Urban energy planning procedure for sustainable development in the built environment: A review of available spatial approaches

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RESEARCH ARTICLE

Switched Reluctance Machine for Transportation and Eco-Design: A Life Cycle Assessment

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ABSTRACT The ultimate goal of this research is to design switched reluctance electrical motors for circular economy. Within this paper, which represents a first step towards the main objective, the authors provide an environmental impact evaluation of a switched reluctance motor, designed for an automotive application through a cradle-to-grave life cycle assessment. The absence of permanent magnets makes this technology appealing from a cost perspective, and yet it is still not used in the transportation field as it is conventionally considered lower efficiency and performances with respect to other widely adopted technologies. In this paper a switched reluctance motor is compared with a permanent magnet synchronous motor on a like-for-like basis, although the magnet free configuration is not specifically designed for installation on the vehicle selected for this analysis. Furthermore, the paper provides a life cycle assessment of an eco-design strategy application to the magnet-free use case, through substitution of copper with aluminum within the stator winding. This research shows that a solution chosen to ensure cost sustainability, could also meet environmental sustainability at an acceptable performance level, if properly integrated in the end-user application.

INDEX TERMS Eco-design, electric motors, electric vehicles, life cycle assessment (LCA), switched reluctance motor (SRM).

I. INTRODUCTION

The electric vehicle (EV) market will see a strong increase with annual sales reaching 40 million units in 2030, based on stated policies scenario reported in the global EV outlook 2023 [1]. All EVs are equipped with at least one electric motor (EM) that works as a converter of electrical into mechanical energy. With respect to the above-mentioned background, EM sustainability, both in terms of cost and environmental impact, plays a very important role in the race towards electrification. In this perspective a Switched Reluctance Motor (SRM) could represent a viable technology as it is well known for its cost-effectiveness as described in [2], where SRM cost reduction potential is presented through a comparison with a permanent magnet synchronous machine (PMSM) and an induction machine (IM). SRMs lower torque density, high torque ripple and acoustic noise have determined a preference of other technologies for road applications, while robustness (with proper mechanical design), that is another characteristics of the SRM [3], together with the cost advantages, make this technology suitable for off-road applications, less sensitive to the intrinsic SRMs drawbacks [4]. Furthermore, robustness could be crucial to enable physical durability in favor of product design for circular economy [5]. A major SRM characterizing feature is related to the fact that it is a magnet free machine, constituted by an active electrical steel core, copper windings and a housing (generally aluminum-based). The absence of rare earths (RE) makes this technology appealing also from an environmental standpoint intended not only as climate change, but also in a broader sense, including other categories as mineral and metal resource usage. Furthermore, the development of such a technology could be attractive in the current geopolitical scenario in which, according to the assessment

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on Rare Earth Permanent Magnet [6], China is dominating all the supply chain stages of NdFeB magnets, accounting for a 58% share of annual global rare earth mining in 2020 and for a 92% share of annual global magnet production. Various papers describe environmental impact evaluation of electric motors through both comparison of different technologies and presentation of new design features, aiming to improve product sustainability. With regard to transportation field, the electric motor environmental impact, focusing also on the rare-earth magnet is evaluated recurrently in literatures [7], [8], [9], [10], and [11], through comparison of synchronous reluctance machine (synRM), permanent magnet-assisted synchronous reluctance machine (PM-assisted RM), PMSM adopting different magnet materials, induction motors (IM) and externally excited synchronous machine (EEsynM). Referring to SRMs, only one Life Cycle Assessment (LCA) study [12] was found in literature and not referred to transportation field, with specific reference to passenger car. Indeed, the magnet free solution is compared with two IMs representative of the low power range (1.5kW). Results indicate the SRM's lower environmental impact in all analyzed categories and a lower life cycle cost, especially due to the lower energy demand during the use phase.

