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Evaluation of the Environmental Benefit of an Eco-design Strategy on the Life Cycle Assessment of a Permanent Magnet Synchronous High-speed Electric Motor

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Abstract

The purpose of this study is to assess the environmental impacts of a Permanent Magnet Synchronous high-speed electric Motor (PMSM) and quantify the environmental savings resulting from the adoption of an eco-design strategy. To this end, a PMSM was identified as a baseline for the study, and a cradle-to-grave environmental life cycle assessment was performed based on primary data. The environmental impacts of the baseline PMSM were compared to those of its lightweighted version, which was obtained by adopting an eco-design strategy focused on aluminum content reduction. Other eco-design strategies were investigated to evaluate additional savings. The results obtained for the baseline PMSM reveal that the procurement and processing of raw materials contribute the most to all impact categories. The results obtained for the lightweighted PMSM reveal that, while reducing the aluminum content does not significantly lower the impacts in any of the most relevant impact categories, reducing the copper content would significantly reduce the use of mineral and metal resources. Lastly, eco-design strategies that focus on permanent magnets would significantly reduce climate change.

Keywords: LCA; Life Cycle Assessment; Electric motor; Permanent magnets; Eco-design.

1. Introduction

As one of the main contributors to climate change (IEA, 2021), the automotive industry is under examination for its role in environmental degradation. Designers are regarded as having a significant role in adapting products to a sustainable society in this context, owing to the necessity of responding to an increasing wave of environmental

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regulations and public awareness (Luttropp and Lagerstedt, 2006). As a result of these considerations, there is a growing emphasis on the development of sustainable products (Lagerstedt, 2003; Luttropp and Lagerstedt, 2006). With the rising electrification of the vehicle fleet in Europe (European Environment Agency, 2022; Eurostat, 2023), there is a need to develop highly efficient, compact, and lightweight electric motors (Tenconi et al., 2014). Furthermore, eco-design strategies must be identified and applied to reduce their environmental impacts by including environmental considerations in the early stages of the design process.

On the one hand, electric motors have gained popularity in this context due to their potential to reduce the climate change impact of the automotive industry (European Commission, DG Climate Action, 2020). On the other hand, a wide range of environmental impact categories, not only climate change, must be assessed to ensure that the benefits of electric motors are not offset by other negative environmental impacts (burden-shifting). Among these, the category related to the use of mineral and metal resources is fundamental to accounting for resource exploitation.

Regarding the state of the art, the application of eco-design strategies to electric motors is a cutting-edge topic. The literature regarding electric motors covers a wide range of applications, ranging from electric vehicles (Hernandez et al., 2017; Nordelöf et al., 2019, 2017; Shao et al., 2023; Tikana et al., 2022) to household appliances (Auer and Meincke, 2018) and industrial machineries (Navarro et al., 2014.; Rassõlkin et al., 2020; Torrent et al., 2011; Yazdani-Asrami et al., 2015). Few publications (Nordelöf et al., 2019, 2017; Orlova et al., 2016; Rassõlkin et al., 2020) consider both the automotive sector and electric motors from a sustainability standpoint, with the bulk excluding crucial life cycle stages such as the End-of-Life (EoL) (Nordelöf et al., 2019, 2017), not focusing on eco-design strategies (Nordelöf et al., 2019, 2017; Rassõlkin et al., 2020), or being outdated (Orlova et al., 2016).

This study aims at exploring the environmental savings derived from an eco-design strategy based on the reduction of the aluminum contained in a Permanent Magnet Synchronous high-speed electric Motor (PMSM) suitable for automotive applications. In terms of the PMSM components involved, the reduction action only affects the housing.

Lastly, insight is given on other eco-design strategies. The break-even points of the reduction of climate change and resource use of minerals and metals are investigated, assuming different mass reduction rates of aluminum, copper, and permanent magnets.

2. Methodology

This study applies the Life Cycle Assessment (LCA) methodology in compliance with ISO (2006a, 2006b). For the sake of transparency, the main assumptions made are explained hereafter. Section 2.1 describes the study's goal and scope. Section 2.2 describes the Life Cycle Inventory (LCI) creation process. Finally, Section 2.3 expands on the adopted eco-design strategy.

2.1. Goal and scope

According to ISO (2006a, 2006b), the goal and scope should include the following definitions: purpose of the study, products under study, system boundary, data sources, and Functional Unit (FU).

