Journal of Remanufacturing
https://doi.org/10.1007/s13243-024-00143-6

REVIEW

Circularity potential of electric motors in e-mobility: methods, technologies, challenges

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Received: 10 November 2023 / Accepted: 1 November 2024

Abstract
The imperative shift toward sustainable development mandates a revolutionary transformation in the transportation sector. While the transition from internal combustion engines to electric motors represents a pivotal step, its ecological impact may fall short of expectations. This undertaking is motivated by the recognition that a truly impactful transition necessitates intricate strategies, addressing resource consumption during manufacturing and minimizing post-use waste. This literature review is dedicated to enhancing the framework of circular strategies within the realm of electric motors, with a specific focus on remanufacturing. The objective is to cultivate a conscientious approach to product development, primarily centered on the four key pillars of circularity: reuse, remanufacture, upgrade, and recycle. The primary goal is to furnish a comprehensive overview of the myriad possibilities associated with reusing products, either in parts or as a whole. Upon introducing the circular approach, this review underscores pivotal enabling technologies essential for a successful transition. These include inspection, disassembly, rewinding, and demagnetization. The ensuing discussion delves into the technological challenges faced and presents cutting-edge solutions poised to redefine the landscape. The concluding section extends the perspective to the future, introducing innovative studies and solutions still in their developmental stages. This review is tailored for decision-makers, policymakers, and researchers, providing them with a valuable overview and facilitating discussions to propel our society toward a sustainable and responsible future in electric motor technology.

Keywords Sustainable development · Electric vehicle · Remanufacturing · Circularity

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Introduction

The recent push for electrification of mobility in Europe[1] leads manufacturing companies involved in the automotive sector to face new challenges and disruptive decisions [22]. On one hand, e-mobility triggered an increase in production volumes and is expected to open new business opportunities. On the other hand, the current production scenario reveals critical situations concerning global supply chains, especially for rare earth elements (REEs) and electronics. Nevertheless, only considering EVs, sales have increased by more than 50% in the last 5 years, with the total number of sold electric vehicles in Europe peaking at over 3 million in 2023.[2] Regulations are playing a crucial role in driving the technical development of the automotive sector all around the globe, starting from the quantification of maximum emissions in terms of CO2 for the transport sector[3] to the end-of-use management of mobility components.[4]

Indeed, the shift towards electric mobility poses significant challenges to automotive manufacturers and suppliers, given that their research and development departments have predominantly focused on conventional combustion-based powertrains over the past century. Not only a change in the product paradigm is envied by policymakers, but also a change in a more sustainable production paradigm when switching to electrification. Circular economy (CE) is adopted as emerging paradigm to support the sustainable development of such an electric revolution, aiming at increasing the resource efficiency of manufacturing, as well as showing potential for new business opportunities, as fostered also by industrial and academic association at various levels.[5] Circular strategies such as repair, refurbishing, remanufacturing, and recycling can extend EV life and reduce environmental impact, providing economic and ecological benefits [52, 165], showing their full potential when both functions and materials are recovered and reused [153] in so-called value retention processes [130]. It has been demonstrated that strategies such as repair [70], maintenance [91], car-sharing [88], and extended producer responsibility [28] can be successfully implemented, and therefore, *remanufacturing* has been taken into consideration as a significant step forward for sustainable development.

A potential avenue for reducing the environmental impact of new products is using remanufactured products, whose implementation has the potential to significantly decrease costs, energy consumption, and material usage, up to 50%, 60%, and 70%, respectively [92]. According to [127] effective product policies aimed at incentivizing eco-design must consider a range of circular strategies, which may at times be contradictory, to address resource-related issues. Batteries are now the most studied component from the viewpoint

[1] Details on the strategies are included in the REPowerEU Plan: https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal/repowereu-affordable-secure-and-sustainable-energy-europe_en#documents

[2] This value includes both BEV (battery electric vehicles) and PHEV (plug-in hybrid electric vehicles). Additional details can be read in the report published online at https://www.iea.org/reports/global-ev-outlook-2024/trends-in-electric-cars

[3] For Europe, please refer to the Regulation (EU) 2019/631 (https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32019R0631) and for US, please refer to the DOT-2022-Sustainability-Plan (https://www.sustainability.gov/pdfs/dot-2022-sustainability-plan.pdf).

[4] See for instance the ongoing updates on the management of end-of-life vehicles in view of circular strategies Commission Delegated Directive (EU) 2023/544 of 16 December 2022 (https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32023L0544).

[5] One example in Europe is represented by the APRA association (https://www.apraeurope.org/).

of reuse and recycle, given their importance concerning material composition and life cycle [104, 126]. Existing studies and pilot cases show that it is possible to extend the useful life of such components by reusing them for different applications, for example as storage units in solar panel plants [154]. However, given the increasing production volumes, issues related to the feasibility of remanufacturing and de-manufacturing arise also for the electric motor (EM). Lack of familiarity with electric machines and the corresponding technologies can hinder the ability of automotive stakeholders to successfully navigate this transition [58]. One of the purposes of the present paper is to introduce the technical aspects of circularity of EMs for the automotive industry, even to those less familiar with the topic.

Scope and organisation of the paper

Circularity potential can be defined as the readiness of the research and industry actors in guaranteeing the implementation of circular strategies for target products of interest, motivated by environmental, economic and social considerations. To this aim, the implementation of circular strategies in the context of EMs needs the adoption of flexible designs and diligent monitoring practices to strike a harmonious balance between reliability and adaptability in light of market and technological advancements. Those strategies entail the utilization of material tracking, remanufacturing, and recycling strategies to optimize the efficient use of resources. However, various challenges need to be addressed, including careful material selection, the integration of design principles that facilitate disassembly, effective management of the reverse supply chain, and the attainment of economic viability.

Key existing technological solutions that enable the reuse, remanufacturing, and recycling of the most common components are investigated and analysed with respect to the literature and latest advancements. For each target use, which may differ according to motor type, maturity of existing technological solutions, as well as challenges, are critically reviewed, aiming to understand promising research guidelines and technological gaps. If examples from electric motors from automotive are not available, the research has been extended to additional types of electric motors, and critically analysed with respect to the possibility to transfer the solution to the automotive sector.

The paper is organized as follows. First, an introduction to the types of EMs is provided to present their different components and the main design and technological differences among the various types, as well as the sustainability framework laying behind the while circularity approach. Then, the method used to identify existing literature is presented in Sect. 2; the target framework for the technical circularity of EMs and the critical review of the existing literature is proposed in Sect. 3. Grounding on this analysis, Sect. 4 identifies the existing gaps, and highlights possible future trends and promising research guidelines. Finally, conclusions and outcomes for future research guidelines are summarized in Sect. 5.

Electric motors

The first focus of the paper is on circular strategies and technologies of EMs used in the automotive industry, and therefore a brief introduction to their architecture is deemed. EMs have evolved from being auxiliary components in automobiles to assisting internal combustion engines (ICE), and now be the primary power source of the powertrain [32, 37, 45, 57]. Compared to ICE, EM are much simpler, and their structure has not changed much over the years. The fundamental principles to convert electrical energy to mechanical energy in rotating machines are shared among different topologies and technologies, and therefore the basic layout of EMs is shared: (i) stator, (ii) rotor, (iii) case, (iv) cooling system, (v) connectors, and other electronics are common to most types as shown in Figs. 1 and 2.

According to [128, 155, 169] EMs in EVs face challenges, including high costs of rare earth permanent magnets (PM) in PM synchronous motors (PMSM), low efficiency in induction motors (IM), poor torque density in switched reluctance motors (SRMs), and limitations in regenerative braking. Generally speaking, PMSMs are best for regenerative braking due to high efficiency, while IMs have a shorter constant power range and generally lower efficiency. SRMs have a wide speed range but limited torque capacity.

A great deal of attention has been paid to PM materials: despite the most common one being NdFeB,[6] different materials such as AlNiCo and ferrite are being explored. AlNiCo magnets, which have been used in industrial applications for decades, have been optimized to achieve higher energy densities and magnetic fields, making them a promising alternative to rare earth PMs [26]. According to [29, 106], ferrite magnets, although not as strong as rare earth PMs, are low-cost and abundant, and advancements in their technology show potential to improve their magnetic properties [15, 170].

There is a wide range of motor types available depending on the design and application requirements in the automotive industry, but only a few could secure substantial market penetration due to their superiority in technology maturity, performance, and efficiency [18, 20]. As per Fig. 3, PM motors are the current leaders in the automotive market, followed by induction and wound rotor motors for the passenger cars sector [40].

Induction machines are promising alternative to PM motors due to their lack of reliance on REE, potential for mass production at a lower cost, and reduced supply chain risk. Despite lower efficiency and torque density, their established position in the automotive industry make them an attractive solution for EVs [123], once manufacturing challenges related to automation and scalable technologies are solved, as in the case of vertical die-casting.[7]

Synchronous motors are preferred, and they come in two varieties: PMSM and salient-pole synchronous machines (SPSM). In PMSMs electric current flows through the stator windings, generating a magnetic field that interacts with the PM on the rotor's surface, creating a torque, that sets the rotor in motion. SPSMs, on the other hand, work on the principle of electromagnetic induction, and salient poles are used to create a non-uniform distribution of the magnetic field, allowing for better control and performance characteristics. The PMSM is commonly used in EVs and can reach peak efficiencies as high as 97% [18, 66].

All the motor types are filled with critical materials, such as copper from the windings, REE from the PMs (if present), or electronics. Given the already existing literature on semiconductors and electronics recovering [44, 105], this work will not focus on this last aspect. Attention will be given to the reuse of functions and materials from the mechanical sub-assemblies of the motor, i.e., stator, rotor, case.

[6] Detailed characterization of commercial types of permanent magnets can be found at https://www.miottisrl.com/en/product/neodymium-iron-boron-magnets-ndfeb/

[7] The description of the case study can be read at https://www.cannon.com/ergos/case-history/

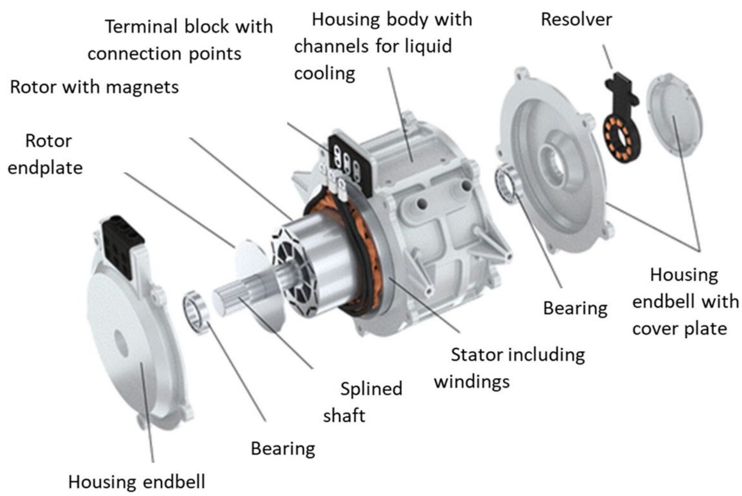


Fig. 1 Exploded view diagram of a permanent magnet synchronous motor showing the spatial arrangement of its components [111]

