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## Article

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

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## Abstract

The CO<sub>2</sub>-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 its usable life to reduce dependency on limited raw materials. Electric motor is one of the most crucial powertrain components, yet studies on the overall ecological profile of production and end of its useable life is limited. This study examines the life cycle assessment (LCA) impacts of electric motors used in passenger cars and potential recycling of its materials. The analysis covers 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 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 manufacturing of crucial vehicle powertrain component 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 up to 25% by 2025 [39]. Due to technological advances, the CO<sub>2</sub> emissions decreased only between 1990 to 2014 and again in 2020 [12]. Despite the Paris agreement of reducing the current emissions to half by 2030, the transport emissions continue to rise [40]. To reduce the emissions of 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. Currently, the world is undergoing a significant energy transition, rapidly moving away from fossil fuels towards cleaner renewable energy sources, aiming to decrease this transport related environmental emissions. The EU Green Deal is currently aiming to help achieve the climate neutrality targets by 2050 and ensuring sustainable transport sector [13]. 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, the electrification in the automotive industry continues to rise with demand towards passenger and cargo transport [10]. Germany 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 [14]. This incentive is expected to support the sales of an estimated 800,000 EVs up until 2029. As the global economy is projected to triple by 2060 with the shift towards electrification in the automotive sector, there is an escalating demand for research

towards sustainable solutions in manufacturing and end-of-life strategies to mitigate reliance on raw materials, reduce share of EV parts in landfill waste and promote circularity with aim to reduce the adverse impacts of climate change to keep the raw materials in the supply chain [24].

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 machine (PMSM). The PMSM is widely used and dominated in the German markets with a share of 64% due to its high-power density and energy efficiency [35]. 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 [20]. The PMSM is responsible for substantial environmental impacts specially in the extraction of raw materials and the production phase. Although, the end-of-life phase has lower impacts compared to production or use phase, other elements that can have a big impact on an electric vehicle's environmental effects include maintenance, the electricity mix for the proportion of various sources used to generate electricity, and the choice of functional unit [25].

The PMSM was valued at 23.0 billion USD in 2024 globally and is anticipated to reach 36.2 billion USD by 2033 [32] due to increasing adoption of electric vehicles and automation technologies. An essential element of the permanent magnet electric motor market 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 are in varying estimated values, there has been several studies on sustainability of recycling e-motors and permanent magnets (PMs) [1,44]. But the scope of those studies did not comprise of comparing the production of e-motors and its recycling. Some studies have covered production or sustainability of e-motors but with different magnet choices [3,18]. The current state of dismantling and recycling of e-motors recovering certain metals (e.g., permanent magnets, aluminum, steel, copper) is somewhat limited. Therefore, an evaluation of the recycling process could provide clear insight into the impact profile and pose potentials for improvement of the base materials used in the production of e-motors.

In the subject matter of sustainability of electric vehicle and its components, there are varying results of LCA studies [17,18,41] and the results are often inconsistent due to lack of data, varying scopes or boundaries of the study and different LCA methodologies [46]. In many cases, the primary data on entire life cycle of electric vehicle or its components are not available. Therefore, many studies rely on secondary data from literature and database with further assumptions [31]. To cover these research gaps and to add valuable contribution towards research and development of sustainable production and recycling process of this essential component of electric vehicles, we aim to assess the life cycle sustainability assessment of e-motors. In this study, we examined the life cycle assessment (LCA) impacts of a PMSM with Neodymium iron boron (NdFeB) magnets 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 machine dataset can be comparable for electric vehicle of specific size and class such as for a Volkswagen ID.3 or similar. The study assesses the environmental impacts of manufacturing and recycling process and identifies the main cause of the environmental impacts to interpret and communicate the essential findings. 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 is not under the scope of the study. For the purpose of simplicity of scope definition, we did not focus our study on PMSM with other magnet types or other types of motor. 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. The results are shown for the LCA 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. The results of the study are

relevant for the LCA research target groups for the development of production and recycling process of PMSM in electric mobility sector.

## 2. Methods

### 2.1. Production of PMSM

The production of electric motors is usually done by direct vehicle manufacturers or suppliers [17]. 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 [30]. 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 discs and laminations are assembled to create the cores. The rotor consists of mostly steel sheets, magnets, screws and shaft. Electrical steel discs and laminations are assembled to create the cores. Laminations should be exceptionally thin and coated to minimize electromagnetic and thermal losses [31]. The stator is the stable part and holds mostly 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 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 [11]. Each housing necessitates bearing shields on both sides in order to be enclosed. The dimensions and weight of the housing may differ significantly, primarily influenced by the stator configuration, cooling and protection specifications (e.g., casting wall thickness), and the installation conditions of the machine within the vehicle [20]. The housing though has the least weight share of 22% but holds the most type of sub-components. Most materials of housing are steel for various sub-components of the housing such as connection bushing, Allen screw, ball bearing, and retaining ring. The Figure 1 outlines the weight share and materials of the components in the PMSM in our study. The rotor holds the highest share of weight (41%) followed by stator and housing. These data were crucial for the implementation of inventory analysis and impact assessment. Main materials for the components of motor production are aluminum, copper, steel and rare earth elements [30].

In 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 [16]. NdFeB magnets consist mostly of neodymium, iron, and boron [30]. 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 ferroboration. 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 the magnet [46]. These processes are included in the boundaries of magnet production. The Figure 2 provides an outline of the basic component manufacturing and motor assembly stages.