The purpose of this study is to assess the environmental savings resulting from the implementation of an eco-design strategy based on lightweighting a PMSM suitable for automotive applications.

For this purpose, first, a PMSM configuration was selected as a baseline, and its potential life cycle environmental impacts were evaluated. Then, the environmental impacts of the baseline PMSM were compared with the ones obtained by reducing the mass of the aluminum contained in the housing. Lastly, different mass reduction rates of aluminum, copper, and permanent magnets were assumed to investigate the potential reduction of the impacts and determine the break-even points at which this reduction becomes significant.

To ensure comparability, both PMSMs are equipped with identical Nd(Dy)FeB magnets inserted into slots stamped on the rotor laminations. The main performance parameters of the powertrain unit under study were provided by the manufacturer as primary data, and they are reported in Table 1. The powertrain unit is composed of two PMSMs with dedicated inverters and a single gearing unit characterized by a transmission ratio of 16.7. Both PMSMs provide the same performance: peak power 240 kW and peak torque 171 Nm.

Table 1. Main performance parameters of the powertrain unit under study

Parameter	**Value**	**Data source**
Peak Power	480 kW	
Peak Axle Torque	5500 Nm	
Continuous Power	2 x 75 kW	
Continuous torque	2 x 1250 Nm	Primary data provided by the manufacturer
Vehicle speed	240 km/h	
System Voltage	850 V	
Maximum Speed	30000 rpm	
Lifetime	150000 km	

The system boundary of the study is cradle-to-grave and includes all the stages of the life cycle of the PMSMs (i.e., raw material acquisition and processing, manufacturing, distribution, use, collection, and EoL) as shown in Figure 1.

For data sources, the Bill Of Materials (BOM) and supplier-integrated primary data were used. Secondary data from relevant LCA databases (i.e., Ecoinvent) or from selected literature studies were used as background datasets and for those processes not directly covered by the core business of the company.

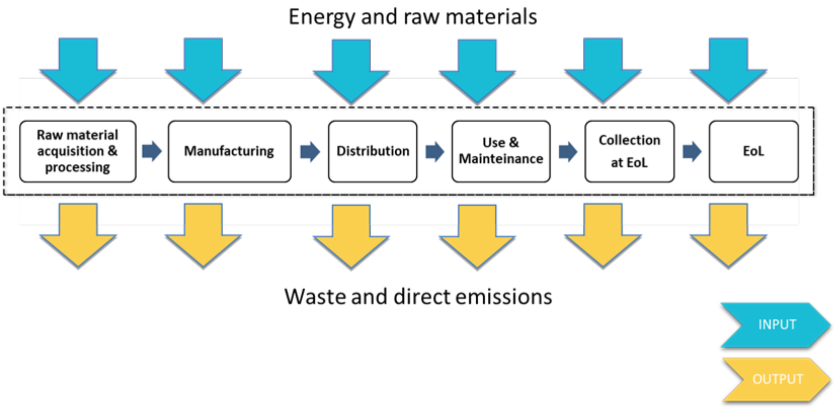

Fig. 1. System Boundary.

Since the purpose of this study is to perform a comparative LCA between two PMSMs that have the same efficiency and service life, the FU was defined as one PMSM with power and torque specifications suitable for automotive applications. However, while in this case the adopted eco-design strategy does not entail the durability and efficiency of the PMSM and the two PMSMs were assumed to be identical in durability and efficiency, in other cases it should not be taken for granted that the adopted eco-design strategy ensures constant durability and/or efficiency of the PMSM.

2.2. Life Cycle Inventory

Regarding the raw material acquisition stage, this study includes the environmental impacts related to material extraction, material processing, and transportation of raw materials and components to the assembly plant. Each of the motor components was modeled in terms of its mass and materials. The quantity of each component was then allotted to each subassembly and finally to the PMSM unit. In this way, the hierarchy of the BOM was maintained, enabling the identification of emission hotspots, i.e., the relative contribution of each subassembly and component to the final environmental impact of each PMSM.

The background datasets were mainly taken from Ecoinvent. When a dataset was not available in Ecoinvent, ex-novo datasets were created based on secondary data available in the literature. This is the case for the dataset related to the production of silicon steel ingots, whose dataset is based on Nordelöf et al. (2017).

