

Review

Circular Economy Aspects of Permanent Magnet Synchronous Reluctance Machine Design for Electric Vehicle Applications: A Review

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Abstract: Innovative technological solutions have become increasingly critical in addressing the transportation sector's environmental impact. Passenger vehicles present an opportunity to introduce novel drivetrain solutions that can quickly penetrate the electric vehicle market due to their shorter development time and lifetime compared to commercial vehicles. As environmental policy pressure increases and customers demand more sustainable products, shifting from a linear business approach to a circular economy model is in prospect. The new generation of economically competitive machines must be designed with a restorative intention, considering future reuse, refurbishment, remanufacture, and recycling possibilities. This review investigates the market penetration possibilities of permanent magnet-assisted synchronous reluctance machines for mini and small-segment electric vehicles, considering the urban environment and sustainability aspects of the circular economy model. When making changes to the materials used in an electric machine, it is crucial to evaluate their potential impact on efficiency while keeping the environmental impact of those materials in mind. The indirect ecological effect of the vehicle's use phase may outweigh the reduction in manufacturing and recycling at its end-of-life. Therefore, thoroughly analysing the materials used in the design process is necessary to ensure maximum efficiency while minimising the environmental impact.

Keywords: electric machines; circular economy; urban transportation; sustainable design



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1. Introduction

Reducing the environmental impact of the transport sector in the European Union is a significant challenge that starts with passenger vehicles. Given their shorter development time and lifetime, these vehicles can benefit from novel design solutions, leading to short-term market penetration [1]. The Global Automotive Consumer Study 2023 provides valuable insights into consumer concerns regarding Battery Electric Vehicles (BEVs). The study, conducted in different world regions (Germany, the United States, India, South East Asia, China, the Republic of Korea, and Japan) with approximately 600 to 5000 participants per region, reported that the driving range, product price, and lack of sustainability were part of the top concerns regarding BEVs. These concerns are heavily influenced by the vehicle's drivetrain development, including the electric motor design. It has been found that the most concerning factor regarding BEVs varies by location. The driving range is the most significant concern in China, Germany, and the United States. In contrast, in India, the lack of sustainability is as significant a concern as the cost ahead of the driving range. The study also found that the top reason to buy a BEV as the next vehicle is mostly the lower fuel cost over the vehicle's lifetime, which necessitates higher efficiency electric machines and drivetrains. Additionally, concerns about climate change are in second place for Germany and third place for the US out of the nine possible reasons for buying an electric vehicle (EV) [2]. Consumers' range expectations are presented in Figures 1 and 2.

The results from the German and United States samples show similar expectations for long-range EVs, as 30% of the respondents expect a 600+ km range in those countries. On the other hand, samples from eastern countries such as India (30%, 300–399 km), China (34%, 400–499 km), and Japan (26%, 300–399 km) show that residents in these countries are content with shorter-range EVs.

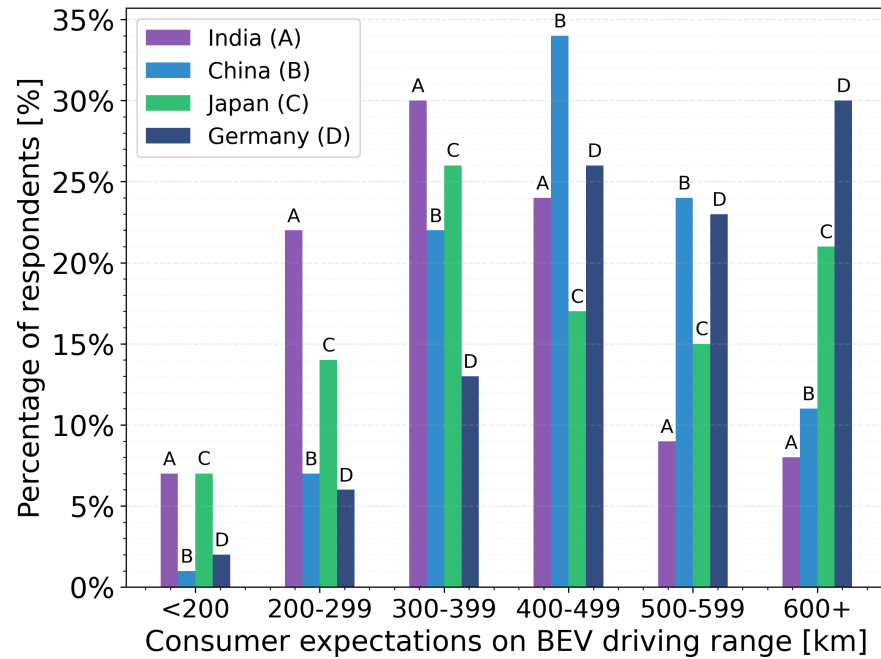


Figure 1. How much driving range would a fully charged all-battery electric vehicle need to have for you to consider acquiring one? A sample sizes of 879 (India), 516 (China), 597 (Japan), 1103 (Germany).

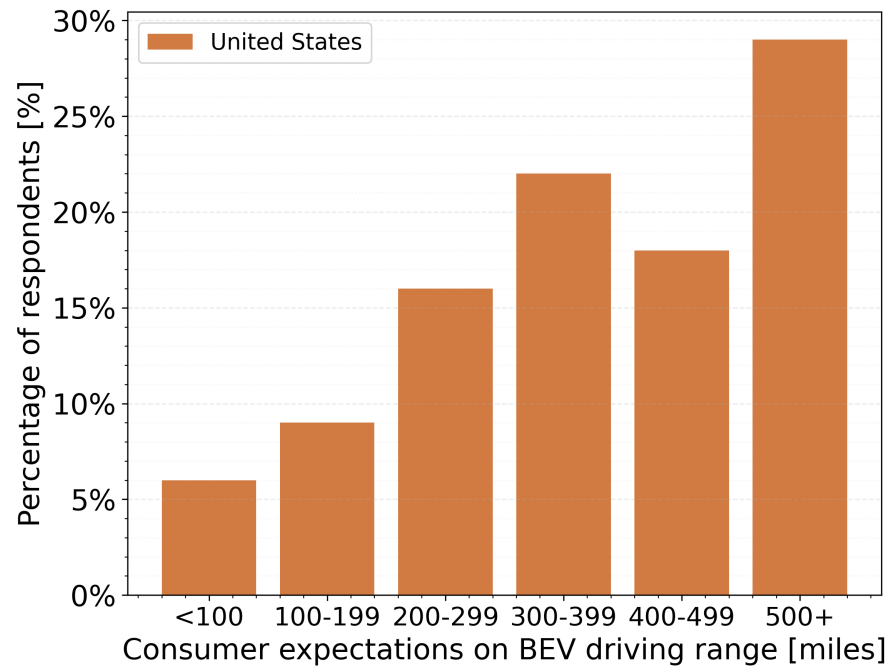


Figure 2. How much driving range would a fully charged all-battery electric vehicle need to have for you to consider acquiring one? A sample size of 1749 (United States) [2]. One mile is equal to approximately 1.609 km.

Environmental policy pressure is expected to increase, and customers will also pressure manufacturers to produce sustainable products [2,3]. It will be crucial for Original Equipment Manufacturers (OEMs) to consider sustainability in their products as it will be a pressure point from the customers' side and in terms of regulation too [2,4]. Furthermore, less maintenance is an essential selling point that requires robust electric machines. The choice of BEV brand is mainly based on overall product quality rather than pricing. However, the most decisive factor considering the use cases is vehicle performance, such as efficiency, power, torque, noise, vibration, harshness, and comfort.

Nowadays, Permanent Magnet Synchronous Machines (PMSMs) are widely used in e-mobility because of their high efficiency and power density [5,6]. Alternative electric motor technologies for BEVs are also available. Still, PMSMs are the most dominant in the case of BEVs and hybrid vehicles because of their 20 times higher torque density than a switched reluctance machine or 200 times higher torque density than an asynchronous machine [7]. Hybrid vehicles are still preferred, but the EV sector is growing rapidly [8]. Most PMSM designs use Neodymium–Iron–Boron (NdFeB) magnets due to their high magnetic flux density [6,9]. However, the supply chain for these magnets is risky, as their availability is restricted to a few regions [5,10]. An eco-efficient product has improved resource security and decreased price volatility [11], so the rare-earth elementless technologies are expected to be more attractive in the future of e-mobility. One emerging example is the Permanent Magnet-Assisted Synchronous Reluctance Machine (PMASynRM), which can be an alternative to other types of PMSM. This machine does not contain expensive rare-earth element magnets, making it a more cost-effective and eco-friendly solution [12].

