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Development of Circular Supply Chain for EV Rare Earth Permanent Magnet Electric Motors: industrial perspectives and configurations for Lombardy region

TESI DI LAUREA MAGISTRALE IN MANAGEMENT ENGINEERING-INGEGNERIA GESTIONALE

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Abstract

The electrification of vehicles represents a revolutionary change in the automotive industry, with traditional internal combustion engines being replaced by electric motors. These components are mostly equipped with permanent magnets made of rare earths, more specifically magnets composed of Neodymium and Dysprosium. Classified by many nations globally as critical, these elements have a high economic importance and are subject to a high probability of supply disruption. Recently, the circular economy, thanks to the recovery strategies it implements, has been identified as one of the main solutions to mitigate the risks of using permanent magnets made of rare earths in electric motors in the automotive industry. To implement circular economy principles, companies have to move from linear to circular business models, through the implementation of supply chain structures recognised as Circular Supply Chains. With the aim of fostering the development of these structures in the Lombardy region, this thesis aims to identify the barriers that currently hinder the implementation of Circular Supply Chains through interviews conducted with actors operating in the electric motor and rare earth permanent magnet supply chain and evaluates possible configurations to recover the studied products, highlighting roles and responsibilities of each actor involved within these structures.

Key-words: Electric vehicles; electric motors; rare earth permanent magnets; circular economy; circular supply chain; Lombardy;

Abstract in italiano

L'elettrificazione dei veicoli rappresenta un cambiamento epocale nell'industria automotive, facendo sì che i tradizionali motori a combustione interna vengano sostituiti dai motori elettrici. Questi componenti montano nella maggior parte dei casi magneti permanenti fatti di terre rare, più nello specifico magneti composti da Neodimio e Disprosio. Classificati da molte nazioni a livello globale come critici, questi elementi hanno un'elevata importanza economica e sono soggetti ad un'alta probabilità di interruzione della fornitura. Recentemente l'economia circolare, grazie alle strategie di recupero che mette in pratica, è stata identificata come una delle principali soluzioni per mitigare i rischi derivanti dall'utilizzo di magneti permanenti fatti di terre rare all'interno dei motori elettrici nell'industria automobilistica. Per mettere in atto i principi dell'economia circolare, le aziende devono passare da modelli di business lineari a circolari, attraverso l'implementazione di strutture di fornitura riconosciute come Circular Supply Chains. La tesi, con lo scopo di favorire lo sviluppo di queste strutture nella regione Lombardia, si propone di identificare le barriere che ostacolano l'implementazione di Circular Supply Chains attraverso interviste effettuate con gli attori operanti nella filiera dei motori elettrici e dei magneti permanenti e valuta configurazioni possibili per il recupero dei prodotti sotto esame, evidenziando ruoli e responsabilità di ciascun attore coinvolto all'interno di queste strutture.

Parole chiave: Veicoli elettrici; motori elettrici; magneti permanenti a terre rare; economia circolare; circular supply chain; Lombardia;

Table of Contents

Introduction

The electrification of vehicles represents a transformative shift in the automotive industry, aiming to replace traditional internal combustion engines (ICEs) with electric power sources. According to McKinsey [1], this transition is driven by both consumer's purchasing behaviours and governmental incentives to accelerate the shift to sustainable mobility. A growing awareness of environmental concerns, together with advancements in technologies and a desire for greater energy efficiency will disrupt the automotive industry. However, the introduction and the progressive shift towards electric vehicles (EVs) creates new sustainability and supply chain challenges, requiring the adoption of circular economy (CE) principles to recover the materials embedded in passenger cars [2].

Between electric vehicles, the main solutions for customers are represented by hybrid electric vehicles (HEVs), plugin hybrid electric vehicles (PHEVs), battery electric vehicles (BEVs) and fuel cell electric vehicles (FCEVs) [3]. Given these different solutions of EVs, a multitude of electric motor types have been used and tested for different vehicles in the recent years. Looking at the different models in the market for automotive sector, it is possible to notice a progressive shift towards electric motors with rare earth permanent magnets (RE-PMs), being a solution able to reach the higher performances and efficiencies [4], [5].

The main drawback of this solution is given by the usage of magnets, specifically Neodymium-iron-boron (NdFeB) ones, that provide high costs and are made of rare earth elements (REEs). Among the 17 elements that comprise this group, RE-PMs use primarily Neodymium (Nd) and Dysprosium (Dy), two of the elements that have raised the attention of the actors involved in many value chains because of their geopolitical importance [6].

As reported by US Department of Energy [7], RE-PMs are crucial elements for technologies leading the energy transition - EVs and wind turbines – and are controlled mainly by China. This nation, controlling the overall value chain from the mining activities to the commercialization of final products, is the leader in the market and sets prices and availability of these goods at global level. This high production concentration (90% of RE-PMs SC activities performed in China), together with rising global political tensions and a growing Chinese domestic market demand, results in a high supply risk for other worldwide countries that rely on the import of these goods. Moreover, China's dominance over RE-PMs supply chain raises some challenges from the sustainability point of view: lack of supply chain transparency, standards and certification schemes regarding environmental and social impacts of Chinese activities are usually cited when addressing this topic [8].

Because of the above-mentioned motivations, REEs embedded into magnets are furthermore considered by different national studies as critical [9], [10]: this definition is commonly used for those materials that have high economic importance and are subject to high probability of supply disruption [11].

Searching for solutions to reduce criticality of materials and build resilient and sustainable supply chains for commodities, five main strategies could be adopted: recycling, substitution, new mines opening and development of alternative products [12]. Between them, the application of CE techniques as recycling is seen as core solution for criticality mitigation [13]. In fact, through strategies that involve the life extension of products and components and recovery of materials, it is possible to increase independence from externally sourced inputs and raw materials, thereby securing part of the resource supply from the regenerative loops [14].

CE, however, is much broader than a recovery process, since it requires also changes at the strategic, tactical and operational levels of management of a company [15]. Therefore, the movement towards CE implies modifications at the supply chain level too, requiring the adoption of circular schemas known as Circular Supply Chains (CSCs). Moving away from the classical take, make, dispose process, these structures ideally generate zero waste because they are designed for restoring and regenerating resources in natural and industrial ecosystems [16]. Given the multitude of changes needed to implement such systems, the development of CSCs is usually accompanied with multiple challenges and barriers [17], [18], [19], [20].

When searching for the adoption of CE and CSCs for the EV electric motor in literature, it is possible to notice that the scientific community has provided very few contributions identifying the system structure and players. Instead, the main objective of publications and projects carried on until now was to provide technical and operational suggestions for recycling the magnets embedded into electric motors, therefore focusing mainly on the application of a unique CE strategy level rather than at supply chain one.

The aim of this study, therefore, is to address this gap examining possible CSC configurations to build up a system for recovering electric motors and the magnets embedded into them, providing challenges linked to the adoption of CSCs through stakeholder engagement by interviews.

More precisely, the study will be focused at Italian regional level, specifically for Lombardy, being the first region of Italy for economic importance and being a national leader in promoting the EV adoption with the highest amount of charging infrastructures of the country [21].

Therefore, to address the above-mentioned objectives of the study, the following research questions (RQ) have been set:

RQ1: *What are the challenges that different industrial actors may face during the development of CSCs for the recovery of EV RE-PM electric motor and embedded magnets?*

RQ2: *What are possible circular supply chain configurations for EV RE-PM electric motor and embedded magnets in Lombardy region?*

To offer a comprehensive analysis, the thesis will be developed in the following sections.

Chapter 1 provides a general overview of electric motors, permanent magnets included within them and circular economy principles underlying this thesis. In this section, the different types of electric motors used in electric vehicles will be analysed in more detail, with a main focus on permanent magnet design. Following this, the value chain of rare earth permanent magnets is proposed, including the players operating in the sector, the risks of supply disruption resulting from the use of rare earths and the solutions that Europe is adopting to mitigate this issue. To conclude the introductory phase, the principles underlying the CE and CSCs are proposed.

Chapter 2, instead, identifies the expected recoverable volumes of RE-PM electric motors within the Lombardy region, with the aim of providing the expected input volumes to the CE strategies at the basis of the CSC structure proposed within the thesis.

In Chapter 3, a systematic review of academic publications and European projects is carried out to identify the different circular economy strategies applicable to the products under consideration to provide the needed knowledge basis to address RQ1. This section also aims to identify possible CSC configurations that can be adopted for the Lombardy region, thus looking for useful solutions to address RQ2.

Chapter 4 analyses the key actors within the reverse supply chain, to identify the focal actors that can execute the strategies identified in the previous sections.

Chapter 5, responding to RQ1, reports the results obtained from the interviews with the actors present in magnets and electric motors supply chain, providing a more direct perspective of the main issues that are hindering the development of CSCs at an industry level.

Finally, Chapter 6, thanks to the results obtained in the previous sections, responds to RQ2 by proposing different CSC configurations for the Lombardy region.

1 Contextual background

1.1. Electric motor technology and trends

An electric motor is an electrical device that transforms electrical energy into mechanical energy. Typically, electric motors functioning derives from the interaction between the motor's magnetic field and electric current in a wire winding to generate a twisting force known as torque, which is then applied to the motor's shaft [22].

Electric motors are composed by two main components that are the rotor and the stator: the first is the moving part, while the second remains stationary. Depending on the configuration of the motor these can be equipped with copper coils or magnets with the purpose of generating magnetic fields that, interacting with each other, cause the movement of the rotor that transmits the mechanical power [22].

As proposed by Rimpas et al. [23] there is a wide range of electric motors for EV propulsion. Between the different possible technologies, alternate current ones are the most used in the automotive sector being able to reach higher rotational speeds and higher powers. Within this category it is possible to identify different architectures that are based on different functioning principles and different materials. Table 1.1 resumes the different technologies that could be embedded into electric vehicles, classifying them in terms of relative performance (cost, average efficiency, power density) materials used in the stator/rotor and readiness level deducted from literature.

In general, despite the different materials it is made of, the electric motor is a very valuable part of the electric vehicle: in fact, this, together with the inverter essential for its operation, accounts for between 6% and 18% of the production costs of a BEV [24]. In addition, taking into consideration the RE-PM motor, it can be noted that the value of magnets embedded can vary a lot depending on the design, performances to be achieved and prices of REEs: as a reference, it is expected that the value can vary between 17% and 28% of the value of the electric motor [25], [26].

Machine type	*Performance*	*Materials*	*Readiness level*
Induction machine	Cost: low Avg. efficiency: low Power density: low	Aluminium, cast iron, copper, silicon steel	Late stage
Synchronous reluctance machine	Cost: medium Avg. efficiency: medium Power density: medium	Aluminium, cast iron, copper, silicon steel	Early stage
Separately excited synchronous motor	Cost: medium Avg. efficiency: low Power density: medium	Aluminium, cast iron, copper, silicon steel	Early stage
Rare earth permanent magnet motor	Cost: high Avg. efficiency: high Power density: high	Nd, Dy, Pr, magnet coatings, aluminium, cast iron, copper, silicon steel	Dominant design

Table 1.1: Electric motor types (own elaboration)

Looking at the different machine types embedded in EVs in the market, it is possible to notice that at the moment the dominant design for EV electric motors is the one equipped with RE-PMs, because of its higher technical performances when compared to other solutions (95% of EVs are equipped with RE-PMs) [27].

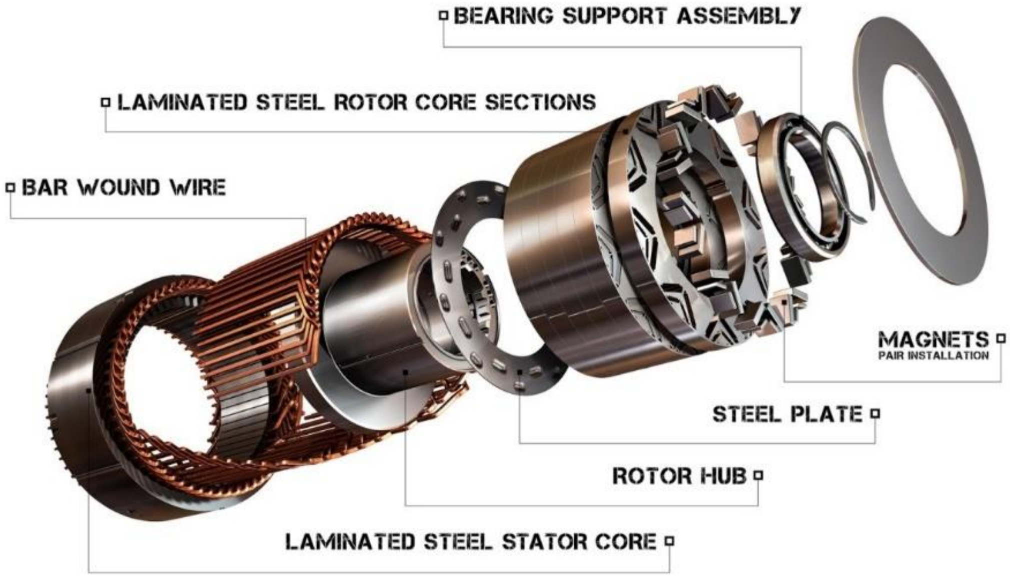

Figure 1.1: RE-PM electric motor (source Electric Cars Report [125])

Passing to the magnets embedded into the electric motor, Ashby et al. and Callister et al. [28], [29] provide the basic knowledge for PMs that in general are classified for their magnetic properties: these are coercivity Hc (remanence to demagnetisation), remanence Br (remaining magnetisation after application of a magnetic field) and energy product BHmax (energy needed to demagnetise a magnet). These properties can be reduced with the increase of working temperatures (until the Curie temperature, limit before losing permanent magnetic properties) and are the main factors that influence performances and costs of PMs. In terms of composition, four major magnetic compounds can be found in the market: two rare earths based – neodymium-iron-boron (NdFeB) and samarium-cobalt (SmCo) and two non-rare earths based – ferrites and aluminium-nickel-cobalt (AlNiCo). Rare earth permanent magnets are preferred due to higher performances reachable and, between them, NdFeB are used for EVs application because of the higher efficiencies and lower weight respect to the other competitive solutions of the same size.

NdFeB magnets are produced as both bonded and sintered magnets, with the latter being considered the best option because of the higher energy product achievable. Approximately 90% of the current market for NdFeB magnets is for sintered magnets [30].

The composition of these magnets is made of iron (65-70% of the weight) and four REEs: neodymium (Nd) (about 20-30% of weight) and praseodymium (Pr), dysprosium (Dy), terbium (Tr) (5-10%) [7], [31]. Specifically, Nd and Pr are used to confer magnetic properties, while Dy and Tr are used to increase coercivity at high temperatures [28], [29].

Because of the critical elements embedded in RE-PM electric motors, other solutions are gaining interest between electric motor manufacturers in the last years. These move from the differentiation in magnets' composition to different designs in terms of motor functioning: between the different possible solutions the usage of ferrite magnets, the synchronous reluctance machine and the separately excited synchronous motors (or wound motor) architectures seem the most promising [27]. Following this trend, Renault and BMW's 5th generation drive system use wound rotor design with copper windings on the rotor, Audi e-tron uses an induction machine and Tesla has announced that will stop producing motors containing REEs [32], [33].

For what concerns the expected future trends in the EVs design, E-mobility Engineering [27] proposes the point of view of with some experts of the sectors: it is pointed out that at current material prices, and assuming a reliable supply chain, it would be hard to motivate a significant reduction in market share of RE-PM machines. Some of them think that motors equipped with magnets will prevail unless the sustainability argument changes things significantly, pointing out that motors not equipped with RE-PMs will provide greater size and weight, lower efficiency and increased reliance on other materials like copper.

1.2. NdFeB magnets value chain and actors

The value chain of rare earth permanent magnets is composed by different processes and actors that lead to the production of the final product to be embedded into the various applications.

As analysed by Smith et al. and Righetti et al. [7], [34], the value chain begins with the mining of the rare earth ores (a concentrate containing different REEs) and passes than to the separation of the singular rare earth oxides. After this step in which the singular oxides are recovered is finished (i.e. Nd, Dy), the refining process transforms rare earth oxides into metals and alloys that are the input material for magnet production. This last step is composed by a series of specific processes that are summarised in Figure 1.2 and lead to the creation of the NdFeB magnet that will be sold for being embedded into the final products.