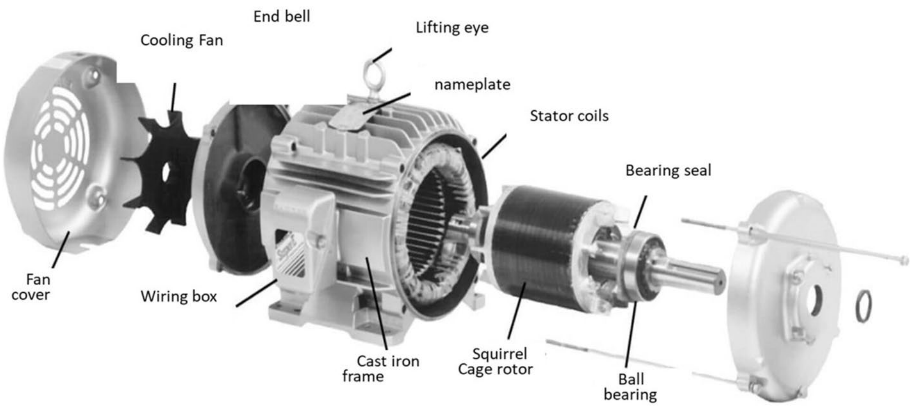
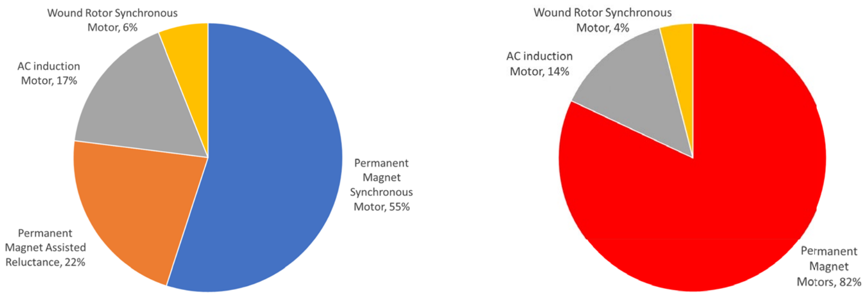


Fig. 2 Exploded view diagram of a three-phase induction motor (https://electricala2z.com/)

Sustainability motivation for circularity of electric motors

The inclusion of EVs and their environmental impact alongside electric motors offers a holistic perspective on sustainable transportation, facilitating a nuanced examination of the challenges and opportunities inherent in electric mobility. In the EU, Regulation 2019/631 sets 95 g and 147 g of CO2/km emission for European cars and vans, respectively, to be met by 2024, and specific targets are set annually for each manufacturer based on average vehicle mass. In the USA, even stricter limits are set by authorities, such as the EPA (environment protection agency) and the national highway traffic safety



(a) (b)

Fig. 3 Distribution of different AC (alternating current) traction motors in BEV (battery electric vehicle) and PHEV (plug-in hybrid vehicle) in (**a**) 2020 [40] and (**b**) 2023 [41]

administration (NHTSA). Such limitations will favour EV sales, expected to raise 67% and 46% for light- and medium-duty vehicles by 2032,[8] respectively.

China's NDC (national determined contributions) targets include achieving carbon neutrality by 2060 and reducing CO2 emissions per unit of GDP by over 65% from 2005 levels [158]. As per estimations, new passenger cars should limit CO2 emissions to around 30 g/km by 2030, reaching zero emissions by 2035. Additionally, new commercial vehicles should aim for a 67% CO2 reduction by 2035 compared to current levels, which equates to a 74% reduction from the 2012 baseline.

Despite a notable reduction in emissions during the operational phase of the vehicle on the road, it is essential to acknowledge that current and prospective regulations solely address emissions stemming from the end product, specifically the vehicle. The environmental impact of EVs or electric motors due to manufacturing has been assessed [42, 90], and is reputed negatively. The European Parliament proposed the reporting of life-cycle CO2 emissions for vehicles starting in 2025. A study [62] conducted according to international life cycle analysis (LCA) standards (ISO-14040 and ISO-14044) revealed the average EU lifecycle climate impact of battery-electric vehicles. Both the European Commission and ACEA (European automobile manufacturers' association) express doubts about the applicability of LCAs for assessing individual vehicle emissions, citing concerns related to complexity and regulatory feasibility.[9] Variations in LCA methodologies among suppliers and OEMs highlight the need for a legal framework to regulate CO2 emissions in the automotive industry. Standardizing LCAs enhances transparency and accountability, aligning with the industry's environmental goals. This standardization can mitigate complexities in vehicle and supply chains, fostering sustainability.

LCA entails an analysis spanning from raw material extraction to disposal, aiding in the comparison of various automotive technologies [6]. This assessment is driven by increasing EV demand, which underscores the urgency of optimizing their environmental performance [96]. Notable advancements in electric motor technology, including rare earth-free motors, align with a more sustainable direction [20].

[8] The original report has been published at https://www.nytimes.com/2023/04/11/business/energy-environment/cars-electric-vehicles-epa.html

[9] The original communication can be found at www.europarl.europa.eu/thinktank/en/document/EPRS_BRI(2022)698920, assessed 11/01/2023.

A critical aspect is determining the overall ecological footprint of EVs. The composition of electric motors for EVs and HEVs (hybrid electric vehicles), detailed in Table 1, underlines the significance of material choices in their environmental impact [129]. As the demand for EVs surges, advancements in electric motor technology, stricter regulations on vehicle emissions, and potential competitive advantages motivate a closer examination of the environmental aspects of electric motors [1, 84, 98].

It is imperative to consider the composition of electric motors. Efforts to mitigate environmental impact should encompass the use of renewable energy sources, the adoption of CE principles, and the optimization of manufacturing processes [31, 109]. Recycling, and quasi-closed-loop systems, combined with increasing renewable energy use, address environmental concerns in electric motor production, promoting sustainability [75, 136].

Improving electric motor efficiency, especially with more renewable energy use, benefits the environment. However, the extent of this benefit varies between different environmental aspects. Considering how motors are used and how long they last is crucial for evaluating their environmental impact. Decision-making using LCA is challenging due to uncertainties, calling for more research in these areas [7]. The full environmental impact of the entire supply chain for green energy technologies and REE mining and production remains unclear. A comprehensive, global study is urgently needed to understand and mitigate the environmental consequences associated with REE production fully. This holistic approach is essential to meet the goals of the Paris Agreement and effectively limit global temperature increases [43, 55, 72]. Sustainable production methods, such as the use of recycled REEs and quasi-closed-loop systems, have been proposed to reduce the environmental impact of magnet production [20]. LCA for PM motors provides valuable insights into their environmental impact, guiding decision-making in the automotive industry toward more sustainable practices [10, 11]. Recycling PM motors, despite their complexity, is increasingly viable and aligns with the demand for EVs and renewable energy [151].

To better understand the effect of alternative PM compositions on sustainability indicators, the comparative analyses of different electric motor types with varying life cycles and geographical locations (Sweden and USA) are presented in Fig. 4, for impact categories of climate change (in CO2/kg) and toxicity (in Comparative Toxic Units COT).

Various other LCA-based studies have explored electric motors and their components, shedding light on their environmental impact [11, 16, 23, 151]. Results show that there is potential for sustainable development of the electric motors' manufacturing, whereas the remanufacturing may depend on the scope as well as on the remanufacturing technologies involved in the circular strategies.

Table 1 Typical material composition of Permanent Magnet synchronous motors [129]

Material	PM-Motor in EVs; 80 kW (kg)	PM-Motor in HEVs; 20 kW (kg)
Steel	34.8	23.1
Aluminum	14.1	4.7
Magnets	2.1	1.4
Cast iron	3	0
Copper	8.5	6.4
Polymers	0	0.6
Elastomers	0	0.1
Liquid	0	7.7
Total	62.5	44

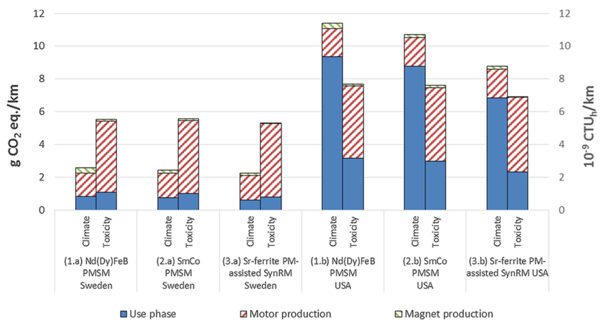


Fig. 4 Impact results per kilometer, illustrating climate change (left units) and non-carcinogenic human toxicity (right units) across various life cycle stages for permanent magnet electric traction motors [110]

Additionally, analysis of permanent magnet motor component production costs (see Fig. 5) highlights the significant expenditures associated with the stator, rotor, and shaft [60]. By implementing function recovery operations—such as reuse, remanufacturing, and upgrades—on these components, production costs will be notably reduced compared to developing new ones. Moreover, in [121], it is apparent that laminations, copper, and magnets collectively constitute nearly 60% of the total price. Consequently, material recovery initiatives have the potential to yield substantial savings within this 60% fraction.

Methodology for state-of-the-art analysis

This section explains the selection of keywords and eligibility criteria for the identification of target articles following a traditional methodology for systematic reviews and meta-analyses (PRISMA) guidelines [117]. The section will also include the analysis of key phrases and frequency of keywords across different regions, as well as a synthetic overview of the selected papers, with respect to circular strategies and enabling technologies.

Design and manufacturing of electric motors in the automotive industry are under an inevitable growth phase which implies that research pertaining to the technical circularity of this product is certainly at its beginning [152]. Therefore, an interdisciplinary approach has been employed to create synergy between different perspectives such as design (according to target component) and production (according to target action and technology).

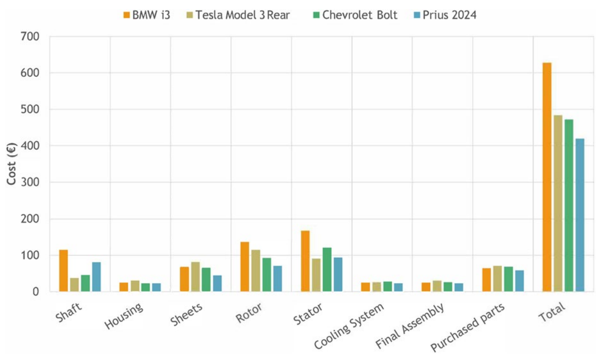


Fig. 5 Cost distribution among components for four benchmarked PMSM models (high production volume) (adapted from [60])

The systematic literature review was conducted through widely recognized academic and industrial databases such as Scopus, IEEE, and SAE, and papers from relevant research groups with industrial connections. The PRISMA was incorporated to preserve the quality of the review. Before query selection, extensive brainstorming sessions were performed to discuss the state-of-the-art electric motors specific to the automotive industry with several members of the department the authors belong to. Ultimately, keywords for queries as shown in Table 2 were devised intending to employ diverging and converging strategies [119], and the execution of queries was based on a simple round-robin algorithm.

The systematic review followed the PRISMA guidelines as shown in Fig. 6 and it employed a rigorous eligibility criterion to ensure the selection of high-quality literature. Eligible articles had to be specific to remanufacture, refurbish, reuse, or recycle of electric motors in the automotive industry, published within the past 30 years, and comply with general quality standards including journal quality, impact factor, credibility, and indexing in renowned databases. Articles with overly broad aims and scope were excluded. By adhering to these criteria, the review aimed to synthesize the most relevant and high-quality literature on the topic. It is worth mentioning as not all papers focus on electric motors, rather many of the articles use the electric motor as target applications. This is why so many articles (71) have been added to the analysis by means of linked references.

The SciVal tool from Scopus has been used to cluster research papers within the academic domain and extract the key metrics presented below.

To identify the key drivers of progress in this field, a range of text keywords were analysed for their frequency across the period of 2018–2023 in the set of full text. The top 15 keywords, intended as the most repeated words in the full text of the article, as shown in Fig. 7 were then identified and refined, and the most frequently used terms have been identified to be “Electric motors”, “Motor”, “Electric Vehicle”, “Permanent Magnet”, “Manufacturing”, and “Recycling”. These key phrases provide important insights into the design, operation, and sustainability of electric motors in the automotive industry. Of particular interest is the focus on PM, which is a key area of research and industry attention. The remanufacturing of PM is a crucial aspect of sustainable manufacturing, as it allows for the reuse and recycling of materials while reducing waste and energy consumption. At the same time, it begins to be clear that until now the main focus for enhancing circularity in electric motors has been the recycling of PM, while other enabling technologies in the process chain of remanufacturing or any other circular strategy have not been deeply investigated yet.

Additionally, a region-wise comparison of these keywords revealed in Fig. 8 that Europe currently dominates this field. Furthermore, recent EU homologations suggest that Europe is poised to make more significant strides in the coming years.

Finally, the identified articles have been categorized according to the topic of interest with respect to this work. Table 3 provides a first overview concerning the target circular strategies to be considered in this article, as well as technologies that are considered key enablers for reaching circularity. In this sense, technical circularity is intended as the set of enabling technologies to allow circular strategies.