For the manufacturing stage, a production flow scheme was used as a primary datum to figure out all of the steps and activities that went into making the PMSM under study. This scheme includes processes such as component manufacturing, assembly, and packaging. Nevertheless, there were no primary data related to energy consumption, ancillary materials use, and waste production. Therefore, after ensuring the comparability between the production flow scheme of the PMSM under study and the one described in Nordelöf et al. (2017), the dataset creation was primarily based on the data provided in Nordelöf et al. (2017). The data taken from Nordelöf et al. (2017) were scaled according to the mass and geometrical characteristics of the PMSM components. It was assumed that the manufacturing facility is in Reggio Emilia (Italy) and that the annual output volume is 5000 PMSMs. While energy consumption, ancillary material use, or waste production were included in the manufacturing stage, the evaluation of material scrap produced during the manufacturing process is not included in this study.

The distribution stage to European retailers was modelled based on electric vehicle sales in Europe in 2022, according to Automotive industry portal (2023).

For the use stage, the energy consumption of an electric vehicle is highly dependent on the vehicle type and driving mission. In this study, the energy consumptions of the baseline and lightweighted PMSMs were evaluated using an ad hoc-developed backward-facing simulation model that takes the longitudinal dynamics of a M1 vehicle into account. A Tesla model S RWD 2020 equipped with the PMSMs under study was assumed as a vehicle segment, while the Worldwide harmonized Light vehicle Test Cycle (WLTC) was assumed as the driving cycle.

The EoL stage was modelled based on the Ecoinvent dataset "Used internal combustion engine, passenger car {GLO}/shredding". The dataset was adapted to account for the difference in chemical composition between an internal combustion engine and the PMSMs under study.

2.3. Eco-design strategy

The eco-design strategy adopted in this study aims at reducing the mass of the PMSM by reducing the aluminum content contained in the housing. Starting from the original housing, a lightweighted version was developed, replicating the essential features like internal interface surfaces, oil cooling passages, sensor location, and flange cover hole patterns while reducing as much as possible the others to obtain a mass reduction greater than 2 kg (Figure 2).

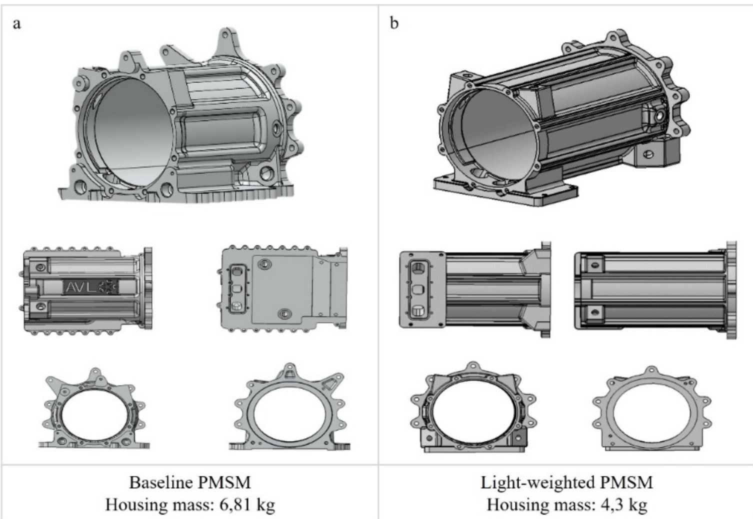

Fig. 2. (a) Baseline PMSM housing; (b) lightweighted PMSM housing.

This solution was chosen as an easy and immediate application of the eco-design principles to maintain the performance of the PMSM (i.e., avoiding possible side effects on its efficiency). Identical efficiencies were assumed for the two PMSM versions because the limited mass reduction rate applied only to the housing does not entail the efficiency of the PMSM. Further and comprehensive investigations may be required to address the potential consequences of this housing configuration.

3. Results and discussions

Figure 3 shows the life cycle environmental impacts of the baseline PMSM for the six more relevant impact categories. As far as climate change is concerned, the baseline PMSM is characterized by 1050 kg CO2eq/FU. Also, the use of mineral and metal resources is the most important impact category. This is measured in antimony equivalents (Sbeq) and accounts for 0.120 kg Sbeq/FU.