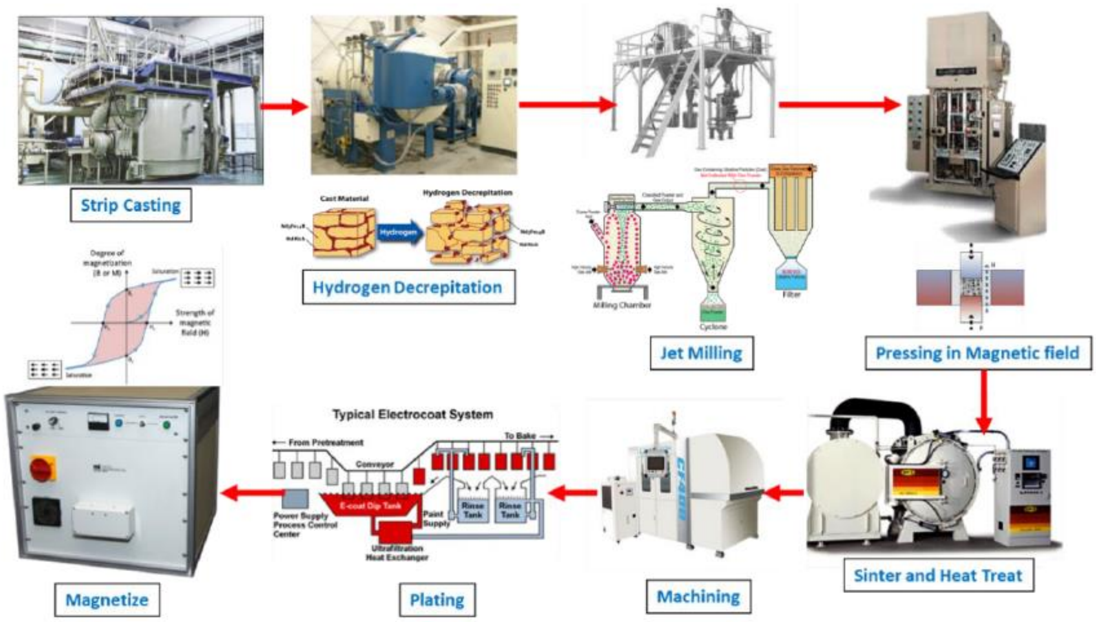

Figure 1.2: Magnets refining process (readapted from: Smith et al. [7])

The application of magnets is seen mainly in technologies promoting the energy transition, particularly in wind turbines and battery electric vehicles. However, as proposed by Righetti et al. [34] their application extends to a wide range of uses, including household appliances such as refrigerators and washing machines, consumer electronics such as mobile phones, headphones and speakers, hard disk drives, actuators and electric scooters. Figure 1.3 shows the results got from Righetti et al. [34], highlighting how different publications taken into consideration in the study propose different shares of magnets embedded into final products.

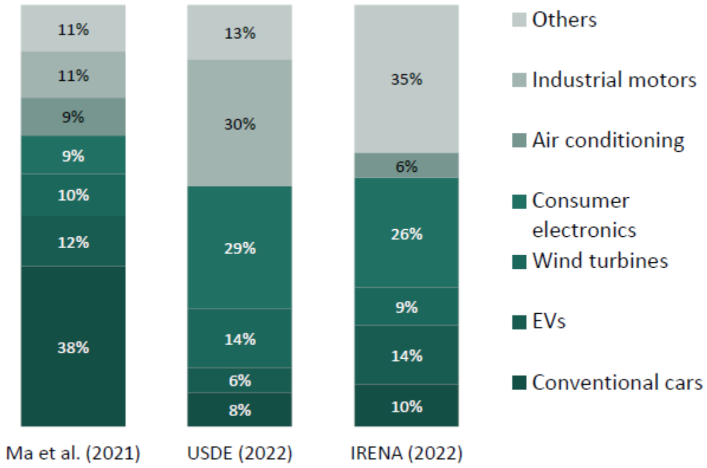

Figure 1.3: NdFeB magnets applications (source: Righetti et al. [34])

Looking at the geographical disposition of the activities to be performed along the supply chain, it is possible to notice that the whole production processes are highly concentrated in China. Having more than the half of the market shares for mining, the Chinese supremacy increases even more for the following steps that lead to magnet production. The country, in fact, dominates the rare earth oxide separation activities having about the 87% of the shares, increasing this value to 91% for metals refining and finally owning the final step of magnets production with 94% of the shares [7], [34].

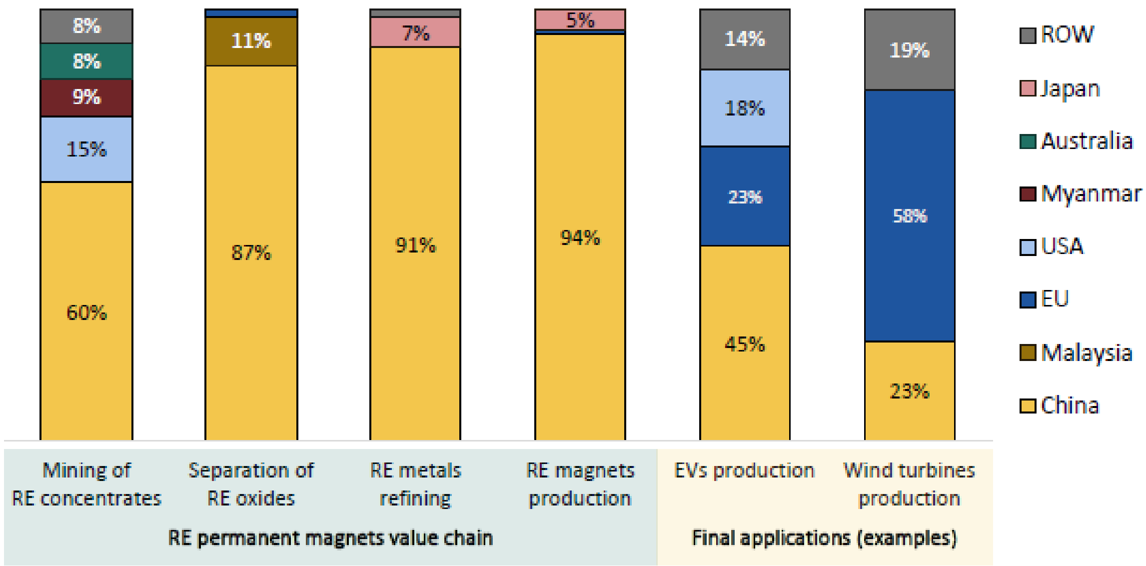

Figure 1.4: Magnets SC activities and global shares (source: Righetti et al. [34])

These values suggest that the Chinese monopoly over these products does not come only from the availability of mines in the territory, but it is also reinforced by the added value activities that transform the mined ores into magnets [7].

When talking about the Chinese control over magnets, usually vertical integration, government support, material costs and availability are represented as competitive levers that protect the Chinese supremacy and permit to provide a price difference of about 20-30% for a magnet produced in Europe compared to a Chinese one [35]. Moreover, when the magnets value chain is analysed, illicit mining is always cited as a further motivation of cost reduction in the manufacturing process: the little attention paid to environmental standards by illegal miners allow them to maintain low internal prices due to their market power [8], [36]. Given these motivations it is very hard for other players outside China to compete in the magnets market, bringing electric vehicle manufacturers (OEMs) to rely mainly on Chinese suppliers [35].

This can also be seen from Figure 1.5, obtained through Google search, which aims to identify the players in the value chain of NdFeB magnets within electric vehicles.

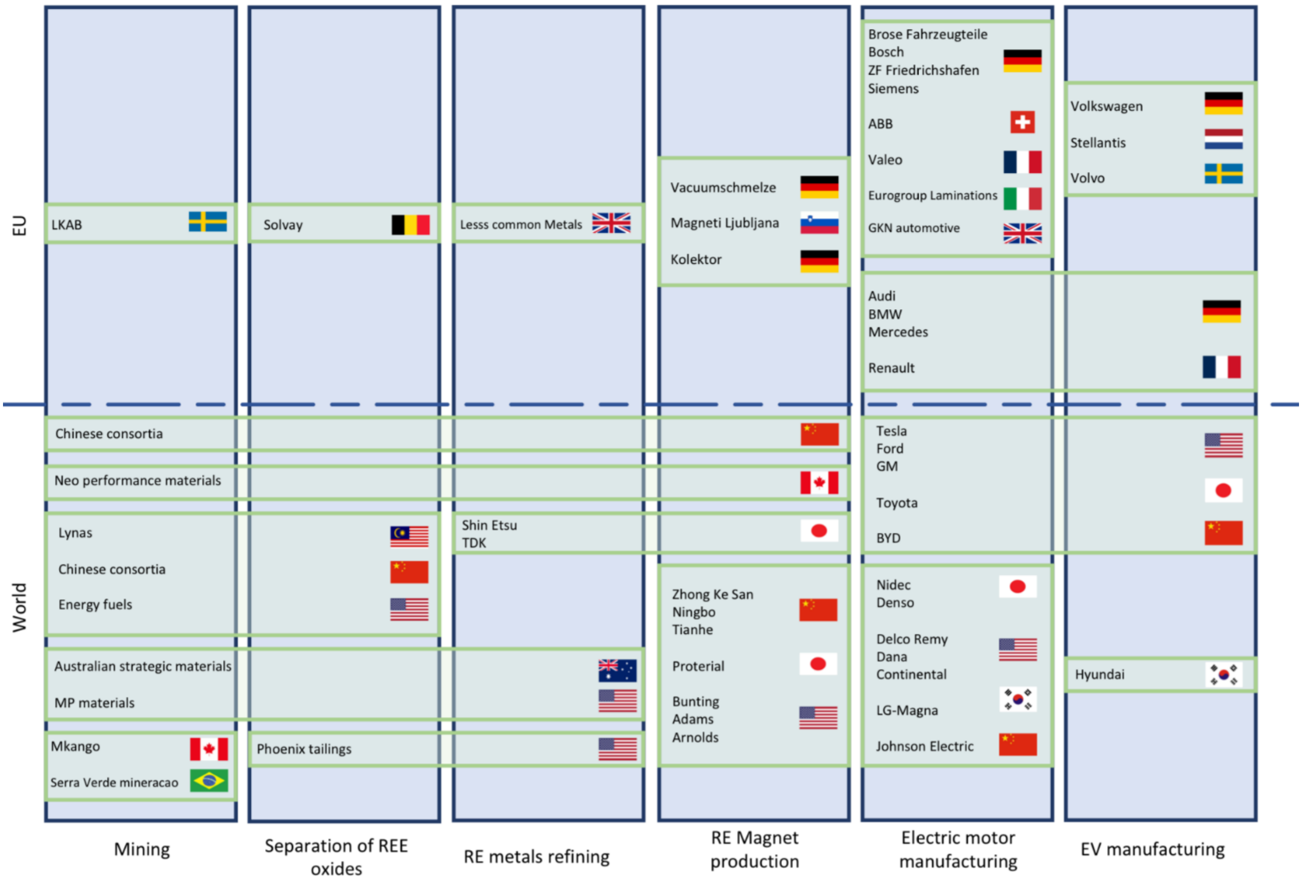

Figure 1.5: Magnets SC actors (own elaboration)

The results shown are in line with the above, with Europe having few industrial players in the upstream value chain. Looking at the rest of the world, instead, in addition to the Chinese dominance for which it is difficult to get information, it is possible to notice how America is moving to build the basis for a domestic supply of rare earth permanent magnets: in addition to the mining activities that take place mainly in the Mountain Pass mine in California, the company MP Materials has announced that will carry out the separation of REE oxides and refining to increase American independence in the production of magnets for EVs, together with General

Motors [37]. Again, in America, the company Phoenix Tailings will provide the necessary processing to obtain materials for the construction of magnets [38]. Looking at other geographical areas, Australian strategic materials plans to carry out all the steps preceding the production of magnets through mining operations in Australia and subsequent processing in Korea [39], [40], while the Japanese Shin-Etsu and TDK focus on the final steps necessary for the construction of magnets [41], [42], [43].

For what concerns Europe, it can be seen that the development of a value chain for the production of magnets is still in its early stages [44]: starting from mining, the Swedish company LKAB has recently announced that has discovered the largest rare earth deposit in Sweden and that this will take 10-15 years before it becomes operational [45]. Passing to the subsequent operations, on the other hand, the Solvay and Less Common Metals companies alone provide the necessary operations to get the right material inputs for the construction of magnets [46], [47]. Related to these activities, the Canadian company Neo Performance Materials, which operates worldwide from the extraction to the production stages of magnets, announced the opening of the first industrial plant capable of processing magnetic materials and manufacturing magnets for automotive applications in Estonia [48].

1.3. The supply disruption risk: European solutions to overcome the issue

The expected surge in demand mainly driven by green technologies (EVs and wind turbines), the limited domestic manufacturing capacity and rising political tensions represent concrete risks for EU's and worldwide players to meet the future demand for rare earth permanent magnets [35], [49].

Moreover, the REEs contained within the magnets (Nd and Dy) include other problematics that go beyond the geographical concentration of the supply chain in China and cause them to be classified as critical by Europe and a multitude of states around the world. These are summarized in the characteristic that takes the name of adaptive capacity of a system, that is the ability of a system to react to changes of the conditions of supply. The main strategies applicable to foster the adaptive capacity are product reuse and recycling, substitution, establishment of stockpiling quantities and material efficiency [11]. Therefore, since these strategies are poorly used and usable for the materials included in the RE-PM of electric vehicles worldwide and given their high geographical concentration, it is possible to conclude that the supply chain for these materials has high risk of disruption [11]. This, together with the high economic importance of these materials, makes them to be considered within the group of elements that take the name of Critical Raw Materials (CRMs).

As it is possible to notice from Figure 1.6, Europe in its study on these materials performed by Grohol et al. [50], positions the group of Light Rare Earth Elements (LREE) containing Neodymium and Heavy Rare Earth Elements (HREE) containing Dysprosium among the most critical materials, having very high levels of supply risk and economic importance.

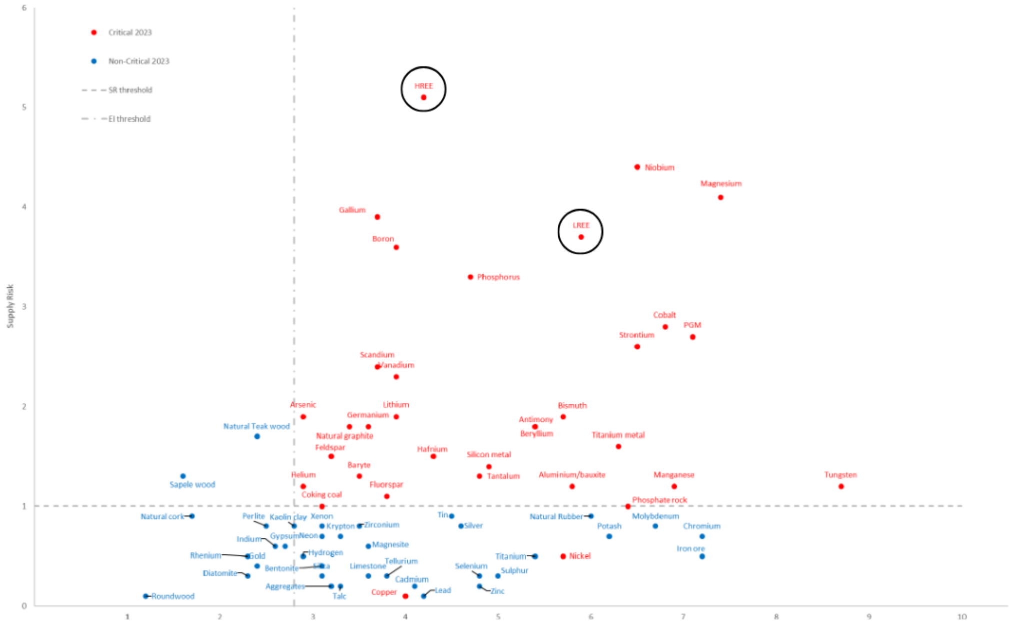

Figure 1.6: EU Critical Raw Materials (readapted from: Grohol et al. [50])

Looking at the market of CRMs is possible to notice that EU will never be self-sufficient from these materials, relying entirely on imports from China: the latter dominates the market being the supplier of 100% of Dysprosium and 85% of Neodymium in the world [50]. China is also the main actor in REE's demand, using 60% of rare earths production [51].

The combination of the above mentioned factors create the perfect conditions for possible supply chain disruptions [50], events that would provoke serious negative repercussions for firms, consumers and economy [52]. Such a phenomena has already taken place in 2011, when prices of Neodymium and Dysprosium exploded by a factor of 20 compared to the beginning of 2010, causing a shock in the market [52].

The EU, given these risks, is putting in place some initiatives to decrease the dependency on Chinese REEs at different levels and across different sectors, identifying in circular economy a promising solution. The main actions in place for securing a more resilient and reliable supply chain of these materials are represented by the following initiatives:

- ***Proposal of the Critical Raw Materials Act*** [53]: through this comprehensive set of actions EU wants to rely on a more secure, diversified, affordable and sustainable supply chain of critical raw materials. To do so, the Act sets clear benchmarks for extraction (at least 10% of the CRMs consumed in EU must come from local mines), processing (at least 40% of the CRMs consumed in EU must be processed and refined locally), recycling (at least 15% of the CRMs consumed in EU must come from recycling activities) and sourcing (not more than 65% of the Union's annual consumption of each strategic raw material at any relevant stage of processing from a single third country) of critical raw materials
- ***Creation of the European Raw Materials Alliance (ERMA)*** [54]: by bringing together all relevant stakeholders along strategic value chains and industrial ecosystems, the alliance will focus on increasing EU resilience in the rare earth elements and permanent magnet value chains. Through investments addressing the entire value chains and precise strategic areas would be possible to reduce the risk of disruptions in this sector.
- ***Proposal of the Directive for End-of-life Vehicles*** [55]: based on the directives 2000/53/EC ('ELV Directive') and Directive 2005/64/EC ('3R type-approval Directive') the legislation about end-of-life vehicles needs to be renewed to target specific materials within vehicles and to promote more circular business models. Being the cited directives based on indicators linked to the overall weight of the End-of-Life Vehicles (ELV), they do not tackle the RE-PMs embedded in electric motors that cover very little percentages in these indexes. Therefore, to address problems that are currently affecting the automotive

industry, the following policy options have been proposed for each of the following areas:

- 'Design Circular': OEMs must provide dismantling information and establish the digital Circularity Vehicle Passport to foster circularity.
- 'Use Recycled contents': OEMs must include precise amounts of recycled materials within vehicles.
- 'Treat better': ELV authorised treatment operators must remove components containing CRMs before shredding activities and favour reuse, remanufacturing, and refurbishment activities prior to recycling.
- 'Collect more': Member States must report numbers of import/export and missing vehicles and settle penalties for the ELV sector if an ELV is sold to illegal dismantlers and for dealers dealing with used spare parts from non-authorised facilities.
- 'EPR': application of Extended Producer Responsibility schema (EPR) to vehicles, obliging OEMs to be responsible of the product placed on the market. By doing so, they will have to ensure the recovery of their vehicles (and embedded components) once end-users dispose their cars through individual or collective collection schemas. According to OEMs, these will be either recovered directly by them or given to other ELV authorised treatment operators.
- 'Cover more vehicles': Inclusion of lorries, buses, and other vehicle categories to the above-mentioned policy options.