Table 2 List of Selected keywords and executed queries looking at titles, abstracts, and keywords

ACCORDING TO	QUERIES
Target action	(re-manufacturing) AND ((electric OR traction) AND (motor))
	(reuse OR revamp OR refurbish) AND ((electric OR traction) AND (motor))
	(recycle) AND ((electric OR traction) AND (motor))
Target component	stator AND (re-manufacturing OR reuse OR recycle)
	rotor AND (re-manufacturing OR reuse OR recycle)
	permanent magnet AND (re-manufacturing OR reuse OR recycle)
	stator windings AND electric motor AND (re-manufacturing OR reuse OR recycle)
	hairpin windings AND electric motor AND (re-manufacturing OR reuse OR recycle)
	motor housing AND (re-manufacturing OR reuse OR recycle)
	motor shaft AND (re-manufacturing OR reuse OR recycle)
	re-manufacturing OR reuse OR recycle AND (motor AND yoke)
	re-manufacturing OR reuse OR recycle AND (electric motors automotive)
Technology	(disassembly) AND ((electric OR traction) AND (motor)
	(demagnetization) AND ((electric OR traction) AND (motor))
	((inspection) OR (diagnostics)) AND ((electric OR traction) AND (motor))
	(reverse AND engineering) AND ((electric OR traction) AND (motor))
	(rewinding) AND ((electric OR traction) AND (motor))

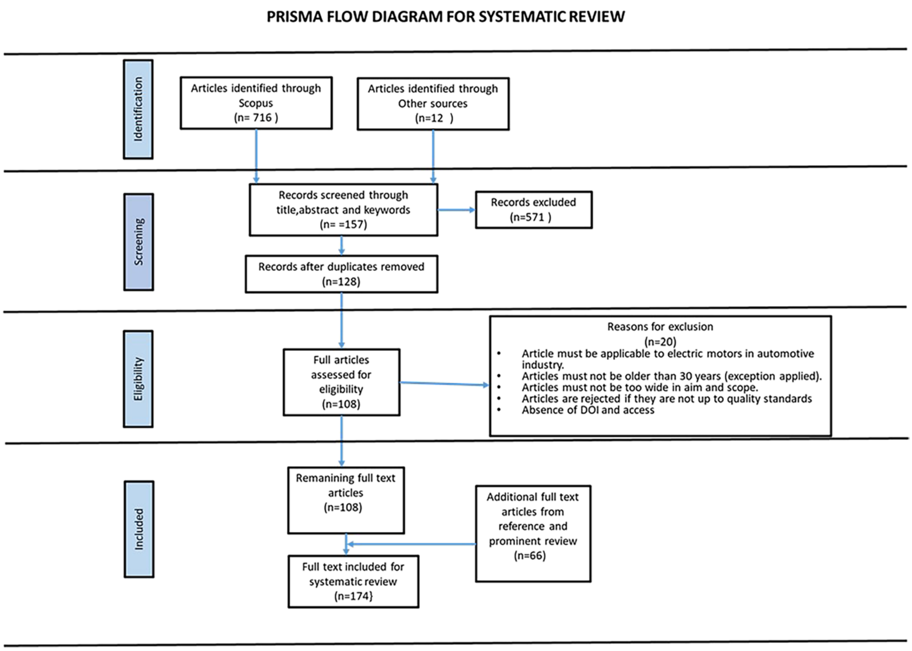


Fig. 6 PRISMA (2020) flow diagram for the systematic review of state-of-the-art

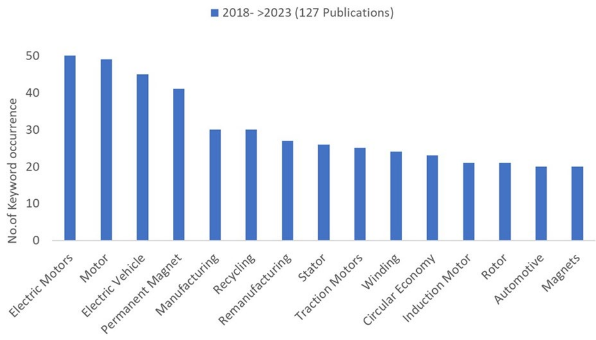


Fig. 7 Top 15 Key phrases scholarly output from 2018 – 2023

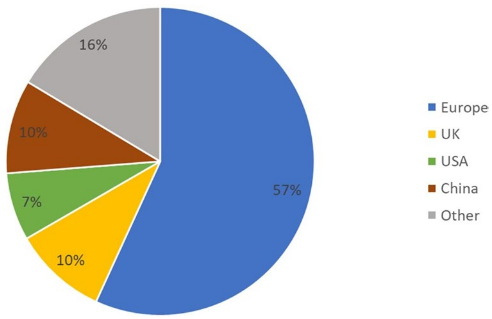


Fig. 8 Top countries/regions in this Publication Set, by Scholarly Output (2018–2023)

Review of circular approaches for e-motors

In this Section, existing approaches for the circularity of electric motors from the state of the art will be presented. Firstly, a framework is introduced emphasizing the potential circular loops that enable electric motors to have multiple lifecycles, based on the required operations. The target application is represented by e-mobility, but also other possibilities will be considered, to have a cross-sectorial approach. The existing circular strategies for electric motors are reviewed, presenting an overview of available key enabling technologies and developments.

Framework for circularity of e-motors

A framework for the general analysis and application of circular manufacturing to electric motors is introduced in this Section, summarizing the possible circular loops for the reuse, remanufacture, upgrade, and recycle of motors, with respect to the involved components. Circularity is best achieved and profitable when not only materials are recovered, but especially when *functions* are restored and product value is kept by extending its life, before the product is finally dismantled and partially or fully recycled [153]. Function recovery – also known as Value Retention [130]—looks at products not as a whole, but as a combination of different components, each of whom can have a second life. As a consequence, the main goal of circularity should be firstly to recover/upgrade the working functions of products, components or sub-components, in order to maximize the product value over its life-cycle

Table 3 Summary of the references cited in this paper clustered by main topic

Circular strategies	**References**
Reuse	[31, 39, 40, 65, 72, 77, 81, 88, 91, 128, 134, 151, 158, 167]
Remanufacturing	[39, 40, 48, 49, 76, 86, 87, 92, 93, 101, 102, 106, 110, 134, 138, 144–149, 157, 168, 170]
Upgrade	[39, 40, 122]
Recycle	[39, 40, 44, 45, 62, 66, 73–75, 79–81, 87, 89, 112, 128, 150, 161, 165, 168, 171, 172]
Redesign	[4, 13, 16, 19, 22, 27, 29, 30, 33, 37, 52, 54, 59, 82, 92, 98, 109, 122, 136]
Key enabling technologies	**References**
Disassembly	[4, 8, 39, 40, 48, 50, 53, 65, 75, 79, 81, 96, 141, 144, 145]
Demagnetization	[10, 66, 75, 81, 88, 171]
Inspection	[5, 8, 36, 39, 40, 60, 65, 83, 126, 142, 153, 154, 167, 169]
Rewinding	[20, 29, 39, 40, 84, 101, 102, 124, 137]
Digital technologies	[9, 31, 64, 102–104]

and minimize the waste of material, energy and consumables. Only if functions cannot be recovered/upgraded, recycling of materials becomes an option. Product circularity is a technology-intensive but also highly efficient process that expects to well know all components and characteristics of the product since the design phase. When dealing with motors, their main components target of circular manufacturing approaches are the case, the stator and the rotor, as introduced in Sect. 1. Each component is the result of several manufacturing processes based on different technologies, and as a consequence, the multi-stage process chain of electric motors may include diverse operations and involve several manufacturing and digital technologies, which will be also presented later in this work.

The graphical representation of the framework is shown in Fig. 9.

When it comes to EM, several levels of circular strategies may be defined, according to the necessary effort in recovering functions or materials. In this work the focus will be on the following four R-strategies: Reuse, Repair, Remanufacturing, and Recycle, as introduced by [69, 132]; Upgrade is also defined hereby to distinguish applications that will be presented later in the paper. The four R's definitions are applied for the electric motor application.

- *Reuse/Repair*: the terms generally refer to the reuse of a product, or of some of its components, after the first life-cycle. In the case of EMs, they shall be reused as they are or following only minor repair actions. There is no modification to the physical assembly with respect to critical components, i.e. rotor, stator and case, and a motor is reused as a whole because it has not yet reached its end-of-life. In some cases, this second use can be done considering different, less-demanding, cross-sector applications. This strategy is currently a common industry practice, given its low technological effort, though it requires a good knowledge of the product.
- *Remanufacturing*: it involves the re-processing of already used products for restoration to their original state or a like-new form through the reuse of as many parts as possible without loss of functionality. A remanufacturing strategy is applied when some of the components cannot be reused just by going through minor repair but shall rather be reprocessed following the disassembly of the original motor. Hence, the reuse of

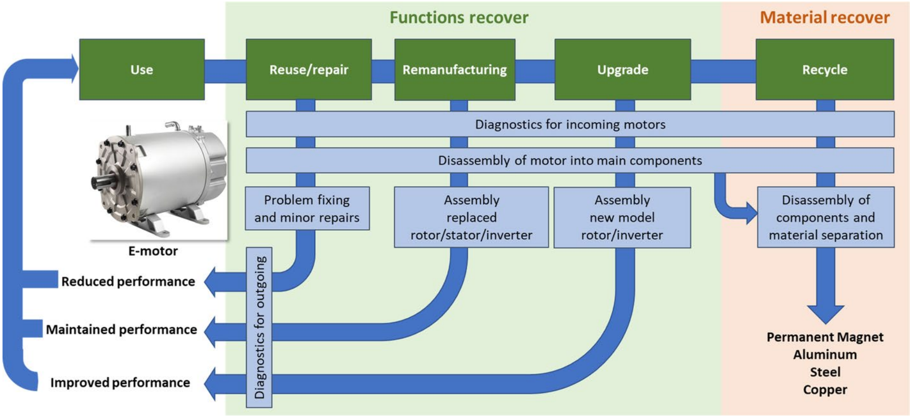


Fig. 9 Framework for the circularity of e-motors

a motor under its original operative conditions is possible only after the reprocessing or replacement of one or more critical components. This strategy implies an excellent knowledge of the motor by the remanufacturer, as well as the availability of replacement components and the availability of remanufacturing technologies. This strategy also includes the manufacturing of EMs with recycled materials.

- *Recycle*: it involves the process of converting material that would otherwise be considered waste, into materials for different products. The motor is dense with aluminum, steel, copper, and rare Earth magnets (where used) which can find application in several different products. In this case, the motor shall go through complete disassembly/crushing operations before being dismantled and materials recovered. Manifold multi-technological processes are needed, from mechanical to chemical processes, thus involving several actors in the value chain to guarantee the effective implementation of this strategy.
- *Upgrade*: hereby, upgrade is defined as the remanufacturing operation aiming to improve the overall product performance and/or functions. In the case of motors, this can occur when one or more of the components are reprocessed so that performances are improved, or when one or more of the components are replaced with new ones having an improved design, leading to empowered functionalities. In this case, the strategy implies both in-depth knowledge of the product design and the availability of manufacturing/remanufacturing resources. Currently, this is still not an industrial practice, but rather a research topic for its potential applications.

The following Sections review the methodologies and applications from the current research and state-of-the-art enabling circular electric motors, with respect to the presented framework.

Recovering functions of e-motors: reuse, remanufacturing, and upgrade

Recovering *functions* aims to maximize the functional value of electric motors by promoting reuse, remanufacturing, and upgrades, as defined earlier in this paper. In this Section, exemplary applications and innovative strategies for the circularity of e-motors as a product, with respect to function recovery, are presented.