Although the SRM is an intrinsically cost-effective and potentially environmentally friendly solution, design strategies could be implemented to furtherly improve this behavior. To pursue this objective, a design strategy focusing on the whole product life cycle, also known as eco-design [13], has been implemented through the change of the stator winding material from conventional copper to aluminum. Material substitution has been recurrently investigated in terms of performances mainly for PMSM designs [14], [15], [16], [17], [18]. Referring to LCA no studies have been found in literature reporting the effect of such a strategy to the best of authors knowledge. The aim of this paper is to present a comprehensive comparative assessment between a benchmark PMSM, (PMSM baseline), with two SRM configurations, namely a copper winding version (CU-winding SRM) and an aluminum winding version (ALU-winding SRM). For this purpose, both the CU-winding SRM and the ALU-winding SRM are virtually installed in the benchmark selected application (baseline vehicle), adopting the PMSM baseline motor, even if the SRM use-case machines are not specifically designed for this vehicle. The SRMs considered in this research are relying on the technical background examined in [19] in which a performance index comparison between the two machines, is described. The configuration with copper winding is preliminarily sized from the electromagnetic perspective and is then virtually re-wound representing the baseline configuration for the aluminum winding version (i.e., the magnetic structure is maintained unchanged, and only the winding material is modified). This study represents an advancement over the state-of-art, as to the best of the author's knowledge, a LCA study of a SRM for transportation doesn't exist. Additionally, modification of winding material, based on a performance proved design, has never been investigated from an environmental standpoint. Furthermore, all the analyses presented within this paper are conducted via in-house (i.e., Dumarey Automotive Italia), custom-developed tools and scripts, by relying exclusively on open-source software, with the exception of the LCA, which is carried out through the software SimaPro [20].

II. MATERIAL AND METHODOLOGY

The LCA methodology applied in this study follows the international standards [21], [22]. LCA includes compiling the so-called Life Cycle Inventories (LCIs) of the environmentally relevant flows (i.e., direct emissions in air, water, and/or soil, material and energy input/output flows, and waste flows) related to all processes involved in the production, use, and end-of-life of a product and, based on these, quantifying the associated life cycle burdens [23].

Section A describes the products analyzed, system boundaries, including data sources and the defined functional unit for this study. Furthermore, a benchmark analysis is provided, through which the baseline for LCA is selected. Section B is dedicated to the LCI and describes how the life cycle phases are modeled, the assumptions and data adopted for each phase. Section C instead provides background related to the propulsion unit (i.e., battery, inverter, motor and transmission) and virtual installation in the vehicle, explaining the methodology adopted and reporting characteristic data with the aim to provide a reliable basis for the environmental impact comparison. Lastly, section D concerns an eco-design strategy, describing potential advantages related to it, not only referred to environmental impact, and reports specific data of this configuration, used in the LCA.

A. GOAL AND SCOPE

The goal of this study is to provide a comparative LCA between a PMSM baseline and two SRM configurations, featuring respectively conventional copper winding and aluminum winding. The aim of this activity is to understand specific differences between two technologies, driving environmental impact and set the basis for future design improvement, of which aluminum winding configuration represents a first eco-design strategy implementation. This study aims to answer the question "What is the environmental burden of travelling one kilometer with a magnet free SRM with respect to a PMSM, manufactured in a specific country for specific vehicle application, and where do these impacts originate?"

A state-of-the-art PMSM motor is considered as baseline to compare with a benchmark SRM design. The PMSM baseline has been selected on the basis of an extensive benchmark analysis including 200 Battery Electric Vehicles on the European market from which a subgroup of motors in a performance range, comparable with the use-case SRM, was derived, relying on published data [24], [25], [26]. A snapshot related to vehicles featuring a single motor architecture, is shown in FIGURE 1, where both peak and homologated

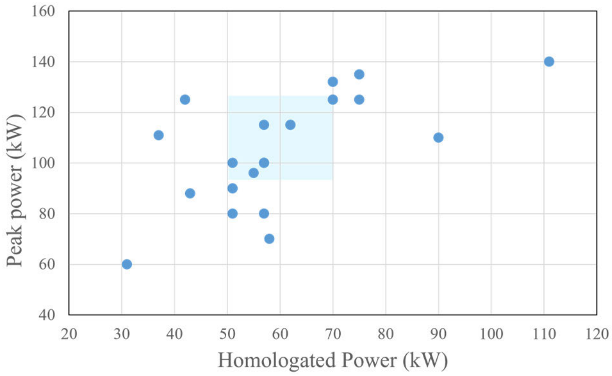

FIGURE 1. Peak power as a function of homologated power.

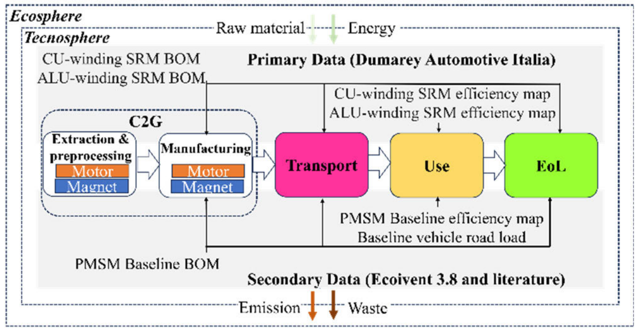

FIGURE 2. System boundary.

TABLE 1. Main motor parameters.