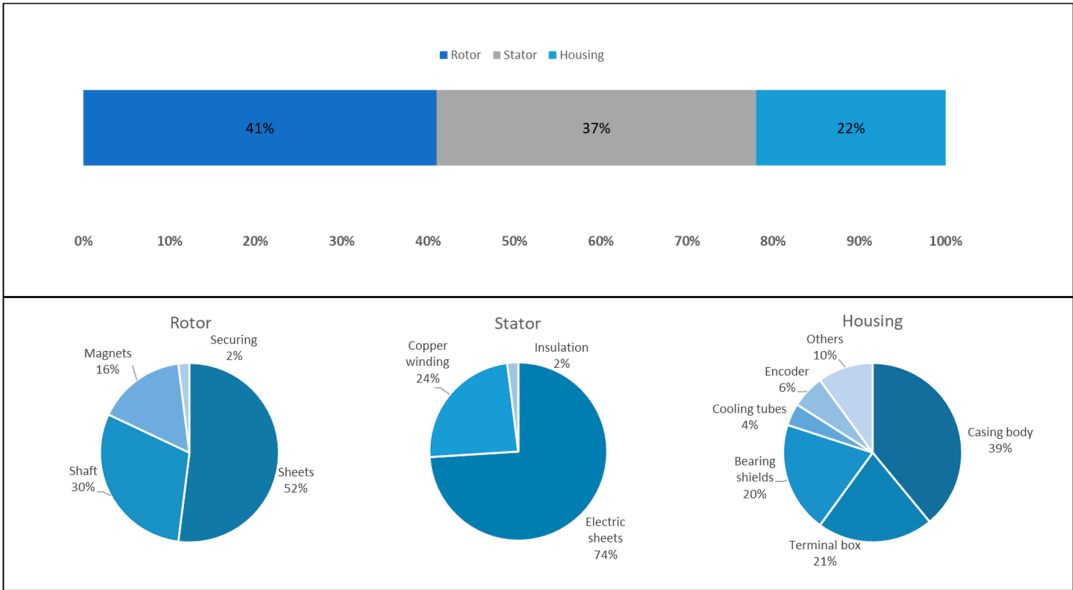


**Figure 1.** Weight share and material distribution of components of PMSM.

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 disperse the heat produced during operation [31]. The immobile component of the electric motor - stator, 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 the rod. When an electric current pass 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 [20]. A description on the specification of our study case of PMSM is outlined in the Table 1.

**Table 1.** Specification of the PMSM in the study.

| Parameters                    | Unit | value   |
|-------------------------------|------|---------|
| Stator outer & inner diameter | mm   | 209/115 |
| Rotor outer & 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. Additionally, other inputs (e.g. electricity/energy) are also considered in the boundaries of the evaluation study. Components vary among vehicle kinds and sizes to meet distinct powertrain needs, regarding both weight and the composition of subcomponents and materials. Modified component design indicates that upstream production activities will be altered [30].

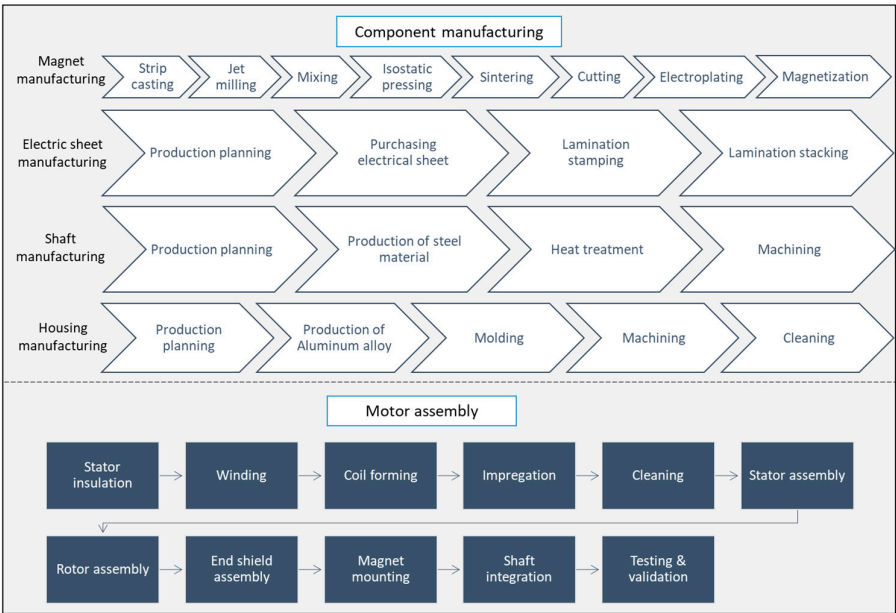


**Figure 2.** Manufacturing process of components and motor assembly.

The engine casing's manufacturing process begins with its formation. 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 [38]. 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 [45]. The hot-work tool steel mold is then cleansed, coated with a releasing agent, and sealed. We then insert cores to define the workpiece's internal shapes. Next, the machine exerts a significant holding pressure throughout the entire solidification process. Once the solidification process is complete, the machine opens, and simultaneously, the ejectors release the components from the mold. The product is extracted and subsequently chilled. When compared to other molding methods, casting offers the benefits of reduced energy consumption and increased material utilization [38]. 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 [20]. 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 [31]. Figure 3 shows the technologies involved in the production of different components.