When it comes to the reuse of EMs, the target is twofold. The first goal consists of using the machine for as long as possible with minimal intervention during its life to maximize its functional value. Predictive maintenance and remote monitoring technologies can be used to identify needs for repair and maintenance, thereby reducing the need for premature replacements. In an early work by [79], it was highlighted that to achieve a successful reuse strategy, information from previous product life should be kept. Specifically, an electronic data log (EDL) was advised to convey information about motor usage, like average power and torque, time spent driving, peak values, etc. This type of information conveying data about both design and usage of products is also at the foundation of the Digital Product Passport, a European initiative to enable product tracking in particular for circular strategies.[10]

The second goal consists of reusing the electric motor in other sectors with respect to that of the original application. Most of the examples of reusing EM in different sectors found in the literature refer to industrial sector and white goods. In [12] small electric motors from various sectors, including automotive, domestic, and industrial applications, are studied considering their reuse as PM synchronous generators (PMSG) in small wind turbines or hydro-power turbines. In order to do so, a possible remanufacturing strategy is proposed, aiming at re-arranging the PMs in the rotor to act on motor performance with respect to the target application. Pioneering analysis on this topic can be found in [76], where the useful life of washing machines is studied, and the case is made for reusing their electric motors, whose lifetime is about two times that of the washing machines they are installed in. Lack of research applications in automotive for reuse of electric motors can be due to various reasons: (i) reuse of a product in the same sector is not a research topic, (ii) lifetime of electric motors for mobility is extremely long, or (iii) the current demand for electric cars does not allow from the business viewpoint the reuse of electric motors. All these considerations may change once e-mobility will increase volumes, also having an impact on business models, such as car sharing and leasing options. In 2022 more than 85 million vehicles have been produced,[11] growing from the year before, and it is expected that by 2030 25% of the annual sell will be of an electric type.[12] The number of electric motors employed in the automotive sector, considering not only traction motors, could easily reach hundreds of million units per year: if the circular strategies reach just a small fraction of the total volume, it could still have a huge impact in terms of money, global emission, and environmental protection and waste production.

Another way of maintaining the functions of an electric motor, rather than only reusing it, is by remanufacturing some of its parts. Remanufacturing is a technology-intensive strategy, since remanufactured components, or components out of recycled ones, involve a diverse set of manufacturing processes. Moreover, it can be noted that research papers report examples where the remanufacturing or upgrade of only one component is studied,

[10] The original communication can be found at www.europarl.europa.eu/committees/it/digital-product-passports-enhancing-tran/product-details/20220510CHE10181

[11] Detailed figures can be found at www.acea.auto/figure/world-motor-vehicle-production/

[12] www.spglobal.com/mobility/en/topic/electric-vehicle-trends.html?utm_source=google&utm_medium=ppc&utm_campaign=PC023665&utm_term=evs%20car&utm_network=g&device=c&matchtype=p&gclid=EAIaIQobChMIpKyR4-XC_wIVjuRRCh0O-wRLEAAYAyAAEgI81PD_BwE

i.e., all works, to the best of our knowledge, relate to the remanufacturing or upgrade of the stator, the rotor, or the cooling system.

For instance, cooling systems may be used as enablers of the upgrading strategy. The paper [118] compares the achievable torque and power improvements yielded by constructing a retrofitted liquid cooling system for a commercial off-the-shelf (COTS) electric motor. It was found that, for the Maxon EC22 100 W motor, 2.58-times higher current and torque output could be safely obtained with the liquid-cooled motor compared to the same, air-cooled, motor, closely matching the motor's thermal ratio, a theoretical value that can be directly calculated from datasheet motor parameters. This empirical validation is the main contribution of the paper and enables future designers to place confidence in and have intuition toward active cooling performance for COTS motors. The measured increase in continuous power output by a factor of more than two between the two cooling methods entailed a mere 2.2% decrease in operating efficiency. This observation suggests that liquid cooling may also have roles in actuators with strict energy consumption requirements, yet that is required to produce high energy output periodically.

Stator remanufacturing and upgrading is an area of research currently focused on two main components: the stator core and the windings. Within the context of stator core remanufacturing, particular attention is being paid to the use of alternative materials for the laminated stacks. The selection of such materials is contingent upon a thorough analysis of how recycled materials may impact the overall performance of the stator [125]. To ensure optimal outcomes, it is essential to conduct rigorous scientific investigations into the characteristics and properties of the alternative materials being considered, as well as their potential effects on the structural integrity and electrical performance of the stator core. Ultimately, the goal of such research is to identify viable and sustainable solutions for stator remanufacturing and upgrades that can enhance the efficiency and longevity of electrical systems while minimizing impact on the environment. The studies presented in [142–145] propose a hybrid stacking method for the stator core of a remanufactured motor to improve its performance. A segmented superposition algorithm is used to calculate the cogging torque, and the reverse chute setting method is employed to reduce it.

In windings remanufacturing, research focuses on the effects on performance, as well as investigating the rewinding process from the technological perspective. Rewinding is an established remanufacturing operation aiming at restoring the stator (mostly in induction motors) to satisfying conditions with respect to energy efficiency. In fact, the electrical apparatus service association[13] published a document on the good practice of rewinding, together with an analysis of the effects of rewinding on motor efficiency [39]. It is proved that for an industrial induction motor, the rewinding may at most reduce its efficiency by 0.2%. Rewinding is also used in an opportunistic way to upgrade the motor with respect to energy performance. In general, it has been reported that changes in the balance between the load-independent losses and the load losses resulting from rewinding can cause the maximum efficiency to point to occur at a load different from that of the original design [19]. Furthermore, rewinding has been investigated from the perspective of sustainability, showing good opportunities when it comes to energy improvement [2]. As a consequence, the upscaling of rewinding to industrial

[13] Namely, the EASA (https://easa.com/).

automatic plants [98] is currently under research, to tackle the expected volume increase from the rise of e-mobility.

In rotor remanufacturing and upgrade, research can be found again on (i) effects of new materials and (ii) redesign of rotor for improved performance. For instance, within the first strategy, installing a new rotor core to meet IE 2 energy efficiency standards by replacing cast aluminum rotors with copper–aluminum rotors [95] proved to be a promising approach. Copper rotors have potential for developing remanufacturing technologies, despite higher raw material costs and manufacturing challenges than aluminum, and could improve energy efficiency and reduce carbon footprint and energy costs [92]. One of the most interesting applications for rotor upgrading falls into case (ii), where the rotor alone is replaced, thus keeping all the other components, with an upgraded one. This strategy is shown to improve the overall motor performance against alternative upgrading strategies. In one example, the rotor is redesigned together with the cooling system [87] ensuring the reliability of the motor under long-term operation and life extension. Here, the PM rotor was used to replace the squirrel-cage rotor of the asynchronous motor, showing improved performance. So as supported by [50] in a vast number of situations it could be advantageous to invest 30–50% of the cost of a new motor to readapt an old one with a healthy core and rotor to its actual load. Another strategy proposed by [85, 86] is magnet direct-reuse as a potential solution to the supply risk of heavy rare earths in high-performance electrical machines. The feasibility of applying surface-mounted PM (SPM) machines in mild hybrid electrical vehicles (MHEVs) is analysed, and practical obstacles are examined. SPM machines are found to be easier for reusing magnets, and a new design that employs segmented magnets with massive glue is proposed. This design reduces dependence on new magnets and promotes magnet reuse. The paper provides a comprehensive analysis of challenges and potential solutions to the supply risk of heavy rare earths in high-performance electrical machines for MHEVs.

Switching to a different type of motor while reusing the same materials is not always a feasible strategy, because different types of motors are designed for specific applications, and their specifications and designs are tailored to meet strict requirements. For example, a motor designed for high speed and low torque is in general not suitable for an application that requires high torque and low speed. Therefore, changing the motor type while using the same materials may require significant modifications to the motor's design, which can be both costly and impractical. However, in some cases, it may be possible to modify or upgrade an existing motor to perform better in a different application while still using the same materials. This can be achieved by redesigning the motor's windings or stator (bearings included) to increase its torque or speed, or by adding a different type of cooling system to enhance its performance. Nonetheless, such modifications should be carried out carefully, considering the motor's specifications and intended application to avoid any unforeseen issues.

A summary of proposed actions for remanufacturing of main components in an exemplary AC induction motor is shown in Fig. 10.

The set of actions for recovering components as a value retention process or even value-adding process in the remanufacturing of motors can be perceived as intricate, and strongly depending on the motor status at the end-of-use, as well as on the circular target application. In this context, design and (re)manufacturing are strongly inter-related.

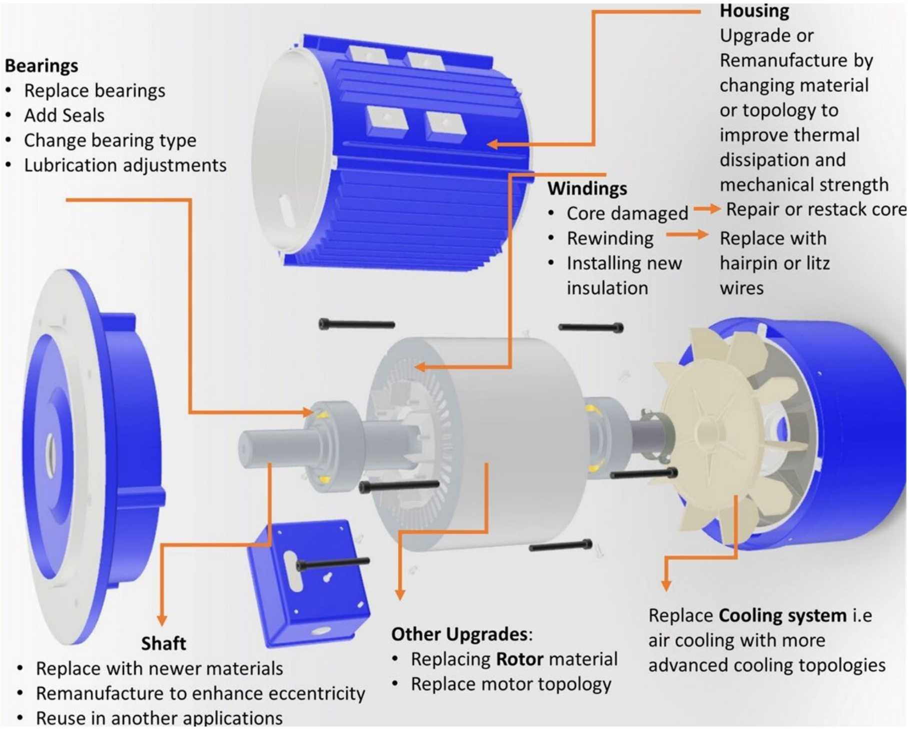


Fig. 10 Example of disassembly and component-wise enhancement for an AC induction motor

Recovering materials in e-motors: recycling

The main business case for material recycling in electric drives is given by the presence of PMs. While recycling of materials such as copper, steel, and iron has already been investigated in both research and industry, the state of the art for PMs is rather different. PMs are made of various alloys based on REE, from Ferrite to Neodymium [24].

The recycling of REEs from PMs presents several challenges, including the cyclical nature of REE prices and the high capital and operating expenditures required to establish profitable recycling enterprises. Safety, environmental impact, and energy efficiency concerns also need to be addressed in REE recycling efforts. Processes that result in valuable recycling by-products or allow the recycling of other components in a device housing the REEs-containing materials can improve the profitability of their recovering. Although recovering REEs from PMs can be more energy efficient and environmentally friendly than obtaining them from primary sources, minimizing the energy used and impact on the environment is crucial [108].

Among them, sintered NdFeB magnets are the strongest PMs available today, as shown in Fig. 11.