1.4. Circular economy as a solution to materials criticality

In an era where sustainability and resource conservation have become paramount, the concept of a circular economy has emerged as a powerful and innovative approach to address the challenges of the linear, take-make-dispose economic model used until now [56]. The Circular Economy represents a fundamental shift in how resources are produced, consumed and managed, aiming at maximising their value while reducing waste, environmental impact and fostering economic resilience [57]. To do so, it is essential for different actors to cooperate with each other, both at company and at institutional level: a transition towards CE, thus, embodies significant modifications at product level, at business model level and at ecosystem level [58].

The system envisioned by CE is composed by products, materials, and resources that are kept in circulation for as long as possible through strategies that have the objective of extending the most their useful life [59].

To analyse CE, this thesis adopts the R10 framework because it contains a well-defined, complete and prioritised set of existing CE strategies [60].

Smarter product use and manufacture	**R0**	**Refuse**	Make product redundant by abandoning its function or by offering the same function with a radically different product
	R1	**Rethink**	Make product use more intensive (e.g. through sharing products or by putting multi-functional products on market).
	R2	**Reduce**	Increase efficiency in product manufacture or use by consuming fewer natural resources
Extend lifespan of product and its parts	**R3**	**Reuse**	Re-use by another consumer of discarded product which is still in good condition and fulfils its original function
	R4	**Repair**	Repair and maintenance of defective product so it can be used with its original function
	R5	**Refurbish**	Restore an old product and bring it up to date
	R6	**Remanufacture**	Use parts of discarded product in a new product with the same function
	R7	**Repurpose**	Use discarded products or its part in a new product with a different function
Useful application of materials	**R8**	**Recycle**	Process materials to obtain the same (high grade) or lower (low grade) quality
	R9	**Recovery**	Incineration of material with energy recovery

Figure 1.7: R10 framework (source: Morseletto et al. [61])

As can be seen from Figure 1.7, the strategies proposed in this framework are mainly divided into three groups that will be considered within the thesis. These are:

- Smarter product use and manufacture: in this category belong the strategies that modify how the product is conceived at the level of design and materials used within them. In this thesis, these strategies will be applied to the RE-PM electric motor.
- Extend lifespan of product and its parts: In this category belong the strategies useful for extending the useful life of products and the components within them. In this thesis, these strategies will be applied to the RE-PM electric motor and the magnets included within it.
- Useful application of materials: In this category belong the strategies related to the recovery of materials within the product and the embedded components. In the thesis, these strategies will be applied to the permanent magnets included in the electric motor.

Moreover, each of the strategies in these categories could provide benefices that go beyond the positive environmental impact: CE in fact, is seen as one of the main solutions to build resilience for entire supply chains thanks to its ability of securing supply of products and materials coming from its loops [61] . Therefore, when the topic of critical materials is discussed, CE and its strategies are usually cited as a solution to reduce criticality [13], [14], [62], [63], [64]. For this reason, the countries aiming to tackle this issue, identify CE as one of the main solutions together with local mining, diversification of suppliers and substitution strategies.

Through the analysis of the national plans and the current literature regarding CE to reduce criticality, it is possible to notice that CE practices are mainly implemented from end-of-life (EoL) perspective, therefore addressing mainly the recycling strategy of the R10 model. To mitigate material criticality issues, it is necessary to look at the circular economy from a broader perspective through the inclusion of strategies that aim to expand the lifecycle of products and components and aim to change product design through circular economy-oriented production strategies and foster (level 1 of the R10 model) [65], [66].

Moreover, the application of circular strategies is seen as one of the solutions of the so-called balance problem: to respond to the high demand of some REE that occur in low concentration within rare earth ores, some others that are not directly required are extracted, creating an overproduction of some elements that have to be stockpiled, resulting in costs and unbalances in the demand-supply mechanism [67].

Focusing on the expected impacts of implementing circular economy strategies for the recovery of permanent magnets in Europe, Righetti et al. [34] proposes a study that aims to identify the percentage of demand that would be met if recycling strategies for magnets were implemented for all product categories containing them until 2050. This analysis includes two different scenarios given different combinations of product collection rate and disassembly efficiency rate. As can be seen from the Figure 1.8, in the best-case scenario, approximately 48% of the demand for magnets by 2050 could be met.

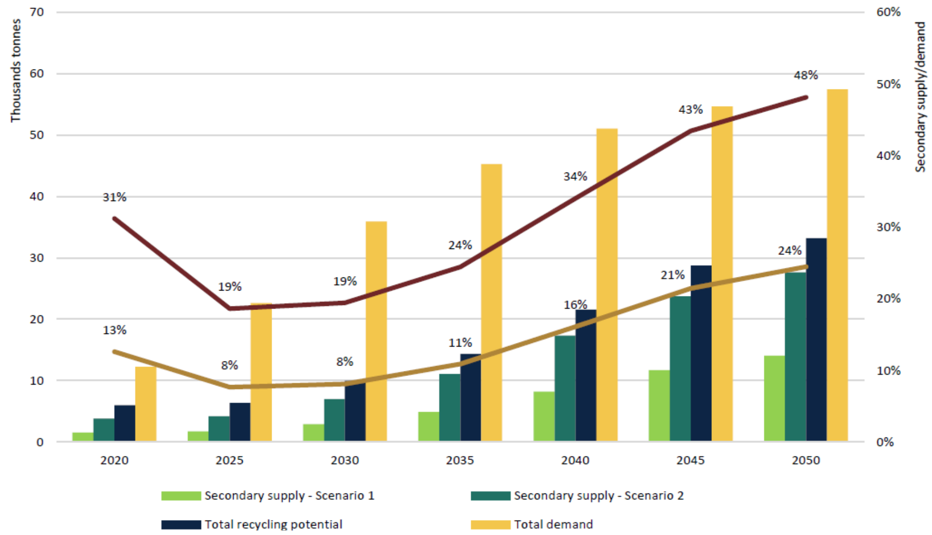

Figure 1.8: Impact of recycling NdFeB magnets (source: Righetti et al. [34])

Bobba et al. [68], on the other hand, proposes a more detailed study, which aims to identify the impact of different circular economy strategies (i.e. not only recycling) for the recovery of Neodymium inside the magnets of electric vehicles only, to propose a new, more comprehensive indicator for the circular economy. This analysis also proposes two scenarios, one more in line with the current situation (BaU) by only including recycling of small quantities and one where full circularity is achieved (CM-sc).

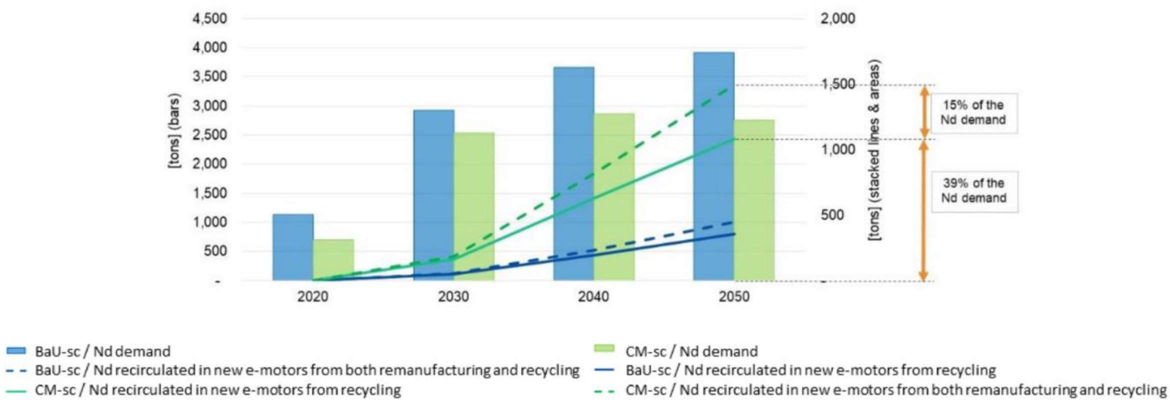

Figure 1.9: Impact of CE strategies on EV RE PM electric motors (source: Bobba et al. [69])

1.5. Circular Supply Chains

Circular supply chain management integrates the philosophy of the circular economy into supply chain management, thus embodying the concepts explained in the previous chapter into a unique system of actors [16].

Circular supply chains (CSC) find their basis on closed loop supply chains and on sustainable supply chains, integrating the reverse loop and processes together with the sustainability concepts. Through the reverse supply chain that includes the processes of recovery, reprocessing and remarketing, the goods are reintegrated into physical flows at different levels of the traditional supply chain (now forward SC). By doing so, it is possible to reduce the materials inputs into upstream activities, thus obtaining more sustainable and robust systems. Moreover, the boundaries of CSCs are expanded by the addition of possible open loop strategies for products/components/materials circulating within the supply chain, resulting in solutions that create ideally zero waste [16].

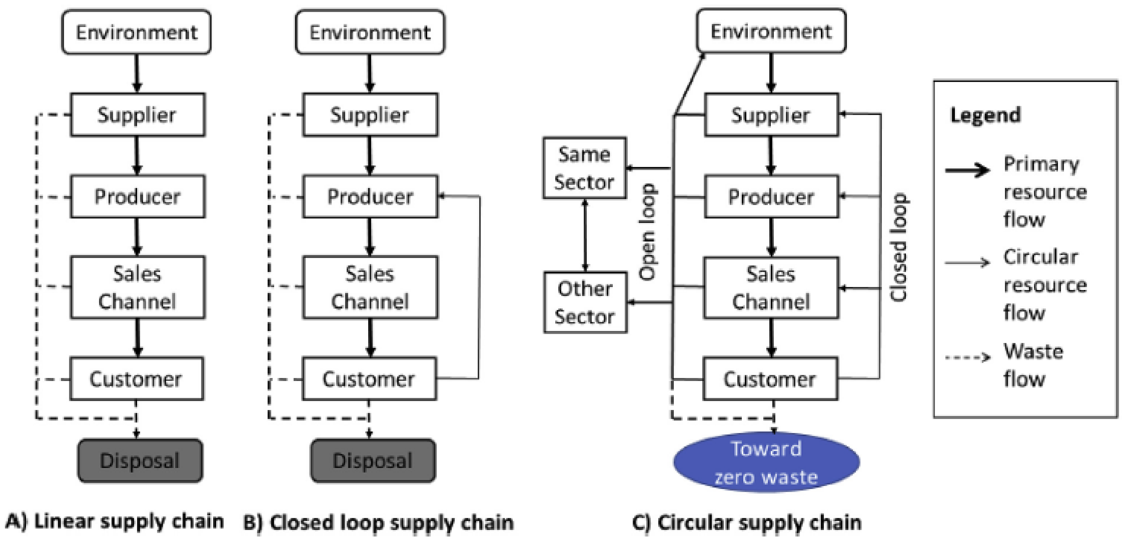

Figure 1.10: Circular Supply Chains (source: Farooque et al. [16])

Adopting CSC is not an easy task because it is necessary to integrate reverse supply chain management functions, together with high levels of coordination, transparency and a clear flow of information along the actors of the system. [69]

Passing to the barriers that hinder the development of CSCs it is possible to notice how several studies have tried to map the state of the art of the barriers identified through systematic literature reviews. The main publications in this field carry out different analyses, dividing the barriers into different categories and then going to analyse the frequencies at which they have been mentioned [17], [18], [19], [20], [70] . Through a reading of the publications dealing with this topic it has been possible to reclassify some of these categories and identify those that appear as the most frequent Table 1.2

aims to summarize what appear as key categories of barriers and to give some examples of the limitations recognised by most of the papers consulted.

Barrier category	*Barrier description*
Technology	1. Lack of informatic system to track take-back initiatives. 2. Lack of technology for quality assessment and control. 3. Lack of technology for the integration of data.
Information, knowledge, skills	1. Lack of skills and training of workforce along the supply chain. 2. Lack of public sector and consumers knowledge.
Economic	1. Lack of financial resources, capabilities, and incentives to implement CE in the SC. 2. Lack of returns in the short term. 3. High costs and investments for CE adoption in the SC. 4. Difficulty of setting the price for recovered products.
Market	1. Lack of alignment on the take-back along the SC. 2. High time consuming and labour-intensive activities for CE. 3. Supply and demand uncertainty for CE goods.
Organisation/Management	1. Lack of leadership and top management support to CE adoption. 2. Different priority of the companies in the strategic plans. 3. Lack of organizational infrastructure to support CSC activities.
Government/Regulation	1. Lack of environmental laws, policy standards and regulations for CSC adoption. 2. Lack of a standard system for performance indicators with regard to measuring CE in SC.
Society/Culture	1. Consumer perception and willingness to choose recovered products. 2. Price sensitivity.

Table 1.2: CSC adoption common barriers (own elaboration)

2 Expected volumes of RE-PM electric motors in Lombardy region

In this chapter, the expected collection volumes of electric motors and RE-PM for the region of Lombardy for electric vehicles will be calculated. The results obtained from this analysis will be useful to understand the expected volumes RE-PM electric motors at regional level and will became inputs for the different circular economy strategies applicable to these components.

2.1. Methodology

The analysis is based on two scenarios showing different levels of collection ambition and is developed based on hypotheses found in the literature. For a clear representation of all the assumptions and sources used, please refer to Appendix A.

The two proposed scenarios serve to identify two different collection ambitions, in a less optimistic scenario (SC1) where EoL vehicles are collected at the same rate as today and an optimistic one (SC2), where the End-of-life Vehicle Directive obliges OEMs to recover ELV through EPR schemas. These two scenarios base their results on the common calculation of end-of-life RE-PM EVs in Lombardy, which will be explained below.

The first step required to carry out this calculation was to identify the volumes of electric vehicles entering Lombardy each year: to do this, the national registrations proposed by UNRAE [71] (Unione Nazionale Rappresentanti Autoveicoli Esteri) for BEVs and PHEVs for the years from 2013 to 2023 were consulted, and the national demand estimate for the same vehicle categories proposed by Motus-E up to 2045 was used [72]. This value is represented in Equation (1.1) with the variable *Imm(t)*.

Subsequently, this value was related to the share of electric vehicles present within the Lombardy region represented in Equation (1.1) with the variable *L*. Finally, by multiplying this value by the adoption rate of electric vehicles with permanent magnet motors (*AR* in Equation 1.1), it was possible to obtain the market introduction of electric vehicles containing permanent magnet motors in Lombardy year by year ($Imm_{EV}(t)$ in Equation 1.1). Assuming then an average vehicle life of 15 years, it was possible to identify the volumes of electric vehicles with permanent magnet motors that had reached the end of their life in Lombardy for each year (EoL_{EV}(t) in Equation 1.2).

$$\boldsymbol{Imm_{EV}(t) = Imm(t) * L * AR} \tag{1.1}$$

$$EOL_{EV}(t) = Imm_{EV}(t-15) \quad (1.2)$$

These values, therefore, represent the total annual quota of engines theoretically recoverable in Lombardy each year. By multiplying this value by the actual collection rates (*CR* in formula C) proposed by SC1 (low collection rate) and SC2 (high collection rate), it will be possible to identify the volumes of secondary supply ($SS_{EV}(t)$ in Equation 1.3) collected for each year that can be reintroduced in the system.

$$SS_{EV}(t) = EOL_{EV} * CR \quad (1.3)$$

In conclusion, it can be seen that the values obtained are easily adaptable to the component to be taken into account: in fact, by multiplying this value by the weight of the magnets inside the electric vehicles (*W* in Equation 1.4) and by a coefficient that takes into account the difficulty of extracting the magnets (*DE* in Equation 1.4), it is possible to identify the expected recovery volumes for the magnets (SS_{NdFeB} in Equation 1.4).

$$SS_{NdFeB}(t) = SS_{EV} * W * DE \quad (1.4)$$

2.2. Results

To have a better understanding of the results obtained for the Lombardy region, it is essential to provide information on the Italian market for electric vehicles in advance. Italy, in fact, represents a particular case when compared to the rest of Europe, given the much lower volumes of electric vehicles registered within the country each year. BEVs and PHEVs introduced to the Italian market account for 4.2% and 4.4%, respectively, of the total number of cars registered in the country, much lower than the European averages of 14.6% and 7.7% for the same vehicle categories [73]. This data, despite a slight increase in recent years, continues to highlight a strong Italian lag in the energy transition that reached an absolute value of 134,715 BEVs and PHEVs placed on the market in 2023 [74].

