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Life Cycle Assessment of Production and Recycling of Materials in E-Motors Used in Transport for Passenger Cars

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Abstract

CO_2 emissions are rapidly rising with new records, and the transport sector is considerably contributing to GHG emissions. The critical transition towards electrification and sustainable development demands a radical change in the transport industry. One of many solutions is to analyze the environmental benefits of optimized vehicle production and recycling of the vehicle components after their usable life to reduce dependency on limited raw materials. The electric motor is one of the most crucial powertrain components, yet studies on the overall ecological profile of production and the end of its usable life are limited. This study examines the life cycle assessment (LCA) impacts of electric motors used in passenger cars and the potential recycling of their materials. The analysis covers the production and recycling of components, crucial elements, and permanent magnets. The results show that housing and rotor production have the highest impacts, mainly due to the presence of steel, aluminum and permanent magnets. The findings discuss e-motor recycling innovations, state-of-the-art methods and emission-reduction potentials of recycling. This paper also covers the understanding that a significant transformation to optimize the resource consumption in the manufacturing of crucial vehicle powertrain components and reduce waste after end-of-life could bring combined ecological advantages.

Keywords: e-motors; electric vehicles; transport; sustainability; LCA; permanent magnets; raw materials; vehicle technology; automotive sustainability

1. Introduction

The transport sector accounted for 22% of greenhouse gas emissions (GHG) in the European Union in 2019 and accounted for up to 25% by 2025 [1]. Due to technological advances, the CO_2 emissions decreased only between 1990 and 2014 and again in 2020 [2]. Despite the Paris agreement of reducing the current emissions to half by 2030, the transport emissions continue to rise [3]. To reduce the emissions of the transport sector on the environment, it is necessary to implement principles that are technical, logistical, and organizational in nature in order to improve transportation efficiency. As a basis for providing solutions to tackle these issues, the world is undergoing a significant energy transition, rapidly moving away from fossil fuels towards cleaner renewable energy sources, aiming to decrease these transport-related environmental emissions. Furthermore, the EU Green Deal is currently aiming to help achieve the climate neutrality targets by 2050 and ensure a sustainable transport sector [4]. A particular aim of this initiative is the implementation of cleaner, more affordable, and healthier modes of private and public transport. On the other hand, electrification in the automotive industry continues to rise with demand for passenger and cargo transport, which aligns with the initiative's

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aim to promote cleaner and healthier modes of transport [5]. Germany, in particular, is expected to see a rise in electric vehicle sales fueled by government incentive programs from January 2026, allocating approximately €3 billion towards the incentive scheme for transport [6]. This incentive is expected to support the sales of an estimated 800,000 EVs up to 2029. Furthermore, as the global economy is projected to triple by 2060 and shift towards electrification in the automotive sector, there is an escalating demand for research towards sustainable solutions in manufacturing and end-of-life strategies. These solutions will help to mitigate the reliance on raw materials and reduce the share of EV parts in landfill waste, as well as promote circularity by aiming to reduce the adverse impacts of climate change to keep the raw materials in the supply chain. This paper discusses an approach to potentially aid in the research and development of solutions towards cleaner mobility, and the discussions are based on the paper submitted at the Electric Vehicle Symposium (EVS 38) [7].

The electric motor is a vital component of the powertrain of electric vehicles. E-motors are composed of resource-intensive raw materials and rare earth elements (REE), particularly in permanent magnet synchronous machines (PMSM). The PMSM is widely used and dominates in the German markets with a share of 64% due to its high power density and energy efficiency [8]. It is a three-phase motor powered by three-phase alternating current that works with three coils arranged in a circle to form the stator [9]. The PMSM is responsible for substantial environmental impacts, especially in the extraction of raw materials and the production phase. Although the end-of-life phase has lower impacts compared to the production or use phase, other elements in the production process that can have a big impact on an electric vehicle's environmental effects include certain material or component production, maintenance, and the electricity mix for the proportion of various sources used to generate electricity [10]. However, if those components are recycled to create new materials or utilized in other automotive applications, it would alleviate the environmental consequences associated with landfill disposal. This would reduce the amount of valuable scrap that ends up in landfills as waste and reintegrate resources such as steel, aluminum, or rare earth elements into their respective supply chains to lessen reliance on raw materials.

The PMSM was valued at 23.0 billion USD globally in 2024 and is anticipated to reach 36.2 billion USD by 2033 [11] due to increasing adoption of electric vehicles and automation technologies. An essential element of the market for PMSM is the implementation of modern manufacturing techniques that improve the production efficiency and performance of these motors. The adoption of these advanced methods has resulted in enhancements in motor durability, thermal management, and overall energy efficiency. Manufacturers are investing in research and development to identify creative methods for optimizing material and technology usage, hence reducing prices and environmental impacts, which further accelerates market growth. While the market share of retrieved materials from electric motors and other EV components is in varying estimated values, there have been several studies on the sustainability of recycling e-motors and permanent magnets (PMs) [12,13]. However, the scope of this research did not explicitly emphasize comparing the manufacturing of e-motors and the effects of their recycling. Several studies have addressed the manufacturing or sustainability of e-motors, but with varying magnet selections [14,15]. The currently available studies on the disassembly and recycling of e-motors for the recovery of specific metals (e.g., PMs, aluminum, steel, and copper) are limited in scope. Furthermore, ongoing research on the design optimization of electric vehicle components and the reduction in material dependency, without compromising efficiency, provides opportunities for continuous evaluation and improvement in sustainability studies. An assessment of the recycling process could produce significant insights into the

impact profile and identify opportunities for enhancing the basic materials utilized in e-motor production.

In the subject matter of the sustainability of electric vehicles and their components, there are varying results of LCA studies [15–17] and the results are inconsistent to compare due to a lack of data, varying scopes or boundaries of the study and different LCA methodologies [18]. In some cases, the primary data on the entire life cycle of an electric vehicle or its components are not available. Therefore, many studies rely on secondary data from the literature and databases, with further assumptions [19]. To cover these research gaps and to add valuable contributions towards the research and development of sustainable production and recycling process of this essential component of electric vehicles, further LCA studies are needed.

Aim and Goal Definition

This study aims to assess the life cycle sustainability assessment of e-motor components with our source of primary data at the German Aerospace Center (DLR) and compare it with the recycling impacts of the materials. In this study, we examined the life cycle assessment (LCA) impacts of a PMSM with neodymium iron boron (NdFeB) magnet manufacturing process, along with the effects of recycling the components recovered from its dismantled and sorted materials at the end of their use phase. The study aims to assess the LCA of the manufacturing and recycling process and identify the environmental hotspots to interpret and communicate the essential findings. The functional unit is expressed as 1 kg of motor production and 1 kg of recycled motor. The results of our LCA study are shown with the impact categories following a discussion. Our discussion covers significant recent advancements, the current state-of-the-art recycling processes for e-motors, and emission-saving potentials. It is to be noted that the study covers the system boundary of e-motor production and the recycling process. The impacts for e-motor production from specific recycled materials or the use phase of the motor are not under the scope of the study. For the purpose of simplicity of scope definition, we did not focus our study on comparing the PMSM with other magnet types or other types of motors. But rather, we focused our assessment on the manufacturing and recycling processes of the PMSM at the material level for each of their sub-components (motor, rotor, and stator), as well as the production and recycling of NdFeB magnets. We have, however, outlined the possibility of design changes with different materials and magnet choices in Section 4.2. The results of the study are relevant for the LCA research target groups for the development of production and recycling processes of PMSM in the electric mobility sector.

2. Methods

2.1. Production of PMSM

The production of electric motors is usually done by direct vehicle manufacturers or suppliers [16]. The main components of the e-motor are the housing, rotor and stator, made of laminated iron sheets, aluminum, steel and copper. Rare-earth magnets such as dysprosium and NdFeB are also included in the component construction.