Parameter	PMSM Baseline	CU-winding SRM
Peak power	125 kW	100 kW
Homologated power	75 kW	60 kW
Peak torque	250 Nm	159 Nm
Base speed	4500 rpm	6000 rpm
Maximum speed	11400 rpm	18000 rpm
EM mass	48	67
Power density	2.6 kW/kg	1.5 kW/kg
Stator/rotor poles	12/12	12/8
Stator outer diameter	242 mm	246 mm
Length to stator bore ratio	1.8	1.2
Cooling method	Water jacket	Water jacket

power (i.e., power continuously available for 30 minutes) are plotted, as they were considered driving parameters for the motor mass and consequently for the LCA. A range for both peak and homologated power, indicating suitable motor selection, is also represented in the Figure. For the purpose of this paper, a BMW motor installed on the i3 is considered as PMSM baseline both for its similarity in terms of performances with the SRM and for the availability of data, as it was widely analyzed in terms of architecture and performances by Oak Ridge National Laboratory [27]. Some of the key performance and architecture parameters associated to PMSM baseline and SRM motors are reported in Table 1. All data relevant for this study, referred to the ALU-winding SRM configuration are included in section D.

The evaluation of the environmental burdens has been performed with a cradle-to-grave approach including electric motor related impact in all life cycle phases (i.e., raw material acquisition, preprocessing, manufacturing, transport, use and end-of-life) as reported in FIGURE 2. All the phases are represented maintaining same colors of the results section in order to facilitate reading. In the figure are also reported specifically primary data, mainly related to SRM configurations and secondary data related to baseline PMSM and vehicle, showing the point of the cycle in which, they are considered. These input data are the motor Bill-Of-Material (BOM), the efficiency maps and the vehicle data relevant for the energy requirement calculation. All other secondary data were derived from the LCA database Ecoinvent v3.8 [28] and from literature. Phases from material extraction to motor manufacturing are grouped into one macro-phase called also cradle-to-gate (C2G) including the two subgroups namely motor (accounting for all components of the motor without magnets) and magnets. The functional unit (FU) is one kilometre (km) driven along the entire lifespan of the vehicle (i.e., 200,000 km), while the country selected for the analysis is Italy as representative of an average European scenario for what concerns the adoption of fossil resources in the electricity production mix as shown in an infographics from the European Council [29]. The LCA database Ecoinvent v3.8 was used as background database while the LCA model was carried out using the LCA software SimaPro. Environmental burdens were calculated through midpoint Life Cycle Impact Assessment (LCIA) indicators (see Section E).

B. LIFE CYCLE INVENTORY

The LCA model of the electric motor adopted for this research, is composed of four main portions called cradle-to-gate (C2G), use, transport and end-of-life (EoL).

Regarding the C2G portion (i.e., raw material acquisition, preprocessing and motor assembly), the approach presented in [8] was followed, where the LCI main data source for the processes involved in material extraction and preprocessing is the Ecoinvent 3.8 database. For some processes related to both motor and magnet material preprocessing and for the manufacturing phase, data related to energy consumption, ancillary materials, waste and emission were retrieved from the LCI reported in [30]. In the manufacturing phase EM BOMs are derived respectively from literature data referred to a teardown activity for what concern the PMSM [27] and from primary data related to both CU-winding SRM and ALU-winding SRM (described in the dedicated section) design with the exception of the coating and insulation material, assumed from literature [31]. In FIGURE 3 is graphically summarized the percentage distribution of used materials, with respective mass values reported in kilograms for PMSM baseline and CU-winding SRM. The absence of magnets in the SRM is visible, however, in order to compensate and ensure the desired performance, the design has a higher active volume, leading to 20kg higher overall mass. The use phase

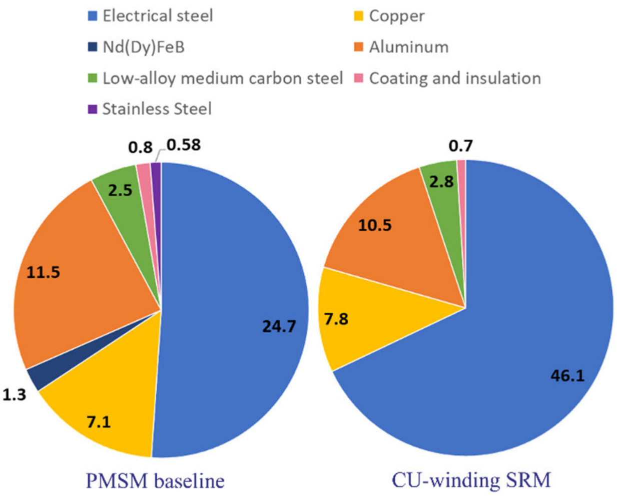

FIGURE 3. Material percentage distribution and mass values.