Analysing the national market in more detail, it can be seen that Lombardy is one of the most virtuous regions when it comes to the issue of electric mobility: with 12509 BEV registrations in 2023, this region accounts for 19% of the national total, and also holds the record as the region with the highest number of public access charging points in the country (9,395 units) [73].

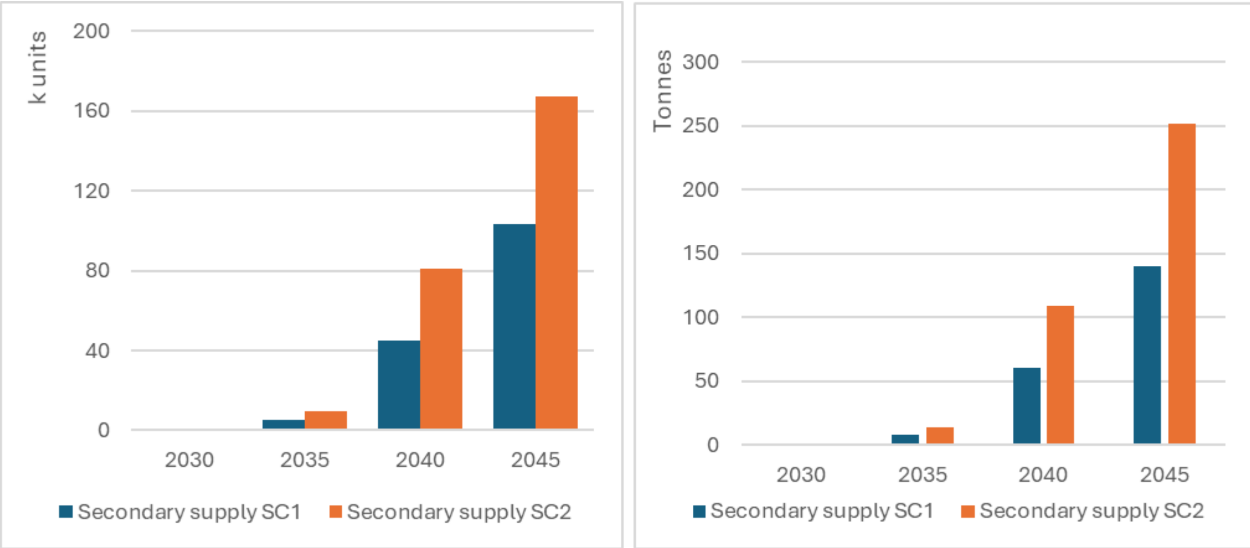

Figure 2.1: Collection of RE-PM electric motors and NdFeB magnets in Lombardy (own elaboration)

Looking at the results obtained with the application of the equations shown before in Figure 2.1, it is expected to provide an input to the various circular economy strategies of about 160,000 electric motors by 2045, equivalent to about 250 tonnes of permanent magnets in the case of high collection rates. In contrast, should this follow the least favourable scenario, approximately 60 per cent less would be recovered in the same year. If the collection of ELVs follows the predictions made, it would be possible to reduce the demand for magnets and electric motors required for the production of new products.

In order to provide an example and to make the values obtained from the analysis more understandable, Figure 2.2 assumes a re-introduction of the collected permanent magnets sent for recycling within the supply chain of electric vehicles[1]. The graph shows how, depending on the different scenarios, re-introduction can partially meet the demand for electric motor magnets in vehicles, reaching 42% of the demand in 2045 under the assumption of scenario 2.

[1] For the calculation of these values, the recycling efficiency rate coefficient was added within Equation 1.4 which is useful to take into account any losses in the recycling processes. Refer to Appendix A for more information.

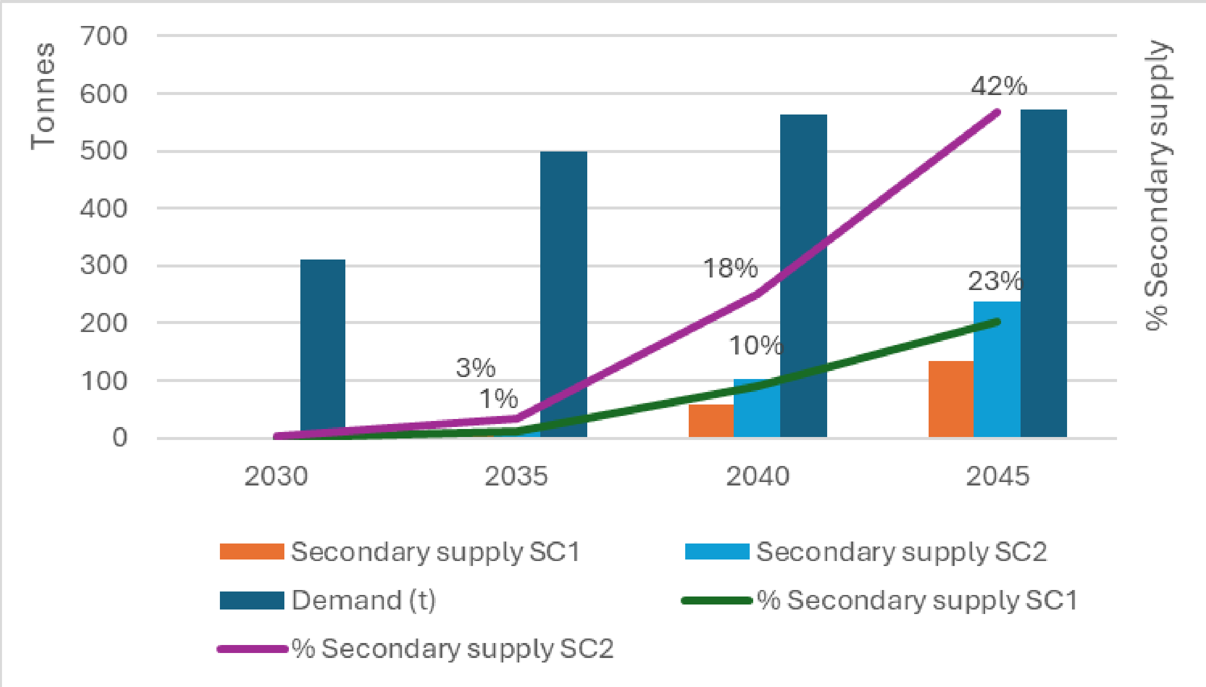

Figure 2.2: Impact of recycling NdFeB magnets from EV in Lombardy

3 Literature review

To have a better understanding of the application of CE strategies and CSC configurations to the electric motor component revision of the literature was performed, addressing the following objectives:

1. Identify the different circular economy strategies applicable to the RE-PM electric motor and the magnets inside them. By doing so, it will be possible to learn about the different possible recovery solutions and provide a useful knowledge base for the development of RQ1.
2. Identify the state of the art of CSC solutions for the recovery of RE-PM electric motors in the literature, in order to identify possible adoptable solutions for solving RQ2.

Due to the high degree of innovation of the topics covered and the high practical relevance of the concepts explored, systematic research was carried out, including both academic publications and European research projects related to the application of CE strategies to recover RE-PM electric motors and embedded magnets.

The following chapters will firstly identify the methodological steps that led to the identification of the samples of relevant studies and secondly present the individual results for the academic and the project literature review. The general discussion of the results got from both the academic LR and projects LR is provided at the end of this chapter.

3.1. Academic literature review

3.1.1. Methodology

Figure 3.1 provides an overview of the research methodology employed, along with key quantitative discoveries. This method involved a comprehensive investigation of literature sourced from Scopus, followed by both quantitative and qualitative assessments of the selected papers.

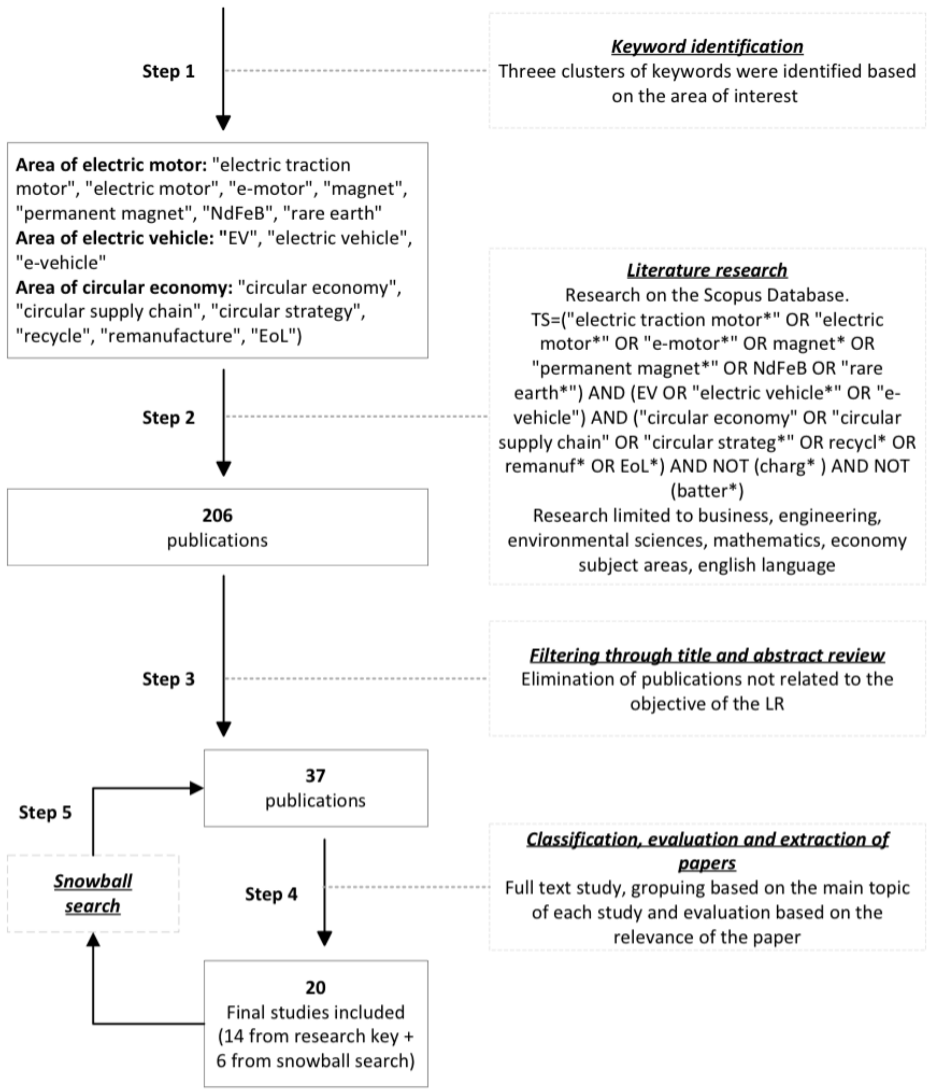

Figure 3.1: Academic literature review process (own elaboration)

The keywords used were selected given their relevance to the concepts underlying the main and the secondary objective of the Literature background, divided into three macro areas: the electric motor one, the electric vehicle one and the circular economy one. For each of these three main areas the keywords were selected through brainstorming activity, manipulated than with the appropriate punctuation and aggregated together with OR and AND operators. The AND NOT operators were used to exclude papers focused on batteries and charging infrastructure since evaluated out of focus for the work and the research areas were added to limit the research only to the desired topics.

Through an iterative process different queries were analysed leading to the one proposed, being able to spot 206 publications. Starting from this sample a first selection of the papers was made reading each title and abstract. Publications not related to the objectives of the LR were eliminated, therefore studies talking about technical solutions to increase performances of electric motor were excluded, together with the ones not dealing with the RE-PM design and the ones deep diving into the technical aspects of magnets recycling. After this first step, 37 papers were identified as potentially valuable.

Therefore, through a full-text reading of all these papers present in the final sample, a qualitative evaluation and classification of each study was made. It was possible to identify three key themes treated by the publications: *Circularity*, *REE and material criticality*, *sustainability/environmental impact*. Being the first category the main focus of the work, the publications within this section were used to set the basic knowledge of the thesis, with the other ones being used for some citations and insights for specific topics in the introductive chapter. After this process 14 papers were identified to be particularly relevant for the thesis, to which were added other 6 obtained through snowball search bringing the overall final sample at 20 studies.

These 20 publications were furthermore categorised, given the different levels at which circular economy has been treated in the literature when related to electric motors. It is therefore possible to identify papers that address the studied topics at two main levels:

1. ***CE strategy level***: the objective of the publications is to identify the different circular economy strategies, evaluating them both from a general and a specific point of view. These papers were useful to address the objective number 1) of the LR. More particularly, the different strategies will be divided into the three categories of CE proposed by the R10 model saw in precedence:
    a. *Smarter product use and manufacture:* the objective of the publications is to address the design of the RE-PM electric motor to facilitate recovery strategies and to propose different solutions for increasing the utilisation of this product.
    b. *Extend lifespan of products and parts:* the focus of the publications is the extension of electric motor and magnets lifecycle through the application of reuse, repair, refurbish, remanufacture, and repurpose strategies of the R10 model.
    c. *Useful application of materials*: the object of recovery is the materials within the electric motor components though magnets recycling.
2. ***Supply chain level***: the objective of the publications is to study circularity at the system level, analysing different actors across the value chain that could create the basis for circular supply chains. These papers were useful for addressing the objective number 2) of the LR.

3.1.2. Results

As shown in Table 3.1 and Figure 3.2, the papers selected as relevant mainly focus on the CE strategy level, more specifically on the recovery of materials within the electric motor. This sub-level is populated mainly by publications dealing with the recycling of permanent magnets: the criticality and the high strategic importance of the materials within these components have pushed research to identify and study in detail the various possible technologies to recover rare elements embedded into magnets.

Level of application of CE	***Publications***
CE Strategy level	General implementation: [68], [75], [76] Smart product use and manufacture: [77] Extend lifespan of product and parts: [78], [79], [80], [81], [82] Useful application of materials: [83], [84], [85], [86], [87], [88], [89], [90]
Supply chain level	[91], [92], [93]

Table 3.1: Application of CE principles in academic LR (own elaboration)

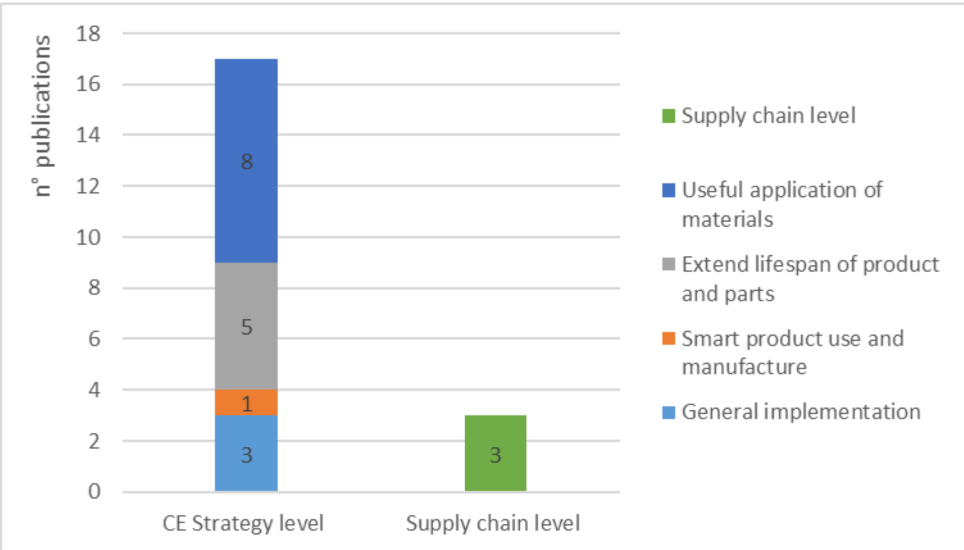

Figure 3.2: Application of CE principles in Academic LR (own elaboration)

The output of the academic LR in terms of number of publications per years is then proposed Figure 3.3, highlighting the growing interest in the recovery of electric motors and embedded magnets in the last years: within the final sample, in fact, the oldest publications date to 2017, underlining at the same time that academic literature is still in its infancy when dealing with CE applied to EV RE-PM electric motors.