The stator is composed of thin layers of specialized steel to reduce the eddy currents produced by the magnetic field [20]. The core is often composed of electrical steel, possessing specific electromagnetic, thermal, and mechanical characteristics. The alloy utilizes silicon to achieve these properties. Electrical steel disks and laminations are assembled to create the cores. The rotor consists mostly of steel sheets, magnets, screws, and a shaft. Electrical steel disks and laminations are assembled to create the cores. Laminations should be exceptionally thin and coated to minimize electromagnetic and thermal losses [19]. The stator is the stable part and holds most of the share of electrical steel sheets and copper

windings. Other components of the stator include materials for coating, such as insulating paint, resin, and others. The conducting wire is situated in the stator slots and functions to generate a magnetic field that interacts with the field produced in the rotor by the magnets and rotor iron core. The insulation of conducting wire comprises a rigid, lustrous coating composed of polyester resins, polyamide resins, or alkyd resins. It was estimated, based on observed documented values, that the enamel coating layer increases the diameter of the bare wire by 10%. The motor housing is an inactive component of an electric motor; however, it plays a crucial role in frame holding, protection, and cooling the active components of the machine [21]. Each housing requires bearing shields on both sides for enclosure. The dimensions and weight of the housing may vary considerably, principally affected by the stator configuration, cooling and protection parameters (e.g., casting wall thickness), and the installation conditions of the machine within the vehicle [9]. Components vary among vehicle kinds and sizes to meet distinct powertrain needs, regarding both weight and the composition of subcomponents and materials [20]. The housing sector, although comprising just 22% of the total weight, contains the highest range of sub-components. The majority of housing materials consist of steel for various sub-components, including connecting bushings, Allen screws, ball bearings, and retention rings. Figure 1 breaks down the weight distribution and materials of the components of the PMSM examined in our analysis. The rotor accounts for the largest proportion of weight (41%), followed by the stator and housing. The data were essential for conducting inventory analysis and impact assessment. The primary materials for motor production components include aluminum, copper, steel, and rare earth elements [20]. In the case of magnets in e-motors, the NdFeB magnets possess the highest energy density compared to other commercially available grades, making them the favored choice for the automotive sector [22]. NdFeB magnets consist mostly of neodymium, iron, and boron [20]. Typical compositions of NdFeB magnets include up to 10% dysprosium, 22–32% neodymium, 67–70% iron, and 1% boron. The fabrication of a sintered NdFeB magnet initiates with the development of a mother alloy including neodymium, iron, and boron via strip-casting. Boron is often provided in its elemental state or as ferroboron. Additional materials beyond base ingredients, such as carbon, may be included to enhance specific qualities. The production of neodymium magnets entails a series of steps. The sintered magnet method processes raw ingredients (neodymium, boron, and iron) by melting them in a furnace and casting them into a mold. Subsequently, the substance is crushed and ground, and the resulting fine particles are compacted into solid blocks by a process called sintering. The blocks are cut into a specified shape and then polished. They are then coated with a protective layer and magnetized. A total energy usage of approximately 32.5 kWh is associated with the manufacture of each kg of primary magnet [14,18,23]. These processes are included in the boundaries of magnet production. Figure 2 provides an outline of the basic component manufacturing and motor assembly stages.

The motor is the complete assemblage that encompasses the stator and rotor constituents. The primary function of the structure is to provide support and housing for the interior components, ensuring their correct alignment and operation. Additional components like cooling systems, bearings, and housing enclosures equip the motor. These characteristics serve to safeguard the internal parts and dissipate the heat produced during operation [19]. The immobile component of the electric motor—the stator is usually constructed from a layered steel core with copper wire windings encircling it. The rotor, situated within the stator, is the component of the electric motor responsible for rotation. Typically, it consists of a central rod and a sequence of conductive bars or coils positioned around it. When an electric current passes through the stator windings, it produces a magnetic field that rotates. The magnetic field and the rotor interact, resulting in torque

generation that causes the rotor to rotate and drive the mechanical load [9]. A description of the specification of our study case of PMSM is outlined in Table 1. The specifications outline an exemplary reference to the power and speed of our studied PMSM of approximately 106 kg to aid experts in motor type and power specifications as a reference scenario in future LCA studies and to improve the technical efficiency of the motor.

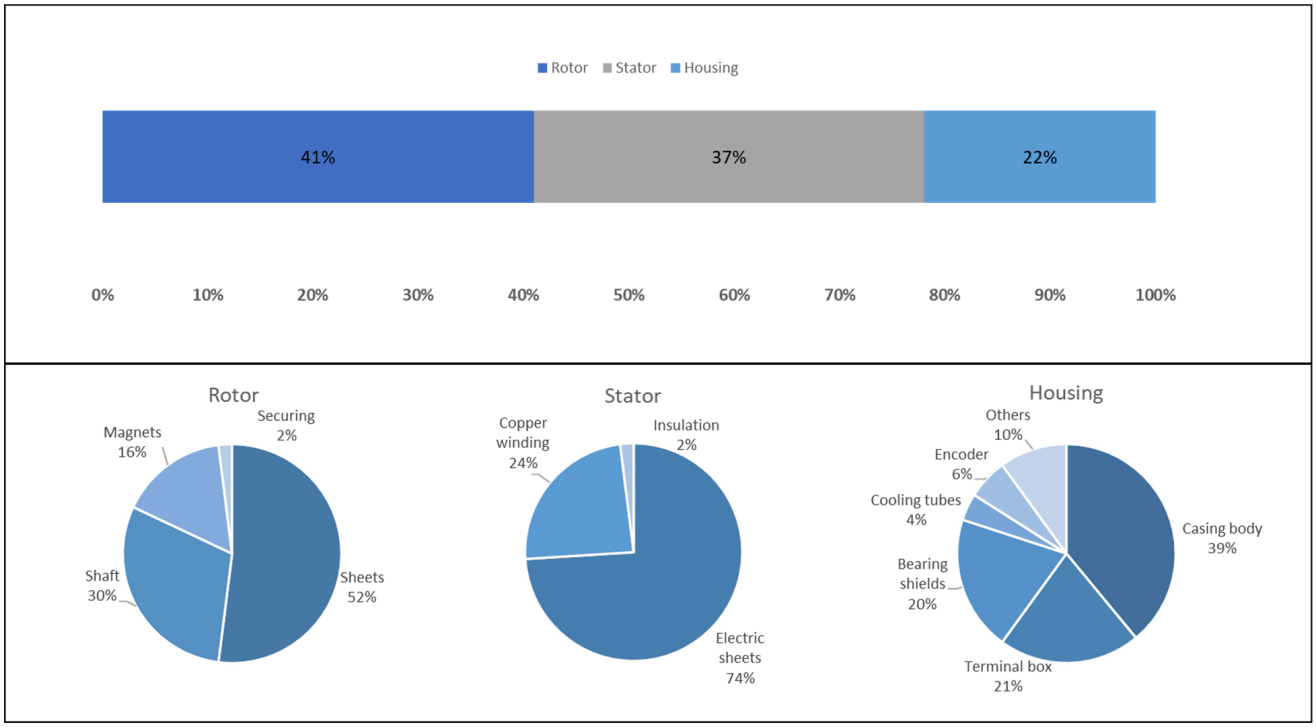


Figure 1. Weight share and material distribution of components of PMSM.

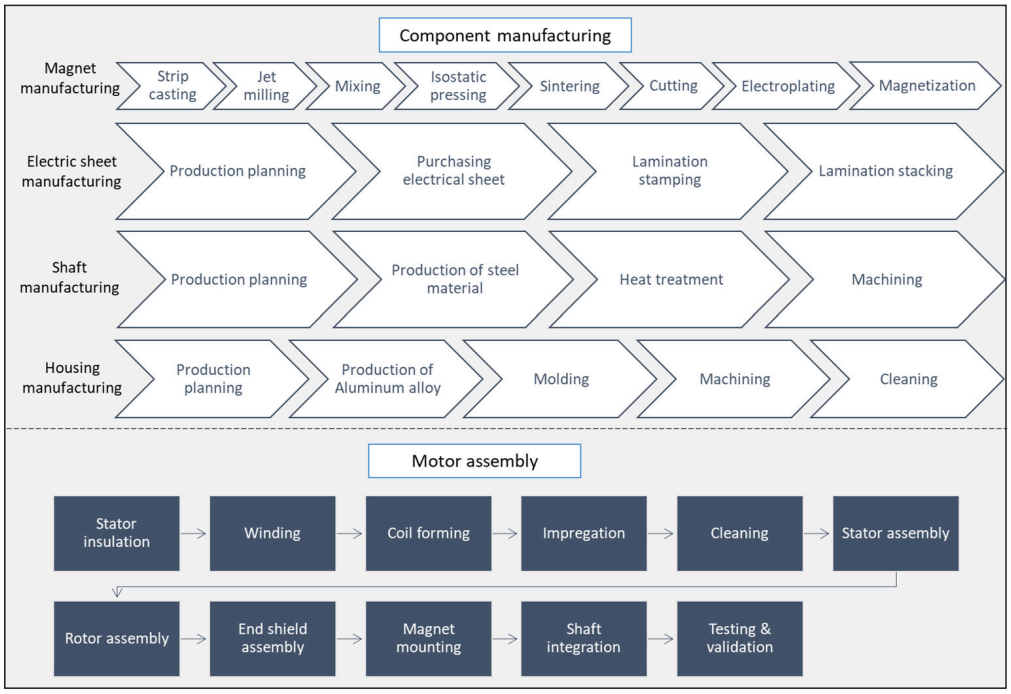


Figure 2. Manufacturing process of components and motor assembly.

Table 1. Specification of the PMSM in the study.

Parameters	Unit	Value
Stator outer and inner diameter	mm	209/115
Rotor outer and inner diameter	mm	230/217
Axial length	mm	100
Magnet thickness	mm	8
Lamination length	mm	95
Power	kW	70–150
Speed	rpm	200

In our study, we considered the raw material extraction, component production and assembly of the PMSM in the system boundary. We considered the production of a complete motor and the recycling of the motor, and expressed the results in functional units per kg of motor produced and recycled. Additionally, other inputs (e.g., electricity/energy) are also considered within the boundaries of the evaluation study.