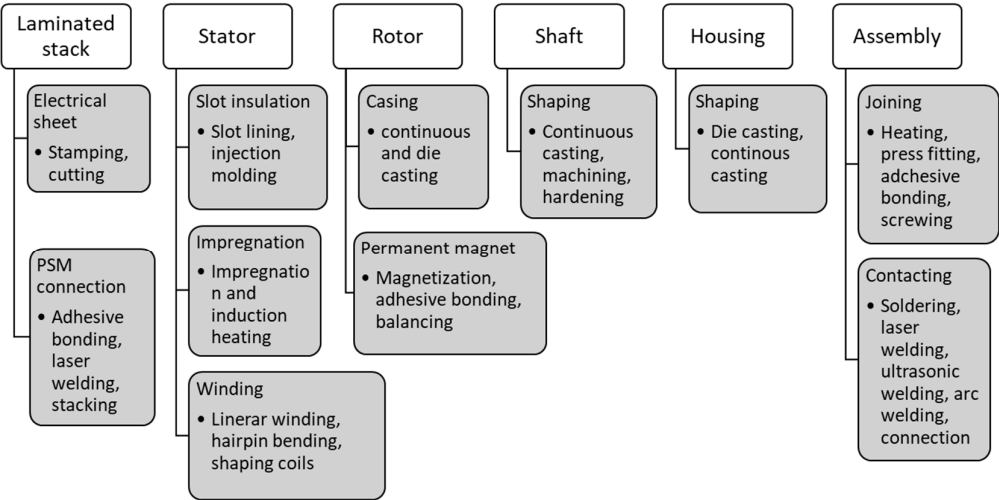


Figure 3. Manufacturing technologies of PMSM.

2.2. Recycling Process

The EU Directive on end-of-life vehicles [28] 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 [44] or the metals such as aluminum, magnesium, copper, and others [38]. 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 [38]. 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 [3]. Therefore, an evaluation on the recycling process could provide clear insight on the impact profile and pose potentials for reducing of emissions of the base materials used in the production of electric machines.

Like other energy conversion and propulsion components, the recycling and remanufacturing process 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 [23,41]. The motor housing is firstly 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 [23]. 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 aluminum, steel and precious metals can be recovered. Figure 4(a) shows a generic breakdown of the recycling process of the electric machine at the end of its useable life.

The majority of materials, specifically aluminum, copper, and steel, are regarded as recyclable, with varying rates of recycling. 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 [23,47]. 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 the magnets are dismantled manually and undergoes recycling like the common metals. It is to be noted that the methodology and processes of dismantling and recycling process of PMSM is derived from compilations of state-of-art scientific papers and expert knowledge at DLR. From the evaluation of the recycling process in the study, we can see that after the collection and sizing, 34.2 kg of non-ferrous (Al, Cu, etc.) metals are obtained from magnetic separation. On the other hand, 69.8 kg of ferrous materials (steel, PMs, others) are obtained from magnetic separation. Through the last phases of pre-sorting of 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 a 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 process.

### 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 arises from rotor production (50.5%) which can be attributed to the 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 [1,3,44]. Rare earth magnets cannot be 100% recyclable and requires 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 [46]. These additional elements are used to improve the magnetic and physicochemical characteristics of the magnets once they have been sintered [44]. 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 [23]. 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 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% [44]. Figure 4(c) shows a simplified process of magnet recycling using pyrometallurgical or hydrometallurgical method based on a summary of various approaches across studies [16,44,45]. The material flow of the magnet begins with 2.7 kg of PMs dismantled from the electric machine followed by 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 recycling of magnets using various methods. Therefore, the material flows are not relevant for a specific method of magnet recycling but rather serves 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 can be achieved from 2.7 kg of primary PMs.