Their excellent magnetic properties can be traced back to the strongly magnetic matrix phase $Nd_2Fe_{14}B$ featuring high saturation polarization and high magnetic anisotropy [174]. On average, the mass of PM used in electric motors is estimated to be

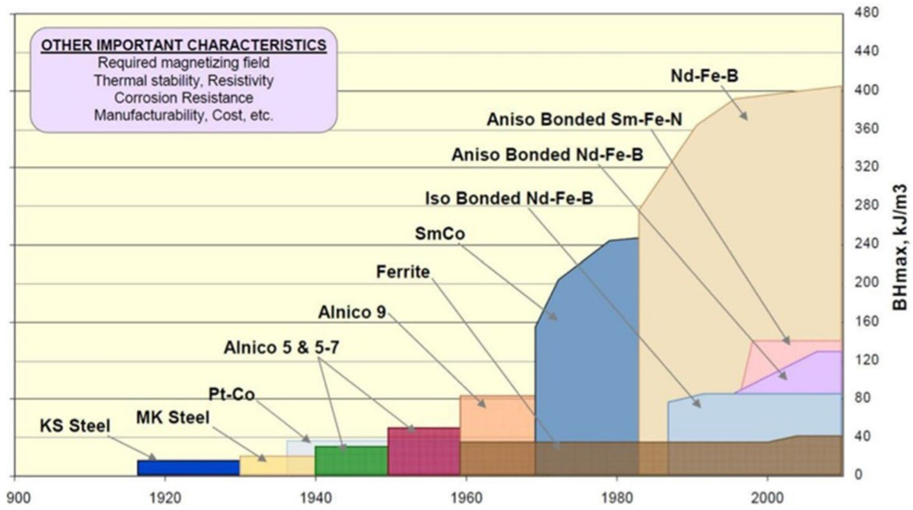


Fig. 11 Improvement in magnet strength over the years [24]

ca 1.25 kg [24] and the price of Nd increased 300% since early 2021.[14] The proportion of neodymium within the magnet material NdFeB averages around 32%, which consequently means a significant price increase for neodymium magnets. Efforts have been made to recover whole magnets from motors and recycling of material from disassembled magnets. Technological challenges can be identified in both recovery and recycling. The disassembly of PMs from motors has to be addressed quite carefully. Moreover, such disassembly strategies change with the type of motor, being SPM or IPM. In the case of IPM, their extraction can be performed with rotor-specific ejectors that press out the magnets from their rotor segments [43], while in SPM, the bandage issue should be first solved. Demonstrators have been lately presented through European or national-funded projects[15] regarding the automatic extraction and later recycling of PMs from electric motors, but the research is still quite open. With respect to recycling, the main issues concern the separation of different REEs, and later the remanufacturing of PMs according to the specific recipe. [157] suggested that standardized alloy mixtures, coatings, and alloy types would help to simplify the recovery of the magnets for subsequent use. For raw material recovery, various approaches and processes have been developed in recent years which can be classified into gas-phase extraction, pyrometallurgical methods, and hydrometallurgical methods such as hydrogen decrepitation [73], sintering, machining, and coating. However, it has been proved that recycled PMs guarantee same performance in traction motors [78, 159, 160], thus fostering the future use of recycled magnets.

[14] Magnosphere. Neodymium magnets with drastic price developments. 2022 [accessed 2023 Apr 14]; Available from: https://www.magnosphere.co.uk/information-permanent-magnet/price-explosion-for-neodymium-magnets-raw-material

[15] See for instance REE4U project at https://ree4eu.eu/

Key enabling technologies

In this Section, a review of current Key Enabling Technologies for the reuse, remanufacturing, upgrade, and recycling of electric motors is provided, with examples from existing applications in the state of the art. The scope is to provide a clear overview of research developments in the field and highlight possible missing gaps for future research directions, with respect to the framework presented in Sect. 3.1.

Inspection and diagnostic of motor end-of-use

Inspection and diagnostics represent key phases of the remanufacturing process since they aim at determining the status of returning products [48]. In the context of circularity, end-of-use (EOU) must be distinguished from end-of-life (EOL), as EOU indicates whether opportunities for value retention exist [130]. Hence, the EOU strategy decisions hinge on factors like physical life prediction, technology life cycles, cost, and technological interplay. According to the outcome of inspection and diagnostics, a decision is taken about the product [87]. The decision to re-use, repair, remanufacture, upgrade, recycle, or replace an electric motor depends on factors such as the root cause of failure, motor application, cost, reliability, performance, anticipated motor life, and energy efficiency [17]. A comprehensive evaluation of these factors is necessary to determine the best option, while not compromising reliability and other critical considerations [38]. Hence, the more precise the inspection is, the better the decision is taken.

The widespread use of electric motors in various industries allows the use of existing bodies on root cause analysis to establish common protocols for inspecting and diagnosing remanufactured motors. At present, there is a compelling opportunity to explore the development of a standardized assessment approach for evaluating the condition and failure of returned electric motors in the automotive industry. This endeavour has the potential to establish a consistent framework that can serve as a reliable benchmark for assessing the quality and performance of these motors. By achieving such standardization, more reliable and consistent outcomes throughout the industry can be established. The absence of common practices for inspecting and diagnosing remanufactured motors makes it difficult to identify the root cause of failures and determine whether they are due to a defect in the original motor or a problem that occurred during the remanufacturing process. Additional research is needed to develop standardized practices for inspecting and diagnosing remanufactured electric motors, as well as to evaluate the performance of these motors under various operating conditions.

The selection and application of inspection and diagnostic methods will be influenced by factors such as running hours and condition of the motor, type of application, failures (as shown in Table 4, and the resources available.

These methods can be used individually or in combination, depending on the specific requirements of the motor and the desired outcome of the inspection and diagnostic processes. Overall, inspection and diagnostic methods are an essential part of the circularity paradigm of electric motors, enabling the extension of motor life and promoting sustainability in both automotive and cross-sector industries. Figure 12 categorizes the motor failure by components, suggesting that bearing and stator-related issues are more prone to make the motor fail.

It has been suggested that if appropriate measures are taken to predict or prevent these failures, motor failures could be reduced by 75% [38]. The installation of sensors in EVs

Table 4 Motor Failure Statistics (Data from IEEE and EPRI motor reliability surveys) [155]

IEEE Survey		*EPRJ Survey*		
Failure Contribution	%	**Failure Contribution**	%	**Average (%)**
Persistent overload	4.2	Stator ground insulation	23	Electrical-related failure 33.3
Normal deterioration	26.4	Turn insulation	4	
		Bracing	3	
		Core	1	
		Cage	5	
Electrical-related total	30.6	*Electrical-related total*	36	
High vibration	15.5	Sleeve bearings	16	Mechanical-related failure 31.35
Poor lubrication	15.2	Antifriction bearings	8	
		Thrust bearings	5	
		Rotor shaft	2	
		Rotor core	1	
Mechanical-related total	30.7	*Mechanical-related total*	32	
High ambient temperature	3	Bearing seals	6	Failures related to environmental maintenance and other reasons 35.35
Abnormal moisture	5.8	Oil leakage	3	
Abnormal voltage	1.5	Frame	1	
Abnormal frequency	0.6	Wedges	1	
Abrasive chemicals	4.2			
Poor ventilation cooling	3.9			
Other reasons	19.7	Other components	21	
Environmental reasons and other reasons total	38.7	*Maintenance-related and other parts total*	32	

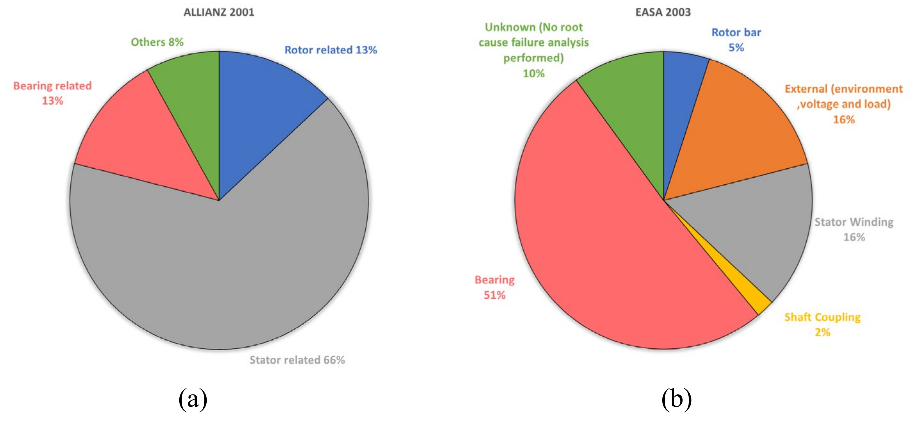


Fig. 12 Failure by motor component by (**a**) Allianz, 2001 [67] for Medium and High Voltage all application motors and (**b**) EASA 2003, for all-purposes EMs [38]

to enable monitoring and early diagnosis as part of the servitization concept has been proposed as a promising strategy to predict and prevent failures [139].

Inspection and diagnostic methods are a set of techniques and procedures used to assess the condition of EMs and determine their suitability for re-using, remanufacturing, or upgrading. The objective of these methods is to assess the possibility of extending the life of the motor and reducing waste by avoiding premature disposal and the need for new production. There are several common inspection and diagnostic methods for electric motors, including visual inspection, testing for resistance, continuity, insulation resistance, static and dynamic testing (load and no-load conditions), vibration, ultrasounds, and infrared thermography [65].

According to [138], static testing is an effective means of measuring the integrity of the motor's insulation system and can also be used for quality assurance when the motor is out of service. On the other hand, dynamic testing provides valuable information about motor systems, including power conditions, load, and physical aspects that can affect the life or operation of the motor. The insights emphasize the significance of both testing methods in maintaining the performance and reliability of electric motors.

Visual inspection involves examining the physical condition of the motor, including its appearance, insulation, and wiring. Electrical testing including voltages, resistance current, and fluxes monitoring. Motor current signature analysis (MCSA) [149] is a non-invasive traditional method for precise current analysis, starting by recording the motor's current during stable operation, followed by the application of the fast Fourier transform (FFT) to assess harmonic amplitudes linked to potential faults [150]. A more recent technique, analysis of currents transient analysis (ATCSA) introduces novel diagnostic approaches, including startup current analysis, where the current demand during startup is recorded and analysed using time–frequency tools, aiming to identify unique patterns signaling fault components and evaluating fault severity [4]. Actual industrial scenarios have demonstrated the effectiveness of transient analysis and the robustness of time–frequency tools in analysing various parameters, irrespective of the machine's state [122]. These techniques aid in achieving a dependable machine diagnostics process. Resistance tests measure the electrical resistance of the windings to determine if there are any faults or open circuits, while continuity testing checks the electrical continuity of the windings to determine if there are any breaks or shorts in the connections. Insulation resistance testing measures the electrical resistance of the insulation to determine its quality and to identify any potential problem that may cause the motor to fail. Load and no-load testing make the motor run with and without applied torque, respectively, to measure performance and efficiency. Vibration analysis measures the vibration of the motor while it runs to identify any potential issues with the bearings, shaft, or other mechanical components [68, 103, 164]. Ultrasonic testing uses high-frequency sound waves to inspect the internal structure of the motor and identify any hidden faults or damage. Infrared thermography uses a thermal imaging camera to identify hot spots or unusual temperature patterns on the surface of the motor, which may indicate internal problems [112].

The selection and application of inspection and diagnostic methods are influenced by factors such as the age and condition of the motor, the type of application, and available resources. These methods can be used individually or in combination, depending on the specific requirements of the motor and the desired outcome of the inspection and diagnostic process. Overall, inspection and diagnostic methods are an essential part of the circularity of electric motors, enabling the extension of motor life and promoting sustainability in the automotive industry.

Bearings are essential components of electric motors, and they should be thoroughly inspected for wear, damage, and proper lubrication [59] to help detect any issues that could cause premature wear or even failure of the motor's bearings, which could ultimately result in significant performance issues.

In addition to the above, several other tests are typically involved in remanufacturing of electric motors, such as:

- rotor and stator testing: such critical components of an electric motor are checked for proper alignment, balance, and continuity. Core loss testing, stray load analysis, winding resistance test, and phase balance test are basic checks to be performed;
- thermal imaging: it is used to detect any hotspots or abnormal heating in the motor's components, which could indicate issues with the motor's windings or bearings;
- noise testing: it is performed to detect any abnormal noise coming from the motor, which could be due to bearing wear, misalignment, or other mechanical issues [82]. [147] proposes a novel repetitive observer (controller) to reuse damaged magnet synchronous motor eliminating torque ripple and acoustic noise, validated by experimental setup.
- lubrication analysis: it involves analysing the motor's lubricating oil or grease to detect any contaminants or wear particles, which could indicate a problem with the motor's bearings or other components [49].
- other: partial discharge monitoring, chemical monitoring including tagging compound, gas/oil analysis.

Finally, once all the tests and inspections have been completed, the motor should be thoroughly cleaned and reassembled using high-quality replacement parts and lubricants. This step helps to ensure that the motor is safe, reliable, and fully functional, meeting the needs of its intended application [56].