The engine housing manufacturing process begins with the formation process. From a theoretical perspective, we can use various casting procedures to produce casings. Die casting and extrusion have become well-established in the realm of large-scale production [24]. Extrusion, similar to die-casting, enables the production of intricate shapes and profiles. To achieve this, we first heat the material and then apply pressure to force it through a die opening. Prior to conducting the casting process on a workpiece, it is necessary to create a mold. Die casting is a permanent mold procedure that can produce up to 80,000 castings [25]. The hot-work tool steel mold is subsequently cleaned, coated with a release agent, and sealed. The cores are subsequently inserted to establish the internal shapes of the workpiece. Following that, the machine applies substantial holding pressure for the entire solidification process. Upon completion of the solidification process, the machine opens, and simultaneously, the ejectors discharge the components from the mold. The product is removed and then cooled. In comparison to alternative molding techniques, casting provides advantages of reduced energy usage and enhanced material efficiency, particularly in applications where complex shapes and high precision are required, leading to reduced waste and lower production costs [24]. Stacks of electrical laminations, insulated from each other, construct the power-generating components of all motor technologies, particularly the rotor and stator. The motor's efficiency increases by suppressing eddy currents [9]. The manufacturing process of electrical steel is highly intricate, requiring the employment of several workers and multiple production stages. Therefore, stator producers purchase electrical steel as a component from external sources [19]. Figure 3 shows the technologies involved in the production of different components.

2.2. Recycling Process

The EU Directive on end-of-life vehicles [26] has established specific objectives to encourage the reuse, recycling, and recovery of materials. According to the directive, the combined weight of materials reused and recovered from the vehicle must amount to 95% of its net weight, with a minimum of 85% from reusing and recycling. Currently, there are few studies done on the recyclability of the PMSM and its impact assessment. Some studies discuss only the recycling of NdFeB [13] or the metals such as aluminum, magnesium, copper, and others [24]. Other studies such as [27] focused on the impact assessment of production and remanufacturing from recycled machines, showing potential emission and material reduction by using recycled materials. Base metals such as aluminum, copper, zinc, and nickel are indispensable for several components in the automotive, aerospace, and construction industries. Their distinctive thermal, mechanical, electrical, and insulating

properties, combined with their remarkable recyclability, make them essential [24]. Yet, the current recycling of some metals (e.g., metals in PMs) is quite limited, and only small amounts of scrap material are returned to the alloy-producing plant [14]. Therefore, an evaluation of the recycling process could provide clear insight into the impact profile and pose potential for reducing emissions of the base materials used in the production of electric machines.

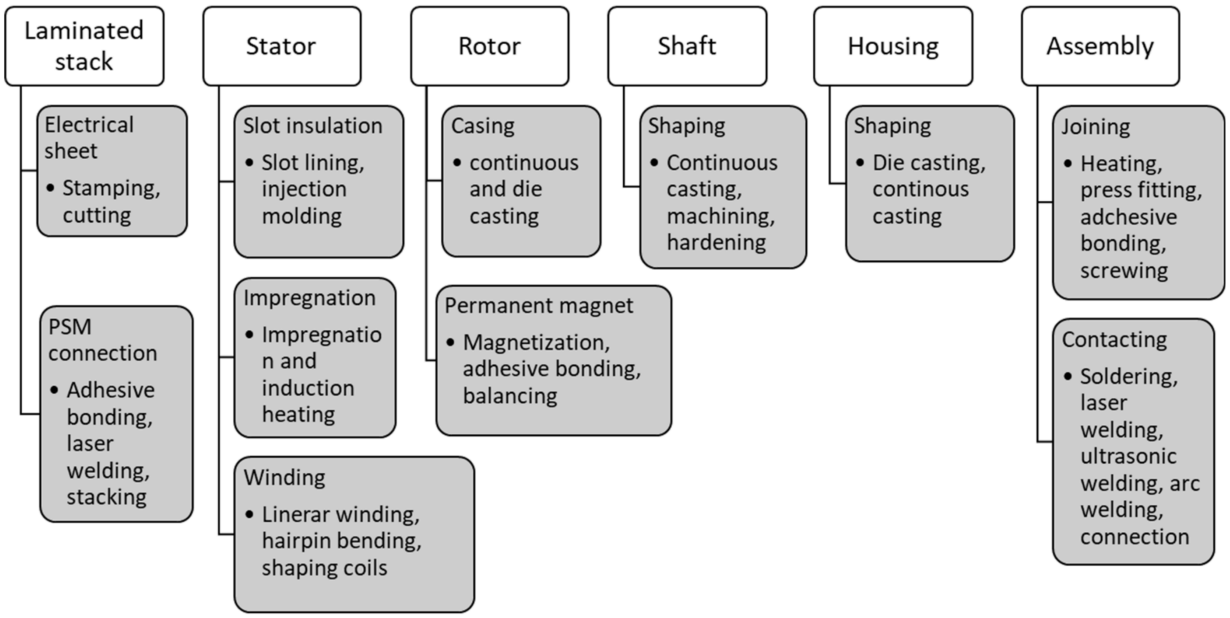


Figure 3. Manufacturing technologies of PMSM.

Like other energy conversion and propulsion components, the recycling and remanufacturing process of materials for an e-motor involves several key steps: collecting the returned products, conducting an initial inspection and sorting, disassembling the motor, separating the metals and PMs, recycling or reusing, inspecting and grading its components, and finally assembling it. If necessary, any materials that need to be disposed of are handled in a controlled manner [17,28]. The motor housing is first opened, and the rotor and stator are detached from each other. The rotor is dismantled, and the copper windings are withdrawn using hydraulic tools. Removing the rotor from the stator on a PMSM can be challenging because of the strong magnetic forces between the shaft and the stator. This task sometimes necessitates the use of intricate tools [28]. The individual components are renovated if necessary and reintroduced into the manufacturing process. After the dismantling process, the components are typically shredded and subjected to magnetic separation to extract iron concentrate, eddy-current separation to obtain a concentrate of mixed non-iron metals, and density separation to separate plastic, dust, and light materials. From the housing cover, cable harness, cooling system, and electronic components, recyclable elements such as aluminum, steel, and precious metals can be recovered. A comprehensive explanation of the recycling process of e-motors, describing the disassembly and other following procedures are outlined in the study [17]. Figure 4a shows a generic breakdown of the recycling process of the electric machine at the end of its usable life.

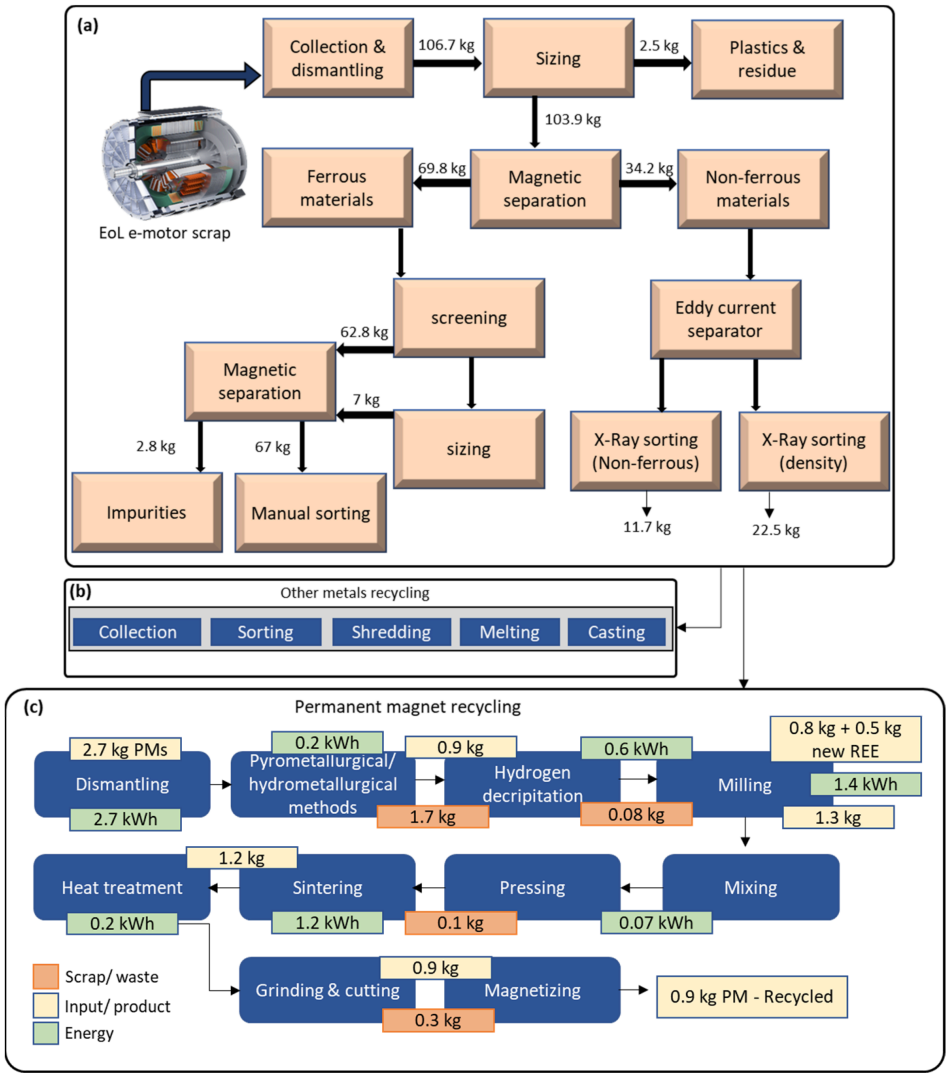


Figure 4. Overview of the complete recycling process of PMSM. (**a**) Motor disassembly and sorting; (**b**) metal recycling processes relevant for aluminum, steel and copper; (**c**) permanent magnet recycling based on compilation of recycling technologies.