covers both the Well-to-Tank (WTT) and the Tank-to-Wheel (TTW) stages. In other words, it comprises all the life cycle stages that span from energy resource extraction to energy conversion in the vehicle. An ad-hoc model for the calculation of the energy used during this stage was developed following [32]. The model is fed with vehicle and propulsion line characteristics and speed profiles. By means of dynamics equations, the use phase energy required for the vehicle under study is obtained. The considered data related to vehicles and propulsion lines, are retrieved from literature and specifically reported in section C, where it is also described the approach adopted for the virtual installation of the SRM configurations in the baseline vehicle.

Regarding the speed profiles, the Worldwide harmonized Light duty vehicles Test Cycle (WLTC) is used as the reference driving cycle for the evaluation of energy request to motion. In compliance with [8] and [33], not the whole energy request by the vehicle was allocated to the electric motor. Instead, only the energy required by the electric motor conversion losses and its mass-related effects on WLTC were considered. Model equations are not reported here for sake of brevity, although interested readers can refer to relevant literature on the topic. Energy requirement calculated over cycle is then extrapolated over the whole lifespan distance (i.e., 200000km). Italian electricity production mix, with shares of electricity technologies valid at 2018, is considered for the LCA, according to latest Ecoinvent version. SRMs, are characterized by a higher torque ripple than PMSMs, leading to higher vibration, noise, and potentially more frequent bearings maintenance operation if not properly sized from a mechanical standpoint, affecting use phase. However, service life of the bearings has not been included in the life cycle assessment as it was considered to have minor impact to both environmental and economic assessment considering that bearings are accounting for a small fraction of the overall BOM. The transportation phase includes operations occurring both over manufacturing and distribution phases,

TABLE 2. Transportation boundaries.

Parts	Distance	Route	Typology
Magnet manufacturing	1000 km	China	Train
Magnet to assembly	17740 km	China to Italy	Ship
Motor Manufacturing	1000 km	Italy	Truck
Motor distribution	1000 km	Italy	Truck

TABLE 3. Recycling scenarios.

Material	Energy	PMSM baseline	CU-winding SRM
Steel	3.3 kWh/kg	27.8 kg	48.9 kg
Copper	1.8 kWh/kg	7.1 kg	7.8 kg
Aluminum	2.4 kWh/kg	11.5 kg	10.5 kg

following the approach explained in [7], according to which all transportation happens within the boundaries of the country considered in the study. All the above, with the exception of magnet transportation for the PMSM baseline configuration, which are modeled assuming production in China and shipment by boat to Italy, where are subsequently assembled. Distances and transport modes considered in the LCA are summarized in Table 2. Concerning EoL, this study follows the approach described in [34]. All metals, corresponding to 99% of the overall considered motors mass, are recyclable, leading to avoidance of new raw material extraction. Thus, for the metals, recycling scenarios were defined assuming to avoid production of material at a certain point of the following lifecycle. These recycling scenarios have been created retrieving benchmark data related to energy required for the various processes from [35]. Specifically for steel, it is taken into consideration the energy to produce steel from scrap through electric arc furnaces. Concerning aluminum, it is considered the energy required to obtain aluminum ingots from melting and casting of the scrap, while referring to copper, it is considered the energy required for the conversion of scrap into copper cathode.

Looking at the magnet recycling environmental impact, extremely promising results are presented in [36] and [37] where magnet-to-magnet recycling in Hard Disk Drive is compared with magnet manufacturing process from virgin material. Even if this process would lead to a strong reduction of the environmental impact, it is not considered in this paper for lack of data related to magnet separation phase in a PMSM. Indeed, in this study permanent magnets are included within the steel scrap scenario. Coating and insulation are not part of the recycling scenario as they were considered not influent for the purpose of this study, being comparable between the analyzed motors and due to their low presence.

Table 3 reports the main data related to the three recycle scenarios for steel, aluminum, and copper.

C. VEHICLE AND PROPULSION UNIT

To fulfill the objective of the study, the SRM has been virtually installed in the baseline vehicle, with the purpose of comparing the two technologies in the same application, even

TABLE 4. Vehicle main data.

