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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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Executive Summary
The transportation sector is contributing to global warming, and the electrification in the automotive sector continues to rise. Electric powertrain component production is resource and energy intensive. As the EU is striving to achieve net zero emissions by 2050, it is important to research and develop strategies for decarbonization in the automotive sector. Thus, recycling poses promising solutions that can help mitigate global warming. This study examines the life cycle assessment (LCA) impacts of a crucial powertrain component—the electric motor. The analysis covers manufacturing and recycling components, as well as the production and recycling of critical elements like permanent magnets. Housing and rotor production are shown to have the greatest impacts, possibly due to materials like steel, aluminum, and permanent magnets. The study and results will also discuss recent advancements and current state-of-the-art recycling processes for e-motors. The results indicate substantial emission savings upon recycling when compared to primary production.
Keywords: e-motor, LCA, recycling, impact assessment, passenger cars

1 Introduction

The world is undergoing a significant energy transition, rapidly moving away from fossil fuels towards cleaner renewable energy sources, aiming to decrease energy-related environmental emissions by 70% by 2050 relative to current levels [1]. The transportation sector currently constitutes over 20% of global greenhouse gas (GHG) emissions and is one of the primary industries contributing to global warming, resulting in a projected rise in the demand for electric vehicles and electric powertrain components [2]. Although the global economy is projected to triple by 2060, achieving the objectives to alleviate the adverse impacts of climate change necessitates the implementation of recycling technologies and an increased use of renewable energy sources. Strategies for emission reduction must be implemented to effectively attain the ambitious goals established by the Paris Agreement, which promotes a global decrease in carbon emissions [3].

The electric motor is a vital component of the powertrain. E-motors are composed of resource-intensive raw materials and rare earth elements (REE), particularly in permanent magnet synchronous motors (PMSM). Presently, limited research has been conducted on the recyclability of e-motors. The current state of recycling of certain metals (e.g., permanent magnets, aluminum, steel, copper) is somewhat limited, resulting in a small amount of scrap material being returned to the alloy manufacturing facility [4]. 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 this study, we examined the life cycle assessment (LCA) impacts of the primary e-motor manufacturing process, along with the effects of recycling the components recovered from the dismantled and sorted e-motors at the end of their use phase. It is to be noted that the study covers the LCA impacts of e-motor production and the recycling process, and not production from recycled materials. Furthermore, we assessed the manufacturing and recycling processes of e-motors at the material level for each of their sub-components (motor, rotor, and stator), as well as the production and recycling of permanent magnets (PMs). Our discussion covers significant recent advancements and the current state-of-the-art recycling processes for e-motors.

2. LCA analysis methodology

In the study, we carried out LCA according to ISO 14040/44 for the production and recycling of permanent magnet synchronous motors (PSM). The system boundary (Figure 1) covers from the cradle (raw material extraction) to the gate (production of one1 functional e-motor). 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 housing of the motor holds the least share of weight (24%) 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 is another stable part of the motor beside the housing and comprises 35% of the weight of the motor. The majority of the materials in stator are steel sheet and copper winding. Other components of the stator includes 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. These processes are modelled using process flows available in OpenLCA software.