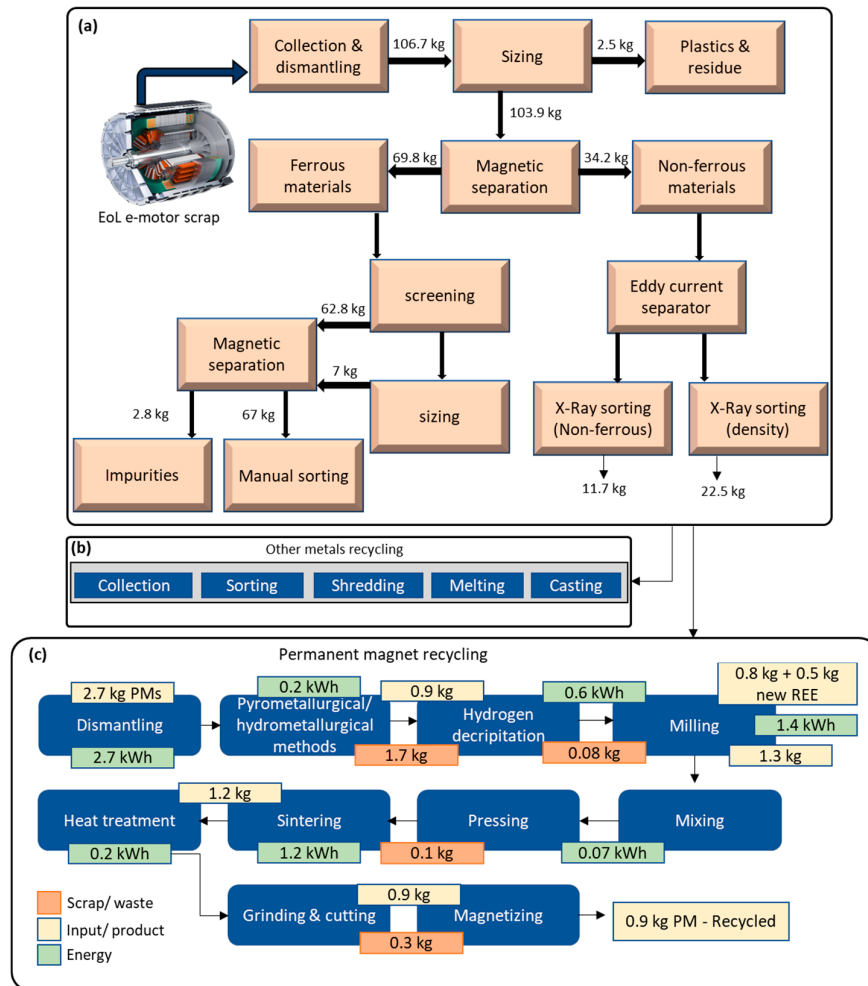


**Figure 4.** Overview of the complete recycling process of PMSM. (a) Motor disassembly and sorting, (b) Metal recycling processes relevant for Aluminium, Steel and Copper, (c) Permanent magnet recycling based on compilation of recycling technologies.

It is important to acknowledge that the processes of hydrogen decipitation, 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 [17,47]. As a result, the recycling process reduces energy consumption by approximately 91% when compared to virgin route of production. The primary manufacturing process uses strip casting to create PM, a feature not present in the recycling process [44]. The properties of PMs are reliant upon temperature, and standard NdFeB magnets are readily demagnetized at elevated temperatures. Demagnetization transpires when the magnet's load exceeds a critical threshold, as may occur during malfunctions such as a short circuit [3]. The maximum operating temperatures for magnets in traction motors can exceed 150 °C, significantly beyond the standard maximum allowable working temperatures of conventional NdFeB magnets. Therefore, to utilize NdFeB magnets in car traction motors, it is essential to enhance their thermal stability [31]. 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 [18]. Due to the variations in the functional unit across different studies, the results are not specifically comparable to each other. But it is worth mentioning the environmental impacts in those studies as they covered variety of topics

in the manufacturing. For example, one study [1] mentions the climate change impacts of virgin magnet production as  $8.54 \times 10^{-4}$  kg CO<sub>2</sub>-eq. and recycled as  $6.29 \times 10^{-4}$  kg CO<sub>2</sub>-eq. The functional unit mentioned in the study was 1kA/m (kilo ampere/ meter). Other studies [18] mentioned the climate change impacts of virgin magnet production as 27.6 kg CO<sub>2</sub>-eq. and 12.4 kg CO<sub>2</sub> -eq. for the recycled production for 1 kg as its functional unit. Other impact categories discussed in these studies ranges accordingly based on the chosen LCA methodology.

#### 2.4. Material Recycling After Screening and Sorting

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 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) [33]. The secondary aluminum has other several 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 [9]. Thus, secondary or recycled aluminum has emission savings to a considerable amount [45]. 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<sup>3</sup> of land use [36]. 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 [36,38].

Crude steel production from primary raw materials is emitting 2.2t CO<sub>2</sub>/ton steel produced [7]. Since steel can be almost infinitely recycled, recycling steel has several benefits on saving CO<sub>2</sub> emissions compared to primary steel production. Pre-consumer and post-consumer steel scrap can be used to make new steel product. Given its inherent magnetism, it is easy to recycle and is the most recycled material in the world [6]. 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 [7]. The EAF method is used for recycling of the 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 [45]. This impact is avoided 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<sub>2</sub> 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<sub>2</sub> and the usage of 1.4 tons of iron ore, 740 kg of coal, and 120 kg of limestone [8,27,38].

Other metals such as copper and brass also have significant scope of recycling. Similar to other metal recycling processes, copper or brass recycling have energy saving potentials due to elimination or mining, refining and production processes related to primary production such as extensive materials, energy and waste generated. Copper is extensively used in the windings for the magnets and brass is used in the coolant fittings in 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 weighted and sorted according to grade and type. The Cu wire is then granulated for further processing such as melting in EAF, refining, castings into ingots or billets, and hot or cold rolling [33,43]. Both primary and recycling processes outputs refined Cu cathode with 99.99% purity [45]. 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. But there also are 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 [26]. Brass on the other hand after been 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 casted material. But the recycled material could still be applicable with reduced shear strength of 6-33% [34].

2.5. Methodology of Life Cycle Assessment

In the study, we carried out LCA according to ISO 14040/44 for the production and recycling of PMSM. ISO 14044 specifies the prerequisites for an LCA study and offers implementation guidance, whereas the ISO 14040 outlines the framework and the guiding principles. The four stages of an LCA are: formulation of a goal and scope, outlining the life cycle inventory, executing the life cycle impact assessment (LCIA) and, the interpretation of 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 [29,37]. The lifecycle inventory phase gathers all pertinent data for the processes inside the system boundaries based on the scope definitions.

2.6. System Boundaries and Scope of Study

The system boundary in our study (Figure 5) covers from the cradle (raw material extraction) to the gate (production and recycling of one functional PMSM). 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. 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 the table 2 shows the input for the production of rotor, stator, housing and other relevant information for executing the LCA. A detailed inventory is available in the Supplementary Table S2 (Table S2).