This review focuses on using Synchronous Reluctance Machine (SynRM)-based drivetrains in mini (A) and small (B) electric cars, which are designed for commuting in urban areas. Consumers in this segment expect a reliable and affordable car for their daily commute, which typically lasts about 15–30 km [13,14] or 90 min per day [15]. The average speed required during commuting is around 34 km/h, with a top speed of 90 km/h according to the urban drive cycle of the United States Environmental Protection Agency [16]. In this use case, it is assumed that the range expectations of the consumers are no more than 299 km. Based on Figures 1 and 2, these consumers are a small portion of the whole society, approximately 6–7% in China and Germany, 12–14% in the United States, but more than 20% in Japan and India.

The aim is to investigate the market penetration possibilities for PMASynRM in many aspects of the circular economy model. This paper is divided into five parts, with Section 2 discussing the Circular Economy (CE) strategies and the ecological impact of the complete drivetrain main components regarding End-of-Life (EoL) treatment. Section 3 compares and reviews the ecological and technical aspects of the materials used for electric machines, such as magnets, aluminium, and copper. Furthermore, it focuses on choosing the suitable electric machine type for the defined requirements considering CE aspects. Section 4 provides a technical summary of the investigated EV segments and drive cycles. Lastly, Section 5 highlights the design aspects of PMASynRM considering the established general requirements and requirements of CE.

2. The Ecological Impact of Drivetrain Components Considering the Circular Economy Model

With the expected increase in the market share of EVs [17], their drivetrains must meet ever-stricter requirements [18]. EV sales are predicted to rise from 2 million in 2020 to 73 million in 2040. By that time, EVs are expected to account for 61% of worldwide car sales, with well over 80% in many developed countries [19]. The European Environment Agency has pointed out that the environmental impact of BEVs depends on four factors: vehicle design, vehicle use pattern, recycling possibilities, and electricity mix. This study focuses on the drivetrain level, having an analogy of electric machine design, drive cycles, and recycling possibilities regarding CE and energy consumption.

During the design optimisation stage, engineers strive to identify the optimal key-performance parameters for a given application by conducting thorough investigations of various topologies and applying multi-disciplinary analysis to the machine [18,20,21]. Due to the complexity and non-linear behaviour of the different components involved, selecting and designing the most suitable electrical machine, inverter, or control algorithm is a non-linear optimisation task that demands consideration of electrical, mechanical, and economic aspects [22,23]. The interdependence between the hardware and software parameters creates a multilevel optimisation task that, if solved sequentially, leads to a sub-optimal solution [22]. The success of this optimisation task depends on the applied business model, economic, and environmental costs. In a linear business model, designers aim to find a design and technology for processing raw material into the final product, whose characteristics suit the application. These products are manufactured, sold to customers, used, thrown out, and replaced by other products at the end of their lifetime without any thought of sustainability. However, this paradigm is now being challenged by the CE model (shown in Figure 3) as environmental policy pressure and sustainability needs of consumers grow [3,24].

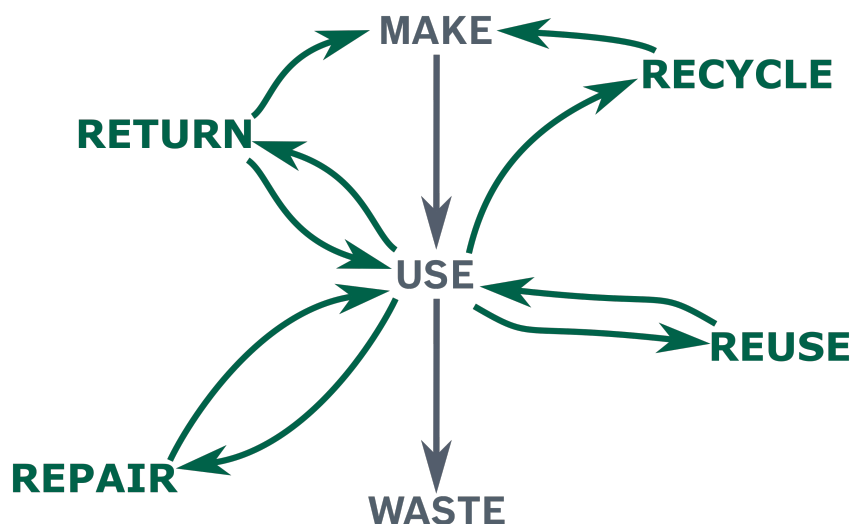


Figure 3. Representation of the circular economy model based on [25], where the grey color marks the linear economic model and the green is the addition of circular economy.

It is estimated that implementing CE strategies can result in significant savings of up to EUR 600 billion in the European Union (EU). This approach can also reduce greenhouse gas emissions and create 2 million additional jobs, potentially boosting the GDP by 1% [11]. Nevertheless, this approach is not fully new [26]; in the case of large power transformers and large power generators, usually not the machine's efficiency but its total cost of ownership is minimized [27]. This measure consists of the sum of the machine's production cost and lifetime losses. Therefore, this measure can be easily transformed and used in CE to consider the machine's carbon footprint during optimisation. It can be considered that a cheaper machine with less efficiency, which is rarely used, can be more environmentally friendly during its whole life-cycle than an oversized, high-efficiency machine.

China has implemented CE policies since 2000 through a top-down approach from the central government. These policies include industrial, finance, tax, and investment guidance documents. Aspirational documents provide future direction but have no immediate financial implications. The policy style ensures flexibility at the provincial and local authority levels. However, this approach poses coordination challenges across local governments, provinces, and industrial sectors. China's recent 14th Five-Year Plan on CE (2021–2025) aims to promote resource conservation and recycling and tackle climate change to achieve carbon neutrality by 2060. The aim is to increase resource productivity by 20%, reduce energy consumption by 13.5% compared to the 2020 level, utilise 320 million tons

of scrap steel, produce 20 million tons of recycled non-ferrous metals, and increase the output value of the resource recycling industry to USD 773 billion. The main obstacle to transitioning to a CE in China is the presence of resource-intensive industries that were once crucial to rapid development [28]. Resource efficiency measures were reported to be less cost-effective in the Russian Federation. Most implementation projects result in higher production costs due to limited demand for resource-efficient goods and services. Russian firms' primary obstacles to implementing CE include complex administrative and regulatory procedures and high costs associated with resource efficiency projects [29]. Moreover, the ongoing conflict between Russia and Ukraine may further hinder the implementation of such measures. Because of that, it is not manageable to build a profitable business solely on the waste of the population, specifically from the waste of electrical and electronic equipment [30]. Nevertheless, creating an industrial ecosystem to ensure circularity theoretically can lead to a significant reduction in greenhouse gas emissions by up to 8.32 million tons of CO₂ equivalent and also result in a total energy consumption reduction of 16.4 million GJ for the leading enterprises of mining and metallurgical production [31]. India's electrical and electronics market has rapidly grown, which has led to a sharp increase in e-waste generation [32]. Pune city lacks guidelines for e-waste management and has no baseline targets, benchmarks, or timelines in place, resulting in operational inefficiency, but aims to capture at least 60% of the e-waste generated over the following years by enabling CE [33]. India also faces significant environmental problems due to its large population. Pollution is a major issue in Delhi, with increasing construction, vehicles, and factories. It is estimated that implementing CE strategies can reduce greenhouse gas emissions by an average of 2.6% and 10.3% in the construction and transportation sectors, respectively. The CE framework might also reduce the material footprint by 8.3%, 8.5%, and 16% in construction, industrial, and transportation sectors [34].

The CE approach can significantly impact vehicle design and recycling possibilities, focusing on the electric traction motor, batteries, and inverter, as those are the main components of a drivetrain. The main principles of CE are (1) its strategies focus on the life-extension of the products, (2) the materials and products are planned to circulate in the economy as long as possible, and (3) the designer has a restorative intention in creating the product. The circulation of the product or its part in the economy can be maintained by reuse, refurbishment, remanufacturing, or recycling (4R strategies, see Figure 3). By optimising the life cycle of an EV using the CE model, the need for new raw materials and energy input can be significantly reduced [1,27,35]. The environmental impact of BEVs during the use phase greatly depends on the electricity mix of the corresponding region [36–38]. For example, case studies are available for Hungary, Belgium, Italy, China, and the US [39–43], showing the apparent differences between the well-to-wheel CO₂ emission of BEVs in those countries depending on the electricity mix, driving style, and vehicle type. Furthermore, the greenhouse gas emissions significantly depend on the electricity mix over the whole life cycle considering the production and EoL phase [44,45], shown in Figure 4. Different considerations of the electricity mix have shown diverging results in different papers [46]. Many studies show [47–49] that overall drivetrain efficiency can reduce the environmental effect of tank-to-wheel (see Figure 4) energy consumption. However, focusing only on increasing the efficiency without considering materials may increase the environmental impact of the production phase and overgrow the inherent benefit during the use phase [50]. Eliminating the tailpipe emission of transportation by switching to EVs can shift the problem without considering the method of energy generation [51]. Alternatively, a zero-kilometre footprint approach is recommended for EV manufacturers [10], which assumes the total emissions during the manufacturing of base parts and the entire supply chain from Cradle to Gate (see Figure 4).