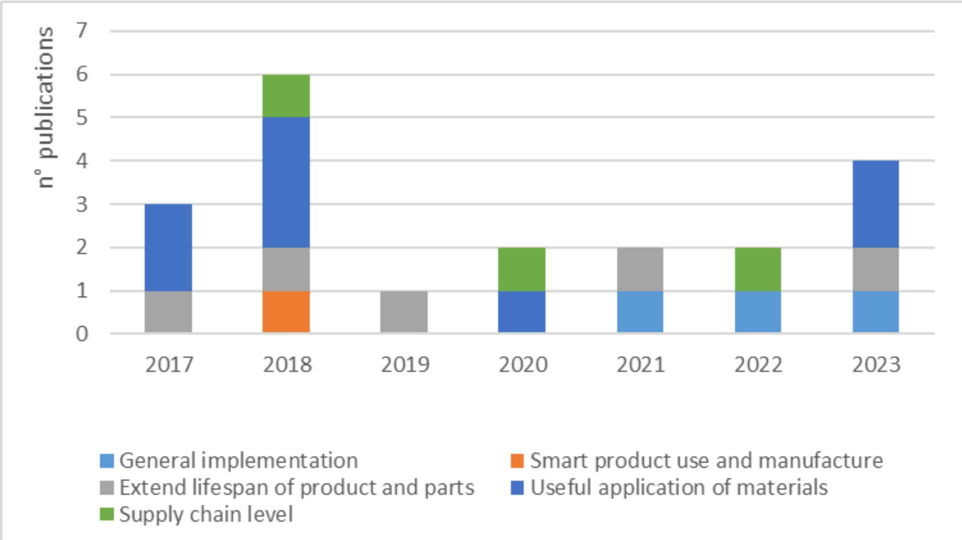

Figure 3.3: Academic LR publications per year (own elaboration)

3.1.2.1. CE at CE strategy level

The results of Figure 3.2 and Figure 3.3 are also highlighted by Tiwari et al. [76], a study that proposes a review of circular economy research for electric motors, focusing on industrial electric motors and on remanufacturing activities. This publication, having a similar objective to the number 1) of this LR, underlines how magnets recycling strategy was the main focus of literature so far, approaching the context of electric motors in a more holistic way. In this study, in fact, were analysed a wider number of publications, including also papers dealing with designs of electrical motors without RE-PM, sustainability topics and recovery of all the materials embedded into the product. Furthermore, this paper highlights a gap in the literature that has been covered by Benfer et al. [75] with a work based on the selection of the best CE strategy to be applied for each component within the engine. According to the methodology developed in this paper, different CE solutions could be applied to extend components life or recover materials for the different parts composing an electric motor, as shown in Figure 3.4.

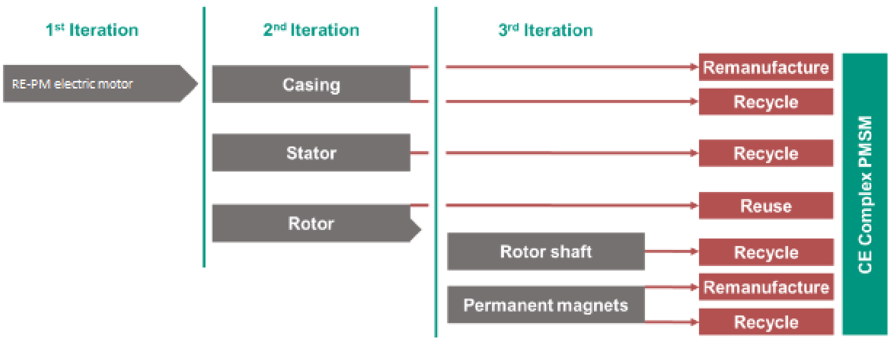

Figure 3.4: Best CE strategies for RE-PM electric motor parts (source: Benfer et al. [76])

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In the end, as for the two already mentioned studies, also Bobba et al. [68] approach the adoption of CE from a general point of view, with a paper focused on the application of an indicator capable of taking into account all the CE strategies possible to correctly assess the circularity of REEs included in EV RE-PM electric motors. The results show how the adoption of reuse and remanufacturing techniques for electric motors can keep in the loop higher amounts of CRMs embedded into permanent magnets.

Trying to implement more virtuous CE strategies under the R10 schema it is possible to find other few papers: Jha et al. [77] addresses the smarter use and manufacture level, proposing an index to evaluate the level of recyclability of a motor based on its design. Passing than at the life extension strategies at the product level, there are only two publications that addressed the electric motor. As far as refurbishment techniques are concerned, Li et al. [78] and Liu et al. [79] have focused on industrial electric motors with the aim of increasing the performance of an end-of-life motor by replacing components with more high-performance ones.

Few are also the papers that discuss the life extension of components from the electric motor, focusing on permanent magnets. For these activities to take hold, it is necessary for the magnets to be disassembled in a non-destructive manner from the motors. In this regard, Heim et al. [80] proposes a process whereby these components are separated using techniques that do not compromise the characteristics of the magnets. Once the magnets have been isolated, it is possible to use them directly in the production of new motors: Upadhayay et el. [81] and Li et al. [82] analyse this possibility, proposing modular magnets and specific solutions for certain types of motor designs, therefore showing how reuse of magnets could theoretically take place.

On the contrary, there are many studies dealing with material recovery from electric motors, mainly for the material fractions included within the permanent magnets. Kumari e Sahu [83] and Diehl et al. [84] Identify all applicable technologies for recycling permanent magnets, evaluating the pros and cons of each solution. Two major possible routes for recycling magnets are presented in this publication:

1. Direct recycling of the permanent magnetic alloy (short loop recycling).
2. Indirect/elemental recycling and extraction of the REE or oxides (long loop recycling).

The main difference between the two possibilities lies in the result obtained after the recycling process: the first (short loop recycling) leads to the recovery of the magnetic alloy, thus allowing to reconstitute a magnet directly from one that has reached its end-of-life. The second (long loop recycling), differently, results in the recovery of the oxides/elements (neodymium, dysprosium, etc), thus obtaining the different REE oxides as if they were extracted, therefore needing the separation and refining activities to be performed before being included in the production of magnets. Figure 3.5 aims to clarify this fundamental difference.

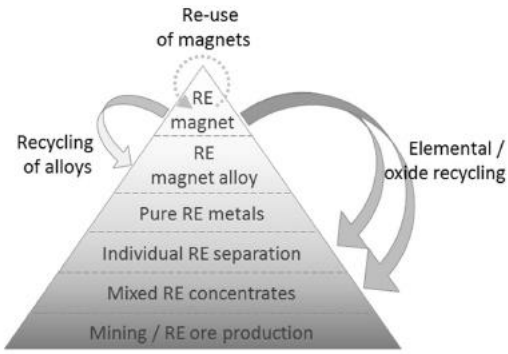

Figure 3.5: Different recycling technologies (source: Diehl et al. [85])

Different technological solutions belong to the two main viable routes: for the first one Upadhayay et al. [81], Kumari e Sahu [83] and Diehl et al. [84] identify the magnet-to-magnet (or re-sintering) and the re-melting/re-casting recycling technologies as the main viable routes. For the second route, Kumari e Sahu [83], Ambaye et al. [85] and Yang et al. [86] present the hydrometallurgical and pyrometallurgical recycling technologies.

To provide as much detail as possible on the different technologies Table 3.2 mentions the most important existing technologies, highlighting the necessary process, pros and cons of each solution deduced from the literature.

Finally, with the aim of studying the performance obtained from magnets derived from recycling techniques, Upadhayay et al. [81] and Prosperi et al. [88] demonstrate that, depending on the recycling processes implemented, the use of recycled magnets can in principle be possible from both an economical and technical point of view.

Technology	*Recycling technique*	*Process*	*PRO*	*CONS*
Magnet-to-magnet recycling (or re-sintering) (HD, HDDR)	Short loop recycling	Convert magnet into powder through hydrogen, mix it with % of virgin powder, grain boundary modification (GBM), milling, alignment, pressing, sintering	Low cost, environmentally friendly, short loop solution	Suitable only for clean, non-oxidized and non-contaminated magnets. Innovative process, needs to be validated at industrial level
Re-melting/re-casting	Short loop recycling	Magnets melted at high temperature, solidification, milling, alignment, pressing, sintering	Microstructural optimization, low content of oxygen (indicator of purity)	High power consumption, low efficiency (20-30% magnet lost)
Hydrometallurgy	Long loop recycling	Direct leaching and iron precipitation, selective leaching with different solutions	Industrial process already tested for other types of recoveries. Can be adopted to all the types of magnets.	Environmental drawbacks provided by the massive usage of chemical solvents, high volumes of recovery to be cost-efficient

Pyrometallurgy	Long loop recycling	Utilization of high temperatures to recover alloys or mixed compounds that later have to be processed for purification	Industrial process already tested for other types of recoveries. Can be adopted to all the types of magnets.	Energy intensive, high volumes of recovery to be cost-efficient

Table 3.2: Recycling technologies (own elaboration)

In conclusion, the papers selected to address the objective number 1) of the LR demonstrated few evidence regarding the application of circular economy strategies other than the recycling of permanent magnets, which appears to be the most studied solution in academic research. It is assumed that the lack of a substantial number of publications dealing with other recovery possibilities is due to the novelty of the product treated: the presence of papers dealing with the remanufacturing of industrial electric motors and the few papers addressing CE from a general point of view, in fact, suggest that this type of activity may also become established for EV electric motors in the future.

3.1.2.2. CE at supply chain level

Among the publications considered, only three papers address the application of the circular economy at the supply chain level, tackling the topic from different points of view.

Between them, Leitner e Grandjean [91] study the recommended recycling routes taking the perspective of the vehicle manufacturer and of the recycling company, providing then insights at both strategic and supply chain level. As shown in Figure 3.6, different possibilities are suggested such as full vertical integration by an OEM for recycling activities, collaboration with recycling companies or collaboration between magnet manufacturers and OEMs or between magnet manufacturers and recycling companies. The selection of one or another possibility also influences the recycling technique used. The study concludes that there is no absolute best recycling technique, but the selection depends mainly on the strategic agreements between the stakeholders involved and the resulting SC structures put in place.

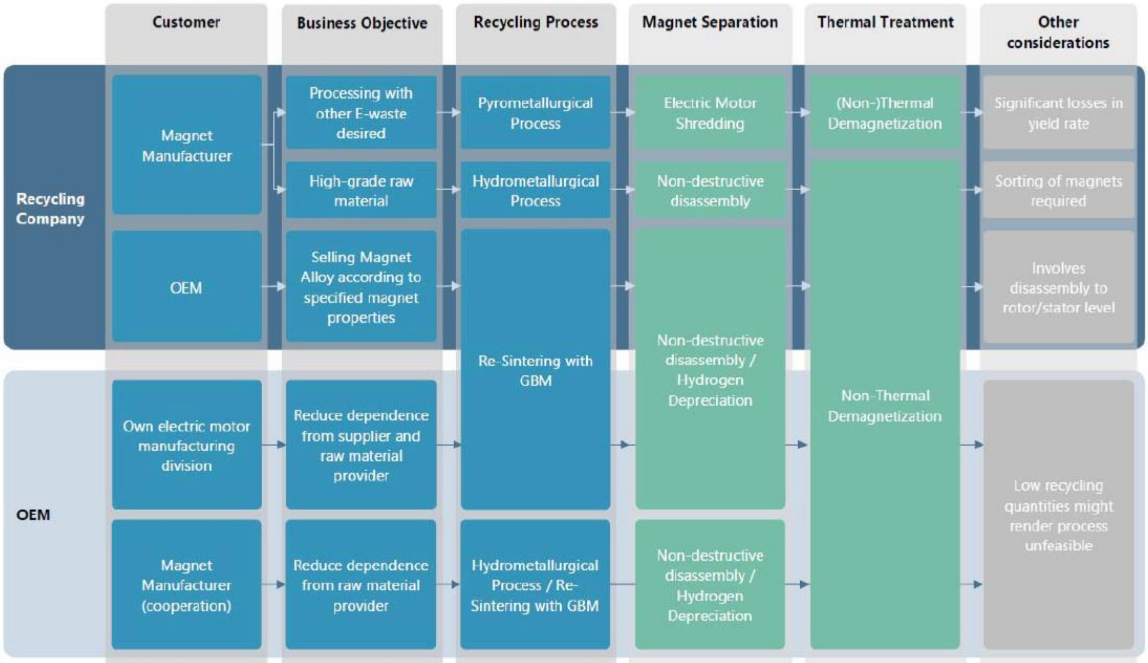

Figure 3.6: Best recycling technology given OEM grade of vertical integration (source: Leitner e Grandjean [92])

Jin et al. [92] instead, utilise a mathematical model to maximise economic, environmental and social benefits by identifying the best locations for centres performing magnet dismantling and recycling activities. Within the model, four major supply chain members are considered: collection centres, EOL products dismantling facilities, NdFeB magnet recycling facilities and sales points.

In the end, Deng et al.[93] tackle the system level with an economic feasibility of an integrated facility that disassembles used EVs and processes components to rebuild "new" EVs through a network simulation model. The paper explores the fact that the already existing facilities dedicated to the same activities for conventional vehicles are unfamiliar with EVs and they are not yet readily adaptable to these new ELV streams mainly due to two incompatibility reasons: the difference in materials and designs and the need for the application of special recovery technologies that are not yet fully mature.

With the aim of addressing objective number 2) of the LR, it can be noted that academic research concerning possible CSC configurations is very scarce, proving visible gaps when addressing CE adoption at the supply chain level. The papers consulted, in fact, approach the topic differently and offer only a few interesting insights that can be adopted to answer RQ2 of the thesis. In particular, the conclusions proposed by Leitner e Grandjean [91] were taken into consideration within the development of the solutions proposed in the thesis, whereas Jin et al. and Deng et al. [92], [93] papers were useful for identifying some actors within their proposed models.

3.2. Projects literature review

3.2.1. Methodology

Figure 3.7 provides an overview of the research methodology employed, along with key quantitative discoveries. This method involved a comprehensive investigation of the projects present at European level on the European Cordis platform.

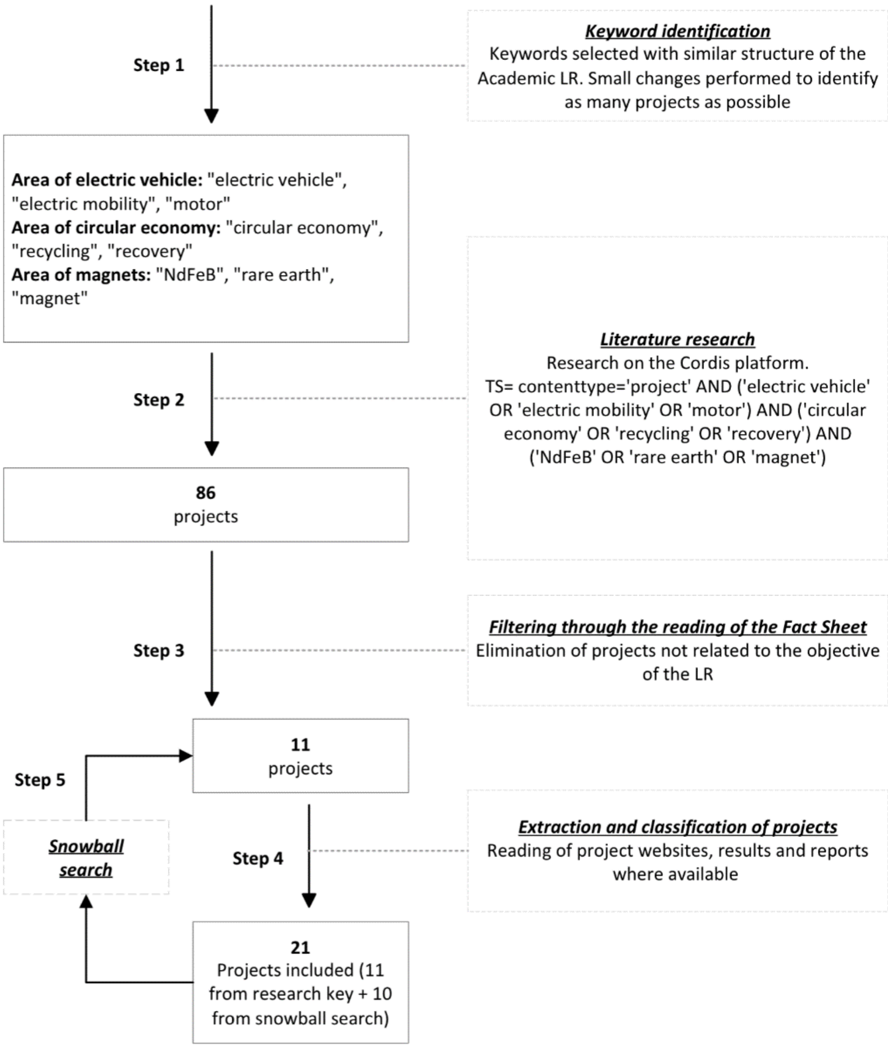

Figure 3.7: Projects LR (own elaboration)

The keywords used were similar to the ones used in the academic LR, with some minor changes deriving from the number of results got with the different combinations of words. As for the previous methodology adopted, three main areas were selected and once the query was completed a sample of 86 projects was found. Through a full reding of the Fact sheet of each project was possible to eliminate projects not aligned with LR objectives, therefore works dealing with European sustainable extraction of REE, EVs batteries, human sciences and motors design without RE-PMs were taken out from the final sample. After having consulted websites, results and reports of the different works, the projects were classified and other 10 projects were identified, being considered as relevant by the ones discovered with the query. Between the 21 projects within the final sample, 13 are concluded and results are available, while 8 are still under development. The summary of the projects consulted is presented in Table 3.3.