According to Figure 3, the raw material acquisition stage (dark blue bars) is the main contributor in all the most relevant impact categories. As far as this stage is concerned, while the main contributor in the climate change category is the rotor, the main contributor in the resource use of minerals and metals is the stator. More specifically, magnets are the main contributors to climate change (accounting for more than 90% of the rotor's impact), while copper windings are the main contributors in the resource use of minerals and metals (accounting for around 100% of the stator's impact). In the case of permanent magnets, the acquisition and processing of neodymium, dysprosium, and other rare earth elements are highly energy-intensive and involve complex extraction and processing techniques. These processes have significant environmental impacts relating to land use, water use, greenhouse gas emissions, and the generation of hazardous waste. In the case of copper, the mining process often causes significant land disturbance, which can result in habitat destruction and biodiversity loss. Moreover, the extraction of copper from ores involves the use of large amounts of water, which can lead to water scarcity in areas with limited water resources. Additionally, the use of chemicals, such as sulfuric acid, in the processing of copper ores can result in the generation of hazardous waste and air pollution.

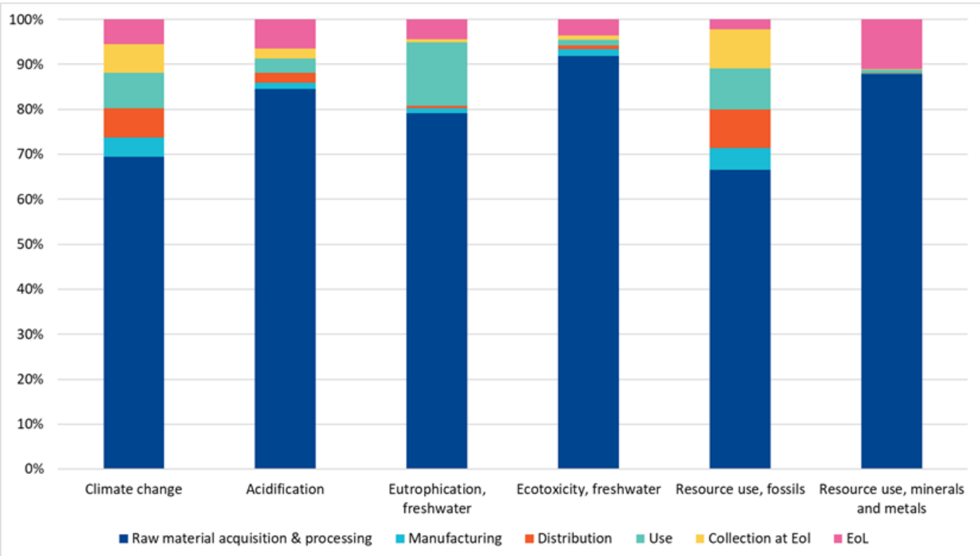

Fig. 3. LCA results for the baseline PMSM.

Figure 4 shows the comparison of the environmental impacts of the baseline and the lightweighted PMSMs for the six more relevant impact categories. Results are normalized to the highest score in each category. The manufacturing stage has the biggest reduction in impacts compared to the PMSM baseline (i.e., a 28% reduction). This is because the machining process for the housing has less of an effect.. The lowest reduction is obtained for the use phase (1% reduction). In fact, the reduction of the powertrain mass by less than 5 kg over a vehicle curb weight of 2041 kg has a low influence on the WLTC energy consumption.

Figure 4 shows that the influence on the environmental impacts of the aluminum contained in the housing with respect to the other materials contained in the PMSMs is minimal. As a result, the environmental impact reduction does not reach 10% for any of the 6 most relevant impact categories, with a minimum of 1% for the resource use of minerals and metals and a maximum of 7% for the use of fossil resources. Lastly, climate change is reduced by 6%.