From the 4R strategies, reusing a component is the most straightforward possibility. This approach only requires testing and cleaning the product, making it an efficient option for extending its lifetime. Remanufacturing and refurbishment, on the other hand, are more complex life-extension strategies. Both strategies focus on recovering the used product on

the component level [52]. The refurbishment aims to restore the product to its original state while maintaining its specifications. Remanufacturing, on the contrary, seeks to implement new operation principles to match the original specifications or to reach new requirements. Remanufacturing should fulfil higher standards than refurbishment. The quality of a remanufactured product should reach the quality of a new product [53,54]. Recycling is not a life-extending strategy but a treatment of the product at its EoL. The CE is not just about extending the lifespan of products but also includes eco-efficiency. This means reducing emissions and waste, improving resource security, and decreasing price volatility for resources [11]. Furthermore, designing electrical machines from highly recyclable materials can be completed without significant performance loss [55–57].

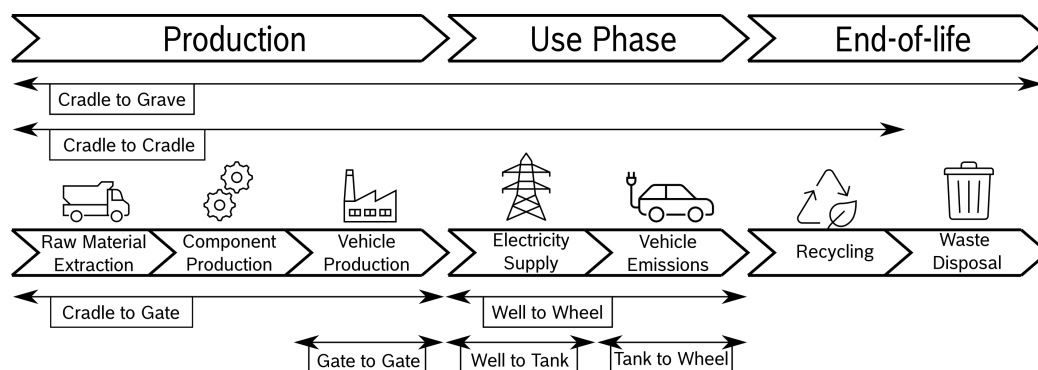


Figure 4. Visual representation of the life cycle assessment of an electric vehicle based on [58].

The 4R Strategies in the Case of Electrical Drivetrain Main Components

The electrification of consumer vehicles is expected to create a considerable amount of EoL products to reuse, refurbish, remanufacture, or recycle every year. While some studies suggest that BEVs produce lower non-tailpipe emissions than internal combustion engine vehicles (ICEVs), others argue that BEVs have a higher environmental impact during the production phase, especially with regards to batteries [38,59]. However, lowering the environmental impact of the use and recycling phase (see Figure 4) may compensate for the emission of the production phase [38]. Most of the studies [60,61] highlight battery production's environmental impact as one of the most significant factors of non-tailpipe emissions, representing 40–50% of the total greenhouse gas emissions. However, the EoL treatment of lithium-ion batteries can considerably enhance the environmental benefits of EVs [38,45]. Reusing batteries for second-life applications can provide time to develop environmentally friendly and economically viable battery recycling technologies [62].

There are limited studies about the EoL phase of EV drivetrains except those focusing on the recycling of batteries [63,64]. Addressing this gap, an ideal recycling scenario where all components are entirely recycled was presented [65]. However, such recycling can be expensive, which hinders its economic viability. Additionally, a conservative CE model that utilises all waste and closes all material loops is practically impossible [66]. Based on the information presented in the study about a 150 kW permanent magnet motor and 150 kW silicon IGBT inverter [65], the carbon equivalent emission of the inverter is approximately 220 kgCO_{2e} in the case of primary materials and 44 kgCO_{2e} when recycled. It is considerably less than the results of the electric motor 542 kgCO_{2e} and 171 kgCO_{2e}, respectively. Nevertheless, the environmental impact of the studied 70 kW inverter's manufacturing is more significant than the corresponding 53 kW SynRM due to the high content of precious metals. Considering shredding and metallurgical processes to obtain precious metals shows that the environmental impact reduction of inverter recycling is much lower than in the case of the electric motor [67].

Car manufacturers typically guarantee EVs up to 160,000 km or 8–10 years. The average distance travelled by car in Europe is 11,300 km per year, which implies that these vehicles can remain in operation for over a decade [68] without considering battery degrada-

tion. In addition, 56% of the motors worldwide exceed their life expectancy, and 68% of the utilised motors are oversized [47,69]. Therefore, recyclable electric machines are unlikely to be available in significant quantities soon for EVs [70]. Three United Kingdom-based automotive companies revealed that most electric machines go to waste at their EoL. These companies deal with electric machines up to 100 kW with a monthly machine production of 10 to more than 100 pieces [52]. While the industry has yet to embrace the machine recycling culture fully, recycling electric machines is predicted to become a new, significant, and profitable industrial sector [47,71]. Shredding and disassembling are the two possible methods for recycling electric machines. Shredded electric machines are cut into pieces and then sorted either manually or automatically. However, the disadvantage of shredding is that different materials may mix, which can negatively impact the quality of the recycled material. For example, combining the iron core lamination material and copper winding produces lower-quality recycled electrical steel. Nonetheless, the copper winding is always remelted to remove the insulation materials and cleanse the copper [56].

On the other hand, disassembling yields more high-quality material for direct reuse or recycling. Although it is difficult to automate the disassembling process as there are many types of electric machines, an automated process for disassembling surface-mounted magnet synchronous machines was developed [72]. However, surface-mounted permanent magnet synchronous machines are just a portion of the electric motor types used worldwide. Figure 5 presents the types and market share of different electric machines used in EVs. Modular electric machine designs are also presented promoting disassembly [69].

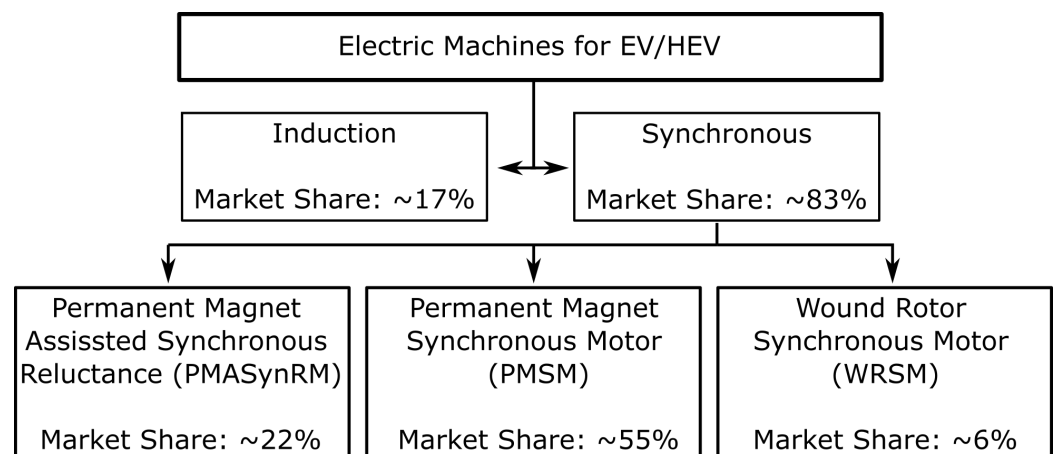


Figure 5. Types and market share of the different electrical machines in 2020 [73,74].

Thus, manual disassembling leads to high labour costs. Furthermore, the lack of automation lowers productivity and control over the process to maintain the quality of the components for reuse or remanufacture [52,56], especially in the case of permanent magnets. The disassembled motor's copper, steel, and aluminium components can be inserted into conventional recycling routes [75] depending on the requirements. On the contrary, an electric machine containing no permanent magnet or copper can be shredded or remanufactured by adding magnets or completely changing its rotor [76,77]. Electric machines should be designed so that the permanent magnets can be easily detached from the rotor as the best result of disassembling can be reached when the electric motor is designed, considering future recycling, meaning the most appropriate permanent magnet, electric machine type, and winding.

3. Suitable Materials and Electric Machine Types for Circular Economy

3.1. Permanent Magnets Used in Electric Vehicles' Traction Motors

The use of rare-earth element (REE)-based permanent magnets in PMSMs has raised concerns regarding their environmental impact. However, manufacturing PMSMs have minimal environmental effects as the magnets account for only a few percent of the total

mass of the motor [5]. While this may seem insignificant for individual machines, the cumulative impact becomes significant when considering the projected future EV stock of 200 million vehicles by 2035 [78]. The most commonly used magnets in electric machines include NdFeB, ferrite, Samarium–Cobalt (SmCo), and Aluminium–Nickel–Cobalt (AlNiCo), each exhibiting different magnetic, mechanical, and thermal properties [79].