The majority of materials, specifically aluminum, copper, and steel, are regarded as recyclable, with varying rates of recycling shown in Figure 4b. The energy intensity required for the shredding and subsequent separation processes, including magnetic separation, is estimated to be 0.066 kWh/kg according to similar studies [23,28]. Insulation materials, polymers, and resins are not often recycled but instead categorized as waste (inert waste for landfill). Previously, the magnets were discarded together with other non-recyclable components of the motor. In this study, we assumed magnets are dismantled manually and undergo recycling like the common metals. The functional unit of our study follows the impacts per kg of the production and recycling of PMSM. To model the study for recycling, we developed the process for the recycling of a complete motor and calculated the impacts based on per kg of motor recycled. To start the evaluation of the recycling process in the study, we can see that after the collection and sizing of the complete motor, 34.2 kg of non-ferrous (Al, Cu, etc.) metals are obtained from magnetic separation from the input of the whole motor of 106 kg. On the other hand, 69.8 kg of ferrous materials (steel, PMs, and others) are obtained from magnetic separation from a whole motor. Through the last phases of pre-sorting materials such as screening, eddy current separator, sizing, or x-ray sorting, a total of 67 kg of ferrous materials and 34.2 kg of non-ferrous materials

are obtained from 106.7 kg of e-motor. Additionally, 5.5 kg of inert waste is determined. The amount of retrieved and sorted metals then follows specific metal and alloy group recycling processes. It is to be noted that the methodology and processes of dismantling and recycling the PMSM are derived from compilations of state-of-the-art scientific papers and expert knowledge at DLR. This state-of-the-art method is subjected to continuous improvement for reducing material losses and improving the recycling efficiency of the motor.

2.3. Permanent Magnet Recycling

Permanent magnet production is a resource- and energy-intensive process in e-motor production. In our evaluation, the primary production process, the majority of the impacts of e-motor production arise from rotor production (78.58%), which would mostly be attributed to PM production. Therefore, it is essential to explore the recycling process of this crucial element in PMSM to navigate the potential of emission reduction and study novel ways to reduce the dependency on virgin materials. Several studies covered topics on PM recycling [12–14]. Rare earth magnets cannot be 100% recyclable and require the addition of REE to reinstate the magnetic properties after certain steps of recycling. This is required due to magnetic material loss in the recycling stages. As NdFeB magnets consist mostly of neodymium, iron, and boron, with minor quantities of other REE, including dysprosium, to utilize NdFeB magnets again after recycling, it is vital to enhance their thermal stability. This is achieved by including specific heavy rare earth elements, such as dysprosium, to substitute for a portion of the neodymium [18]. These additional elements are used to improve the magnetic and physicochemical characteristics of the magnets once they have been sintered [13]. The recycling route can be discarded if the magnets are not corroded or have lost their magnetic properties. In this case, the magnets can simply be dismantled, tested and reinserted in the rotor. From the evaluation of the production process of PMSM, we considered 2.7 kg NdFeB magnets in the evaluation obtained from the primary data. Current studies have looked into different ways to recycle NdFeB magnet scraps, such as direct reuse, reprocessing through hydrogen decrepitation, pyrometallurgy, hydrometallurgy, electrochemistry/electrometallurgy, bio-metallurgy, and often a mix of these methods [28]. These methods, including hydrogen decrepitation, disassemble the rare earth minerals into a fine powder to recycle magnets. The hydrogen decrepitation method has demonstrated efficacy in removing nickel coating from magnet surfaces, causing it to separate in the form of thin sheets. The hydrogenated powder is then isolated by passing it through a permeable drum and a mechanical sieve to eliminate any residual nickel particles. This powder is then reprocessed to create magnet material once again, with a loss of magnetic strength of up to 3% [13]. Figure 4c shows a simplified process of magnet recycling using a pyrometallurgical or hydrometallurgical method based on a summary of various approaches across studies [13,22,25]. We have assumed this as well for our magnet recycling approach. The material flow of the magnet begins with 2.7 kg of PMs dismantled from the electric machine, followed by a series of steps. The figures of energy input, material losses, addition of new input, and waste produced are based on estimations of scaling values from relevant studies that followed the recycling of magnets using various methods. Therefore, the material flows are not relevant for a specific method of magnet recycling but rather serve as a single estimate of various methods. This approach can be refined and re-evaluated in future investigations of magnet recycling and its environmental impacts. From the magnet recycling process in our study, we assumed the recycled magnet of up to 0.9 kg could be achieved from 2.7 kg of primary PMs.

It is important to acknowledge that the processes of hydrogen decrepitation, jet milling, and sintering also need a substantial amount of energy. Nevertheless, these stages are identical in both systems. However, the primary production method of generating 1 kg of sintered Nd-Fe-B magnets requires 32.5 kWh of energy, whereas the PM recycling process consumes 2.94 kWh of energy [16,23]. As a result, the recycling process reduces energy consumption by approximately 91% when compared to the virgin route of production. The primary manufacturing process uses strip casting to create PM, a feature not present in the recycling process [13]. The characteristics of PMs are dependent on temperature, and typical NdFeB magnets are easily demagnetized at high temperatures. Demagnetization occurs when the magnetic load surpasses a critical limit, which may happen during failures such as a short circuit [14]. The highest operating temperatures for magnets in traction motors may surpass 150 °C, considerably above the standard maximum permissible working temperatures of typical NdFeB magnets. Consequently, to use NdFeB magnets in automotive traction motors, it is imperative to improve their thermal stability [19]. The recycling methodology is beneficial only if the magnetic properties and thermal stability can be restored at the optimum level.

It has been observed that the recycling magnets have a more favorable impact on the environment compared to the virgin production approaches [15]. Due to the variations in the functional unit across different studies, the results are not specifically comparable to each other. However, it is worth mentioning the environmental impacts in those studies as they covered a variety of topics in manufacturing. For example, one study [12] mentions the climate change impacts of virgin magnet production as 8.54×10^{-4} kg CO_2-eq. and recycled as 6.29×1^{-4} kg CO_2-eq. The functional unit mentioned in the study was 1 kA/m (kilo ampere/meter). Other studies [15] mentioned the climate change impacts of virgin magnet production as 27.6 kg CO_2-eq. and 12.4 kg CO_2-eq. for the recycled production of 1 kg of magnet as its functional unit. Other impact categories discussed in these studies range accordingly based on the chosen LCA methodology.

2.4. Material Recycling After Screening and Sorting

Following the dismantling process, the retrieved materials are collected and undergo a specific recycling process based on the metal alloy type. Our investigation yields 67 kg of ferrous materials and 34.2 kg of non-ferrous materials from a total of 106.7 kg of e-motor. Aluminum, steel, copper, and brass constitute the majority of metals recovered from the categories of ferrous and non-ferrous materials. Traces of inadequate quantities of other metals, including nickel and zinc, are present. Since each metal possesses distinct recycling methods and rates, they are segregated post-dismantling to follow their respective recycling processes.

Aluminum is used extensively and comprises the majority of material proportions in the production of e-motors. Virgin aluminum production includes the processes of bauxite mining, alumina extraction, anode manufacture, electrolysis/ingot casting, and material transformation (casting or forging) [29]. The secondary aluminum has several other processes, such as scrap transportation, scrap processing, remelting, machining, and material transformation by casting or forging. Primary aluminum can be added to achieve the desired quality and purity levels. The recycled aluminum does not have mining, alumina extraction, or anode manufacturing, leading to significant raw material savings [30]. Thus, secondary or recycled aluminum has emission savings to a considerable amount [25]. Studies also show that recycling one ton of aluminum can conserve up to 8 metric tons of bauxite, 14,000 kWh of energy, 6300 gallons of oil, and 7.6 m^3 of land use [31]. Recycling aluminum enables a 95% decrease in the amount of energy used

(0.78 kWh/kg Al recycled; primary aluminum production requires 15.7 kWh/kg) and only produces 5% of the greenhouse gas [24,31].