Project acronym	*Project Title*	*Main objective*	*EU Funding [€]*	*End date*
EREAN [94]	European Rare Earth Magnet Recycling Network	Develop innovative, environmentally friendly direct and indirect recycling strategies for the permanent magnets in the motors and design-for-reuse solutions	3 901 642	31/08/2017
REProMag [95]	Resource Efficient Production Route for Rare Earth Magnets	Develop an innovative, resource-efficient manufacturing route for Rare Earth magnets, permitting to manufacture complex-shape magnets through recycling and 3D printing	5 726 365	31/12/2017
DEMETER [96]	Training Network for the Design and Recycling of Rare-Earth Permanent Magnet Motors and Generators in Hybrid and Full Electric Vehicles	Develop innovative, environmentally friendly direct and indirect recycling strategies for the permanent magnets in the motors and design-for-reuse solutions	3 802 512	31/08/2019
REE4EU [97]	Integrated high temperature electrolysis (HTE) and Ion Liquid Extraction (ILE) for a strong and independent European Rare Earth Elements Supply Chain	Develop a closed-loop system for permanent magnets through two novel process technologies: Ionic liquid extraction (ILE) and high temperature electrolysis (HTE)	7 522 490	30/09/2019

SUSMAGPRO [98]	Sustainable Recovery, Reprocessing and Reuse of Rare-Earth Magnets in a Circular Economy	Develop a recycling supply chain for rare earth magnets in the EU	12 977 445	30/11/2023
OCARINA [99]	Novel recycling and reprocessing of permanent magnets	New feasible recycling technology of end of life (EOL) magnets	150 040	19/04/2024
REEcycle [100]	An environmental-friendly alternative to recovery Rare Earth Elements from spent NdFeB permanent magnets by electrochemical recycling process	Determine indirect recycling of selected REEs through innovative electrochemical approaches	187 624	30/04/2025
VOLTCAR [101]	Design, manufacturing, and validation of ecocycle electric traction motor	Renewed e-motor design to improve sustainability, allowing for circular value chains, recycling and reduced use of rare resources	5 997 135	31/01/2026
REEPRODUCE [102]	Dismantling and recycling Rare Earth Elements from End-of-life products for the European Green Transition	Setting up, for the first time, a resilient and complete European REEs-recycling value chain, at industrial scale for the recovery of REEs at competitive cost compared to REEs primary production in China with environmentally friendly and socially sustainable technologies	10 051 919	30/04/2026
HEFT [103]	Novel concept of a low-cost, high-power density and highly efficient recyclable motor for next generation mass produced electric vehicles	Develop a synchronous motor for Evs that will be recyclable, cost-efficient and will require fewer materials	3 476 515	31/05/2026

REESilience [104]	Resilient and sustainable critical raw materials REE supply chains for the e-mobility and renewable energy ecosystems and strategic sectors	Develop a recycling supply chain for rare earth magnets in the EU. Build a production system for Rare Earth materials and magnets and create new market opportunities for critical raw materials more sustainably produced in the continent.	9 734 435	30/06/2026
REMANENCE [105]	Rare Earth Magnet Recovery for Environmental and Resource Protection	Develop new processes for the recovery and recycling of rare earth (RE) containing neodymium iron boron magnets (NdFeB) from WEEE	3 722 000	30/06/2016
REECOVER [106]	Recovery of Rare Earth Elements from magnetic waste in the WEEE recycling industry	Develop two new different routes for hydro/pyro metallurgical recovery for WEEE	5 995 741	30/11/2016
CarE-Service [107]	Circular Economy Business Models for electric mobility through advanced reuse and remanufacturing technologies and services	Develop non-ownership-based models to set-up innovative supply chains that performs systematic remanufacturing and reuse of HEVs parts	6 229 505	30/11/2021
VALOMAG [108]	VALOrisation of MAGnets	Propose a disassembly of EOL applications and assess short loop recycling technologies and hydrometallurgical processes.	2 000 000	01/03/2023
INSPIRES [109]	INtelligent and Sustainable Processing of Innovative Rare-Earth magnetS	Recover and supply REE through new dismantling and recovery procedures for PMs included in household appliances and test new circular economy pathways with key industrial partners.	n.a.	31/12/2023

NEW-RE [110]	New-Re	Development of a hydrometallurgical pilot plant to recover NdFeB magnets inside hard disk drive HDD	3 600 000	01/01/2024
INSPIREE [111]	Industrial Production of mixed Rare Earth Elements oxides and carbonates from spent magnets recycling	Realize the first industrial-scale plant in Europe for the dismantling and recycling of REEs from spent NdFeB magnets (HDD) and EoL e-motors) trough PM disassembly and REE recovery by hydrometallurgy	3 245 429	31/03/2027
MORE [112]	Motor Recycling	Development of specific and innovative concepts and technologies for the recycling of components and materials of the drive train of electric and hybrid vehicles	n.a.	31/08/2014
RECVAL [113]	InnovativeRE-use and ReCyclingVALue Chain forHigh-PowerM agnets	Develop efficient holistic processes for the reuse and recycling of Nd-Fe-B high-performance permanent magnets.	n.a.	31/06/2017
REASSERT [114]	Reassert	Extend application of CE strategies beyond recycling through reuse, remanufacturing and refurbishment strategies	n.a.	n.a.

Table 3.3: Projects LR results (own elaboration)

As in the case of the academic LR, the results obtained from the research were categorised in the same way, based on projects main objectives.

3.2.2. Results

As can be seen from Table 3.4, it is possible to notice that, also for the European projects, the main focus of research was on the recycling of magnets within ELVs and, in this case, also within general electrical waste (WEEE) and household appliances.

Level of application of CE	***Projects***
CE Strategy level	General implementation: CarE-Service, RECVAL, MORE Smarter product use and manufacture: VOLTCAR (not finished), HEFT (not finished) Extend lifespan of product and parts: REASSERT (not finished) Materials level: EREAN, DEMETER, REProMag, VALOMAG, REE4EU, SUSMAGPRO, REMANENCE, REECOVER, INSPIRES, New-Re, INSPIREE (not finished), REEsilience (not finished), OCARINA (not finished), REEcycle (not finished), REEPRODUCE (not finished),

Table 3.4:Application of CE principles in Projects LR (own elaboration)

Therefore, addressing objective number 1) of the LR, for the concluded projects for which results are available, it is possible to highlight the same evidences identified in the academic LR. In this case, differently from above, it was possible to understand how recycling processes are trying to develop at industrial scale, including the recovery of WEEE and household appliances through the concept of 'urban mining'. These EoL products were also taken in consideration by many projects because they are found in large quantities nowadays. The main objective of projects is therefore to test and validate at laboratory and semi-industrial level the complete recycling of materials mainly embedded into Hard Disk Drives, through automated disassembly operations and recycling (direct and indirect) of the magnets inside them. Among the final sample of finished projects with a focus on recycling, few deal solely with the electric vehicle stream: these are EREAN and DEMETER, projects with the objective of training young talents that settled some knowledge also for design for reuse application for electric motors.

Passing to other results that do not only deal with magnet recycling, CarE-Service analysed a circular economy business model for electric vehicles, therefore entailing reuse, remanufacturing and recycling of components embedded within EVs: useful for having a circular approach to electric vehicles, this project does not include the recovery of the electric motor, focusing mainly on batteries and other components. The German national projects MORE and RECVAL projects, instead, addressed the complete recovery of electric motors within EVs: starting with the extraction of the motor from the ELV, different recovery routes were analysed for different electric motor designs. In the following bullet list the results of the two projects will be reported:

- Reuse, Repair, Refurbish, Remanufacturing of the electric motor: life extension at product level is in principle possible, with usual repair/substitution of the bearings or copper windings. Magnets are not usually replaced given their good conditions in EoL electric motors.
- Reuse and Repurposing of the magnets: life extension at component level is feasible. To recover magnets demagnetisation is suggested. Thanks to high temperatures reached in this activity, in fact, coatings and glues applied to magnets are removed, therefore making it simple to recover magnets. If the demagnetisation doesn't take place, a mechanical force should be applied by a machine not subject to magnetising forces. However, given the good conditions of magnets in EoL electric motors, a reuse of this component in the same application is difficult to occur because there's not a high demand for replacing damaged magnets. Therefore, it is more probable that magnets could be reused in the production of other products though repurposing activities.
- Recycling of magnets: possible following direct and indirect recycling.

Looking then at the projects not finished yet, it can be noted that part of the research is investing in engine design to ensure a higher level of recyclability (HEFT, VOLTCAR), in the implementation of reuse, repair, refurbish and remanufacture strategies to extend electric motor lifecycle (REASSERT), in the implementation of recycling plants at industrial level (INSPIREE, REEPRODUCE, REESilience) and in the application of new, more eco-friendly recycling technologies (OCARINA, REEcycle).

Finally, addressing LR objective number 2), it is possible to notice that in the final sample there aren't projects that have the main objective of treating CE at supply chain level. However, through a more detailed analysis of the results within the sample, it was possible to find some useful material: although it was not the main objective of the project, some of them did some research at supply chain level, providing results from different points of view. The most important ones from this point of view were REE4EU and MORE. More precisely, the latter provides different circular economy structures at system level, analysing and comparing different scenarios for different motor designs provided. The recovery structure, as shown in Figure 3.8, is composed of car wreckers that collect EOL EVs at regional level, automated disassembly plants that recover the magnets at national level and a centralised recycling facility performing hydrometallurgical recycling at European level.

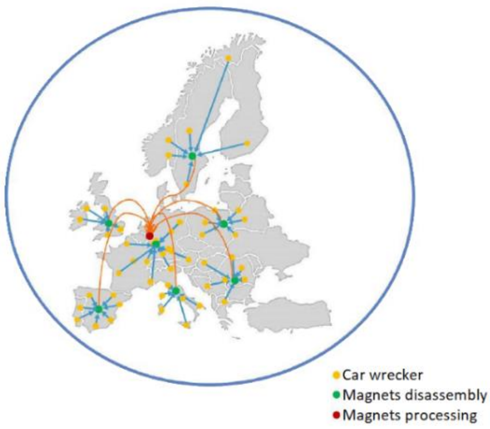

Figure 3.8: Geographical configuration of NdFeB magnets recovery (source MORE [113])

REE4EU, instead, in a complementary study of its project performs a Value chain stakeholder analysis, identifying a possible structure as seen in Figure 3.9. The objective of this secondary paper is to provide an overview on the most relevant stakeholders connected to REE topic, identifying SMEs and large industries that are present at European level. With a focus on automotive applications, this paper provides a description and an analysis of all the players present in the project value chain with a focus on permanent magnets component.

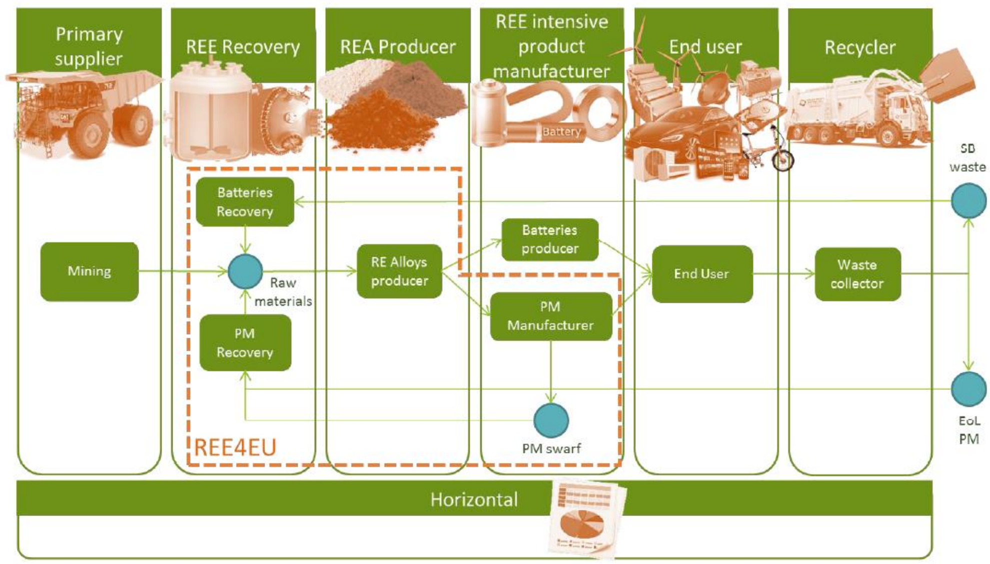

Figure 3.9: Magnets Value chain stakeholder analysis (source: REE4EU [98])

3.3. Discussion of results of the Literature review

In conclusion, addressing objective number 1) of the LR, it can be noted that both academic and projects LR show their focus on the application of the circular economy to recover materials embedded into the electric motor with the recycling of the magnets. In fact, the projects and papers studied focused mainly on the technological and operational aspects of this activity, making it appear as the most valuable solution. Wanting to go beyond the different recycling possibilities, some results showed how other circular economy strategies can be applied to extend the lifecycle of the electric motor and magnets, despite the much smaller number of publications: in principle, it is possible to apply reuse and repurposing strategies to magnets and apply reuse, repair, refurbishment, remanufacturing activities to the electric motor.

With regard to objective number 2) of the LR, however, the little results show important gaps which will be addressed within the thesis in the following chapters.

As a result of the LR, it was therefore possible to map the different CE strategies applicable to electric motors and the magnets included within them, also taking into account the different operations to be carried out within the supply chain as shown in Figure 3.10.

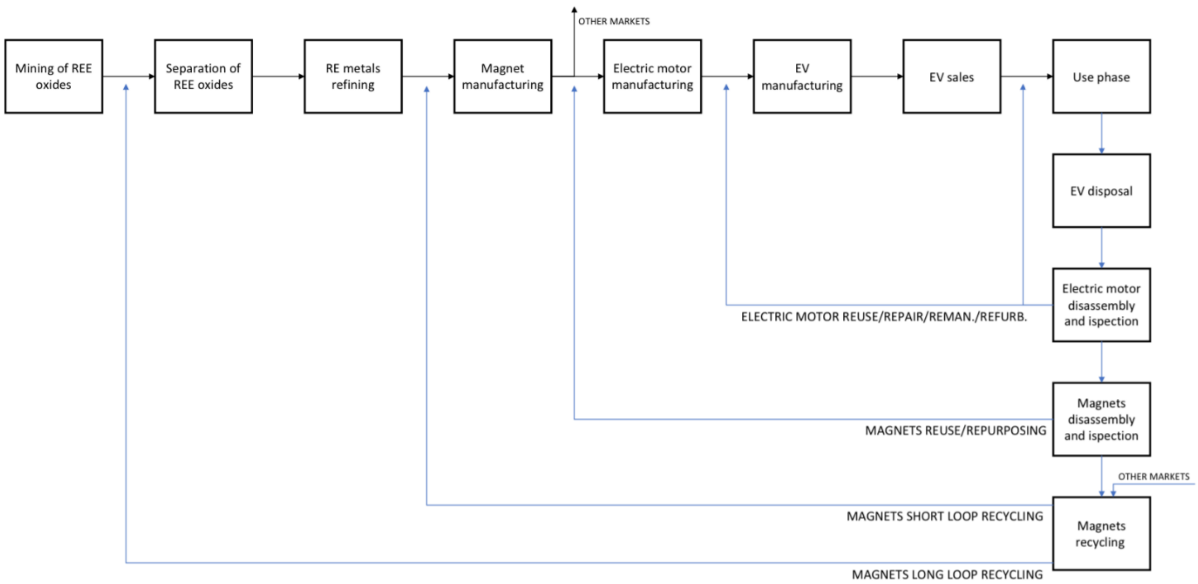

Figure 3.10: Basic CSC structure for RE-PM electric motors and magnets (own elaboration)

Figure 3.10 thus represents the basic CSC structure on which the subsequent research of thesis was carried out. Starting from this, in fact, it was possible to research the key actors for the development of reverse SC. Again, starting from Figure 3.10, the possible actors to be involved in the interviews were identified and depending on the players' roles within this structure, the different CSC configurations for the Lombardy region were identified.

For better understanding a detailed description of the different applicable strategies is therefore given:

- **Electric motor reuse, repair, refurbishment, remanufacturing:** These strategies try to extend the lifecycle of the electric motor. Once the product has been disassembled from the vehicle and inspected, depending on whether it needs to be repaired, refurbished, or remanufactured it can re-enter in the forward supply chain at different levels: it can either serve the spare parts markets or renter in the production of new electric vehicles.
- **Magnets reuse and repurpose**: these strategies try to extend the lifecycle of magnets. Once the engine is disassembled from the vehicle, a further non-destructive disassembly of the embedded magnets is needed. Once extracted, the magnets will be inserted within electric motors or into other applications that need their use.
- **Magnets short loop recycling**: this strategy involves disassembling the engine from the vehicle and magnets from the engine, that undergo the processes necessary for hydrogen decrepitation to obtain the magnetic powder that is the input for the construction of new magnets.
- **Magnets long loop recycling**: this strategy involves disassembling the engine from the vehicle and magnets from the engine, that undergo the hydrometallurgical or pyrometallurgical recycling processes necessary to obtain REE oxides that need to be separated and refined for the construction of new magnets.

4 Key reverse supply chain actors

Given the CSC structure proposed in the last chapter, this section aims to identify the key industrial actors present globally to implement the reverse SC to recover electric motors and permanent magnets obtained through Google search.

4.1. Electric motor reuse, repair, refurbishment and remanufacturing

The market for car parts is very broad and well structured, with companies basing their core business on the sale of car parts in the aftermarket. The parts circulating in this market can be of different types: new, used, repaired or remanufactured parts. Depending on the nature of these, therefore, different actors become part of the chain leading to the resale of these parts on the market.