While SmCo magnets offer advantages such as high thermal stability, which could be beneficial in specific applications (as shown in Figure 6) [80], there are no expected high-temperature load conditions for BEVs generally considering their cooling capacities. Therefore, the superior thermal properties of SmCo magnets are not required in most cases. SmCo magnets are unsuitable for electric traction motors due to their lower performance than NdFeB magnets and higher cost [81]. AlNiCo magnets are prone to demagnetisation due to their low coercivity [82]. Because of that, its use in electric transportation is only presented for variable flux machines [83] but not at the scale of EVs. Emerging magnet types, such as samarium–iron–nitride (SmFeN) compound variations, exhibit comparable performance to NdFeB magnets [84]. However, SmFeN magnets are not yet widely available in the mass market. Nonetheless, their potential introduction could potentially reshape the future electric machine market.

Currently, most PMSM designs in vehicles utilise NdFeB magnets due to their high magnetic flux density [6,9]. Neodymium is a REE that is considered to be a Critical Raw Material (CRM) essential for low-carbon emission technologies and the economic competitiveness of the European Union [8]. However, the known reserves of neodymium on Earth are limited, which raises concerns about its availability. Nevertheless, Sweden recently announced the discovery of Europe’s largest deposit of rare-earth elements in the Arctic region, including neodymium, praseodymium, and dysprosium [85]. This discovery could alleviate the supply constraints to some extent. The demand for NdFeB magnets is expected to rise significantly, not only for BEVs but also for hybrid vehicles, e-bikes, and heavy-duty vehicles [8]. The increasing economic demand for REEs faces challenges due to the high-risk supply chain, which can substantially impact the price of EVs and potentially reduce their attractiveness to consumers [1]. Recent events such as the COVID-19 pandemic and geopolitical conflicts in Europe have highlighted the vulnerability and reliability issues of the primary materials supply chain [10].

The high-risk supply is based on the availability being restricted to a few regions. Currently, most permanent magnets and their raw materials are produced in China, making the supply chain vulnerable to disruptions [5,10]. Another concern with rare-earth elements is that they are often mined as compounds containing highly radioactive materials [86]. The mining and production processes involved in high-volume REE extraction can significantly harm the surrounding environment near the mines and the factories. Strict policies are necessary to ensure the protection of human health and the environment during rare-earth element production [10,86]. Environmental impacts from rare-earth element production have already been observed outside of China in countries like the US, India, and Brazil, where mining activities have polluted local soil, water, and air, adversely affecting wildlife and vegetation [87].

Although recycling may provide a significant amount of magnets, the environmental impact depends greatly on the recycling method. There are many different projects founded by the European Union focusing on rare-earth element magnet recycling as the European Rare Earth Magnet Recycling Network (EREAN, [88]), Sustainable Recovery, Reprocessing and Reuse of Rare-Earth Magnets in a Circular Economy (SUSMAGPRO, [89]) or the European Training Network for the Design and Recycling of Rare-Earth Permanent Magnet Motors and Generators in Hybrid and Full Electric Vehicles (DEMETER, [90]). Recycling by manual dismantling yields more recyclable quality material than shredding and is environmentally preferable to primary production. Moreover, manual dismantling helps recover other materials from the electric machine, such as electrical steel, copper, and aluminium. Shredding provides a significant 90% lower recovery rate and degradation in the recovered material’s quality [91]. Significant electronic waste accumulates 50 million

metric tons per year globally [86]. Recycling electronic waste might theoretically fulfil the rare-earth element demand for magnets in EVs. One of the main problems with the recycling of magnets is that extracting materials from various machines and gadgets is challenging.

In producing NdFeB magnets, the general processes include sintering and bonding, followed by applying a protective coating on the polished magnets [5]. The nickel coating has one of the highest environmental impacts regarding magnet-to-magnet recycling of NdFeB magnets [9]. However, magnet-to-magnet recycling can substantially reduce the overall environmental impact by more than 64%. For example, producing one kilogram of NdFeB through magnet-to-magnet recycling only requires 0.0005–0.001 kg of additional raw materials, compared to 1.3–3.0 kg of raw materials needed for primary production [9]. In terms of the feasibility of recycling NdFeB magnets as the recycling routes for aluminium, copper, and steel alloys are already established, approximately 7.4 million vehicles with an average electric power of 72 kW are needed to operate a commercially feasible NdFeB magnet-based electric motor recycling plant for an OEM [71].

In response to the high price volatility and non-stable supply chain of NdFeB magnets, there is a growing interest in electric motor applications using ferrite magnets [92]. Ferrite magnets have the lowest price/performance ratio compared to NdFeB, SmCo, and AlNiCo magnets, reaching the requirement for a mass-market magnet material, as defined by [84]. Comprehensive reviews of permanent magnet manufacturing, including ferrite magnets, can be found in [84,93]. However, academic studies on ferrite magnet recycling are relatively limited [94]. The recycling of ferrite magnets is generally considered not economically viable due to the low cost of raw materials and the high cost of reprocessing [55,95]. However, a comparative life cycle assessment of NdFeB, SmCo, and ferrite magnet-based electric machines revealed that ferrite magnet-based electric machines exhibit the lowest carbon equivalent emissions, human toxicity index, land use, and respiratory inorganic emissions [50]. This finding suggests that ferrite magnet-based electric motors are an environmentally friendly alternative for low-power applications. Unlike NdFeB magnets, ferrite magnets have a low coercive force, which decreases at low temperatures, while the other's decreases at high temperatures (see Figure 6), which is important to consider for demagnetisation [96].

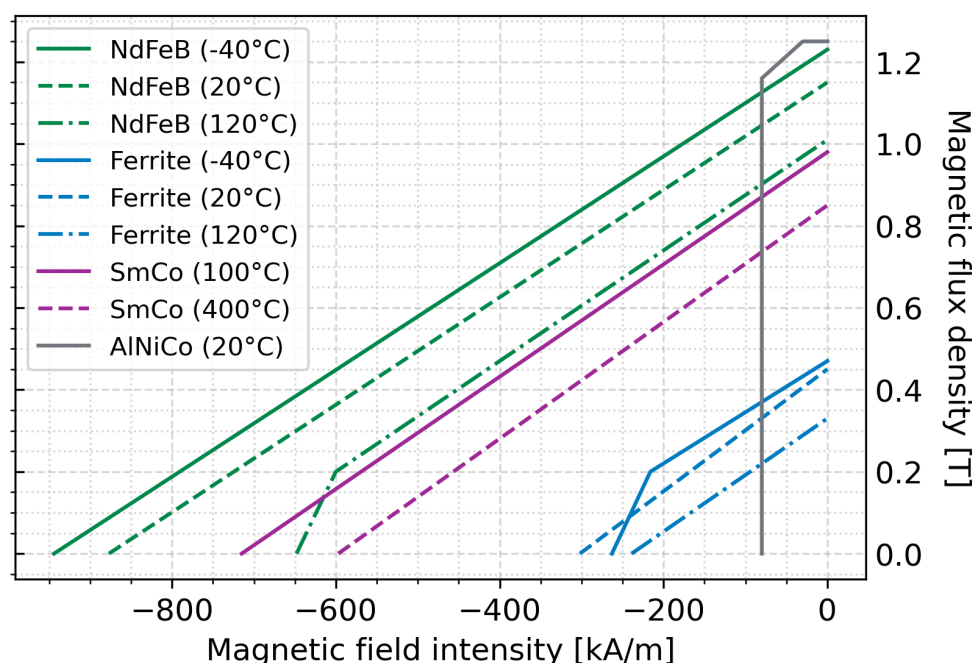


Figure 6. B-H curve of a NdFeB, a SmCo, a ferrite, and an AlNiCo magnet at different temperatures based on [79,97,98].

Comparing a ferrite and a hydrogenation disproportionation desorption recombination recycled NdFeB magnet indicated that the recycled magnet exhibited comparable or better electromagnetic properties than the low-cost ferrite magnets [70,99]. Despite the complex fabrication process involved in recycling magnets, the price of recycled uncoated magnets is significantly lower than that of newly manufactured rare-earth magnets, making them competitive with ferrite magnets [70]. To increase the corrosion resistance of the magnet, metallic coatings are applied, which raises its manufacturing costs [100], which, on the other hand, decreases its competitiveness. Ferrite magnets cost less than recycled NdFeB magnets in terms of performance per cost [96,99]. Based on the available information, NdFeB and ferrite magnets are considered in the following for choosing the suitable electric machine type.