Crude steel production from primary raw materials emits 2.2 t CO_2/ton of steel produced [32]. Since steel can be almost infinitely recycled, recycling steel has several benefits in saving CO_2 emissions compared to primary steel production. Pre-consumer and post-consumer steel scrap can be used to make new steel products. Given its inherent magnetism, it is easy to recycle and is the most recycled material in the world [33]. Two primary methods of steel manufacturing are basic oxygen steelmaking (BOS) and electric arc furnaces (EAF). The processes involved in the BOS method that is used for primary steel production encompass ore mining, coke production, sintering, pelletizing, blast furnace operation, basic oxygen furnace operation, and ingot casting. The processes involved in the EAF include the transportation of scrap metal, the melting of the scrap metal in an electric furnace using electric energy, and the casting of the resulting molten metal into ingots [32]. The EAF method is used for recycling scrap material. In addition to the main result, there are two further outputs: co-products, such as EAF slag, and certain by-products. Studies have shown that the primary steel production process significantly impacts the environment, especially in terms of harm to human health. The blast furnace's consumption of coke and the sinter plant's consumption of iron ore were responsible for this impact [25]. This impact is avoided by utilizing scrap in the recycling process. As a direct supply of iron units, scrap is occasionally added to the blast furnace, lowering greenhouse gas emissions. Scrap is essential for reducing industry emissions and resource consumption. Using steel scrap in the production process also reduces CO_2 emissions by 58%. For example, each ton of scrap used in the production of steel prevents the emission of 1.5–1.9 tons of CO_2 and the usage of 1.4 tons of iron ore, 740 kg of coal, and 120 kg of limestone [24,34,35].

Other metals, such as copper and brass, also have a significant scope for recycling. Similar to other metal recycling processes, copper or brass recycling has energy-saving potential due to the elimination of mining, refining and production processes related to primary production, such as extensive materials, energy and waste generated. Copper is extensively used in magnet windings, and brass is used in coolant fittings in the housing. For the recycling process of Cu, the scrap Cu is first collected at its end-of-life from the motors through manual dismantling. The scrap is then weighed and sorted according to grade and type. The Cu wire is then granulated for further processing, such as melting in EAF, refining, casting into ingots or billets, and hot or cold rolling [29,36]. Both primary and recycling processes output a refined Cu cathode with 99.99% purity [25]. There are additional inputs of materials in secondary production, such as quartz sand, sulfuric acid and slightly higher use of natural gas, all of which are absent in primary production. However, there are also considerable savings of energy in secondary copper production with respect to raw materials and energy used in primary production, such as copper ore mining, quick lime, ferrous or sodium sulfate, and diesel [37]. Brass, on the other hand, after being sorted and cleaned, is subsequently melted in furnaces that reach high temperatures. The process of melting facilitates the segregation of copper and zinc, which are the primary constituents of brass. As a consequence, a liquefied brass mixture is obtained, which can be formed into different configurations. Following the process of melting, the molten brass is transformed into solid ingots or other desired forms, depending on its intended purpose. Contemporary brass typically consists of 67% copper and 33% zinc. For the presence of these alloys, the recycled brass usually does not reach the same density as the original cast material. However, the recycled material could still be applicable with a reduced shear strength of 6–33% [38].

2.5. Methodology of Life Cycle Assessment

In the study, we carried out LCA according to ISO 14040/44 [39,40] for the production and recycling of PMSM components and materials. ISO 14044 specifies the prerequisites for an LCA study and offers implementation guidance, whereas ISO 14040 outlines the framework and the guiding principles. The four stages of an LCA are as follows: formulation of a goal and scope, outlining the life cycle inventory, executing the life cycle impact assessment (LCIA), and interpreting the study. The study's purpose and scope, together with all of its fundamental presumptions, are established in the first phase. This covers the functional unit, the system boundaries, the allocation process, and the description of the product systems, in addition to the temporal and geographical framework. Additionally, an explanation of the LCIA's methodology, evaluation, assumptions, data, and quality, as well as any limitations found, should ideally be included in an LCA study [41,42]. The lifecycle inventory phase gathers all pertinent data for the processes inside the system boundaries based on the scope definitions. We have taken these points into consideration during the course of our study.

2.6. System Boundaries and Scope of Study

The system boundary in our study (Figure 5) covers the production of our PMSM and its recycling. The use phase is not considered in the study, as we limited our scope to analyze the production impacts and the recycling impacts of the components and materials. The study is a part of the Matic-m project at DLR to focus on methods and technologies for the circularity of materials in Germany. Therefore, the background data follows the market assumptions in Germany. The production is assumed at DLR, with the raw materials accounting for standard transportation of the materials. The machine dataset can be comparable for an electric vehicle of a specific size and class, such as a Volkswagen ID.3 compact wagon or similar. The motor is the complete assemblage that encompasses the stator and rotor constituents. The boundaries included sub-component production, such as housing, shafts, magnets, and steel from primary sources, as well as assembly of the sub-components. The modeling approach assumed for the recycling of motor, materials in the motor, and PMs are discussed in Sections 2.2 and 2.3. It also includes the disassembly of the sub-components, sorting the ferrous and non-ferrous materials, and recycling of the materials. We have used the ReCiPe 2016 v1.03, midpoint (H), as the LCA methodology. The inventory included in Table 2 shows the simplified input for the production of rotor, stator, housing and other relevant information for executing the LCA. A detailed inventory is available in Supplementary Table S2.

Table 2. General inputs for the evaluation.

Processes	Amount	Unit
Production		
Stator	37.3	kg
Rotor	43.8	kg
Housing	25.9	kg
Recycling		
Collection	106.7	kg
Plastic residue	2.5	kg
Ferrous materials	69.8	kg
Non-ferrous materials	34.2	kg

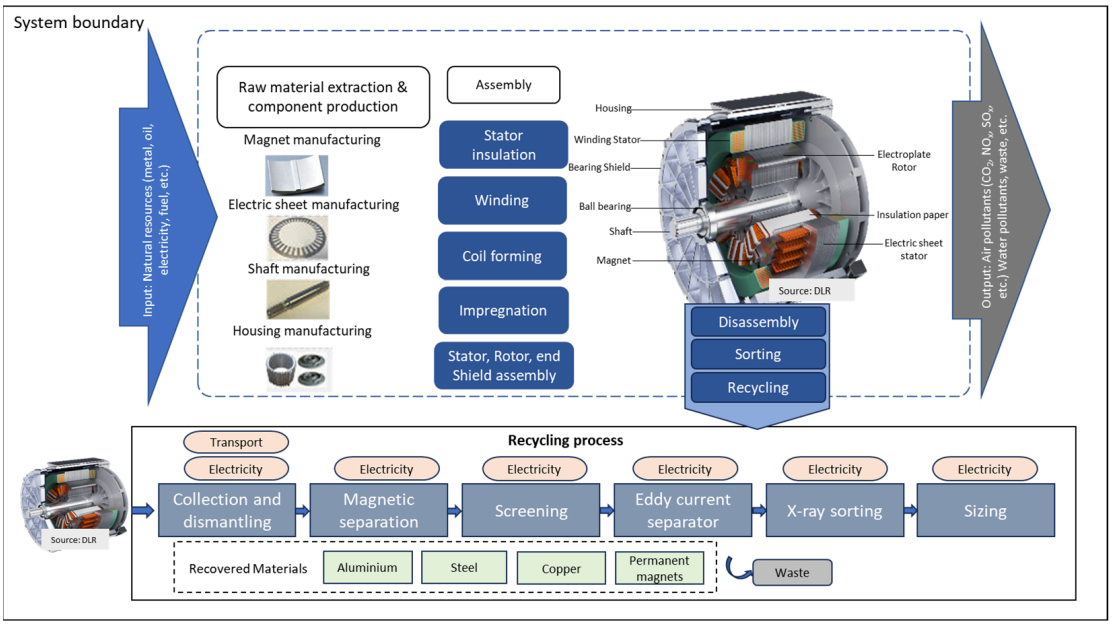


Figure 5. System boundaries of the study.

The housing of the motor holds the least share of weight (22%) and comprises mostly aluminum for the casing and end shields of the motor. Other materials are steel for various sub-components of the housing, such as connection bushing, Allen screw, ball bearing, and retaining ring. The stator comprises 37% of the weight of the motor. The majority of the materials in the stator are steel sheets and copper winding. Other components of the stator include materials for coating, such as insulating paint, resin and others. The rotor holds the majority of the weight (41%) and comprises steel sheets, rare earth magnets, steel for end disks, the shaft, the feather key and the Allen screw. The processes are modeled using process flows available in ecoinvent v3.12 in the OpenLCA software V2.6.1. The cut-off method is used for the ecoinvent flow data, setting the cut-off criteria at 1% of the mass. No further assumptions on allocations are made. The data for the study includes various sources, such as the primary data from expert knowledge at DLR via personal communication and relevant scientific papers. The missing data were added based on assumptions from scientific literature references [12,16,21,28,42–45].