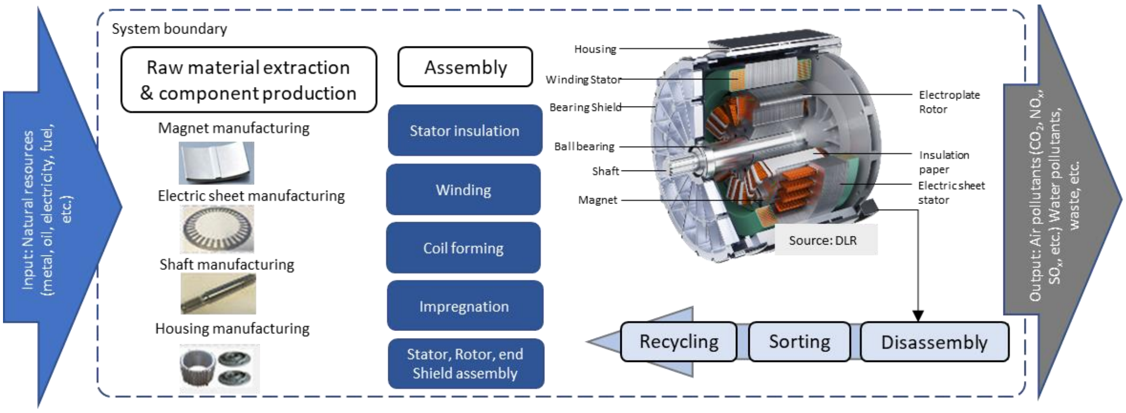

Figure 1: System boundary of production and recycling of e-motor

2.1 Primary e-motor production

The type PSM is the most widely used and dominated in the German markets (64%) due to its high power density and high efficiency[5]. 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 [6]. The stator is composed of thin layers of specialized steel to reduce the eddy currents produced by the magnetic field [7]. 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 [7]. The stator is the immobile component of the electric motor, usually constructed from a layered steel core with copper wire windings encircling it. 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 revolve and drive the mechanical load [8]. 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 the magnetic field of the stator interacts with the rotor, it generates an electromotive force in the conductors of the rotor, which in turn creates a magnetic field that opposes the stator's magnetic field. The interaction between the magnetic fields of the stator and rotor produces the torque required for the motor to carry out mechanical tasks [7]. A description on the specification is outlined in the table 1.

Table 1: Specification of the permanent magnet synchronous motor [9]

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

The components such as sheet, shaft and housing are mainly produced through die casting and extrusion processes after considering the raw material extraction and processing. Main materials for the components of motor production are aluminum, copper, steel and REE [4]. In case of magnets in e-motors, Neodymium-alloy (NdFeB) magnets possess the highest energy density compared to other commercially available grades, making them the favored choice for the automotive sector. NdFeB magnets consist mostly of neodymium, iron, and boron. The main components of the motor are the rotor and stator made of laminated iron sheets, aluminum or copper bars insulated from each other. 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 [6]. 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 [8]. 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, we can execute the crucial stage of the process, which involves the infusion of liquefied metal. 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 [10]. 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 [8]. 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. Approximately 200–400 kg of electrical steel are utilized per kilowatt of electricity in a hybrid electric powertrain [8].

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 [11]. These processes are included in the boundaries of magnet production. The primary function of the housing 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 [7]. In the evaluation process, we considered the raw material extraction, component production and assembly of the PSM in the system boundary. Additionally, other inputs (fuel, electricity, energy) are also considered in the boundaries of the evaluation study.

2.2 Potential recycling e-motor

The EU Directive on end-of-life vehicles [12] 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 PSM, and its impact assessment. Some studies discuss only the recycling of NdFeB [13] or the metals such as aluminum, magnesium, copper, and others [14]. 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 [15]. The motor housing is 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 [15]. The individual components are renovated if necessary and reintroduced into the manufacturing process.
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 [11]. 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 along with the common metals. From the evaluation of the recycling process, we can see that after 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.

2.2.1 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 (50.8%) that comprises of PM. Therefore, it is essential to explore the recycling process of this crucial element in PSM to navigate the potential of emission reduction. Several studies covered topics on PM recycling [16–18]. In this study we aimed to extend the research specific relevant to our production process primary data and identify the potential emission reduction. NdFeB magnets consist mostly of neodymium, iron, and boron, with minor quantities of other REE including dysprosium and/or praseodymium. 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 PSM, we considered 2.7 kg NdFeB magnets in the evaluation obtained from the primary data. At the moment, researchers are looking 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 [13]. 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% [15].