Companies that base their business on the resale of used car parts are many and are part of a well-established market. This activity at the local level is mainly done by car wreckers who, recovering end-of-life vehicles, disassemble the parts and resell them directly in the market or after repairing activities. These figures are many and form a very important network at local level. Expanding the boundaries of action, there are web platforms that serve a much broader customer base: at national level, the main ones are B-parts, Ricambi Pro, Auto Spare Parts FIR and Ovoko, which, via their websites, make it possible to buy electric motors in good condition mainly from crashed cars. Moving on to the international level, the main ones are RockAuto, Autodoc, Daparto and platforms that allow the exchange of parts between privates such as Ebay and Subito.

Turning to companies that remaufacture and refurbish car parts, there are fewer companies in the market globally. Through the research carried out, it was noted that in recent years the number of people offering these types of services has increased and become increasingly important, given their fundamental role in the development of more circular and sustainable practices. The main association that brings together companies operating in the remanufacturing market is APRA (Automotive Parts Remanufacturers Association) which, with its US, Europe and Asia divisions, aims to represent the interests of companies operating in automotive remanufacturing.

Analysing these companies in more detail, it was possible to notice that the companies producing parts for OEMs also hold important positions in remanufacturing: in the case of electric motors, in fact, it was noted that the companies identified in Figure 1.5 are also the main players in this market. In addition to these, it was possible to identify other independent companies operating in the remanufacturing sector in the B2B market, i.e. serving OEMs as customers, and in the B2C market, i.e. serving end customers. The aim of Table 4.1 is to identify these companies and to find out whether they handle the electric motor component.

Company name	*Headquarters Location*	*Number of employees*	*Current electric motor remanufacturing*
BBB industries	US	>10000	Yes
Cevam	France	201-500	No, similar components (starters, alternators)
Vege	Tunisia	51-200	No, ICE
D&W Diesel Inc.	US	201-500	Yes
Aer technologies	US	201-500	No, car electronic remanufacturer
Remante group	Czech republic	51-200	No, similar components (starters, alternators)
Borg automotive group	Denmark	1001-5000	No, similar components (starters, alternators)
Carwood	UK	201-500	Yes

Table 4.1: Independent remanufacturing companies (own elaboration)

The results of the research show that remanufacturing of the component under examination is carried out by only a few companies globally, given the low volumes of electric vehicles that have reached the end of their life to date. Among these, D&W Diesel Inc. mainly remanufactures DC motors while BBB industries and Carwood also offer service for PHEV and BEV traction motors. However, the research revealed that many of the companies studied offer remanufacturing operations for components similar to those of the electric motor like starters and alternators. When the volumes of these increase, it is assumed that the extension of the range of services offered may also include the electric motor, given the similar skills needed already in the company.

4.2. Magnet recycling

The magnet recycling market, unlike the previous ones, is much less structured and the companies operating in this sector are of totally different sizes Table 4.2 shows the main global players, specifying the recycling technology adopted and the powder production capacity for each of them.

Company name	***Headquarters Location***	***Number of employees***	***Recycling technology***	***Current capacity***
Mag REEsource	France	11-50	Hydrogen Decrepitation	50 t/y
Hypromag	UK	2-10	Hydrogen Decrepitation	100 t/y
REEfine Technologies	France	2-10	Hydrogen Decrepitation	n.a.
Heraeus Remloy	Germany	1500-2000	Pyrometallurgy	n.a.
Rocklink	Germany	51-200	Hydrometallurgy	n.a.
Itelyum	Italy	501-1000	Hydrometallurgy	500 t/y
Ionic technologies	Ireland	11-50	Hydrometallurgy	30 t/y
Cyclic materials	Canada	11-50	Hydrometallurgy	10 t/y
REEcycle	US	2-10	Hydrometallurgy	n.a.
Geomega	Canada	11-50	Hydrometallurgy	1600 t/y
Noveon	US	51-200	Hydrogen Decrepitation	1000 t/y

Table 4.2: Magnet recycling companies (own elaboration)

The results show that most of the companies present globally are still in the start-up phase and were created from patents developed at university level: this is the case of Mag REEsource, Ionic Technologies, REEcycle and Hypromag. These companies, having developed patents and pilot plants thanks to state funding and partnerships with companies in the sector, are close to the industrial development of their technologies. Other medium-small companies developing in this market are REEfine Technologies, Cyclic materials, Geomega and Noveon. The latter, in contrast to the others that focus mainly on recycling technology, is active in the production of magnets and has recently received significant funding from private equity funds to increase its production volumes [115]. As with Noveon, Hypromag has also recently attracted the interest of important players in the market, given its acquisition by Mkango resources Ltd [116]. The entry of these players, indeed, may push the magnet recycling market to develop at an industrial level. Among the most structured companies found through this research are Heraeus Remloy, Rocklink and Itelyum. The latter is an Italian company that has proposed to build a recycling plant in the region of Lazio with an initial capacity of 500 tonnes per year starting in 2024, hoping to expand to 20000 tonnes/year in the future [117]. Together, these companies will increase recycling volumes for these components worldwide and in Europe.

Finally, wanting to identify the most widely used recycling technology at the industrial level, it is possible to notice that hydrogen decrepitation and hydrometallurgy are the two solutions most often considered by market players.

5 Interviews

5.1. Methodology

Given the exploratory nature of the thesis and the different positions of the actors involved in the interviews, a semi-structured interview scheme was adopted. This type of interview was chosen because it allows flexibility and adaptability of the questions, achieving a good balance between structure and freedom of dialogue with the interviewees [118].

This methodological approach was implemented to answer RQ1 of the thesis. In addition, given the freedom granted by the type of interview, the secondary objective was to obtain information that could be useful in solving RQ2 of the thesis.

5.1.1. Data collection

In order to answer RQ1 of the thesis, various stakeholders of the supply chain were involved with the aim of obtaining the most accurate and complete picture possible of the current and future prospects of implementing CE strategies for the recovery of electric motors and permanent magnets. Therefore, when the selection process started, a brainstorming activity was carried out to identify the possible valuable stakeholders of the supply chain under analysis, having a clear idea of the different circular economy strategies applicable thanks to Figure 3.10. As Table 5.1 shows, both internal and external stakeholders of the supply chain were selected to obtain the most comprehensive picture of the subject under analysis.

Supply chain position	***Company role***
Actor of the supply chain	Magnet manufacturing Electric motor manufacturing OEM EV distribution and export Car wrecker Car parts remanufacturing Magnets recycling Extended producer responsibility (EPR) company
External	Academia, Research

Table 5.1: Valuable stakeholders to be interviewed (own elaboration)

After identifying possible actors, the process of selecting companies was limited to national borders wherever possible, in line with RQ2. The respondents reached are listed in Table 5.2, indicating the position of their company in relation to the SC, the role of the company, the focus of the respondent within the company and the reference letter used in the results chapter.

Supply chain position	***Company role***	***Interviewee focus***	***Reference letter***
SC actor	OEM	Magnetic materials	*A*
SC actor	Car wrecker	Car wrecker	*B*
SC actor	Magnets recycling	Operations director	*C*
SC actor	EPR company	R&D	*D*
SC actor	Car parts remanufacturing	Business development	*E*
External	Academia	Chemistry professor	*F*
External	Academia	Economics professor	*G*
External	Academia	Chemistry researcher	*H*
External	Research	Magnetic materials researcher	*I*
External	Academia	Mechanics professor	*L*

Table 5.2: Actors interviewed (own elaboration)

The interviews, following the methodology outlined above, covered different topics, given the different supply chain position of each interviewee. Therefore, keeping in mind the common objective of the interviews, the dialogue with the different actors was articulated in different ways, following the questions in the Interview Protocol in Appendix B.

The interviewees were informed of the topics discussed prior to the interview and, to facilitate the dialogue, Figure 3.10 was shown to them, with the aim of providing a clear picture of the different circular economy strategies applicable to the context discussed. The interviews lasted between 30 and 60 minutes and were conducted by the author via online videocalls in Italian and English. These were then recorded with the consent of the interviewees in order to carry out a more precise analysis of the data.

5.1.2. Data analysis

After the interviews, a detailed transcription was carried out manually. Subsequently, all transcripts were examined and divided by CE strategy addressed by the interviewee. Once the main topics covered by each interview were identified, for each actor and for each loop addressed, the barriers mentioned, the motivations that would drive the adoption of the selected CE strategy and the expected timeframe for the implementation were identified. For most actors, the possible participation in European projects to recover electric motors or magnets was also asked.

After this process the barriers were then categorised and, in doing so, it was possible to identify the main barriers that emerged from the various actors interviewed, highlighting barriers common to the different circular economy strategies that hinder the implementation of a CSC to recover products and components under investigation.

5.2. Results

The interviews revealed the actors' interest in the topic of motor and magnet recovery: of the ten interviewees, seven declared that they were involved in EU-funded projects through their company. This value, although insignificant from a statistical point of view, underlines the general interest of the sector in the topic addressed in this thesis.

Due to the fact that the interviews were not particularly structured, it was possible to obtain a more general overview of the different circular economy strategies applicable to the context dealt with and the barriers that are currently hindering the industrial implementation of these.

Starting then with the analysis of specific circular economy strategies, most of the interviews focused mainly on the recycling strategy of permanent magnets. With interviewees *C, D, F, G, H, I*, in fact, it was possible to make comparisons of the two possible recycling techniques: despite the major barrier of the scarce presence at European level of players capable of transforming the rare earth oxides obtained from long loop recycling into metals useful for the production of magnets, this recycling method appeared to be the most interesting at industrial level in the short term. Taking advantage of a better-known technology such as hydrometallurgy in fact allows a plant to be run in a more flexible manner: the possibility of feeding magnets from different origins and of different qualities into the recycling process appears to be an important feature in order to saturate the production capacity of a plant of this type in anticipation of more substantial flows of electric motors in the future. In addition, as reported by *F* and *G*, such a plant can also be used for the recovery of other elements, thus resulting as a less risky investment in case the expected recovery volumes for permanent magnets are smaller.

Regarding short-loop recycling, on the other hand, the main barrier lies in the lack of precise information on the composition of the magnets entering the recycling process, as confirmed by *D* and *I*: this problem does not allow control over the quality of the output magnets, thus running the risk that the products obtained will perform less well than the input magnets. As this is a more innovative process requiring very controlled working environments, it is a viable alternative for the recovery of magnets in the long term. In fact, by allowing a shorter loop, this strategy results in reduced environmental impacts and shorter production times for recycled magnets.

Moving on to life extension strategies, actors *A*, *E* and *L* addressed the topic of the possible remanufacturing and refurbishment of the electric motor for electric vehicles. These strategies are indeed possible and preferable to recycling, given the higher value retention and the better environmental impact of such activities. In fact, *A* stated his company's willingness to recover this component for remanufacturing in the future and *E* confirmed the technical feasibility of these operations given the previous expertise in electronics in his company. In addition, *L* stated that remanufacturing practices are currently being tested for scrap electric motors that do not reach the market because of production defects. The main constraints related to these strategies lie in the design of the motor: in fact, the lack of standardisation for electric motors and the current design practices not aimed at favouring product remanufacturing, represent the two main barriers. In addition to these, it was pointed out that many electric vehicles currently have different platforms in terms of electric motor, therefore making it difficult to apply these strategies for different vehicle models. These problems were identified also by *B* for the reuse and repair strategies.

Passing to the most cited barriers by the interviewees, the lack of a major position by the policy maker and the current low volumes of end-of-life electric motors represent the main barriers limiting the current implementation of all recovery techniques for treated components. These barriers, being identified by all the interviewees, are general and affect the implementation of all the different circular economy strategies.

Finally, turning to the expected time horizon for the implementation of the various circular economy strategies and the main drivers, it was possible to note that most of the interviewees agreed on a possible medium- to long-term implementation. More specifically, the timeframe would be shorter with the intervention of the policy maker forcing the recovery of ELVs and longer if the main driver would be the economic one, which is in any case a sufficient motivation for recovery to take place in the future given the high value of the electric motor.

Table 5.3 maps all barriers identified by the actors, broken down by category and circular economy strategy influenced.

Barrier category	*Barrier description*	*CE strategy involved*
Market	1. Current low volumes of ELVs.	All
	2. High REE prices volatility influencing prices of the finished goods.	Long/short loop recycling
	3. Unstable prediction of EV recovery.	All
Technology	1. Current absence in Europe of a technology able to transform REE oxides into REE metals.	Long loop recycling
	2. Low level of automation in disassembly processes given the low levels of standardisation of electric motor	Long/short loop recycling
Policy	1. Lack of clear guidelines on how to recover the studied components	All
	2. ELVs lost outside Europe.	All
	3. Lack of incentives to foster investments in magnets recycling.	Long/short loop recycling
	4. Excessive bureaucracy to make recycling plant operative.	Long/short loop recycling
SC structure	1. Absence of important players in the upstream part of the value chain.	Long/short loop recycling
	2. Little vertical integration of companies.	Long/short loop recycling
Management	1. Focus in the short-term profitability.	All
	2. Recovery solution not addressed from a strategical point of view.	All
Information	1. Missing information on product specification when arrive at EoL.	All
	2. Missing information useful to understand how to disassemble parts.	Remanufacturing, Long/short loop recycling

Society/culture/knowledge	1. Acceptability of introducing recycled content into virgin products.	Long/short loop recycling
	2. Patents could limit the development of recycling techniques	Long/short loop recycling

Table 5.3: List of barriers identified by the interviewed actors (own elaboration)

5.3. Discussion of results

Between the barriers identified by the interviewees, it is possible to notice how most of them could be overcome in the future. The entrance in force of the proposed end of life directive at European level, in fact, will solve many of the problems expressed by the interviewees. Thanks to the intervention of the policy maker, in fact, most of the problems within the Information category and the Policy category would be resolved. Thanks to the application of EPR schemes, moreover, it will be possible to increase the collection of end-of-life vehicles, making it easier to implement CE strategies when higher numbers of electric motors will arrive at end of life. For what concerns the other barriers, it is believed that the expected increase of volumes for this component, together with its high value, will create many possibilities of developing profitable businesses in the future, therefore pushing companies of the sector to find solutions to overcome Technological and SC structure barriers. As confirmed by the interviewees, in fact, the high value of the electric motor makes it an interesting product to be recovered for companies, that appear favourable to the application of CE strategies. This fact suggests that in the future the barriers in the Management category could be overcome, together with the Society ones given customer's increasing awareness of sustainability subjects and possible reduction of prices of vehicles embedding recovered components.

6 CSC configurations for Lombardy region

In order to answer RQ2 of the thesis, this chapter aims to identify possible CSC configurations for the Lombardy region. The results proposed in this chapter are the result of the combination of results obtained through LR, research of the key players of the reverse SC and the interviews conducted.

After having performed the above-mentioned chapters, it has become clear that a structure for the recovery of electric motors and the magnets included in them will come to be structured in Europe, given the high strategic importance of the materials included in magnets, the high value of the electric motor and Europe's growing attention to this topic. Examples of this are the publication of the CRM act, the proposed revision of the End-of-Life Vehicles Directive, the increasing number of academic publications and European projects dealing with the different CE strategies and the growing presence (albeit at different levels of development) of realities capable of managing the different circular economy strategies related to these components. This was also affirmed by the supply chain actors interviewed, who pointed out that the industrial sector is becoming increasingly interested in developing solutions capable of recovering electric motors and the magnets inside them.

The configuration of the CSC capable of recovering these components is still unknown and depends mainly on how the players included in the recovery will structure and relate to each other and how the end-of-life vehicle legislation will address the issue. Within the players that can take part in the CSC, the OEMs have the predominant position: based on their strategic decisions and their levels of vertical integration, they can influence the configuration of the chain capable of recovering components by following two main solutions: the one that will be defined as *OEM centric* or the one that will be called *Fragmented*. In turn, these two configurations may be established in different ways that will be explained below.

The main difference underlying the two proposed configurations lies in the OEM's desire to re-introduce reverse flow within the boundaries of their company at the product, component, and material levels, thus addressing the various circular economy strategies as important strategic levers for their business. In the *OEM centric* solution, in fact, it is assumed that the OEM is also the manufacturer of its electric motors and therefore plays a key role in the re-introduction of the electric motor and magnets within its production lines.

This configuration, depending on the competences present in the company and the OEM's level of vertical integration, can be articulated in different ways. Figure 6.1 shows the situation at the lowest level of vertical integration, where the OEM only deals with the production of its own vehicles and electric motors, while forming important relationships with other players to carry out the activities of product collection, motor remanufacturing and magnet recycling.