Moreover, within the automotive sector, electric motors are extensively integrated products, incorporating ancillary components like transmissions, linkages, power electronics, and various other modules. In the remanufacturing industry, the inspection and disassembly procedures necessitate comprehensive consideration of these interdependent elements. Each constituent must be meticulously evaluated to uphold the overall performance and reliability of the complete motor.

The ultimate decision regarding the EOU of motors depends on crucial factors such as initial expenses, energy efficiency, non-operational time, and costs associated with disassembly, which play a pivotal role. Moreover, the choice is significantly influenced by the motor's topology and its intended applications. According to [3], efficiency and energy costs are the standalone factors in the repair-or-replace decision matrix. It is important to underscore the economic significance of non-operational time in this context. Traditionally, the decision to repair or replace electric motors was primarily economics-driven, but today's emphasis on efficiency and energy costs is paramount. Critical considerations encompass reliability, performance, anticipated motor lifespan, and the availability of suitable replacements. Among these factors, reliability, especially when achieved through motor customization, stands as a pivotal element in ensuring a long and productive motor life.

As mentioned in [74], the decision to disassemble a product to recovery its functions and materials is not one to be taken lightly. The consequences can be far-reaching, impacting cost [61], manufacturing setup, and time constraints. Therefore, manufacturers must consider all relevant factors, including the condition of the product, the availability of replacement parts, repair feasibility, and the potential benefits of remanufacturing. Additionally, when it comes to motor inspection and diagnostics, the type and severity of the problem, available resources, and expertise, as well as the non-invasive (visual inspection, electrical testing, lubrication analysis, and thermal imaging) or invasive (rotor and stator testing, mechanical inspection and performance testing) method chosen, all need careful evaluation. While non-invasive methods are generally faster and cost-effective, invasive techniques tend to offer greater comprehensiveness and accuracy. The selection of an assessment method should ultimately be guided by the specific requirements of the situation. In this context, [81] have proposed a method for detecting stator slot magnetic failures without the need for disassembly. It is interesting to note that remanufactured products require comprehensive inspection of cores, disassembled parts, and finished products. This rigorous examination is necessary to ensure that the remanufactured products meet the required quality standards, not only to instil confidence in the second user but also to avoid after-sales costs to the producer since all products are sold on warranty.

Disassembly

Disassembly of electric motors may include operations such as unscrewing, disassembling components from the case, extraction of PMs (if present), separation of windings from the main stator core, and disassembling of shafts. Whereas all these operations can be performed manually, the quest for making circularity of EMs a competitive business approach requires to push for full or partial automation. In this context, industrial and collaborative robots are among the most used resources, given their flexibility. Examples can be found in state-of-the-art, with special interest devoted to electric motors from other sectors, like washing machines [77, 93] or even bicycles [46].

However, when it comes to automated disassembly of drive train EMs, not only the product variety in terms of different types of motors should be considered, but also the motor status. From the viewpoint of the motor type, the challenges are given by the size and weight of motors to be handled, up to 60 kg of mass for an envelope of around $500 \times 500x500\ mm^3$, if fixtures and pallets are included; this calls for high-payload robots or customized disassembly machines with large working volume. Hence, in this context, robots can be usually coupled with press-stations for extraction operations involving high torques [52]. The same approach is also used when it comes to the automated extraction of PMs, where magnetization and applied resins should be considered. Solutions with this respect have been pioneered by [80].

As a consequence, a comprehensive disassembly system for electric motors includes not only mechanical but also thermal operations, as heating by induction for demagnetization to ease the disassembly and get rid of the resins is required. With this respect, the disassembly plan may change according to available technologies and inspected motor conditions, calling for novel and multi-disciplinary solutions. [71] for instance, analyses the complexity of the disassembly electric motors by combining the estimation of the technological efforts of disassembly operations for various types of motors. Two interesting comments can be noticed from this work: firstly, the disassembly phase has the highest cost factor compared to material cost and assembly cost, for the IPM motor they consider, because advanced disassembly technologies have not been developed yet.; secondly, the disassembly of rotor from the stator core and of the magnets from the rotor have been found as the most complex and cost-intensive operations, because of challenges in the motor handling, involved forces and the presence of glue for the magnets.

Meanwhile, [140] presented a methodology that assesses the complexity and accessibility of disassembling parts for remanufacturing, taking into account practical constraints. The methodology employs metrics to determine the optimal disassembly route for a given product. To illustrate the evaluation process, the authors [140] provided a case study of an electric motor with an integrated speed reducer unit. They identified and combined parts to simplify both assembly and disassembly, focusing on the retrieval of the rotor sub-assembly. Furthermore, they evaluated two possible disassembly routes using the metrics of disassembly complexity and part accessibility.

Moreover, when addressing circularity, it is also important to figure out how to integrate smoothly the returning products in the same plant where new ones are manufactured. Indeed, if remanufactured components are used for new motors, the manufacturing system should also be adapted to such variable incoming components, with respect to type and condition, leading to hybrid manufacturing/remanufacturing systems. Hybrid manufacturing/ remanufacturing systems combine traditional manufacturing processes with remanufacturing techniques to create a more sustainable and efficient production approach. However, implementing hybrid manufacturing/ remanufacturing systems poses several challenges. One major hurdle is the need for advanced technologies and machinery capable of integrating different manufacturing and remanufacturing processes seamlessly. The same assembly system or assembly automation can barely be adapted for disassembly and remanufacturing operations, leading to dedicated investments by the manufacturing company. Moreover, these investments strongly depend on the target product type as well as product volume. In an evolving sector such as electric mobility, uncertainty plays a crucial role. Hence, agility and flexibility to guarantee a suitable and efficient manufacturing system should be analysed [52].

Winding

This section aims to provide an overview of the latest advancements in winding and rewinding technologies for electric motors used in the automotive industry within the frames of recycling and re-winding, and of potential impact on the future of EVs, in the context of technical circularity. The practice of upgrading electric motor windings, commonly known as re-winding, has gained popularity in the automotive industry. Debunking the suspicion that re-winding may result in higher core losses, the EASA highlights the importance of adhering to best practices during rewinding processes. Windings play a critical role in determining the performances of electric motors, for torque, speed, and power output [14, 51]. Advanced winding techniques, including concentrated and distributed windings, have been employed in the automotive industry to improve the efficiency and performance of electric motors [65]. Efficient alternative motor rewind methods reported in [120] such as mechanical stripping, automatic winding, and trickle varnish, cut downtime, enhance reliability, save costs, time, and downtime expenses, and maintain motor efficiency, resulting in substantial savings for the end-users.

Windings play essential roles in the motor's lifecycle stages, including remanufacturing, re-using, upgrading, and recycling. Remanufacturing involves replacing worn or damaged components of windings, extending functioning lifespan. Similarly, re-using electric motors from old or scrapped vehicles by testing the condition of their windings can save energy and resources by reducing the need for new motor manufacturing. Enhancing the performance of electric motors by upgrading their windings is considered a cost-effective alternative to purchasing a new motor. Moreover, upgrading or re-winding can also improve the motor's efficiency, power output, lifespan [98] and performance [2] essential in various applications, helping to save costs in the long run, especially when the motors are subjected to heavy use. [38, 39] explain that rewinding a motor can improve its performance and reliability by also modifying the winding configuration and copper content.

Reducing conductive loss can be achieved by increasing the copper content and converting to a traditional, hand-inserted winding. Increasing slot fill can also improve heat transfer, reduce IR loss and winding temperature, and increase motor efficiency. These modifications can improve the motor's resistance to moisture and service factor, allowing it to withstand wider variations in voltage, ambient, and starting conditions. Starting options such as wye-delta, part-winding, and double delta connections can reduce inrush current and starting torque. When re-winding a motor stator, the winding shape can be changed by altering the number of turns of wire, the strands in hand, the pitch of the winding, or the shape of the coil. However, changing the winding shape can affect the motor's performance and may require adjustments to other components, such as the air gap, stator geometry, rotor, or control circuitry [134].

Despite its benefits, the remanufacturing and repairing of windings is hindered by complications and low return on investment. Redesigning motor windings [84] to reduce material usage while maintaining or improving efficiency will also become increasingly important as efficiency levels are ramped up higher in the pursuit of circularity objectives. New winding shapes as shown in Fig. 13 improve the efficiency, size, weight, power density, and cost-effectiveness of the motors.

Another possibility in rewinding is that of replacing existing wires with higher-compressed conductors, as highlighted by [135] enhancing fill factor and power density. However, direct compacting methods have limited industrial implementation, primarily due to uncertainties regarding the impact of compression on insulation characteristics.

The growing demand for more energy-efficient and reliable electric motors has led to increased attention towards the use of hairpin windings [53], despite contending with skin effect it has the potential to provide energy savings and reliability by reducing winding resistance, increasing power density [124], and robust and compact design [27]. Issues still need to be addressed on the complexity and cost of manufacturing, considering the bending and welding of hairpins, which shall be done in-line. Proposed solutions include improvements to manufacturing lines for hairpin stators and the use of laser technologies for welding [114]. The overall goal is to create a programmable, flexible, and reliable coil forming and joining setup for hairpin windings. The increasing popularity of hairpin windings [5], not only for high-end motors but also for more commercial and mass-production ones, will have a direct and strong impact on the remanufacturing of electric motors, which might see the replacement of traditional connectors with hairpins.

A compelling alternative as a winding technology in the realm of electric motors is represented by Litz wires. These intertwin multiple individually insulated strands aim to minimize skin effect losses and ultimately enhance motor performance [134]. However, recent market trends indicate a preference among original equipment manufacturers (OEMs) for hairpin windings as their favoured choice.[16]

Finally, recycling electric motors at the end of their useful life can be done by separating their windings from the rest of the motor and processing them to recover valuable materials like copper. Therefore, effective utilization of electric motor windings in the automotive industry can contribute significantly to sustainability and CE goals.

According to the association of electrical and mechanical trade,[17] copper is fully recyclable, so, the only option remains for old worn-out windings is recycling and recovering

[16] The original communication can be found at https://www.openpr.com/news/2706420/hairpin-stator-market-demand-volume-growth-ratio-industry

[17] The original communication by the association can be found at AEMT. Copper in a circular economy. [accessed 2023 May 2]; Available from: https://www.theaemt.com/DB/news-webpage/copper-in-a-circular-economy

(a) (b) (c)

Fig. 13 Different wire configurations: (**a**) Hairpin wires, (**b**) Single round conductor, (**c**) Extruded and profiled Litz wires [134]

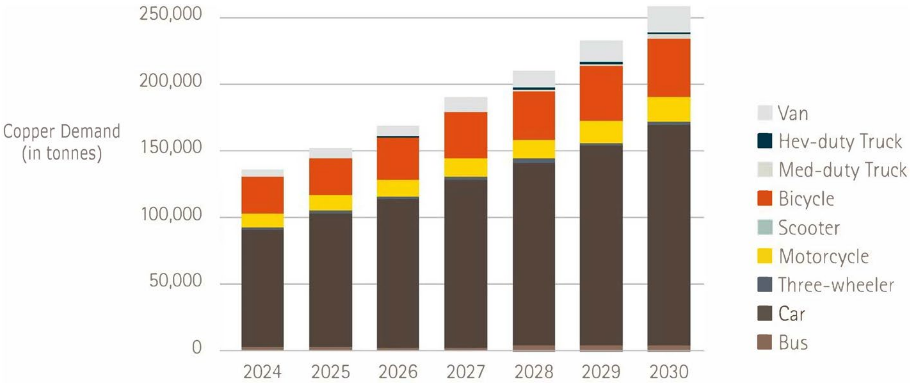


Fig. 14 Utilization of copper (tonnes) annually for electric vehicle's traction motors windings [25]

the copper that can be reused for forming new windings. The treatment of copper coating for recycling can be achieved through mechanical separation, chemical stripping, thermal treatment, or electrochemical methods. These approaches enable the removal of the coating, facilitating the recycling of copper.

Increasing adoption of electric traction motors in on-road vehicles will lead to a surge in demand for copper, which, for EV motors only, is expected to exceed 250,000 tonnes annually by 2030 as shown in Fig. 14. However, the industry must balance this demand with sustainability concerns and invest in the development of more efficient electric motors and alternative materials to replace copper, as already shown in preliminary studies [25].