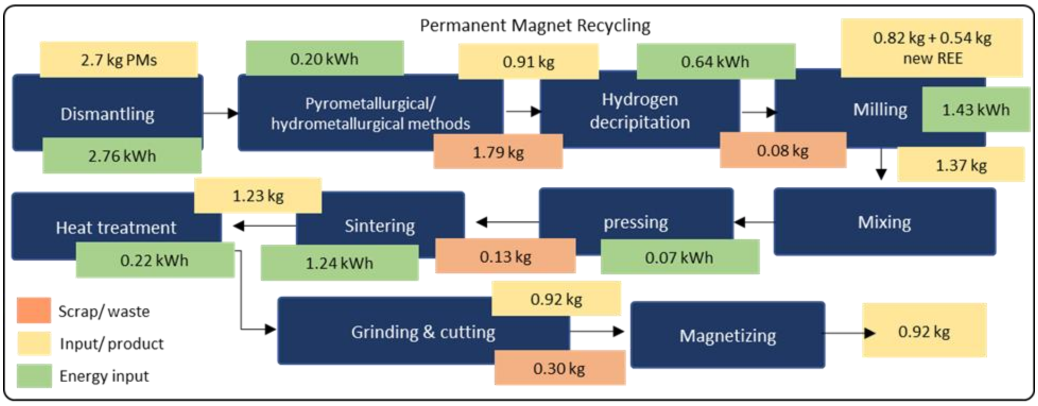

Figure 2: Recycling process of NdFeB magnets

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. 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 [19].

2.2.2 Retrieved metal recycling

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). The secondary aluminum process has several stages 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. Thus, secondary or recycled aluminum has emission savings to a considerable amount [20]. In addition, 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 [21].

Crude steel production from primary raw materials is emitting 2.2t CO_2/ton steel produced [22]. Since steel can be almost infinitely recycled, recycling steel has several benefits on saving CO_2 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. 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 [23]. 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 [24]. 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_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 [25, 22].

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 [23]. Both primary and recycling processes outputs refined Cu cathode with 99.99% purity [26]. 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 [27]. 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% [28].

3. Life cycle impact assessment

In our findings we see that the production of the rotor has the most significant impact (50.58%) because of the inclusion of PMs that housing has the greatest influence throughout the production phase due to steel, and aluminum production. Recycling the electric motor at the end of its lifespan can minimize additional effects and reliance on primary resources. We calculated that after 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.

Since the recycling steps bypasses the primary production route, energy consumptions in primary stages such as mining of oxides and reduction of pure elements that require up to 33 kWh/kg PM production can be avoided.

3.1 Life cycle impact assessment

The LCA impact assessment has been done by using the ReCiPe methodology comprising of 18 midpoint categories.
In the category of climate change for primary production, the rotor and housing accounts for the majority of impact contributions (51% 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. In battery housing, the housing production accounts for 0.8 kg CO_2-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%). In the category of climate change, the recycling process results in 2.3 kg CO_2-eq. cmopared to primary production of 8.6 kg CO_2-eq. The other impact categories are outlined in the table 2. As outlined, the recycling process contributes to substantial emission savings in all the impact categories.

Table 2: Life cycle impact assessment results of primary production and recycling process of e-motor

Impact category (ecoinvent 3.10 LCIA Methods/ReCiPe 2016 v1.03, midpoint (H)) – E-motor	**Primary production**	**Recycling**	**Unit**
Acidification: terrestrial	0.1	0.01	kg SO_2-eq.
Climate change	8.7	2.3	kg CO_2-eq.
Ecotoxicity: freshwater	1.7	0.6	kg 1,4-DCB-eq.
Ecotoxicity: marine	2.3	0.8	kg 1,4-DCB-eq.
Ecotoxicity: terrestrial	88.3	56.8	kg 1,4-DCB-eq.
Energy resources: non-renewable, fossil	2.0	0.6	kg oil-eq.
Eutrophication: freshwater	0.01	0.001	kg P-eq.
Eutrophication: marine	0.001	0.004	kg N-eq.
Human toxicity: carcinogenic	7.1	3.4	kg 1,4-DCB-eq.
Human toxicity: non-carcinogenic	77.3	5.9	kg 1,4-DCB-eq.
Ionizing radiation	0.5	0.2	kBq Co-60-eq.
Land use	0.5	0.2	m^2 *a crop-eq.
Material resources: metals/minerals	0.8	7.8	kg Cu-eq.
Ozone depletion	4.28E-06	1.3E-06	kg CFC-11-eq.
Particulate matter formation	0.02	0.01	kg $PM_{2.5}$-eq.
Photochemical oxidant formation: human health	0.03	0.01	kg NO_x-eq.
Photochemical oxidant formation: terrestrial ecosystems	0.03	0.01	kg NO_x-eq.
Water use	0.1	0.02	m^3