3.2. Comparison of Different Machine Types with Rare-Earth Element and Non-Rare-Earth Element Magnets

In-wheel drive is another promising type of EV drivetrain. A vernier motor is an unexcited inductor synchronous motor that produces a large displacement of the axes of maximum and minimum permanence with a slight displacement of the rotor angular position. This motor is useful in applications requiring low speed and high torque, where mechanical gearing is undesirable, as in-wheel drives [101]. Several studies support that permanent magnet vernier motors (PMVMs) can satisfy the target characteristics for the application in a small EV truck [102,103]. Nevertheless, the price of rare-earth magnets is hardly stable and prone to demagnetisation. Using ferrite magnets combined with sintered NdFeB magnets instead of bonded ones can successfully solve these problems while maintaining the same torque, power, and efficiency requirements [104]. Although some studies indicate that PMVM may have superior torque capabilities to a general PMSM [102–104], comparing its performance to a PMSM with the same required dimensions for in-wheel direct drive, PMVM requires a longer stack length resulting in a larger active motor volume and lower volumetric torque density [105]. Even though promising electric machines were presented on a theoretical level [102–104], it was shown that those are primarily suitable for in-wheel drive applications, but even then, PMVM does not have much more advantage over the investigated fractional-slot concentrated winding PMSM [105]. For this reason, and since the in-wheel drive solution for EVs is rare, PMVM is not considered suitable for the aim of this particular research.

Spoke-Type Permanent Magnet Synchronous Machines (STPMSMs) are also considered for in-wheel drives. Compared to a commercial SPMSMs for the same electric motorcycle application, STPMSMs might have higher self-inductance, field-weakening capability, and the same average torque and efficiency at a more comprehensive speed range [106]. Considering electric vehicle applications with shaft drives, one of the most recent solutions is a variable-flux spoke-type permanent magnet synchronous motor whose air gap flux density can be adjusted by swivelling the magnetic pole directions of the permanent magnet [107]. Even using ferrite magnets, an STPMSM can be competitive in efficiency, torque, and power compared to the Toyota Prius 2004 Interior Permanent Magnet Synchronous Motor (IPMSM) [108–113]. Therefore, it is a suitable option for traction applications, even for retrofitting a light electric vehicle with a fully electric drive based on the requirements set by the L6 European vehicle class [114,115]. Even though compared to most of the different rotor configurations of PMSMs for EV applications considering Surface Permanent Magnet Synchronous Machine (SPMSM) and IPMSM, other types of IPMSM, such as interior, U-shaped, and V-shaped PM, have slightly higher efficiency, considerably lower weight and somewhat lower armature current density than STPMSM [116].

Electric vehicles based on purely synchronous reluctance traction motors have yet to be commercially available [117]. Although it has been known for years that SynRMs can reach IE4 level efficiency [118,119], it has also been newly revealed that it can reach ultra-premium efficiency (IE5) [120]. However, the power factor of this type of electric motor is low [117,121], which necessitates a higher current-rated inverter. Numerous studies have

sought to increase the power factor of synchronous reluctance topologies without utilising permanent magnets [122–124]. Nevertheless, in electric vehicle applications, where high power- and torque-density are vital [125], permanent magnets are used to enhance the characteristics of the initial synchronous reluctance topology [126]. Although for a drivetrain solution with ferrite magnets, STPMSM might be beneficial because more magnets can be fitted into the rotor [127], low-power ferrite magnets are also widely used in PMASynRMs due to their cost-effectiveness and eco-friendliness [50,96]. The potential for mini and small-category EV applications of this motor type has been proven by the SYRNEMO project [128] and by designing and optimising a PMASynRM for an EV implemented within the TELL project [129,130].

The cross-sections of an SPMSM, SynRM, and PMASynRM are shown in Figure 7. Comparing the average torque of an SPMSM, an STPMSM, a SynRM, and a PMASynRM type electric motor with ferrite magnets to an SPMSM with NdFeB magnets assuming equal volume for all alternatives, the average torque is lower compared to the reference motor [12]. Nevertheless, this issue can be resolved by increasing the motor’s volume or enhancing its electromagnetic and mechanical design [128]. The electric vehicle drivetrain industry has the option to design bigger electric machines using rare-earth magnet-less solutions like ferrite-based PMASynRMs or SynRMs to fulfil customer expectations, different from the consumer electronics industry [8,10]. For example, comparing a NdFeB-, a SmCo-based PMSM and strontium–ferrite-based PMASynRM for the same requirements, the stack length of the PMASynRM should be 7% longer and the mass of magnets 58.4% higher than the NdFeB-based PMSM machine. Although the mass of magnets is higher, the environmental burden, like climate change and human toxicity of PMASynRM, has the lowest negative effect from cradle to gate and during operation. Furthermore, assuming the same production volumes and similar production methods, a PMASynRM costs 42% less. This difference comes from the magnet material cost [96]. The PMASynRM with ferrite magnets can be a cost-effective alternative to other types of PMSMs [12].

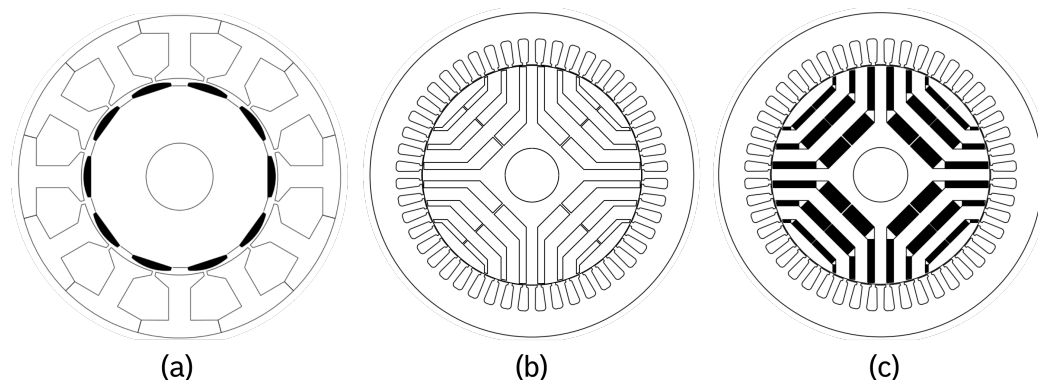


Figure 7. A 2D cross-section of (a) SPMSM, (b) SynRM, and (c) PMASynRM topologies based on [131].

3.3. Ecological Aspects of Aluminium and Copper Windings

Besides the permanent magnets for several toxicity categories in the cradle-to-gate manufacturing of electric machines, copper production is the main contributor and significantly affects the manufacturing costs as well [96]. The high aluminium and copper content of a general electric motor contributes around 8% of total production-related emissions of the EV [51]. Furthermore, an average BEV requires four times more copper than an ICEV [1]. According to the ISO 14008 standard [132], the monetary valuation of environmental impacts involves two fundamental concepts. The first is the “environmental good”, which refers to the object or resource in the environment being valued. The second one is called the “impact indicator”, which measures the change in environmental good’s quality. This impact indicator is then assigned a monetary value to quantify the extent of its impact [133]. Comparing the monetary impact value of ore extraction in Euros per kilogram shows that if the iron ore extraction is defined as 1 EUR/kg, then for the aluminium, it is

0.159 EUR/kg, for the copper 132 EUR/kg and neodymium 202 EUR/kg, considering the common materials used in electric machines [117]. Furthermore, the monetary impact value of the steel sheet, aluminium components, and copper wire production is 2.16 EUR/kg, 3.27 EUR/kg, and 277 EUR/kg, respectively [134]. Due to the environmental issues related to copper [51,96,134], the easier recycling and lower mass density of aluminium [135], the significantly lower price of it [136], its abundance [137], and higher flexibility in manufacturing [138,139], the use of aluminium has re-emerged as a possible winding solution over copper in the case of electric machines. Even though aluminium has ~65% higher resistivity (2.83 $\mu\Omega\text{cm}$), ~47% lower thermal conductivity (210 W/m $^{\circ}\text{C}$), and ~41% higher thermal expansion coefficient (19.63 mm/mm) considering pure metals [140,141].

Various studies have been conducted to explore the use of aluminium winding in IPMSMs [142–144] using aluminium hairpin windings [117,137,139] even proposing a uniquely shaped winding cross section [145]. The aluminium conductors have lower frequency-dependent AC losses at a high-speed range than copper. Losses occurring in a winding at high-frequency range can be attributed to both DC loss (I^2R) and other factors such as skin and proximity effects, as well as the circulating current effect marked as AC losses shown in Equation (1).

$$P_{winding} = P_{DC} + P_{AC}(P_{eddy}, P_{circ}) \quad (1)$$

The DC loss is only influenced by the amplitude of the applied current and DC resistance. The skin effect occurs when high-frequency alternating currents flow through a conductor, resulting in higher current density on the surface than in the core due to the generated eddy currents. Proximity effect loss refers to the losses in a strand caused by an external magnetic field generated by surrounding strands. When the armature field flux leaks into the slot during heavy load, an inductance imbalance between bundle strands can occur, generating circulating currents. AC loss depends on several factors, including conductor dimensions, frequency, and amplitude of the magnetic field [146,147]. For a more precise estimation of the eddy current loss, FEM-based magnetic field calculations are used, which consider both the axial (B_{ax}) and radial (B_{rad}) components of magnetic induction [148,149]. The axial and radial components of the eddy current loss for rectangular-shaped conductors can be found in Equations (3) and (4). The amount of eddy current loss is inversely proportional to the conductive material's specific resistance (σ). Aluminium has 64% higher specific resistance than copper, so it is expected to have lower eddy current losses [141]. Comparing the AC losses of copper and aluminium conductors that have been designed for the same winding concludes that the difference in the AC/DC loss ratio, which exponentially increases after the break-even point at around 300 Hz, is in favour of aluminium winding [150].

$$P_{eddy} = P_{ax} + P_{rad} \quad (2)$$

$$P_{ax} = \frac{1}{24\sigma} (B_{ax} \cdot \omega \cdot d)^2 \quad (3)$$

$$P_{rad} = \frac{1}{24\sigma} (B_{rad} \cdot \omega \cdot h)^2 \quad (4)$$

where $\omega = \pi f$ is the angular frequency, and d and h are geometrical parameters. To offset the inherently higher DC losses of aluminium winding, increasing the slot-filling factor reduces the resistivity [142,145]. "The inherent benefit of hairpin winding over stranded round wires is the high slot fill factor. . ." [139]. The hairpin winding solution is commonly used in automotive applications due to its easy and low-cost assembly [142]; because of automated manufacturing processes, the accuracy of winding placement is significantly higher [139].