Demagnetization

Demagnetization refers to the operation that is needed to re-use PMs recovered from rotors. Indeed, for new rotor manufacturing, or rotor remanufacturing, PMs may be assembled when they are not magnetized to avoid complications in the assembly process, due to magnetic forces. Magnetic properties of PMs depend on the coercivity of the material, that is the ability of the magnet to withstand demagnetization. Hence, tested methodologies for demagnetization have the goal of overcoming coercivity to make magnets reusable. Most of the methods are based on thermal processes, i.e. heating, however, also nonthermal demagnetization using resonance damping demagnetization at room temperature can be used. In [64], two practical methods are reported to demagnetize a magnet:

1) exposed a magnet to a decaying sinusoidal magnetization field, the magnetic domains will ideally become randomized inside the material, effectively demagnetizing the magnet.
2) bringing an Nd-Fe-B magnet above a certain temperature will make it experience a loss of magnetization lasting until it goes through another magnetization process. This loss increases with temperature until the magnet is completely demagnetized. This occurs when the temperature is equal to, or higher than, the Curie temperature of the material.

[64] investigates the latter method, since the first one leads to powder clump, due to residual magnetization, and prevents the powder from being used since it must be completely demagnetized for further operations. Different demagnetization temperatures are used for experimental investigations, from 300 °C to 650 °C. The IPM is recycled by thermal demagnetization, manual extraction, and mechanical crushing, followed by re-pressing and magnetization. A clear influence of the demagnetization temperature on the magnetic performance of the recycled magnets was observed. The coercivity of the recycled magnets is reduced with demagnetization temperature, which also reduces the squareness-factor of the B-H curve. The magnetic performance of the recycled powders was measured and compared to the original powder. Dimensionally identical magnets were created, and their B-H demagnetization curve was measured by a hysteresis graph. The resulting demagnetization curves are shown in Fig. 15.

Low-cost methods for demagnetization based on heating have been further explored in more recent years. For instance, [9] use large blocks of NdFeB PMs of dimension 10 cm×7 cm×2 cm and with easy axis along the shortest dimension, that are shown to demagnetize when heated on a planar induction heating device. The initial magnetization of the magnets is reduced by a factor of 10 within a period of 30 min, in which the surface temperature of the magnet reaches 225 °C. This method simplifies the demagnetization process of the PM in wind turbine generators as part of the rapidly increasing demand for improved recycling capabilities of the same. Issues may arise since PMs are usually coated with nickel to avoid corrosion. Indeed, [166], the authors reports that demagnetizing EV drive rotors through heat treatment produces contaminated scrap magnets that can be processed for re-use using etching and self-abrasion techniques in a rotating drum.

A collection of methods for extracting, demagnetizing, and recovering NdFeB PMs from various products is presented in [174]. A special process named hydrogen processing of magnet scrap (HPMS) is mentioned and explained by [167], and applied to hard disk drives. With this process, either the voice coil assemblies from the hard disk drive or

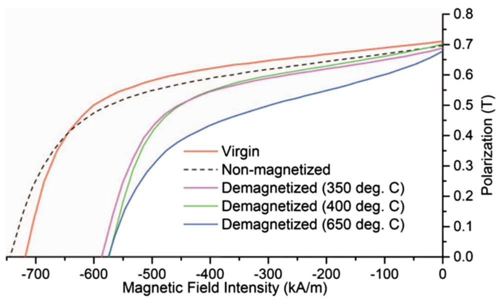


Fig. 15 Demagnetization of original powder (virgin), non-magnetized recycled powder, and demagnetized recycled powder [64]

the cropped corner from the drive are exposed to hydrogen at atmospheric pressure and room temperature. The overall reaction in hydrogen results in about 5% volume expansion, and as the magnets are brittle, they break apart resulting in friable hydrogenated powder. The coercivity of the powder becomes so low that the hydrogenated material is essentially soft magnetic and is no longer magnetically attracted to ferrous components in the scrap. Another relevant application of demagnetization in drive motors of washing machines was proposed in [146], through thermal demagnetization and removing the resin bounding.

More in general, when it comes to re-use, remanufacturing, upgrading, and recycling of motor components with PMs, demagnetization must be included as key steps along the process chains, thus involving technologies that are not yet fully established at the industrial level.

Digital technologies

The circular approaches of electric motors in the automotive industry can benefit greatly from the application of digital technologies, which can optimize resource utilization, enable new circular business models, enhance supply chain tracking and management, improve product design and end-of-life management, increase customer engagement, and reduce environmental impact [54, 115]. A synergy between product usage and process running is also envisaged in [97].

One promising digital technology in this regard is that of *reverse engineering*, which involves generating a Bill of Materials from a used motor to automatically identify its components, assembly structure, and, where possible, disassembly operations, only by scanning the motor and digitally processing the picture to identify its main components. Although still under research, this could provide valuable insights into the design and remanufacturing of electric motors, ultimately reducing waste and promoting circularity [133]. With this respect, reverse engineering would support those remanufacturers not having access to the original design of motors, hence supporting the successful identification of feasible disassembly plans.

Remote monitoring technologies [101] offer real-time insights into the operating conditions of electric motors, such as energy consumption, temperature, and vibration levels. This enables manufacturers to identify areas of inefficiency and reduce waste in their operations. For instance, remote monitoring can identify anomalies in motor performance, which can help manufacturers determine the need for maintenance or upgrades, thereby reducing the likelihood of breakdowns and extending motors' lifespan. This ultimately leads to less waste associated with motor replacements and disposal. For instance, remote monitoring can enable predictive maintenance [91], that can be used to monitor the performances of electric motors using data analytics and machine learning algorithms and predict when they are likely to fail. This information can be used to plan maintenance activities, reduce the need for premature replacements, and extend the life of the motors. Despite the need for further investigations, predictive maintenance can also help manufacturers identify potential design flaws, thereby improving the durability of future models.

Furthermore, remote monitoring can facilitate the development of closed-loop supply chains by providing manufacturers with crucial information about the usage and performance of their products, thereby identifying opportunities for reusing and recycling materials and reducing the environmental impact of motor production and disposal. Two interesting enabling technologies for remote monitoring are the internet of things (IoT) [156] and embedded sensors. For example, Bosch [94] has used microsensors to record data during the lifecycle of their power tool motors and intends to connect these tools to a data reader to eventually determine whether the motors can be re-used or not. Wise sensorization of automotive components has been also proposed by [97]. However, given the amount of data that are collected, advanced analytics are needed. For example, [116] introduces a novel data fusion system (DFS) for automatic electric motor fault diagnosis. The DFS combines advanced integrated analysis of stray fluxes, current signals, and thermographic data using both stationary and transient signal processing techniques. It reliably detects various motor faults like broken rotor bars, misalignment, and bearing issues. An Artificial Intelligence (AI) algorithm enhances diagnosis in real-time, reducing downtime and maintenance costs. While initially developed for induction motors, the DFS is expanding to other motor types and holds potential for motor manufacturing quality control by spotting fabrication anomalies. This is a good example to show the potentialities of Artificial intelligence (AI) and machine learning (ML). Within this context, data-enhanced algorithms can be used to optimize the design and performance of electric motors, with the aim of reducing their environmental impact and increasing their efficiency [35, 99, 102, 131, 172]. By analysing vast datasets generated during the operation of electric motors coupled with known physical relations and properties, AI- and ML-enhanced models can provide insights into EOU decision making [63]. These models can be used as evaluation kernels in multi-objective optimization algorithms. In this way, Pareto-optimal performance of remanufactured and upgraded motors are identified to foster redesign and manufacturing automation towards industrial circularity of electric motors.

Finally, at value chain level, blockchain technologies [8, 161] are well-suited to support the circularity of electric motors in the automotive industry. By providing an immutable, decentralized ledger of transactions, blockchain can be used to track the life cycle of electric motors, from the extraction of raw materials to their disposal [152]. This information can be used to promote transparency and accountability in the value chain, as well as to support the development of closed-loop ones for electric motors.

Future trends, existing gaps, research guidelines

In this section, the authors intend to consolidate and expand upon the analysis derived from the preceding sections to outline future trends. By conducting a thorough evaluation of present trends concerning the CE of electric motors in the automotive industry, the authors propose a collection of promising future trends that exhibit significant potential for promoting sustainability, minimizing waste, and enhancing the performance of electric motors. These trends have been deemed viable for adoption within the automotive industry over the next 5 to 10 years.

1. *Design for disassembly recyclability/reuse/durability*: The concept of DRR&D [21, 30, 141] involves designing products with the end of life in mind, and, with regards to issues mentioned above, for easy disassembly, recycling, and durability, aiming to reduce waste and improve sustainability. This approach offers several benefits, including waste reduction, conserving resources, and improving the sustainability of products [137, 140]. In this context, design should strongly interact with engineering and manufacturing, by establishing systematic feedback from the production and post-use to the design itself. The main challenge is how to make companies process and manage products manufactured by others. Another useful unified visual representation tool is "Disassembly Map

method" that promotes serviceability and repair by providing a comprehensive analysis of design solutions and disassembly processes [30].

2. *Hybrid manufacturing/re-manufacturing systems*: This trend emphasizes the need for facilities that can integrate the processes of manufacturing new electric motors and remanufacturing used ones in the same location [153]. By having these processes integrated into one plant, companies can minimize waste, reduce transportation costs, and streamline production. Moreover, this trend aims to facilitate the sharing of resources, such as equipment and personnel, which results in cost savings and improved efficiency [107]. As a consequence, the usual operations of the manufacturing/remanufacturing system become more complex, since motors to be remanufactured may need special attention for inspection, decision for remanufacturing or recycling, as well as management of components [52] than new ones. As for other sectors, scalable automation represents a key challenge for a successful industrial uptake.
3. *Materials aspects in design and (re)manufacturing*: The type of electric motor selected for a particular application can significantly impact its sustainability and efficiency [29]. For instance, the use of PM motors can improve energy efficiency, and using ferrite-based magnets will reduce the use of new REEs, while the use of induction motors can decrease the environmental impact of the motor's manufacture and disposal. However, the expected increase in the volume of electric motors expected for the future may change the trend: in fact, PMs may not be available for mass volumes, thus fostering alternative motor design. As a consequence, the available technologies for remanufacturing should follow, as they may become obsolete quite soon. For instance, some motor components (such as casings and flanges) could be manufactured using secondary aluminum, as in [33] where it is utilized in the context of brake calipers production through rheocasting (metal injection in a semi-solid state), which further benefits the environment by reducing CO2 emissions due to lower metal heating temperatures. Additionally, near-net shape manufacturing and thickness reduction can contribute to lightweighting the component and minimizing subsequent processing, leading to a further reduction in environmental impact. Indeed, new available designs of motor types may become a source of technological innovation for remanufacturing systems, by pushing enabling technologies to be continuously adapted, improve energy efficiency, and address sustainability concerns in electric motor design and manufacturing by optimizing material selection and (re)manufacturing processes.
4. *New winding technologies*: recent developments and push for new winding shapes are intriguing OEMs and researchers to improve efficiency and performance in electric motor winding technologies. The buzz around the hairpin and other flat winding shapes suggests that they perform better than conventional round windings due to better fill factor and thermal performance [100]. It will be interesting to witness how product design and manufacturing [171] will be shaped to cater to these new technologies. [113] aimed to use additive manufacturing to create hairpin layouts with reduced losses compared to conventional designs. Suitable materials with high conductivity and minimal ecological impact were explored. They evaluated the loss performance of the additive manufactured hairpin layouts, comparing them with traditional copper hairpins, and showed that strategically chosen alloys with asymmetric configurations can match the performance of conventional hairpin windings. This would have disruptive consequences for the motor value chains, as traditional winding suppliers and stakeholders, as providers of winding technologies, should re-think the business.
5. *Design modularity* [2, 34, 47, 89, 173]: The use of modular designs for electric motors can facilitate easier disassembly, repair, and remanufacturing, leading to a reduction

in waste and costs.[18] For example, stators and rotors can be designed with standardized mounting interfaces, facilitating convenient removal and installation processes. By incorporating separate units for the bearings, their replacement becomes feasible without the need for complete motor disassembly. The housing can be equipped with detachable panels or access points, enabling easy accessibility to internal components, and thereby promoting maintenance efficiency. To enhance adaptability, the cooling system can adopt modular heat sinks or cooling modules that can be conveniently added or replaced as required. Moreover, electrical connections can be designed using standardized connectors or terminal blocks, streamlining the process of connecting or replacing wires. This design approach allows for the replacement of specific components instead of discarding the entire motor, which contributes to push circularity approaches.[19] By allowing easy disassembly and replacement of individual components or sub-systems, modularity enables efficient repair, upgrade, or replacement of only the faulty parts, rather than the entire motor. However, implementing modularity can be challenging, particularly for new types of motors, such as in-wheel and axial-flux motors, which have tightly integrated and complex designs that can make disassembly difficult.[20] In addition, compatibility issues between different types of electric motors can hinder the interchangeability of components, making it laborious to achieve modularity. To overcome these challenges, standardization and archetyping can be adopted in the design of components (materials included) of electric motors. This will facilitate the integration of different motors with varying designs, specifications, and materials, enabling efficient disassembly, repair, remanufacturing, upgrade, customization (retrofitting), or replacement of individual components or sub-systems.