Table 2. General inputs for the evaluation.

| Processes         | Amount | Unit |
|-------------------|--------|------|
| <i>Production</i> |        |      |
| Stator            | 37.3   | kg   |
| Rotor             | 43.8   | kg   |
| Housing           | 25.9   | kg   |
| Electricity       | 120    | kWh  |
| <i>Recycling</i>  |        |      |

|                       |       |    |
|-----------------------|-------|----|
| Collection            | 106.7 | kg |
| Plastic residue       | 2.5   | kg |
| Ferrous materials     | 69.8  | kg |
| Non-ferrous materials | 34.2  | kg |

The housing of the motor holds the least share of weight (22%) 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 stator are steel sheet 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 of steel sheets, rare earth magnets, steel for end disks, shaft, feather key and Allen screw. The scope of the study also included the recycling of the electric machine. The scope of the study does not extend to the use phase of the PMSM as we aimed to assess only the production and recycling impacts of electric machine. The processes are modelled using process flows available of ecoinvent v3.10 in OpenLCA software. The data for the study includes various sources such as the primary data from expertise knowledge at DLR, ecoinvent database and relevant scientific papers. The missing data were added based on assumptions from scientific literature references. The cut-off method is used for the ecoinvent flow data setting the cut-off criteria at 1% of the mass.

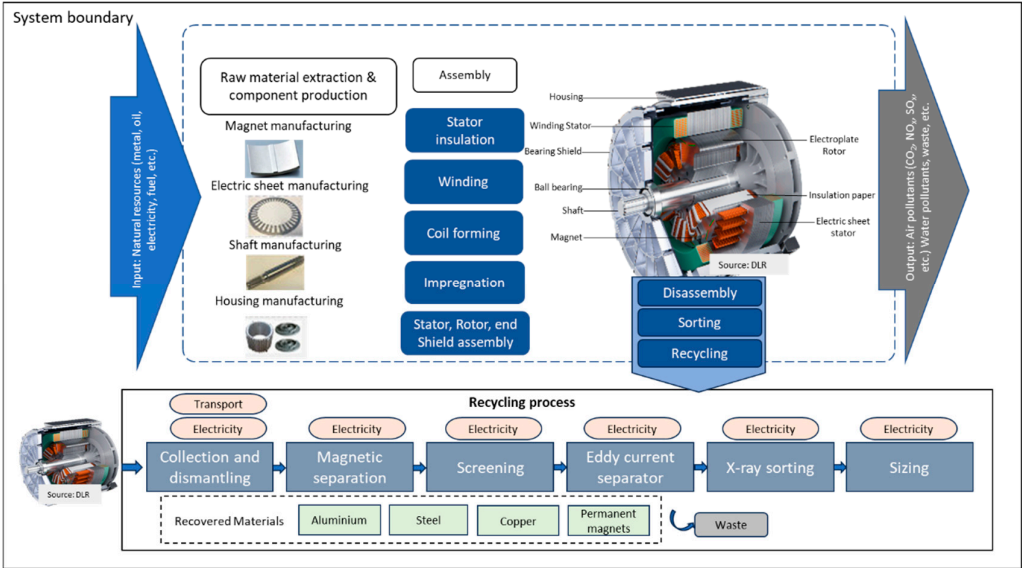


Figure 5. System boundaries of the study.

3. Results

3.1. Life Cycle Impact Assessment—Production and Recycling

In this section, we outlined the life cycle impacts for production and recycling of PMSM. The LCA impact assessment has been done by using the ReCiPe methodology comprising of 18 midpoint categories. In the category of climate change, the recycling process results in 2.3 kg CO<sub>2</sub>-eq. compared to primary production of 8.6 kg CO<sub>2</sub>-eq. The other impact categories are shown in Figure 6. As outlined, the recycling process contributes to substantial lower emissions in all the impact categories except two categories: Material resources: metals/minerals ( $8 \times 10^{-1}$  kg Cu-eq./kg primary motor production and  $7.8 \times 10^0$  kg Cu-eq./kg recycling motor) and Eutrophication: marine ( $1 \times 10^{-3}$  kg N-eq./kg primary motor production and  $4 \times 10^{-3}$  kg N-eq./kg recycling motor). An overview of other impact categories is provided in the Supplementary Table S1 (Table S1).