Evaluating the energy consumption of particular drivetrains, including electric machines, on different drive cycles is essential for automotive applications where the working point varies over the whole operation. For a direct-drive PMSM over urban and highway

drive cycles, the aluminium winding reduced the torque of the machine by 18% compared to the copper winding, but the constant speed zone was extended by 20%. The efficiency decreased by only 1.17% in the urban cycle but with 14.7% less weight and 67% less winding costs [151]. For an IPMSM fitted with three types of copper winding and three types of aluminium and investigated over the Extra-Urban Drive Cycle [152], the efficiency difference was between 1.3–2.9% greater in favour of copper. However, the material cost was approximately 90% lower, and the overall weight was around 3 kg lower in favour of aluminium [142]. Comparing PMASynRM with ferrite magnets and aluminium hairpin winding to a PMSM with NdFeB magnets and copper round-wire winding for the same vehicle requirements shows that the PMASynRM has similar energy consumption (18.9 kWh/100 km) based on the WLTP and CADC 150 drive cycle than the investigated PMSM (19.0 kWh/100 km). Furthermore, the monetary impact value of the reference PMSM (790.6 EUR/kg) is 96.1% higher than the PMASynRM (30.8 EUR/kg), and the raw material cost of PMASynRM (45 USD) is 77% lower than the PMSM (195.2 USD) [153]. A well-designed hairpin winding lowers the DC losses of aluminium winding, and the AC/DC loss ratio at a higher speed range is also lower than a general copper-wire winding [150]. Thus, there is a possibility of using an aluminium hairpin winding without compromising efficiency and reaching the torque and performance requirements of the selected urban drive cycle. Comparing the two materials shows that aluminium winding provides a cost-effective and lightweight alternative to copper windings, especially if the focus is on design for cost [154], design for remanufacturing [155], or design for low environmental impact [156], except aiming for the high torque and power. There is still a gap in studies on synchronous reluctance machines and permanent magnet-assisted synchronous machines with aluminium windings.

4. Technical Summary of the Suitable Electric Vehicle Category

PMASynRM is an electric machine type that shows potential for EV applications without using rare-earth element magnets despite its higher inherent torque ripple and lower power factor than a general IPMSM [92,157,158]. PMASynRMs using ferrite magnets generally have lower torque density than REE-based IPMSMs for similar EV applications [128,157]. Because of that, the previous [128,159–161] and recent [129,162–165] research investigated ferrite magnet-based PMASynRMs in a power range of 25 kW to 69 kW and a torque range of 83 Nm to 182 Nm at a speed range of 0 rpm to 14,000 rpm. The research mostly refers to the TELL project's EV [130] and the FreedomCAR and Vehicle Technologies (FCVT) requirements specified by the U.S. Department of Energy [166], which covers mini (A) segment electric vehicles with 2WD and one electric machine drivetrain and might be appropriate for small (B) segment electric vehicles with 4WD and two electric machine drivetrains [167].

4.1. Characteristics of Mini (A) and Small (B) Segment Electric Vehicles

The EV Database [168] has collected information about most electric vehicles aiming to accelerate the adoption of sustainable transport by maintaining an easily accessible database. Upon analysis of the Rated Energy Consumption published by the vehicle manufacturer and the Unladen Weight EU (UW), there is no significant difference in energy consumption between the mini and small segments as per the representation of the investigated vehicles in Figure 8. The Unladen Weight EU (UW) refers to the weight of a vehicle without any additional load or passengers, as defined by the European Union (EU) regulations. In Figure 9, the WLTP range and the UW are compared. The weight increase is strongly related to the battery capacity increase shown in Table 1. The average power of the investigated electric vehicles for mini and small electric cars are 54 kW and 102 kW, respectively, as shown in Table 1. The average torque is 155 Nm and 287 Nm, and the top speeds are 129 km/h and 149 km/h. Notably, there is more than an 80% increase in power and torque capability from mini to small segment that helps to reduce the time needed for acceleration to 100 km/h by 44%.

Table 1. Comparison of mini (A) and small (B) electric cars by EV Database [168], where V_{max} abbreviates maximal speed, Acc. means Acceleration, NBC means Nominal Battery Capacity and UW is Unladen Weight (EU) [168].

	Power [kW]	Torque [Nm]	V_{top} [km/h]	Acc. [s]	NBC [kWh]	UW (EU) [kg]
Min. A	33	113	125	11.6	17.6	1012
Max. A	66	210	135	19.1	36.8	1248
Avg. A	54	155	129	13.0	25.0	1121
Min. B	70	220	135	7.9	23.8	1281
Max. B	150	395	167	9.9	67.5	1757
Avg. B	102	287	149	9.0	39.0	1573
A to B	88%	85%	16%	−44%	56%	35%

In the case of Nominal Battery Capacity (NBC), there is a 56% increase between the two segments, meaning 14 kWh on average. The lithium-ion batteries are the most common type of batteries used in transportation [169]. Based on [170], the gravimetric energy density of those can be around 250 to 400 Wh/kg. However, the average gravimetric energy density is around 265 Wh/kg, according to [171]. It is important to keep in mind that this refers only to the energy stored per unit mass of the battery's active components, excluding the mass of the housing and other accessories. A 14 kWh increase in energy density would mean at least approximately 53 kg. The average UW increase is 452 kg, representing at least 35% in battery weight.

The average energy consumption increase, summarised in Figure 8, from the mini to small category is approximately 3.3%. It is negligible to the vehicle's battery capacity and range increase (see in Table 1 and Figure 9). The battery capacity and the vehicle range are in solid correlation in contrast to the power, torque, UW, and energy consumption increase between the two segments, meaning a highly efficient drivetrain.

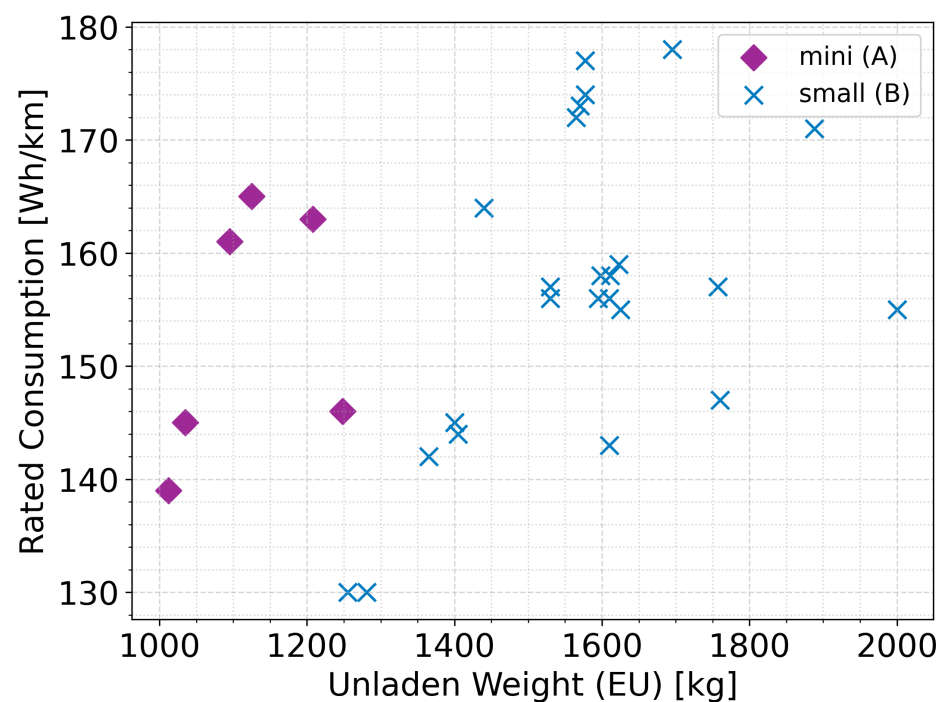


Figure 8. Correlation between the Unladen Weight and WLTP range based on [168,172].