6. 3D printing revolutionizes repair, offering on-demand spare parts, cost reduction, and sustainability support across industries. It empowers consumers for self-repair and aligns with circularity goals. Challenges involve digitizing parts, but a new framework [163] simplifies 3D-printed replacements. Experience and handling part complexity are key to success. As 3D printing advances, it enhances sustainability, extending product lifetimes and enabling localized, personalized repair.

Even if this present paper focuses on the technological aspects of circular electric motors, the economical side of CE cannot be neglected. The adoption of circular business models that promote the reuse, remanufacturing, and recycling of materials and components can significantly reduce waste and costs if a holistic approach to circular strategies is adopted [162]. By implementing these models, companies can extend the lifespan of their products, reduce their environmental impact, and improve their reputation. Novel business models however must prove themselves to be economically sustainable to be appealing for companies. In the case of CE of electric motors, the value chain is not established yet, i.e., there are no regulations about how to collect motors from the users, as well as who are the actors involved with strategic interest in it.

[18] See for instance the recommendations at https://goinfinitum.com/remanufacturing-electric-motors/

[19] A public communication can be found at Cockerill S (2020) Battery innovation is accelerating, but modularity is the key to decarbonising transport. Available via: https://www.linkedin.com/pulse/battery-innovation-accelerating-modularity-key-sam-cockerill/

[20] Motivations can be found at https://traxial.com/blog/why-arent-all-electric-vehicle-motors-axial-flux-yet/

Research guidelines for design and manufacturing/remanufacturing of electric motors

The adoption of circular strategies for electric motors requires a paradigm shift that prioritizes the potential for remanufacturing, upgrading, and recycling. To achieve sustainable, efficient, and long-lasting electric motors, researchers must overcome several challenges, starting from the design of future electric motors to their manufacturing, remanufacturing and utilization in novel business models. In the following section, research guidelines are suggested that build on the previously described trends in electric motor design and manufacturing/remanufacturing. For each research guideline the implications for design and manufacturing/remanufacturing are provided, to highlight the holistic approach of the proposed work.

- Designing sustainable electric motors is a complex process that involves careful consideration of factors such as disassembling and upgrading, compatibility with different applications, and recyclability. To achieve sustainability, designers must ensure that motors are easily disassembled, enabling efficient component removal and replacement during remanufacturing. Moreover, designers should focus on upgradeability to allow the replacement of outdated components with newer, more efficient ones. Motor specifications such as size, weight, and other requirements could also be considered to ensure the easiness of disassembly and remanufacturing, according to available key enabling technologies. Finally, cross-sectorial applications of remanufactured motors could enlarge the designer's solution space and increase the competitiveness of companies focused on the remanufacturing business.
- In order to increase the running hours (i.e. the lifespan) of electric motors to reduce complaints and returns [148], it is crucial to carefully select durable materials and components that can extend the lifespan of electric motors. To ensure the long-term sustainability and viability of electric motors in a circular context, it is important to focus their design on durability and reliability [18] aiming to reduce the need for frequent replacements, thereby lowering maintenance costs and reducing downtime. By embracing this challenge, we can ensure that electric motors play a crucial role in building a more sustainable future, contributing to a more sustainable and cost-effective CE.
- Designing electric motors for the automotive industry using second-hand materials is a challenging yet rewarding task for designers. It requires creativity and resourcefulness, resulting in unique and innovative designs that might not be feasible otherwise. Incorporating recycled materials such as copper, aluminum, and steel, promotes efficient use of resources, reducing the need for new materials, and contributing to circular principles and sustainability. By incorporating recycled materials, designers can help reduce the carbon footprint of manufacturing, meet the growing demand for environmentally conscious products, and gain a competitive advantage in the market. Furthermore, such designs align with government regulations to reduce the industry's environmental impact and help manufacturers avoid penalties or fines.[21] The use of sustainable materials, such as recycled metals or bio-based polymers, would reduce the environmental impact of electric motors.[22] At the same time, the use of recycled materials poses challenges for manufacturing/remanufacturing since the variability of materials during the

[21] The original document is the Commission Regulation (EU) 2019/1781 (https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32019R1781).

[22] This is encouraged by automotive companies (https://www.renaultgroup.com/en/news-on-air/news/the-circular-economy-applied-to-electric-vehicles/

production process would become quite high, and the required material level to guarantee the correct motor functionalities must be satisfied.

- The winding shape of an electric motor stator determines its characteristics, such as voltage drop, current, fill factor, and power output. Different winding shapes can be used to achieve different performance characteristics, in terms of torque, efficiency, or noise [36]. Despite their complexity, cost, and incompatibility with certain motor types, hairpin winding is a promising technology that provides higher power density and reliability. Improved manufacturing lines and laser welding can help mitigate these challenges. Copper Rotor IM with rectangular wire hairpin windings show interesting performances, but they may have high eddy current losses [123]. Advancements in winding technology are critical to improving efficiency, performance, and cost-effectiveness, which are necessary for the future of EVs. Various winding technologies have been reviewed, and hairpin coils are advantageous for high copper fill factors. Future actions to enable the complete penetration of hairpin windings in transportation include new winding concepts and flexible and automated manufacturing processes. In this case, manufacturing becomes the key challenge for a successful implementation at an industrial scale. Operations such as bending and welding are crucial to be investigated.
- Designing electric motors to be lighter in weight and operate with lower noise levels presents a challenge for the automotive industry. While reducing the use of raw materials and decreasing the carbon footprint of production can benefit the environment, there are potential trade-offs to consider, such as compromised strength and durability that can lead to increased waste over the product's life cycle. The use of more sophisticated and expensive design and manufacturing processes to achieve lower noise levels [13] may also increase the environmental impact of motor production, undermining the goal of achieving an effective circularity. Nonetheless, reducing noise levels can lead to a more comfortable environment for individuals and enhance social sustainability. In summary, careful consideration of the benefits and disadvantages of this approach is necessary to ensure a sustainable and efficient CE[23].
- Available examples from the research show the potential of upgrading and remanufacturing small-scale motors (e.g. washing machines). However, automotive electrical traction motors have different sizes and weights involved, much larger than those reported in applications from literature. As a consequence, key enabling technologies that have been presented in this work need to be investigated for application to electric motors from automotive and possibly be scaled up. In particular, the integration of such key enabling technologies in fully automated remanufacturing systems represents a key challenge since product handling involves critical weights and sizes, as well as high product variety. Additionally, the number of electric motors available from vehicles is expected in the next 30 years to be in the order of ten to thousand million, pushing for flexible solutions with fast scaling potential.

The research guidelines depicted above could not be put in place if the value chain does not adapt and make it possible. From the perspective of the circular value chains, it can be noticed that some actors are still missing, thus on one hand preventing immediate implementation of circular strategies and, on the other hand opening potential new business

[23] Support to this strategy is described by Infinitum. Why Remanufacturing Electric Motors is a Big Idea. [accessed 2023 May 2]; Available from: https://goinfinitum.com/remanufacturing-electric-motors/

opportunities. Examples relate to suppliers of remanufactured components for several manufacturers, or logistics aspects for returning motors. As for other products with reverse value chains, new business models should be studied, such as those based on servitization.

To conclude, the circularity of electric motors is based on an interdisciplinary approach grounding on the effective interaction between design and manufacturing/remanufacturing. Hence, smooth information feedback between the two areas should be investigated.

Conclusion

This work presents the current state of technical circularity of electric motors in automotive. The approach here used is that of the process–product duality, targeting scientists and researchers in both academia and industry to enlighten the main aspects of a topic of crucial importance for our planet and modern economy. Technical circularity has been firstly introduced, and then investigated in detail and discussed focusing on its 4 main pillars: reuse, recycle, remanufacturing and upgrading. One of the main aspects drawn from the literature review is the crucial role played by the circularity of functions in promoting sustainability in the automotive industry: maximizing the functional value of electric motors manufacturers can reduce waste, improve efficiency, and promote sustainability in their operations. From the 4 main pillars, a number of key-enabling technologies and strategies have been proposed to promote a solid wider CE for electric motors in the automotive sector to support a more sustainable industry.

The broad overview of the existing research and industrial practices has been used to lay down the basis for an integrated and comprehensive approach toward the main objective of reducing the waste of resources and increasing the competitiveness of industries.

The results of the analysis show that the circularity of electric motors in the automotive industry has potential to develop novel relevant technological and business opportunities when the key challenges are addressed. New businesses can flourish throughout the whole circular chain, from the collection of parts to be reused/upgraded/recycled, to their disassembly, at every component level, from the distribution of parts to the remanufacturer to the development of new plants and machines to perform the tasks automatically once the volumes will allow it. From the technological point of view, much has still to be done and studied to make the whole process sustainable, and profitable, and still make products with performances to meet customers' requirements.

Remanufacturing is one the newest and most important approach in the paradigm of the technical circularity, and re-windings and re-magnetization processes have been highlighted and discussed as key techniques for restoring motor performance and efficiency during remanufacturing. These processes, combined with proper quality control measures, ensure that remanufactured motors meet or exceed the performance of new units.

The review here presented include a section where the look moves to the future, with a number of promising approaches introduced to advance the circularity of electric motors. Future trends in this field include the integration of emerging technologies and approaches to enhance design, manufacturing, and diagnostic capabilities and optimize motor performance. By leveraging newer technologies, manufacturers can reduce waste, improve efficiency, and promote sustainability in their operations. The development of new digital technologies will continue to play a critical role in supporting the circularity of electric motors in the automotive sector and will be essential to promoting a more sustainable future.

The strong relationship between design decisions and manufacturing/remanufacturing strategies and technologies has been shown as a key step for future research and development.

Overall, the results of this study provide information for decision-makers in the automotive industry, as well as policymakers and researchers, in the development of more sustainable and environmentally friendly electric motor technologies in the automotive industry.

Acknowledgements The Authors thank the multiple anonymous Reviewers that provided productive comments to improve the paper until its present form.

Author contributions M.C.M and A.S. wrote the paper and prepared Figs. 3, 4, 5, 6, 7 and 8. R.P. contributed to write Sect. 1 and Sect. 5. A.D.G., M.G., G.M. and T.T. discussed the analysis, revised the paper and contributed to the final manuscript.

Funding This study was carried out within the Horizon Project PERMANET, the MOST – Sustainable Mobility Center and the ECOSISTER -Ecosystem for sustainable Transition in Emilia-Romagna. It received funding from the European Union: PERMANET Horizon (G.A. 101178444), and Next-GenerationEU (PIANO NAZIONALE DI RIPRESA E RESILIENZA (PNRR) – MISSIONE 4 COMPONENTE 2, INVESTIMENTO 1.4 – D.D. 1033 17/06/2022, CN00000023).This manuscript reflects only the authors' views and opinions, neither the European Union nor the European Commission can be considered responsible for them.

Data availability Not applicable.

Declarations

Competing interests The authors declare no competing interests.

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