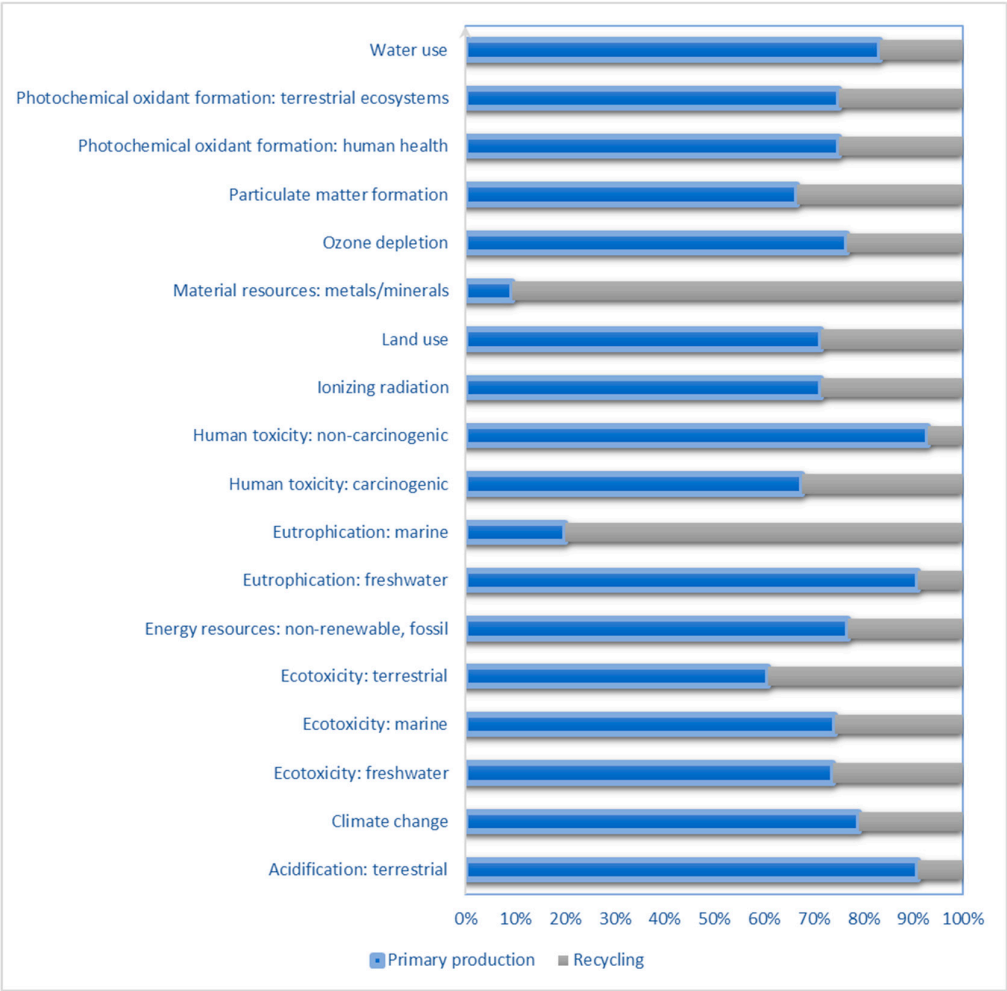


**Figure 6.** Midpoint impact categories for production and recycling.

In the category of climate change for primary production, the rotor and housing accounts for the majority of impact contributions (50% and 35% respectively). Primary contribution of impacts from rotor are caused due to rare earth magnet production (31%). Other contributions are from insulating coating and steel production of various sub-components. For the contribution of housing, the housing production accounts for 35% of CO<sub>2</sub>-eq/kg motor. Majority of the impacts are caused from aluminum production followed by steel and brass production. The stator production accounts for the least impact contributions (14%). The impacts in stator production accounts from insulation coating production, insulating materials, steel and copper production and other minor materials. Figure 7 outlines the impact distribution of the main components.

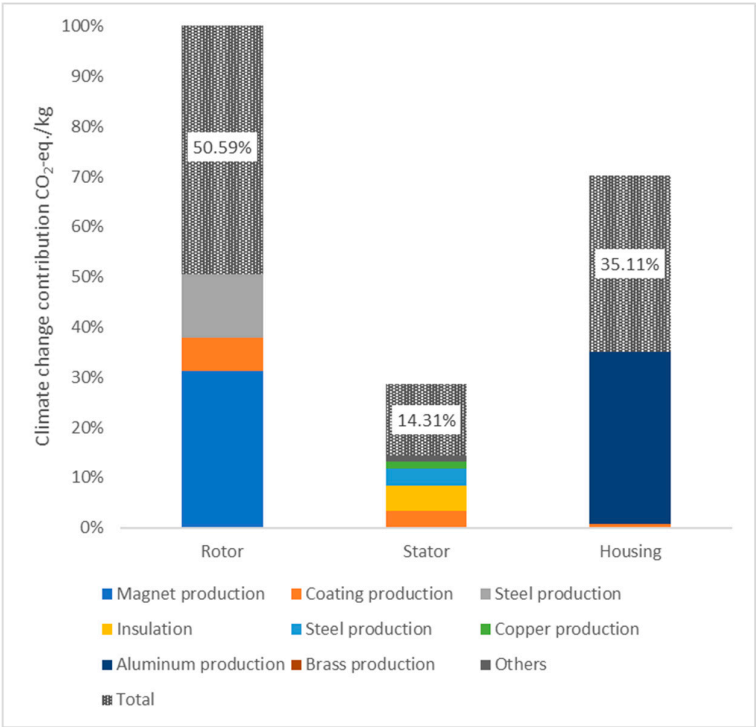


Figure 7. Impact contribution of components in the production phase.

3.2. Sensitivity Analysis

We conducted a sensitivity analysis of the most contributing parameters to test the stability of the impact assessment results. High values (+20%) and low values of (-20%) for parameters of the production phase. The results did not show any major shifts for any categories but has slight benefits towards impact reduction when the production was faced with reduction of -20%. This can suggest the reduction or optimization of materials in the production phase can have overall contribution to emission reduction. The results of sensitivity assessment are presented in detail in the Supplementary Table S3 (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 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 [39]. Therefore, recycling products and keeping a circular loop of materials are crucial to sustainable manufacturing [41]. 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 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.

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.