3. Results

3.1. Life Cycle Impact Assessment—Production and Recycling

In this section, we outlined the life cycle impacts for the production and recycling of PMSM. The LCA impact assessment has been done by using the ReCiPe methodology, comprising 18 midpoint categories. In the category of climate change, the recycling process results in 5.5×10^0 kg CO_2-eq./kg e-motor. compared to primary production of 9.56×10^0 kg CO_2-eq./kg e-motor. The other impact categories are shown in Figure 6. As outlined, the recycling process contributes to substantial lower emissions in most of the impact categories except a few categories such as material resources: metals/minerals (7.84×10^1 kg Cu-eq./kg e-motor in primary motor production and 2.57×10^3 kg Cu-eq./kg e-motor in recycling process); human toxicity: non-carcinogenic (2.37×10^1 kg 1,4-DCB-eq./kg e-motor in primary production and 8.91×10^1/kg e-motor in recycling process); and ecotoxicity: freshwater (1.31×10^0 kg 1,4-DCB-eq./kg e-motor in primary production and 2.13×10^0 kg 1,4-DCB-eq./kg e-motor in recycling process). Some impact categories, like particulate matter formation and photochemical oxidant formation for both human health and terrestrial ecosystems, do not show significant variation between the two processes. An

overview of all the impact categories is provided in Supplementary Table S1. In general, the recycling process has lower impacts than the primary production process, but the impact categories that have higher impacts in the recycling process of the PMSM can be attributed to material losses, the addition of virgin materials for the quality of retaining useability of materials, and other factors such as sensitivity to rare materials present in the e-motor.

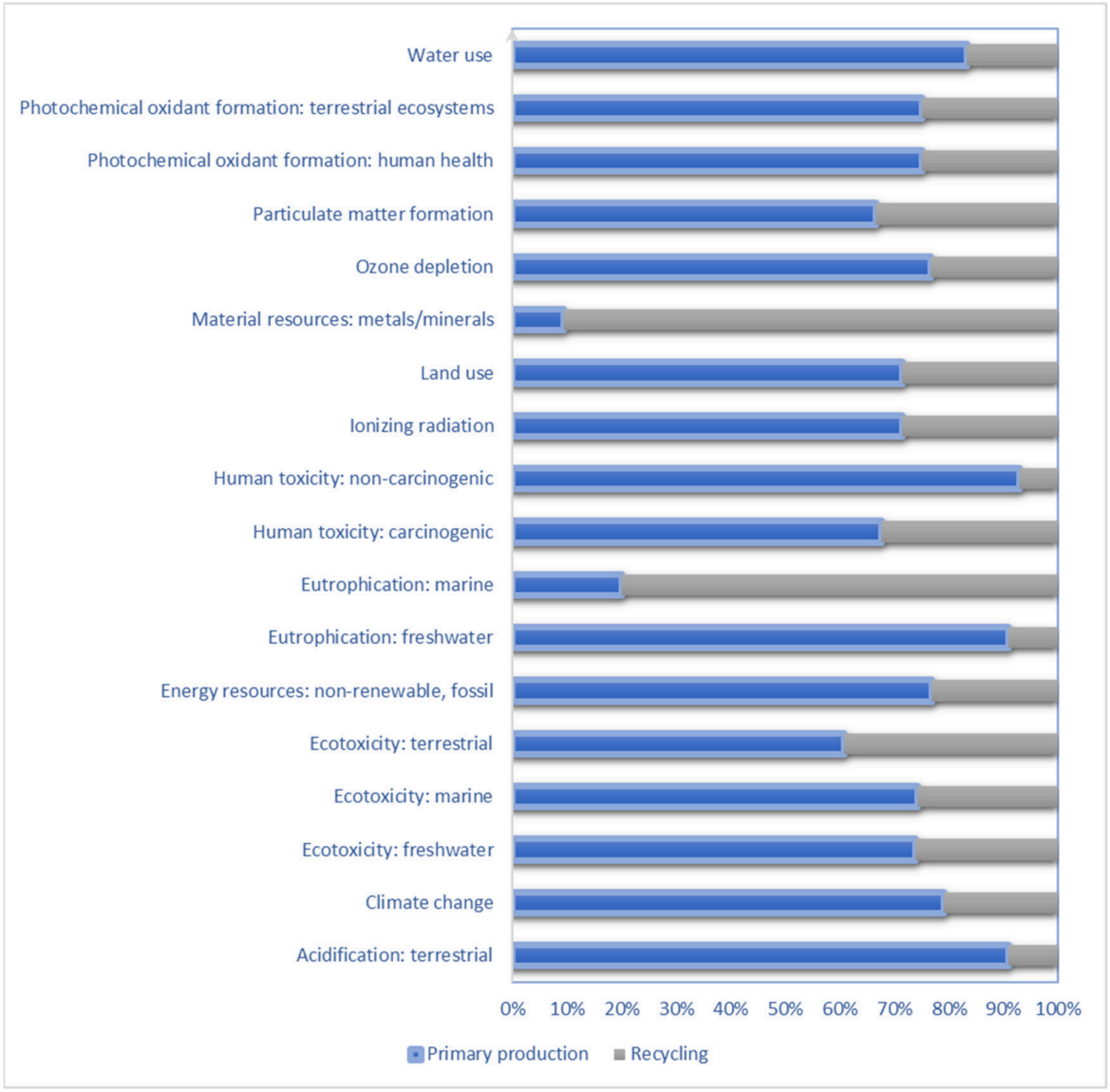


Figure 6. Midpoint impact categories for production and recycling of PMSM.

In the category of climate change for primary production, rotor and housing account for the majority of impact contributions (78.5% and 18.8% respectively). Figure 7 outlines the impact distribution of the main components. The primary contribution of impacts from the rotor is due to rare earth magnet production (60%). Other contributions are from the insulation coating and steel production of various sub-components. For the contribution of housing, the housing production accounts for 18.85% of CO_2-eq/kg motor. The majority of the impacts are caused by aluminum production, followed by steel and brass production. Stator production accounts for the least impact contributions (6.23%). The impacts in stator production come from insulation coating production, insulation materials, steel and copper production, and other minor materials.

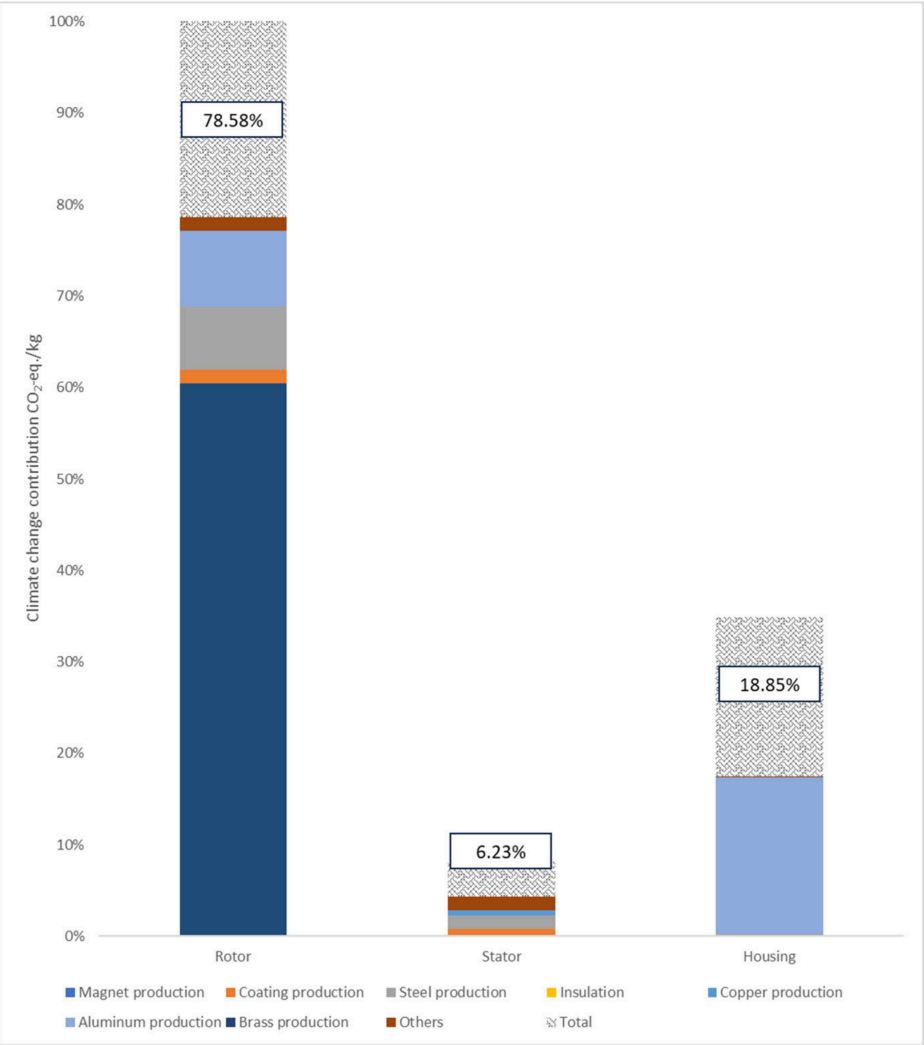


Figure 7. Impact contribution of components in the production phase.

