)FeB, from which the NdFeB magnets are produced. By skipping the mining and purification processes, significant energy savings are also made possible. Like this, a preliminary analysis shows that for every ton of recycled magnet produced, more than 11 tons of CO_2 emissions are avoided [154], additionally, achieving a REEs recovery of 90% or more, less than 5% of the original REE is used in the recycling process, reducing the energy and mining implications of this activity [148].

Specific results provide even better news about recycling processes: When recycling is used instead of virgin production, there is a significant 96% decrease in ozone depletion. Another significant environmental advantage of recycling is the 90% decrease in smog when compared to virgin production. This demonstrates how recycling improves air quality. Also, recycling significantly lowers the potential for acidification compared to virgin production, by 64%; shows a 93% reduction in eutrophication potential; reduction in carcinogenic and non-carcinogenic effects of 81%; reduction of respiratory effects by 88%; lowers the potential for ecotoxicity with a 74%; reduction of 85% in fossil fuel depletion [149].

In conclusion, adoption of recycling methods can be justified from a variety of perspectives, including environmental effect, energy conservation, and resource protection [119].

8 Conclusions

8.1. Introduction to the chapter

The need for circular economy solutions is evident in today's dynamic technological environment, where the need for energy, food, and raw materials are continually increasing. The priority placed by the European Union on preserving vital resources, in particular rare earth elements, emphasizes the necessity of sustainable recycling methods. The recycling of electric motors, especially permanent magnet synchronous motors and permanent magnets, which are widely used in modern technology, contain enormous potential. This chapter highlights the conclusions drawn from this study and its structured as follows.

- Section 8.2 describes the concluding remarks of the study, the most relevant findings and contributions are shown in a synthesized manner.
- Section 8.3 introduces the limitations of the study. This will help to provide results transparently and to inform about the constraints under which the research was conducted.
- Section 8.4 describes guidelines for future research for scholars and practitioners.

8.2. Final remarks and contributions

Although research on permanent magnets within the context of the circular economy has shown growth in recent years, this growth is not proportionate to the overall increase in journals publications. Consequently, it can be inferred that interest in this topic remains relatively underdeveloped, resulting in several information gaps and potentially hindering progress in sustainable resource management.

Furthermore, within the available literature, most studies predominantly focus on recycling permanent magnets through indirect routes such as hydrometallurgy and pyrometallurgy. These approaches are associated with significant environmental issues, including waste contamination and high energy consumption. What's more, they often miss the opportunity to fully harness the potential of reintegrating end-of-life magnets directly into the supply chain.

On the other hand, within the literature, there is a discernible interest among certain researchers in exploring the feasibility of reusing permanent magnets as a strategy within the circular economy framework. Nonetheless, findings have underscored the crucial necessity for standardizing the dimensions and performance of magnets employed in the industry. This is imperative because the current variability in magnets significantly impacts the potential profitability of the reuse process, thus posing a formidable challenge to achieving circularity.

In order to reduce this gap, this study makes a novel contribution to the direct recycling literature by elucidating the efficient integration of an end-of-life recycling line for permanent magnets. To achieve this, it has been identified the various stages through which a magnet must pass, starting with its initial collection and closing with the final magnetic performance tests.

The recycling line starts with an initial stage which involves collection and a thorough condition assessment, followed by carefully disassembly, efficient demagnetization, and precise magnet extraction. Then, a coating and adhesive removal process is performed to prepare the magnets for characterization and subsequent pulverization.

The pulverization process includes hydrogen decrepitation and depending on the outcome requirements, it can follow the sintered route or the bonded route. The first one comprises milling, degassing, aligning, pressing, sintering and annealing. Meanwhile, the second route encompasses the following processes: HDDR, milling, mixing, aligning and pressing. It should be highlighted that both routes converge in the last steps of machining, coating, magnetizing and performance analysis.

Moreover, this study includes both economic and environmental analyses, which are indispensable for delving deeper into the feasibility of the permanent magnet recycling production line.

The economic analysis was centered on computing the annual cost of producing bonded and sintered permanent magnets through recycling routes, revealing that the costs per kilogram are lower than the current market selling price of permanent magnets. This outcome suggests the feasibility of adopting a recycling production line that holds profit potential. Concurrently, the evidence scrutinized in the environmental impact analysis highlights that recycling lines have fewer detrimental effects on the environment, as they reduce energy consumption and result in lower CO_2 emissions.

8.3. Limitations

The main limitation of this study lies in its reliance on existing literature and secondary sources as primary data, resulting in a notable absence of empirical evidence derived from direct experimentation or field studies. While the comprehensive analysis of the literature, patents, companies, and projects provided a thorough understanding of the topic and valuable insights, the absence of first-hand empirical data restricts the depth and scope of the conclusions.

Similarly, in the economic assessment of chapter 6, calculations performed using ranges may be susceptible to error propagation, potentially affecting the results and introducing some level of uncertainty.

8.4. Future research

To advance in the understanding of permanent magnet recycling and address the growing demand for sustainable materials in the modern world, future research efforts should focus on different sub-topics:

A vital avenue for future research in the field of permanent magnets recycling lies in the exploration and development of automation processes, particularly in the assessment and disassembly of electric motors, and potentially, the extraction of permanent magnets prior to demagnetization. Automation has the potential to completely transform the recycling sector by boosting output, efficiency, and accuracy. Therefore, future research should focus on creating cutting-edge automation systems that not only increase productivity but also support the primary goals of a circular economy and sustainable resource management.

In addition, developing customized permanent magnet extraction systems is a crucial area of future study. These devices would smoothly connect with automated procedures and be essential for maintaining the surface integrity of the magnet and eliminating damage while being extracted. Most current methods for recovering magnets include human or semi-automated procedures that may unintentionally affect the magnets surface which would reduce its effectiveness and potential for recycling.

Finally, another highly significant area for future research lies in the standardization of permanent magnets and the subsequent establishment of standardized parameters for the recycling process. While it is true that full standardization may not be immediately foreseeable, initiatives aimed at standardizing the shape and performance of permanent magnets would greatly aid the implementation of circular economy strategies. Similarly, it is recommended to investigate novel electric motor designs, incorporating the concept of 'design for recycling.' This approach would not only optimize the recycling process but also contribute to the advancement of sustainable practices.

9 Bibliography

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