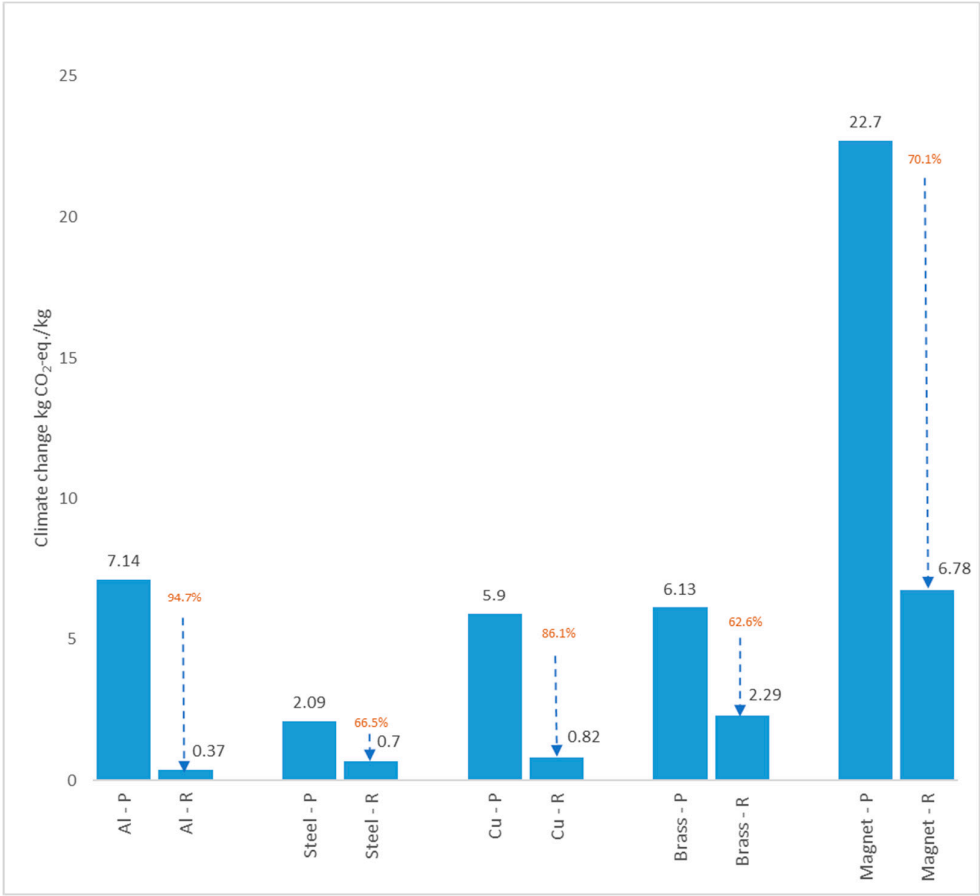


**Figure 8.** Emission reducing potential of recycled materials (R) and primary materials (P) commonly used in PMSM.

Primary aluminum manufacturing emits 7.14 kg CO<sub>2</sub>-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. 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 bauxite, 4 kg fluorides and 14 kWh electricity [11,36]. 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%) are also observed in the evaluation. Copper and brass are used extensively in the e-motor production. Copper or brass recycling have energy saving potentials due to elimination or 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<sub>2</sub> emissions between 65-85% and conserves 85% of the energy required for primary manufacturing [43]. Brass recycling decreases the overall energy need by 29% and reduces the impact on climate change by 30% compared to traditional brass production [34].

4.2. Alternative Design Options

It is beneficial to outline to the vehicle manufacturers the influence of design changes in the early phase and how the sustainability metric can change consequently [11,17]. 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 to select an optimum design based on the preference towards sustainable options. The experts and specialists on electric motor at DLR worked to evaluate the design possibilities and the types of alloys in details. This can provide aid to the manufacturers decide on best option based on their preferences on weight reduction, lower emissions or higher circularity. In our study, though we did not define the environmental impacts of these design choices, the choice of different alloys or recycled alloys are estimated to contribute to positive or negative environmental impacts. For example, in the housing choice, the recycled Aluminium 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 the CO<sub>2</sub> emissions. The cast iron option would contribute to increase of both weight and the CO<sub>2</sub> emissions. Likewise other components and their design choices could either improve or reduce the weight, efficiency and environmental impacts. The varied weights of different alloys are attributed to densities and properties of different metals. An extensive study on the efficiency and environmental profile on 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                                                                                                                                                     | Recyled Al-alloy                                                    | Recycled Al-alloy                                                                                                                           | Mg-alloy                                                       | Cast iron                                                                   |
|                | [AlSi12Cu1(Fe)]                                                                                                                                              | [AlMg4Fe2]                                                          | [AlMg6Si2MnZr]                                                                                                                              | [AZ91]                                                         |                                                                             |
|                | 27.8 kg                                                                                                                                                      | 28.8 kg                                                             | 28.2 kg                                                                                                                                     | 18.2 kg                                                        | 75.9 kg                                                                     |
| Stator         | Retracted winding - Coil gets wound externally and are retracted into the stator slots, thin wire and high number of windings possible, more effort required |                                                                     | Hairpin winding - Copper wire gets formed into a U shape hairpin. It is inserted into the stator slot and welded to coils on the open side. |                                                                |                                                                             |
| Rotor          | PMSM - NdFeB magnet:                                                                                                                                         | PMSM - NdFeB magnet:                                                | PMSM - SmCo magnet: Integrated magnet, more material required than NdFeB magnets for similar efficiency                                     | Electric excited synchronous motor:                            | Asynchro us motor:                                                          |
|                | Integrated magnets, high efficiency & power density, most common type                                                                                        | Surface magnets, high efficiency & power density, easy to dissemble |                                                                                                                                             | No rare-earth magnets required; rotor losses need to be cooled | No rare-earth magnets required, robust against mechanical and thermal loads |
|                |                                                                                                                                                              |                                                                     |                                                                                                                                             |                                                                |                                                                             |
|                |                                                                                                                                                              |                                                                     |                                                                                                                                             |                                                                |                                                                             |
|                |                                                                                                                                                              |                                                                     |                                                                                                                                             |                                                                |                                                                             |
|                |                                                                                                                                                              |                                                                     |                                                                                                                                             |                                                                |                                                                             |
| Bearing shield | Al alloy                                                                                                                                                     | Recyled Al-alloy                                                    | Recycled Al-alloy                                                                                                                           | Mg-alloy                                                       | Cast iron                                                                   |
|                | [AlSi9Cu3(Fe)]                                                                                                                                               | [AlMg4Fe2]                                                          | [AlMg6Si2MnZr]                                                                                                                              | [AZ91]                                                         |                                                                             |
|                | 3.8 kg                                                                                                                                                       | 3.7 kg                                                              | 3.6 kg                                                                                                                                      | 2.3 kg                                                         | 9.7 kg                                                                      |