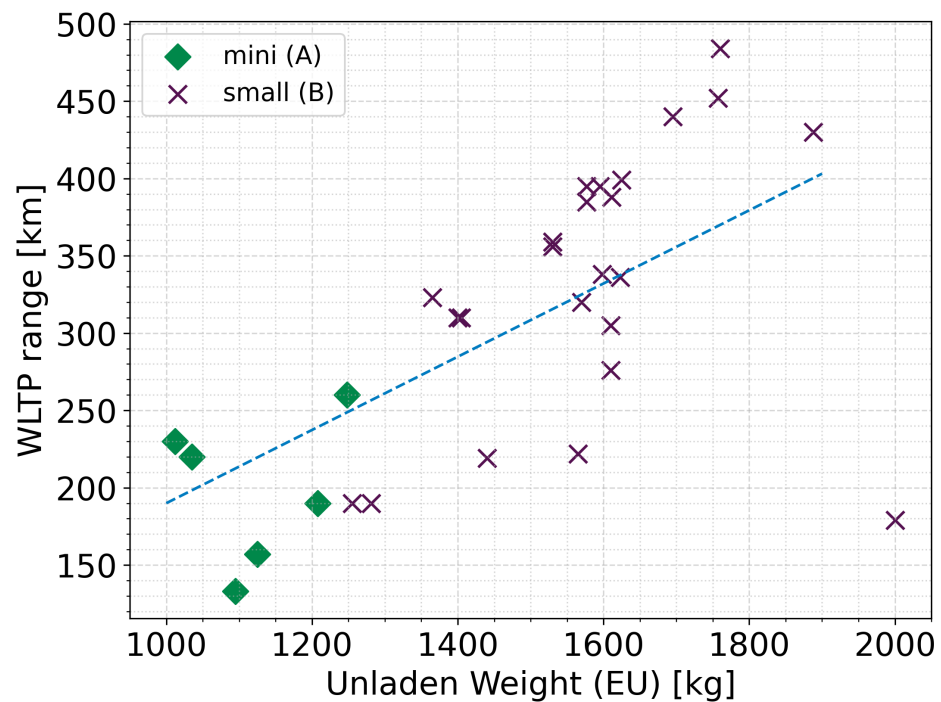


Figure 9. Correlation between Unladen Weight and WLTP consumption based on [168,172].

4.2. Characteristics of Different Urban Drive Cycles

As the TELL project's EV [130] is specifically made for the urban environment and the FCVT [166] also presents similar requirements, the characteristics of urban drive cycles are investigated. Drive cycles are designed to replicate typical driving conditions, simulating real-world scenarios that vehicles commonly encounter. It aims to assess performance, energy consumption, range, and efficiency. However, these tested parameters are heavily influenced by the driver's actions in real-life situations, as the motor's efficiency relies on factors such as speed and torque [173]. A comprehensive description of the corresponding area is necessary to calculate results for different regions accurately. Various studies address the same issue, highlighting that internationally legislated drive cycles provide an imprecise approximation of regional geography, urban infrastructure, and traffic [174]. Figure 10. illustrates different drive cycles for New York, US [16], Xi'an, China [175], and Florence, Italy [176]. The comparison of these drive cycles is in Table 2. Additionally, certain studies estimate the characteristics of Pune, India [177], Beijing, China [178], and Debrecen, Hungary [179].

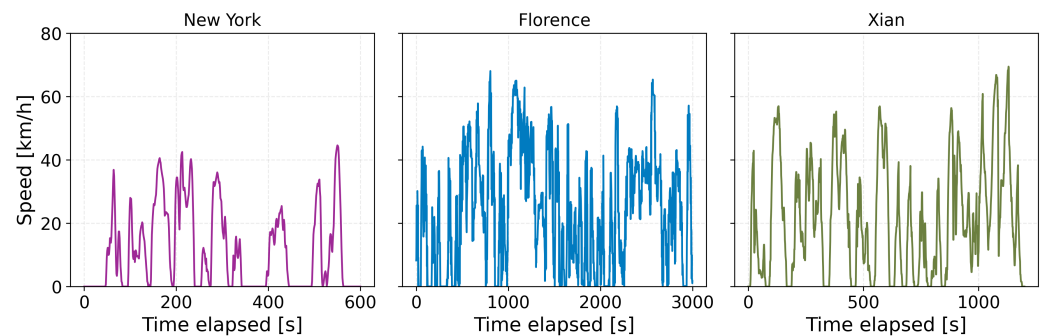


Figure 10. Drive cycles of New York [16], Xi'an, China [175], and Florence, Italy [176].

Table 2. Comparison of City Cycle of EPA [16], New York, US. [16], Xi'an and Beijing, China [175,178], and Florence, Italy [176], drive cycles. Dist. means distance, and V_{avg} means average speed.

	New York	City	Xian	Beijing	Florence
Time [s]	600	1385	1200	2535	3000
Dist. [km]	1.90	11.99	7.33	14.42	20.36
Idle time [%]	40.93%	20.42%	17.60%	24.40%	15.51%
Stops [1/km]	5.80	1.50	1.51	1.24	2.26
V_{avg} [km/h]	11.36	31.14	21.98	20.49	24.43
V_{max} [km/h]	44.58	91.25	69.45	69.40	68.05

BEVs offer a significant advantage over ICEVs in energy consumption, particularly in urban and inter-urban environments. This advantage is primarily attributed to regenerative braking, which allows for the extension of the vehicle's range [1]. Ref. [40] demonstrated that regenerative braking could contribute 10–20% of a vehicle's total energy consumption, depending on driving style, topography, and traffic conditions. This feature plays a crucial role in enhancing the vehicle's range. Furthermore, regenerative braking has the additional benefit of reducing local particulate matter emissions in urban driving conditions by preserving the mechanical brake system from wear and tear [1]. EVs with similar structures consume less energy per kilometre in urban areas than those powered by internal combustion engines [180].

5. Electric Machine Design with Circular Economy Aspects in Electric Vehicles

The IEC 60034-30-1 standard [181] defines efficiency classes for low-voltage AC machines. In this efficiency range, the IE1 class represents the standard efficiency values for the machines, while IE4 defines the super-premium efficiency class [182,183]. Figure 11 shows the efficiency of electric machines to the rated power. The development of high-efficiency electric drivetrains is a priority to achieve sustainability goals as it consumes most of the energy stored in the batteries of the BEV. The environmental impact of premium efficiency (IE3) and super-premium efficiency class machines during the production phase can be higher than a lower efficiency class electric machine due to their more complex manufacturing process and material choice [69]. However, more efficient electric machines can save a significant amount of electricity during operation [92,184]. Electric vehicles based on purely synchronous reluctance traction motors have yet to be commercially available [117]. Although it has been known for years that SynRMs can reach IE4 level efficiency [118,119], it has also been newly revealed that it can reach ultra-premium efficiency (IE5) [120].

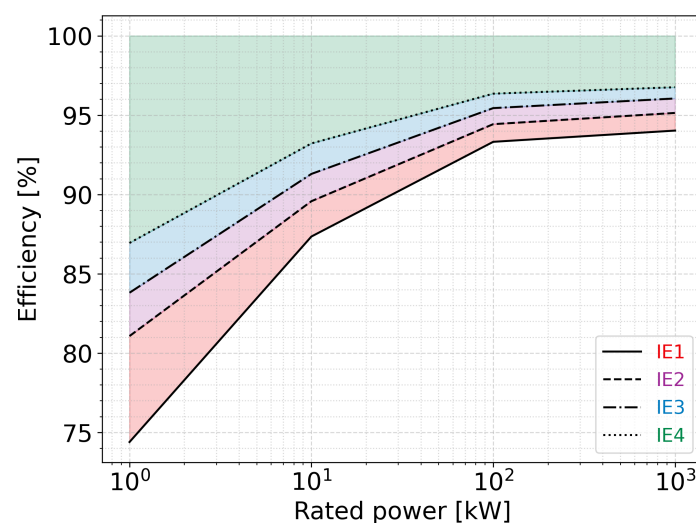


Figure 11. Efficiency of different IE class four pole electric machines based on the rated power [181].

One cause for the unavailability is the low power factor [117,121], which necessitates a higher current-rated inverter. Numerous studies have sought to increase the power factor of synchronous reluctance topologies without utilising permanent magnets [122,123]. Nevertheless, in electric vehicle applications, where high power- and torque-density are vital [125], permanent magnets are used to enhance the characteristics of the initial synchronous reluctance topology [126]. Low-power ferrite magnets are widely used in PMASynRMs due to their cost-effectiveness and eco-friendliness, as presented beforehand. The potential for electric vehicle applications of this motor type has been extensively explored in the literature [124,127–129].