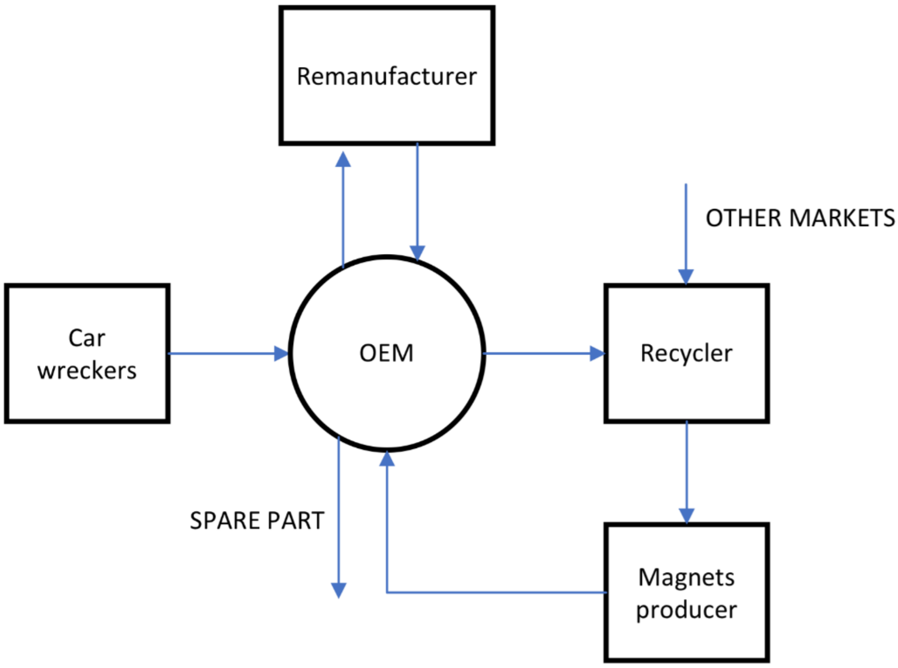

Figure 6.1: OEM centric configuration with low levels of vertical integration (own elaboration)

This configuration for the *OEM centric* solution appears to be the most realistic in the short/medium term, given the activities currently carried out by most OEMs. Regarding the activities carried out by other actors through collaborative relationships or partnerships, it is assumed that the activity of collecting electric motors is carried out by the car wreckers: already present with a very extensive network in the territory, they can recover end-of-life vehicles from end-users and dismantle the electric motor component that will be sold to the OEM. Subsequently, the latter, depending on the state of the component and their strategic objectives, can decide which circular economy strategy to apply to the component under examination: in the case OEM wants to reintroduce the entire electric motor into the production of new vehicles, remanufacturing and refurbishment activities will probably have to be carried out by independent actors called remanufacturers.

If, on the other hand, the company wants to apply the reuse or repair strategy, it is assumed that these components are resold on the market as spare parts for vehicles already on the road. Finally, if the company prefers the recycling strategy, it is assumed that it will create partnerships with companies specialising in this field, which, by applying the various possible recycling technologies seen in the previous chapters, will enable other actors to build new magnets from secondary material to be incorporated into the OEMs' new engines.

This structure, depending on the competences present in the company and the strategic objectives of the OEMs, may be articulated differently: with greater vertical integration, in fact, it is possible for the manufacturer of electric vehicles to incorporate the activities carried out by the other actors with whom it establishes relations in Figure 6.1. It is possible, in fact, that OEMs develop competencies in remanufacturing activities, as well as extend their boundaries to magnet recycling and collection activities. These different configurations are depicted in Figure 6.2 and it is believed that these may take hold in the long term, if the *OEM centric* configuration proves to be the main one adopted in the market.

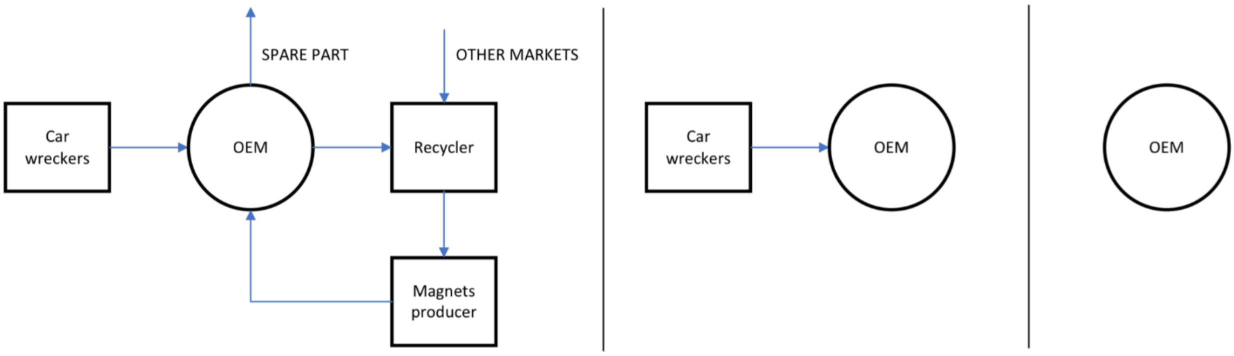

Figure 6.2: OEM centric configuration with high levels of vertical integration (own elaboration)

Looking at the current market, it is possible to notice that some OEMs are moving towards this configuration: this is the case of Stellantis with the inauguration of its first circular economy lab [119] and of Renault with the opening of its Refactory [120].

Turning to the *Fragmented* solution, the OEM holds a minor position within the recovery chain. It is assumed, in fact, that they do not take part in the production of their own electric motors and are therefore not directly interested in the recovery of the motor and magnets, as they do not identify the circular economy strategies as important strategic levers for their businesses. In this case, as shown in Figure 6.3, the car wrecker, being the owner of the motor recovered from end-of-life vehicles, can freely decide to whom to resell this component. It is possible, in fact, for this figure to resell the electric motor to the public as a spare part applying reuse and repair strategies, to give the motor to remanufacturers (in this case they can be either independent figures or manufacturers of electric motors) or to supply the product to recyclers, who will then recover the materials included in the magnets. In order to be able to get the greatest economic value, it is considered more likely that car wreckers will try to find solutions for reuse, repair and remanufacture strategies first and for recycling later.

Subsequently, the remanufacturers can either resell the motor to the public as spare part or to the OEMs who, like the electric motor manufacturers, play the role of mere supply chain customers in this configuration. However, given the low levels of adoption of CE principles of the OEM, it is expected that in this configuration most remanufactured electric motors would serve the spare parts market, not being reintroduced into the production of new vehicles. For what concerns recycled magnets, instead, it is possible that these could re-enter in the production of electric motors depending on the willingness of the electric motor recycler to embed recycled materials withing the production of new electric motors or follow open loop solutions therefore becoming part of other products.

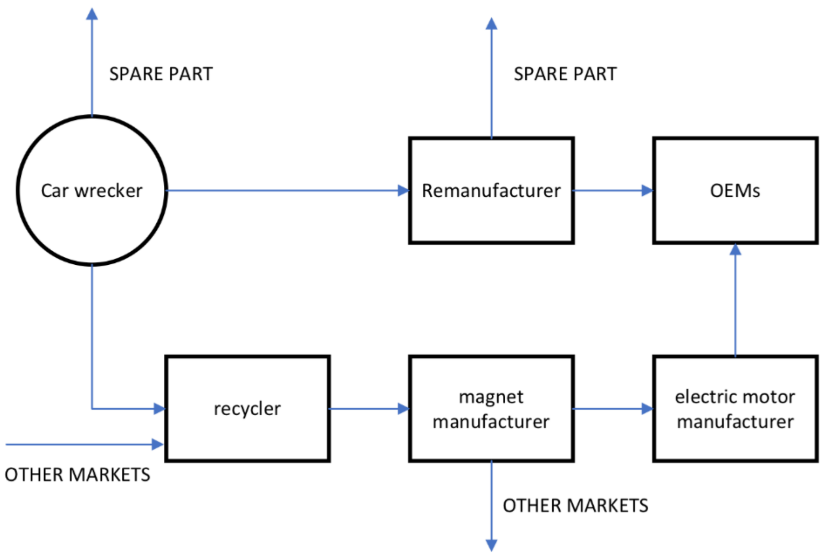

Figure 6.3: Fragmented configuration with low levels of vertical integration (own elaboration)

For this solution, as for the previous one, the situation with the lowest level of vertical integration has been presented, representing more closely the current reality. As before, depending on the different levels of vertical integration of car wreckers and electric motor manufacturers, it may take on different configurations such as those depicted in Figure 6.4. More specifically, the possibility in which car wreckers include motor remanufacturing activities and in which electric motor manufacturers include remanufacturing, recycling and magnet production activities are proposed. As before, it is believed that these may take hold in the long term if the *Fragmented* configuration proves to be the main one adopted on the market.

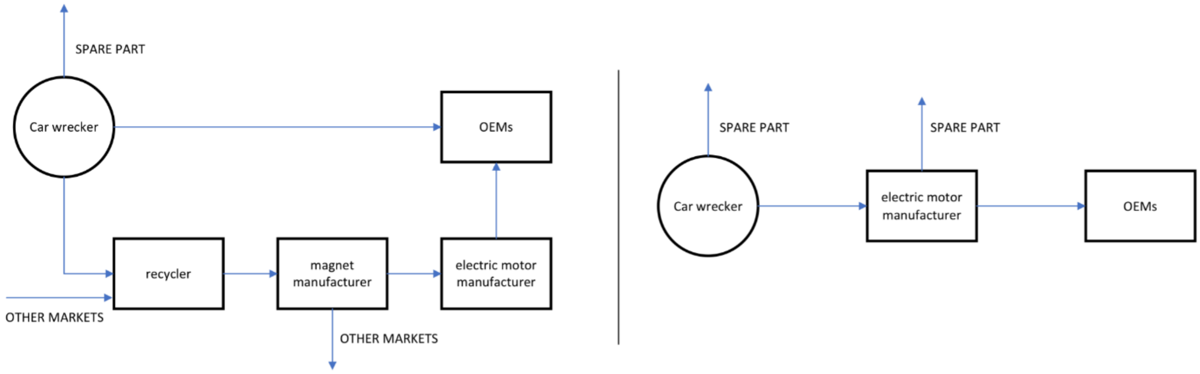

Figure 6.4: Fragmented configuration with high levels of vertical integration (own elaboration)

Wanting to compare the two proposed solutions, Table 6.1 lists some possible advantages and actions to be implemented for the two configurations to take hold.

Configuration	***Advantage***	***Needed action***
OEM centric	• OEMs have info over their products to implement CE strategies and develop ad hoc recovery solutions. • OEMs could establish more stable and sustainable supply (both environmentally and economically) • OEM possible implementation of servitisation models • Possible full adoption of circular principles	• Strong strategic commitment into circular economy of the OEM. • OEM has to produce own motors • Strong collaboration between OEMs and other players providing services
Fragmented	• More players and competition in the market • Market based on traditional customer/supplier relationship • Possible open loop strategies	• Less adoption of circular principles: probably recycling loop preferred (reuse and remanufacturing loops to serve only the spare parts market) • Need of standardisation end informative flow between players

Table 6.1: Advantages and needed actions for the configurations proposed (own elaboration)

As can be seen from Table 6.1, the *OEM centric* solution would guarantee more advantages for the OEM and for the general implementation of circular economy strategies: it is assumed, in fact, that a situation in which a single central actor manages the entire recovery chain can be more efficient and can allow the circular economy to express at its full potential, not having the problem of lack of information and favouring business models more oriented towards circularity and the application of all possible recovery strategies. For this to happen, however, the OEM has to identify itself as a promoter of these activities, internalising the production of the electric motor, basing part of its production on the flows coming back from the recovery strategies, and establishing important collaborations with partners.

On the contrary, for the *Fragmented* solution, the advantages are more equally divided among the actors taking part in the chain: a solution of this type would foresee a situation in which the OEMs hold less important positions, thus favouring a more natural development of the market, which can be formed by a greater number of companies competing with each other. Relationships in this type of configuration may be more traditional customer/supplier type between players. This proposal, however, would not guarantee a full application of circular economy principles: given the OEM's low orientation towards CE, it is more likely that engine remanufacturing strategy would serve mainly the spare parts market, instead of being reintroduced into the production of new vehicles. It is therefore believed that the strategy of recycling magnets can be favoured and that magnets from second material would serve the same SC actors or others according to open loop strategies. For this set-up to take hold, given the absence of a central figure, it is necessary that the standardisation levels for these products are much higher and that there is an information flow between the different players that is useful for applying the different circular economy strategies.

Turning to the geographic distribution of these solutions to find a proper configuration for Lombardy, it can be seen that both schemas can be developed in a decentralised and local basis only for end-of-life vehicle collection activities, given the capillary position of car wreckers. In fact, the key reverse supply chain actors that enable the application of the various circular economy strategies are few at European level: moreover, by centralising flows, the actors performing these activities, both in the *OEM centric* and in the *Fragmented* configurations, will be able to aggregate volumes as much as possible, thus making their processes more efficient and profitable. This geographic structure is mainly valid in the short/medium term, given the few players that are able to carry out these operations nowadays. In the future, when potentially one of the proposed configurations will be adopted as the main solution and higher volumes of EoL electric motors will be available, it is possible that the decentralisation of these activities will take place, specifically for configurations that prioritise life extension strategies at product level, creating regional configurations for electric motor remanufacturing. Therefore, adapting these two solutions for the Lombardy region, it can be expected that the collection of vehicles at the end-of-life could take place by car wreckers within the region, to then move on to the activities of remanufacturing, refurbishment, recycling and production of magnets at a national or more probably European level, at least in short-medium term.

In the end, thinking about which CE strategy would be preferred within the configurations, the work has shown how literature addresses mainly recycling options though the recovery of the materials embedded into magnets. Between the different recycling technologies long loop recycling has appeared to be the most viable solution in the short/medium term, with short loop recycling being preferred in the long term. At the same time, it is possible to notice that the industrial players performing these activities are very small, compared to the ones able to perform remanufacturing and refurbishment activities. The higher retention of value and the better environmental impact of the life extension strategies compared to the recycling ones makes it believe that these strategies could be preferred, even if the final decision depends on the preferences of the actors in the proposed CSC configurations.

7 Conclusions

The aim of the following thesis was to examine the gap found in the literature concerning the application of CSC structures for EV RE-PM electric motors by answering the RQs posed in the introductory chapter, focusing on the identification of solutions for the Lombardy region. The work is developed through various chapters that follow the logical development of how the work was carried out. Chapter 1 details the product under consideration and illustrates the context in which the EV RE-PM electric motors are found. This chapter also provides the knowledge basics concerning the application of circular economy principles and Circular Supply Chains.

Chapter 2, on the other hand, proposes a study of the expected volumes of electric motors to be collected in the coming years for the Lombardy region to make the reader aware of the volumes of electric motors to be collected in the coming years at regional level.

Chapter 3 then carries out a literature study to identify the different circular economy strategies applicable to the electric motor and the magnets inside them and to identify possible CSC solutions proposed in the literature. The analysis of the academic LR and the projects LR shows that so far the literature has mainly focused on the application of recycling strategies for permanent magnets, showing little evidence of the application of more virtuous circular economy strategies and the application of circular economy at the supply chain level. At the end of this phase, it was possible to construct the basic CSC structure on which the subsequent chapters of the thesis were based.

Through the development of Chapter 4, the key actors that can take part in the CSC structure proposed at the end of Chapter 3 are proposed, showing that the industrial realities capable of applying magnet recycling are few and small at a global level. Similarly, the actors able to carry out remanufacturing are not many, showing however that they are larger realities dealing with components similar to those of electric motors.

Chapter 5, responding to RQ1, set out to interview industry actors that can take part in the CSC framework identified in Chapter 3. Through the interviews conducted, it was possible to identify the main barriers that are hindering the development of CSC and to get a direct feedback on how the industry is interested in the recovery of this component. In the discussion section of the results, it is expressed how the barriers that are hindering the development of CSC in the future can be overcome, therefore permitting CSC to be established.

In conclusion, Chapter 6, thanks to the results obtained from the other chapters, proposes two possible CSC configurations, highlighting how the OEM plays a fundamental role in the recovery of electric motors. Wanting to adapt these configurations to the Lombardy region, it is shown how in the short/medium term it is expected that these configurations could develop at a national or European level, leaving only the activity of collecting end-of-life electric motors at a regional level. Subsequently, should either of these configurations take hold, it is possible to imagine that some activities will be carried out at regional level, especially for remanufacturing strategies.

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A Appendix A

The calculations made are based on the assumption of keeping constant values for the parameters used along the years: depending on how the market and technologies may evolve in the future, these values may change over time.

Parameter	***Value***	***Reference***
L	19,3%	Value got as an average between the values of BEV registered in Lombardy from [73], [121]
AR	95%	Value got from [27], [35]
Avg. life	15 years	Value got as an average between the values of Avg. life from [35], [122]
CR	SC1: 50%	Value got from [123]
	SC2: 90%	Value got from [34]
W	1,5 kg	Value got from [7], [35]
DE	90%	Value got from [124]
Recycling efficiency rate	95%	Average value got from [89]

B Appendix B

Questions
Is the company currently engaged in any recovery activity or project to recover the electric motor or the magnets embedded in the EV engines?
Does the company plan to engage in the recovery of magnets embedded in the EV engines?
When the recovery of these products is it more likely to happen?
What could be the main driver for the adoption of CE strategies to recover the components under analysis?
What are the key challenges for the engagement in circular initiatives for magnets and electric motors?
What would be needed to implement CE strategies? (internally and externally)

List of Figures

List of Tables

List of Abbreviations

ICE: Internal Combustion Engine

EV: Electric Vehicle

PHEV: Plug-In Hybrid Electric Vehicle

BEV: Battery Electric Vehicle

PM: Permanent Magnet

REE: Rare Earth Element

RE-PM: Rare Earth Permanent Magnet

CE: Circular Economy

CSC: Circular Supply Chain

NdFeB: Neodymium Iron Boron

REO: Rare Earth Oxide

OEM: Original Equipment Manufacturer

CRM: Critical Raw Material

EoL: End od Life

ELV: End of Life Vehicle

EPR: Extended Producer Responsibility

LR: Literature Review

RQ: Research Question