|        |                               |                        |                                           |
|--------|-------------------------------|------------------------|-------------------------------------------|
| Screws | Stainless steel [X4CrNi19-12] | Carbon steel [42CrMo4] | Recycled stainless steel<br>[X4CrNi18-12] |
|        | 0.04 kg                       | 0.04 kg                | 0.04 kg                                   |

4.3. Extent of Relevancy of Other Studies and Future Scope

Studies show that the global market for PMs are expected to rise significantly to 54.1 billion USD due to widespread dependency of PMs in the automotive sector [16]. On the other hand, there are also significant research advancement towards magnet-free [42]. Currently there are relevant publications in the scientific community in the study area of electric motors and its sustainability covering variety of motor types, magnet types and magnet-free motors. An extensive overview of several relevant LCA studies of electric machines is covered at [37]. But they are provided in varied forms, scope of studies, functional unit, LCA methodologies, databases, software used, motor types and magnet types or powers as shown 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 production and recycling of e-motors.

Table 4. Relevant studies comparing sustainability of electric machines.

| Reference | Motor Type & Scope                           | Functional Unit  | Overview of results                                                                     |
|-----------|----------------------------------------------|------------------|-----------------------------------------------------------------------------------------|
| [31]      | EV traction PMSM; detailed manufacturing LCI | 1 traction motor | GWP: 200–400 kg CO <sub>2</sub> -eq. Hotspots: copper, electrical steel, NdFeB magnets. |
| [29]      | PMSM (NdFeB), PMSM (SmCo), PM-SynRM          | 1 motor          | GWP: 150–350 kg CO <sub>2</sub> -eq. NdFeB highest; ferrite lowest.                     |
| [37]      | PMSM vs Induction                            | 1 motor          | PMSM has higher resource depletion; induction has higher copper/steel impacts.          |
| [23]      | NdFeB magnet production                      | 1 kg magnet      | GWP: 50–100 kg CO <sub>2</sub> -eq/kg magnet. Mining + solvent extraction dominates.    |
| [22]      | NdFeB magnets                                | 1 kg magnet      | GWP: 70–200 kg CO <sub>2</sub> -eq/kg. High acidification and toxicity impacts.         |
| [4]       | Rare-earth supply chain                      | 1 kg REE         | Energy: 200–600 MJ/kg REO. High emissions from solvent extraction.                      |
| [5]       | Recycling vs primary production              | 1 kg NdFeB       | Recycling reduces GWP by 60–80% vs primary production.                                  |
| [2]       | Industrial PMSM vs induction                 | 1 motor          | PMSM higher GWP due to magnets; induction higher due to copper.                         |
| [48]      | Switched reluctant motor - SRM (no magnets)  | 1 motor          | GWP: 100–200 kg CO <sub>2</sub> -eq. Lower resource depletion than PMSM.                |

|      |                              |                 |                                                                                      |
|------|------------------------------|-----------------|--------------------------------------------------------------------------------------|
| [21] | PMSM vs induction vs SRM     | 1 powertrain    | PMSM highest resource depletion; induction highest mass; SRM lowest overall impacts. |
| [19] | Ferrite PMSM vs NdFeB PMSM   | 1 motor         | Ferrite reduces GWP by 20–40%, but increases mass and reduces efficiency.            |
| [15] | Rare-earth mining + refining | 1 kg NdPr oxide | GWP: 30–80 kg CO <sub>2</sub> -eq/kg oxide. High water pollution indicators.         |
| [3]  | 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 cradle-to-gate 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 put up with some assumptions based on scaled values. It is to be noted that the replication of the model could result in variation of results. The reason could be attributed towards different factors such as different functional units or LCA methodologies, use of different LCA software tools 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 done using variety of electricity mix and testing only 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 efficiency and environmental profile on these design options with different alloys, recycled alloys and varied choices for different components is recommended for future research scopes.

5. Conclusion

A state of art LCA approach was applied to this study on the production and recycling process of the electric traction motors, specifically on PMSM with NdFeB magnets. The LCA model compared the production process and its end-of-life recycling with its emission reduction potential at recycling. 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 although comes as an end approach after considering testing or reuse, still could provide impact benefits over discarding the component towards landfills. The recycled magnets could make major contribution to the circular economy and reduce the dependency of rare materials from outside Europe. As a result, recycling products and maintaining a circular loop of resources are essential components of environmentally responsible manufacturing. Though there are still concerns over the purity and efficiency of recycled magnets, recycled magnets can still approach the recovery of need towards PMs for use 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. 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 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 sector.

**Supplementary Materials:** The following supporting information can be downloaded at the website of this paper posted on Preprints.org, Table S1: Life cycle impact assessment for production and recycling of PMSM, Table S2: Extended inventory of production process of PMSM, Table S3: Sensitivity analysis of production by varying different contributing parameters.

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