Figure S1 in the Supplementary Materials outlines additional impact contributions and shows the impact distribution across all impact categories. It also shows that the majority of impacts lie in the rotor and housing production across the impact categories. This can also be typically attributed to the presence of steel, aluminum and PMs present in the rotor and housing. For the contribution of the recycling process, our analysis reveals that the majority of the impacts of the recycling of a complete motor lie mostly in magnet and aluminum recycling, accounting for mostly above 95% across all impact categories. This could be attributed to the fact that magnets have low recovery rates, and the addition of virgin REEs is always required to restore the quality of the magnetic properties [13,18,23]. Additionally, minor inefficiencies and material losses in the recycling process could contribute to impacts as well.

3.2. Sensitivity Analysis

We conducted a sensitivity analysis of the most contributing parameters to test the stability of the impact assessment results. We used high values (+20%) and low values (−20%) for parameters of the production phase. The high and low values have been defined and vary depending on prospective design choices to factor in the design for circularity aspect and improve the environmental performance outlined within the study scope of the project. The results did not show any major shifts in any categories, but there were slight benefits in impact reduction when production experienced a −20% reduction. These

findings can suggest that the reduction or optimization of materials in the production phase can have an overall contribution to emission reduction. The results of the sensitivity assessment are presented in detail in Supplementary Table S3.

4. Discussion

A significant amount of materials found in e-motors are recycled within a very intricate value chain. The product's material composition and lifespan differ significantly depending on the specific materials used, as each individual metal or sub-component has distinct rates of degradation or recycling routes. If we consider the disposal of the products without recycling, the impacts rise substantially compared to recycling. Sustainable manufacturing emphasizes the production of goods and the implementation of procedures that are cost-effective, reduce negative effects on the environment, prioritize the preservation of energy, and guarantee the well-being of employees and the local community [1]. Therefore, recycling products and keeping a circular loop of materials are crucial to sustainable manufacturing [17]. Recycled magnets taken from PMSM have a significant potential to support the circular economy and advance Europe's reliance on REE imports because of their extensive use in electromobility. The quality and recyclability of recovered magnets could have been impacted by adhesives, corrosion coatings, and efficient processes, as shown in the magnet recycling process. Enhancing efficient processes, such as adhesives that break down readily at lower temperatures, higher magnet purity and varied approaches for magnet recycling could provide for smoother magnet extraction. Functional recycling procedures have shown that recycled materials can function comparably to new ones. But certain problems persist, such as impurity uptake and coercivity loss. Scaling short-loop recycling procedures and creating automated disassembly technologies could provide a pathway to establishing a viable circular economy for NdFeB magnets.

For the production phase, the majority of the impacts, as shown in the results of Section 3.1, lie at rotor and housing production across all impact categories due to the presence of rare earth PMs, aluminum and steel. For the recycling phase, the impacts arise mostly from PMs and other common metal recycling, such as aluminum and steel.

4.1. Emission Saving on Recycling

Figure 8 shows the contribution to environmental impacts of the materials in the category of climate change for primary and recycled processes of production or all materials. The primary production route is observed to have higher impacts.

Primary aluminum manufacturing emits 7.14 kg CO_2-eq. However, our assessment reveals that the climate change emissions from recycling disassembled aluminum are 94.7% lower (0.78 kWh/kg Al) than those from primary production (15.7 kWh/kg). Secondary or recycled aluminum does not require electrolysis and therefore results in lower carbon emissions. Approximately 15,700 kWh of electrical energy is needed to create one ton of primary aluminum [24,29]. Recycling utilizes around 5% of the energy consumed in primary production. Recycling aluminum is beneficial as recycling does not change the structural integrity or quality of the material, and 1 kg of aluminum recycling saves 8 kg of bauxite, 4 kg of fluorides and 14 kWh of electricity [21,31]. Steel is employed in laminated stator and rotor core, shafts, ball bearings, screws and other parts of e-motor production in notable quantities. In our evaluation, emission reduction of 65% is observed from primary production. Similarly, emission reduction for other materials, for instance, copper (86.7%), brass (36.3%) and magnets (69%), is also observed in the evaluation. Copper and brass are used extensively in e-motor production. Copper or brass recycling has energy-saving potential due to the elimination of mining, refining and production processes related to primary production, such as extensive materials, energy and waste generated. Similar

studies also indicate the utilization of copper scrap yields substantial environmental advantages, as it lowers CO_2 emissions between 65 and 85% and conserves 85% of the energy required for primary manufacturing [36]. Brass recycling decreases the overall energy need by 29% and reduces the impact on climate change by 30% compared to traditional brass production [38].

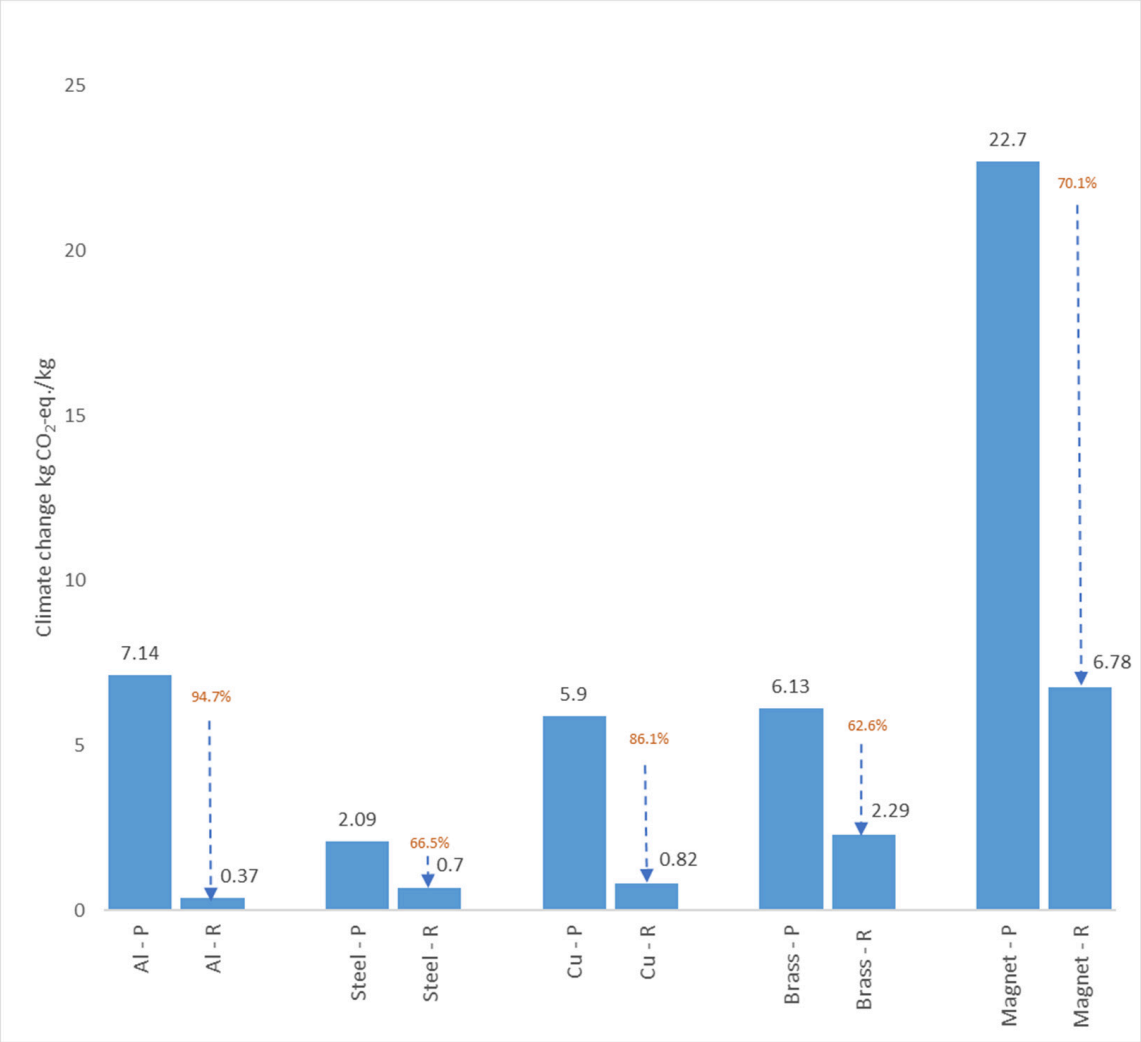


Figure 8. Emission reducing potential of recycled materials (R) and primary materials (P) commonly used in PMSM.