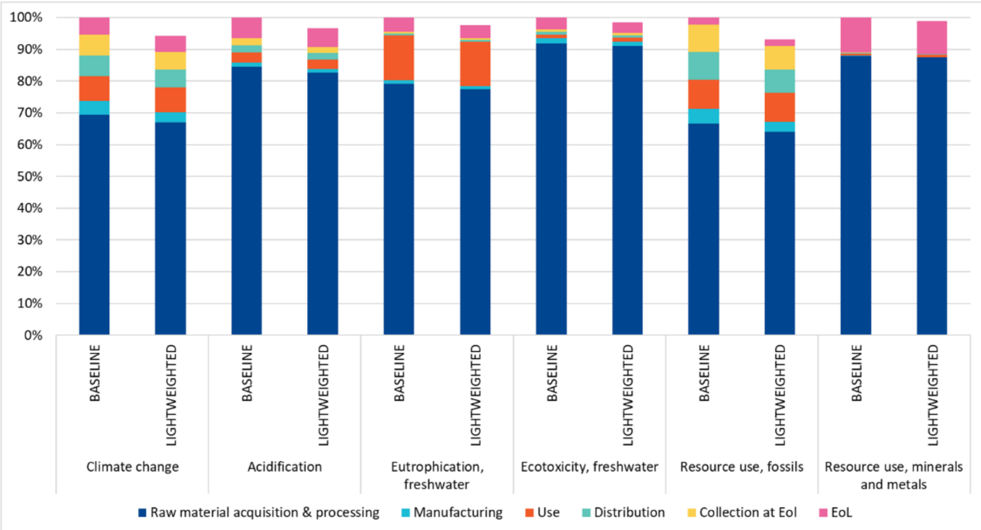

Fig. 4. Comparison of the LCA results between the baseline and lightweighted PMSMs.

Figure 5 looks at the break-even points where each environmental impact is significantly reduced (i.e., by at least 10%) because of the mass reduction of a certain material. The environmental impact categories of climate change and resource use of minerals and metals are investigated using variable mass reduction rates of the aluminum contained in the housing (Figure 4a-4b), copper contained in the stator's windings (Figure 4c-4d) and permanent magnets contained in the rotor (Figure 4e-4f). Copper was chosen because, focusing on the category of resource use of minerals and metals, which is the one representing the exploitation of critical resources, it is the main contributor to the impact. Permanent magnets were chosen because, focusing on the category of climate change, they are the main contributors to the impact and they account for the majority of the PMSM's bulk (i.e., 14 kg).

In the following results, the FU is omitted to avoid influencing the results with an additional variable.

Considering the aluminum reduction, Figure 4a-4b depict an analysis of the break-even points in terms of climate change and resource use of minerals and metals. According to Figures 4a-4b, even a 100% reduction in the amount of aluminum contained in the PMSM housing does not significantly reduce the impacts of both climate change and the use of mineral and metal resources. In fact, the break-even threshold is not reached in either of the two impact categories.

Considering the copper reduction (Figures 4c-4d), the break-even points in terms of climate change and resource use of minerals and metals were estimated. According to Figure 4c, even a 100% reduction in the copper contained in the stator windings does not significantly reduce the impact of climate change. On the other hand, Figure 4d shows that reducing the copper content in the stator by roughly 16% would result in a significant reduction in the impact on resource use of minerals and metals.

According to Figure 4e, the ideal magnet-free PMSM would reduce the climate change impact by 45%. According to Figure 4f, the ideal magnet-free PMSM would reduce the use of mineral and metal resources by 10%.