3.2 Potential emission saving on recycling

Figure 2 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.

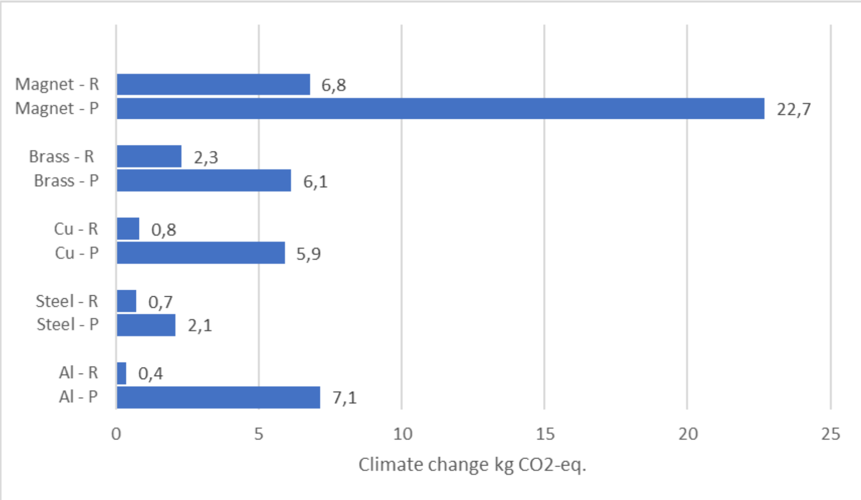

Figure 3: Impact assessment in the category of climate change for primary (P) and recycling (R) of materials from e-motor

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. 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 [29]. 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_2 emissions between 65-85% and conserves 85% of the energy required for primary manufacturing [30]. Brass recycling decreases the overall energy need by 29% and reduces the impact on climate change by 30% compared to traditional brass production.

The environmental profile of the recycling routes have been shown to be better than the virgin production routes [16]. Due to the variations in the functional unit across different studies, the results are not 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 [31] mentions the climate change impacts of virgin magnet production as 8.54×10^{-4} kg CO_2-eq. and recycled as 6.29×10^{-4} kg CO_2-eq. The functional unit mentioned in the study was 1kA/m (kilo ampere/ meter). Other studies [16] 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 for 1 kg as its functional unit. Other impact categories discussed in these studies ranges accordingly based on the chosen LCA methodology.

4. Conclusion

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 [32]. Therefore, recycling products and keeping a circular loop of materials are crucial to sustainable manufacturing. 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.

Acknowledgments

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Simone Ehrenberger leads the 'Environment and Transformation' group at the Institute of Vehicle Concepts at the German Aerospace Center (DLR). With more than 15 years of professional experience in research and development, she is a specialist in technology assessment and market analysis of vehicles. Her research focuses on the ecological evaluation of vehicles and the analysis of future vehicle markets. In addition, she represents Germany at international level in working groups of the International Energy Agency's (IEA) Technology Initiative for Hybrid and Electric Vehicles (IA-HEV), including the Assessment of Environmental Effects of Electric Vehicles. Simone Ehrenberger studied geoecology at the Karlsruhe Institute of Technology. As part of her doctoral thesis, she focused intensively on the ecological assessment of future vehicle technologies, considering new materials and drive train systems.