4.2. Alternative Design Options

Outlining the impact of early design changes to fit for design for circularity and sustainability can be beneficial to the vehicle manufacturers [16,21]. This can be implemented either with sustainable materials or alternative alloy choices. Therefore, we have provided a summary in Table 3 of some alternative design options to outline the understanding of the emission profile and to assist manufacturers in selecting an optimum design based on their preference towards sustainable options. The experts and specialists on electric motors at DLR worked to evaluate the design possibilities and the types of alloys in detail. This can assist manufacturers in selecting the optimal alternative based on their preferences for weight reduction, reduced emissions, or enhanced circularity in motor design. In our analysis, we did not define the environmental impacts of these design selections; however, we project that using various alloys or recycled alloys will have both beneficial and non-beneficial environmental effects. For example, in the housing choice, the recycled

aluminum alloy [AlMg4Fe2] could see an improved environmental benefit. The magnesium alloy [AZ91], on the other hand, could contribute to weight reduction but could significantly increase CO_2 emissions. The cast iron option would contribute to an increase in both weight and CO_2 emissions. Likewise, other components and their design choices could either improve or reduce weight, efficiency and environmental impacts. The varied weights of different alloys are attributed to the densities and properties of different metals. An extensive study on the efficiency and environmental profile of these design options with different alloys, recycled alloys and varied choices for other components is recommended for future research scopes.

Table 3. Different design options to consider sustainable choices.

Components	Alternative Design Options				
Housing	Al-alloy [AlSi12Cu1(Fe)] 27.8 kg	Recycled Al-alloy [AlMg4Fe2] 28.8 kg	Recycled Al-alloy [AlMg6Si2MnZr] 28.2 kg	Mg-alloy [AZ91] 18.2 kg	Cast iron 75.9 kg
Stator	Retracted winding—coil gets wound externally and is retracted into the stator slots; thin wire and a high number of windings are possible; more effort is required		Hairpin winding—copper wire gets formed into a U-shaped hairpin. It is inserted into the stator slot and welded to coils on the open side.		
Rotor	PMSM-NdFeB magnet: integrated magnets; high efficiency and power density; the most common type	PMSM-NdFeB magnet: surface magnets; high efficiency and power density; easy to disassemble	PMSM-SmCo magnet: integrated magnets; more material required than NdFeB magnets for similar efficiency	Electric excited synchronous motor: no rare-earth magnets required; rotor losses need to be cooled	Asynchronous motor: no rare-earth magnets required; robust against mechanical and thermal loads
Bearing shield	Al alloy [AlSi9Cu3(Fe)] 3.8 kg	Recycled Al-alloy [AlMg4Fe2] 3.7 kg	Recycled Al-alloy [AlMg6Si2MnZr] 3.6 kg	Mg-alloy [AZ91] 2.3 kg	Cast iron 9.7 kg
Screws	Stainless steel [X4CrNi19-12] 0.04 kg		Carbon steel [42CrMo4] 0.04 kg	Recycled stainless steel [X4CrNi18-12] 0.04 kg	

4.3. Extent of Relevance of Other Studies and Future Scope

Studies show that the global market for PMs is expected to rise significantly to 54.1 billion USD due to widespread dependency on PMs in the automotive sector [22]. On the other hand, there are also significant research advancements towards magnet-free motors [46]. Currently, there are relevant publications in the scientific community in the study area of electric motors and their sustainability covering a variety of motor types, magnet types and magnet-free motors. An extensive overview of several relevant LCA studies of electric machines is provided in [41]. However, they vary in terms of form, scope of study, functional unit, LCA methodology, database, software used, motor type and magnet types or powers, as summarized in Table 4. In many cases, due to these variations, the results are incomparable yet valuable for the researchers. Therefore, in this study, we aimed to extend the contribution towards this research area of the production and recycling of e-motors.

Table 4. Relevant studies comparing the sustainability of electric machines.

Reference	Motor Type and Scope	Functional Unit	Overview of Results
[19]	EV traction PMSM; detailed manufacturing LCI	1 traction motor	GWP: 200–400 kg CO_2-eq. Hotspots: copper, electrical steel, NdFeB magnets.
[42]	PMSM (NdFeB); PMSM (SmCo); PM-SynRM	1 motor	GWP: 150–350 kg CO_2-eq. NdFeB highest; ferrite lowest.
[41]	PMSM vs. induction	1 motor	PMSM has higher resource depletion; induction has higher copper/steel impacts.
[28]	NdFeB magnet production	1 kg magnet	GWP: 50–100 kg CO_2-eq/kg magnet. Mining + solvent extraction dominates.
[47]	NdFeB magnets	1 kg magnet	GWP: 70–200 kg CO_2-eq/kg. High acidification and toxicity impacts.
[48]	Rare-earth supply chain	1 kg REE	Energy: 200–600 MJ/kg REO. High emissions from solvent extraction.
[49]	Recycling vs. primary production	1 kg NdFeB	Recycling reduces GWP by 60–80% vs. primary production.
[50]	Industrial PMSM vs. induction	1 motor	PMSM has a higher GWP due to magnets; induction is higher due to copper.
[51]	Switched reluctance motor—SRM (no magnets)	1 motor	GWP: 100–200 kg CO_2-eq. Lower resource depletion than PMSM.
[52]	PMSM vs. induction vs. SRM	1 powertrain	PMSM has the highest resource depletion; induction has the highest mass; SRM has the lowest overall impacts.
[53]	Ferrite PMSM vs. NdFeB PMSM	1 motor	Ferrite reduces GWP by 20–40%, but increases mass and reduces efficiency.
[45]	Rare-earth mining + refining	1 kg NdPr oxide	GWP: 30–80 kg CO_2-eq/kg oxide. High water pollution indicators.
[14]	PMSM with recycled NdFeB	1 motor	GWP reduction: 50–70% vs. primary magnets.

Input regarding the weight and composition of components and sub-components is necessary to create a realistic and complete life cycle assessment. Nevertheless, such data might be challenging to acquire, as public vehicle powertrain characteristics are typically articulated in terms of power or torque. The absence of inventory data for e-motors about material composition and mass, particularly when technical specifications evolve to accommodate various automobile applications, can also contribute to varied results from published sources. Thus, in LCA modeling, we have to put up with some assumptions based on scaled values. It is to be noted that the replication of the model could result in variation in results. The reason could be attributed to different factors such as different functional units or LCA methodologies, use of different LCA software tools (GaBi, Simapro, etc.) and databases, and different versions of databases. Continuous improvements in recycling technology have the potential to optimize material recovery and minimize energy usage. Further advancements can be made using a variety of electricity mixes and testing only the renewable source of electricity production for a more optimized impact profile. Utilizing sustainable energy sources for recycling plants and optimizing transportation logistics management can effectively reduce emissions. Another scope is an evaluation on the drive efficiency, environmental profile and sensitivity analyses on these material choices with different alloys, recycled alloys and varied choices for different components is recommended when data is made available in future research scopes. Expanding the scope of LCA studies to compare with other crucial EV components, such as battery, or to show the impact contribution analysis of EVs, showing the impacts of powertrain components would provide a basis for a complete picture of sustainability profiles.

5. Conclusions

A state-of-the-art LCA approach was applied to this study on the production and recycling process of the electric traction motor materials, focusing on NdFeB magnets and other metals. The LCA model compared the production process and its end-of-life recycling with its emission reduction potential at the recycling stage. The production impacts are attributed to the rotor and housing production resulting from the PMs, aluminum, and steel manufacturing. The recycling impacts are attributable to the PMs' recycling and other regular metal recycling processes. The results reveal that recycling materials after the disassembly results in a reduction in impacts, and the emission-saving potential can range from 66 to 95% based on the specific recycled material. The findings of our results discussed the state-of-the-art recycling process and the need for a significant transformation to optimize the manufacturing and recycling of this crucial powertrain component. This would bring added benefits and reduce waste after the usable lifetime of the motor. The recycling process for the materials that are used in electric motors is complex and involves a substantial amount of the materials that are used. The material composition of the product and its lifespan are drastically different depending on the particular materials that are utilized. This is due to the fact that every single metal or sub-component has a unique rate of degradation or recycling route. The impacts of recycling can be significantly lower when compared to the impacts of disposal without recycling. The recycling process, while an end approach after testing or reuse, can still provide benefits over discarding the component in landfills. The recycled magnets could make a major contribution to the circular economy and reduce the dependency on rare materials from outside Europe. As a result, recycling products and maintaining a circular loop of resources are essential components of environmentally responsible manufacturing. Although concerns remain about the purity and efficiency of recycled magnets, these magnets can still meet the demand for PMs used in electromobility. Continuous advancements in recycling technology offer the potential to maximize the efficiency and amount of material recovered while simultaneously reducing the amount of energy consumed. If there is no significant material degradation or reduction in quality due to impurities affecting the efficiency of the motor, then the recycling process could be beneficial. For further advancements, a full cradle-to-grave LCA study can be conducted for a complete life cycle impact profile. The LCA approach can adapt the investigation towards circularity assessment, economic aspects, criticality, and social indicators to broaden the scope of the study. A significant reduction in emissions can be achieved through the utilization of renewable energy sources for production and recycling plants and the optimization of technologies in the transport and automotive sectors.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/wevj17050249/s1, Figure S1: Impact contribution of components of e-motor production for ReCiPe 2016 v1.03, midpoint (H) impact categories; Table S1: Life cycle impact assessment for production and recycling of PMSM; Table S2: Extended inventory of production processes of PMSM; Table S3: Sensitivity analysis of production by varying different contributing parameters.

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