Most of the studies [124,127,128] utilise permanent magnets inside the rotor. However, it is crucial to consider the potential damage to the magnet during disassembly if a permanent magnet is built into the rotor. Electric machine disassembly yields more quality recyclable material than shredding. Surface-mounted permanent magnets can be removed with less effort, and the EoL of the machine promotes the reuse of the magnet and remanufacturing or recycling of the rotor core [69]. However, it is important to keep in mind that when designing an electric motor with surface-mounted permanent magnets, the magnets are exposed directly to the armature field, which can lead to irreversible demagnetisation [47]. Ferrite magnets, in particular, have low magnetic coercivity and are sensitive to demagnetisation [12]. Additionally, surface-mounted magnets cannot withstand high centrifugal forces, so a sleeve is needed to hold the magnets in place at higher speed ranges [185,186]. A study on alloy and carbon fibre sleeves found that when a constant mechanical air gap length is adopted, the decrease in the sleeve thickness would significantly increase the air gap magnetic flux density and stator iron loss. In addition, as the sleeve thickness increases, the rotor eddy current loss and rotor temperature increase too [186]. Furthermore, the sleeves directly affect the disassembling process of the electric machine.

High-speed operation is common in electric vehicles, and ensuring that the rotor is mechanically robust is crucial. In SynRMs, the flux barriers reduce the mechanical robustness of the rotor. Introducing radial ribs is a possible solution to increase the resistance to the stresses caused by the centrifugal force. On the other hand, the radial ribs create a potential short-circuit through the flux barrier. As a cross saturation effect occurs, it reduces the saliency ratio and the torque output [187]. Increasing the number of radial ribs and reducing their thickness can balance the mechanical load and electromagnetic distribution [188]. Additionally, using titanium as a non-magnetic material to reinforce the rotor has been investigated, consequently increasing the electromagnetic performance of the motor [189]. However, in some instances, such as with ferrite magnet-based PMASynRM, radial ribs may provide additional flux paths, protecting the magnets from demagnetisation at higher loads [128].

For optimal results, it is recommended to use a curved flux barrier that follows the natural path of the flux lines [128]. Fluid-shaped barriers [187,190] are the top choice as they obstruct the direct direction (d-axis) flux path less compared to rectangular barriers and show similar behaviour in the quadrature direction (q-axis) than other types of SynRM (see Figure 12). This results in a higher saliency ratio, torque output, and less torque ripple [188]. The disadvantage of this topology from the design point of view is that it is impossible to precisely approximate the splines of the barrier with most of the FEM solvers using linear elements [187], for example, in the case of the most widely used open-source solver FEMM [191]. Isogeometric analysis can be an alternative solution, but it is not yet commonly used in electromagnetics [192,193]. The other disadvantage is that fluid-shaped flux barriers cannot accommodate standardised, “off-the-shelf” ferrite magnets [187,188], making the magnets’ manufacturing more complicated and costly.

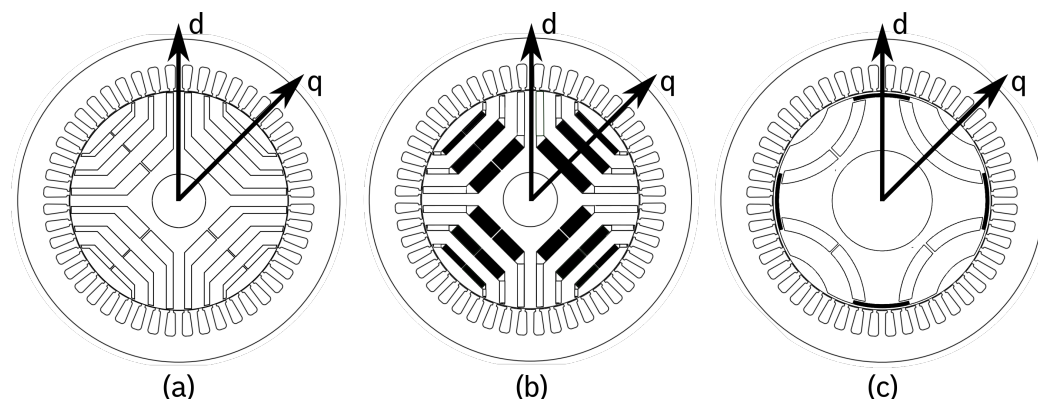


Figure 12. A 2D cross-section of (a) SynRM [131], (b) PMASynRM [131] and (c) FI-PMASynRM [194] topologies.

Flux-Intensifying Permanent Magnet-Assisted Synchronous Reluctance Machines (FI-PMASynRMs) were recently proposed [194–196], offering a solution for reducing the irreversible demagnetisation of ferrite magnets. This topology involves placing permanent magnets on the surface of the rotor in the d-axis instead of the q-axis in the flux barriers. This approach has been shown to offer enhanced output torque and reduced torque ripple with a limited amount of permanent magnets, helping to avoid irreversible demagnetisation, especially in flux-weakening operation [195]. Furthermore, the FI-PMASynRM maintains its saliency ratio regardless of the increasing current, unlike a SynRM [194]. In [194], a comparison of an SPMSM, a SynRM, and an FI-PMASynRM is presented. In terms of torque production, FI-PMASynRM (15.95 Nm) is ahead of the SynRM (8.65 Nm) by 84.4% and SPMSM (11.93 Nm) by 33.7%. Thus, FI-PMASynRM is a possible alternative to conventional permanent magnet-assisted synchronous reluctance machines considering circular economy aspects, mainly disassembling the machine and using a low amount of non-rare-earth element-based permanent magnets.

6. Summary

It is becoming increasingly important for products to be sustainable and environmentally friendly, especially in the automotive industry. As an electric vehicle has no tailpipe emission, OEMs and vehicle manufacturers focus more on the environmental footprint of the manufacturing process as it can be directly influenced. The zero-kilometre footprint can quantify the ecological impact of manufacturing because it could be more easily regulated than indirect emissions as it is highly dependent on the energy mix and independent of OEMs.

Significant differences exist in the overall environmental impacts during the battery electric vehicles' production, use, and end-of-life stages. Different electric machine designs have different levels of efficiency, compactness, cost, and long-term material supply, so finding a single optimal solution is challenging. Implementing strict life cycle management policies to address the life cycle cost and economic impact while improving mileage by increasing efficiency and reducing vehicle weight is crucial.

The use stage of an electric motor is the longest period of its life cycle. Generally, electric machines are designed to operate in normal conditions for 15–20 years, more than the average life cycle of a vehicle. In addition, most motors worldwide exceed their life expectancy, and most utilised motors are oversized. A more extended use phase of the machine decreases the environmental effect of the production stage related to the whole life cycle. From the vehicle design point of view, the lifetime mileage can be maximised by optimising durability and maintainability in the case of the electric drivetrain, as well.

Before changing the materials used in the product, it is crucial to consider their environmental impact and effect on the machine's efficiency. Alternative materials such as ferrite magnets or aluminium winding for the design and production of electric motors are only environmentally beneficial if the overall efficiency remains the same or improves.

However, manufacturers alone cannot make the necessary changes. A change in consumer approach is also needed, with individuals choosing the smallest possible car that meets their needs. In conclusion, the new generation of economically competitive and sustainable electrical machines must be designed to be restorative.

Future research will focus on the optimisation of a FI-PMASynRM rotor topology considering the established technical requirements and the restorative design aspects of the circular economy.

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Data Availability Statement: The data presented in this study are openly available in Toroid-project/SynRM/review repository, GitHub at <https://github.com/Toroid-project/SynRM/tree/main/review> (accessed on 12 March 2024).

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

BEV	Battery Electric Vehicle
EV	Electric Vehicle
OEM	Original Equipment Manufacturer
PMSM	Permanent Magnet Synchronous Machine
NdFeB	Neodymium–Iron–Boron
PMASynRM	Permanent Magnet-Assisted Synchronous Reluctance Machine
SynRM	Synchronous Reluctance Machine
ICEV	Internal Combustion Engine Vehicle
EoL	End-of-Life
CE	Circular Economy
EU	European Union
4R	Reuse, Refurbishment, Remanufacturing, or Recycling
REE	Rare-earth element
SmCo	Samarium–Cobalt
AlNiCo	Aluminium–Nickel–Cobalt
SmFeN	Samarium–Iron–Nitride
CRM	Critical Raw Material
EREAN	European Rare-Earth Magnet Recycling Network
SUSMAGPRO	Sustainable Recovery, Reprocessing and Reuse of Rare-Earth Magnets in a Circular Economy
DEMETER	Design and Recycling of Rare-Earth Permanent Magnet Motors and Generators in Hybrid and Full Electric Vehicles
PMVM	Permanent Magnet Vernier Motor
STPMSM	Spoke-Type Permanent Magnet Synchronous Machine
UW	Unladen Weight EU
FI-PMASynRM	Flux-Intensifying Permanent Magnet-Assisted Synchronous Reluctance Machines
NBC	Nominal Battery Capacity

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