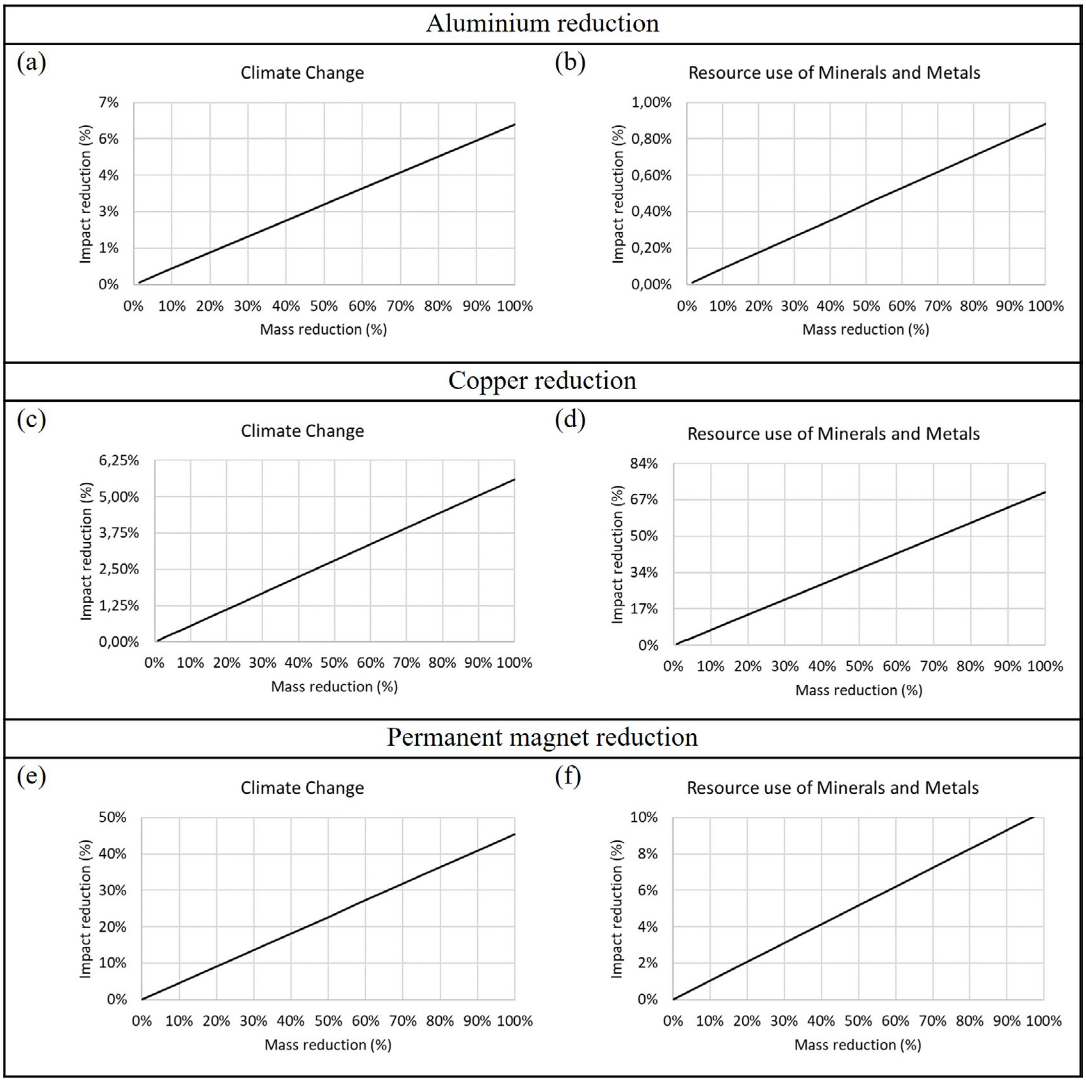

Fig. 5. Investigation of the break-even points of the reduction of climate change and resource use of minerals and metals adopting different mass reduction rates of (a-b) aluminum contained in the housing; (c-d) copper contained in the stator's windings; (e-f) permanent magnets contained in the rotor.

4. Conclusions

The LCA assessment conducted on the baseline PMSM shows that the raw material acquisition stage is the most relevant life cycle stage in all the main relevant impact categories. Resource use of minerals and metals results as the most relevant impact category due to the critical resources involved in PMSM production.

As far as the raw material acquisition stage is concerned, the main contributors to the impacts are the stator and the rotor, for which copper windings and permanent magnets are crucial, respectively.

A lightweighted PMSM was designed by means of a reduction in the amount of aluminum contained in the housing without affecting its efficiency. Compared to the baseline, the lightweighted PMSM shows a not significant reduction in environmental impacts if the focus is on the entire life cycle of the PMSMs. This is due to the minimal contribution of aluminum to the PMSM's environmental footprint and, on the other hand, to the limited mass reduction compared to vehicle mass, which results in only a 1% reduction in the impact of the use phase of the lightweighted PMSM. This result suggests that efforts should be focused on other critical materials. A break-even analysis was conducted with varying aluminum, copper, and permanent magnet contents. Varying the copper content revealed that a reduction of around 16% of the copper windings' mass in the stator would result in a significant reduction of the impact on the use of mineral and metal resources. The ideal copper-free PMSM would reduce the impact of the use of mineral and metal resources by more than 67%. Varying the permanent magnet reduction rate revealed that a 20% reduction of the permanent magnet's mass would result in a significant reduction in the impact of climate change. The ideal magnet-free PMSM would reduce the climate change impact by 45%.

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