Parameter	Data
Curb Weight	1345 kg
Rolling resistance coefficient	0.00715
Reducer ratio	9.665
Wheel diameter	0.694 m
Frontal Area	2.8 m^2
Aerodynamic drag coefficient	0.29
Transmission efficiency	97%
Inverter efficiency	97%
Battery efficiency	99%
Charging efficiency	94%

considering the not optimal matching between SRM design and the selected vehicle. Main vehicle data and propulsion unit efficiencies used for calculation of the energy required are summarized in Table 4. All vehicle data are published in [24], [25], and [26], except for the rolling resistance coefficient assumed on the base of vehicle characteristic following [38]. Efficiencies of the propulsion unit with exception of the electric motor, have been considered with fixed values following the approach explained in [8]. However, for the SRM configurations, transmission ratio (TR) has been selected in a way to ensure that both vehicle performance is comparable to the reference vehicle and to guarantee a better usage of the motor efficiency map over WLTC. The reducer ratio has been increased to 16, enabling a better match between the top speed of the vehicle and max speed of the motor. The shift towards higher speed, in addition to a better usage of the efficiency map, has been judged favorable for the potential contribution to mitigate the effects of torque ripple (which is inherently high in SRMs).

Indeed, torque ripple is still present at high speeds, but its effect is 'damped' due to the higher rotational speed of moving parts. In terms of performances, a parameter defined as "acceleration reserve", is taken into consideration following the approach explained in [38] and calculated as the difference between the wheel force and the road load, both divided by vehicle curb weight. FIGURE 4 reports the acceleration reserves and required power curves relative to the baseline vehicle with PMSM and with SRM, both with the baseline and the newly selected TR. The shift of the SRM curve from lower to comparable acceleration reserve with respect to baseline PMSM is evident. The force required to drive the vehicle, known also as road load, has been determined from vehicle data, as mentioned in section B, to allow evaluation of indirect effect coming from the motor mass. Nevertheless, the curve obtained through simulation is compared with two different testing activities, executed at different time but on same vehicle model, to show simulation robustness. In FIGURE 4 is reported a comparison of vehicle required power, simulated considering published vehicle data with that obtained from coast down target coefficients present

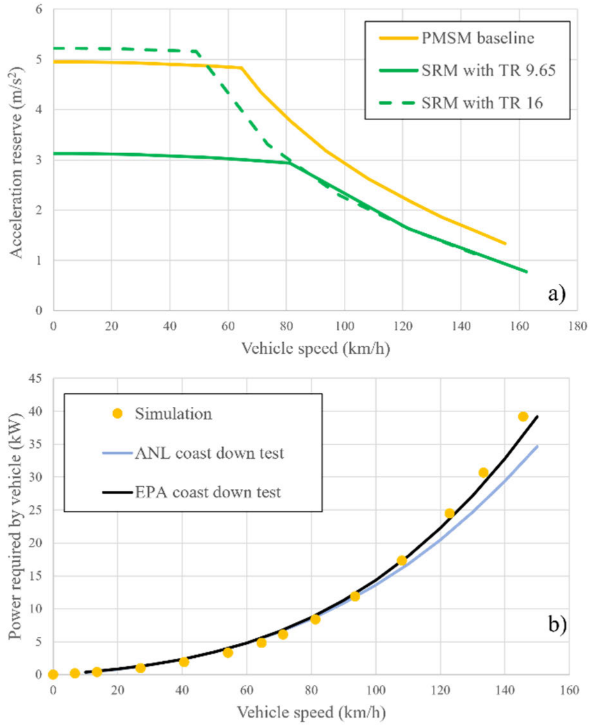

FIGURE 4. a) Acceleration reserve in relation to vehicle speed for reference vehicle and SRM with original and selected TR b) Reference vehicle required power calculated and measured in relation to vehicle speed.

in the literature available test reports from EPA and Argonne National Laboratory [39], [40]. A good correlation between data coming from simulation and testing can be observed. To determine the energy to be considered in the LCA, the efficiency maps of the two motors were considered. The baseline PMSM efficiency map has been retrieved from [27], while the SRM map results from in-house performed electromagnetic analysis, and represents the maximum electromagnetic torque-speed capability. FIGURE 5 reports the two efficiency maps showing specific trends for the two considered technologies and the respective WLTC operative points. It is possible to note a wide torque-speed envelope for the SRM. This, as already mentioned, indicates that the machine is not specifically targeted to the application at hand, demonstrating a considerable margin for improvement in terms of torque density and mean efficiency. It is also possible to appreciate the different position of the cycle operative points over the map, due to the TR. The specific energy losses values, calculated according to the assumptions described in the LCI and using the above-mentioned efficiency maps and vehicle data, are respectively 28 [Wh/km] for the PMSM and 32 [Wh/km] for the CU-winding SRM.

D. ECODESIGN STRATEGY

Eco-design of electric motors, and more in general of vehicles, is historically associated with efficiency improvement. Nowadays, however, design strategies for life cycle and for

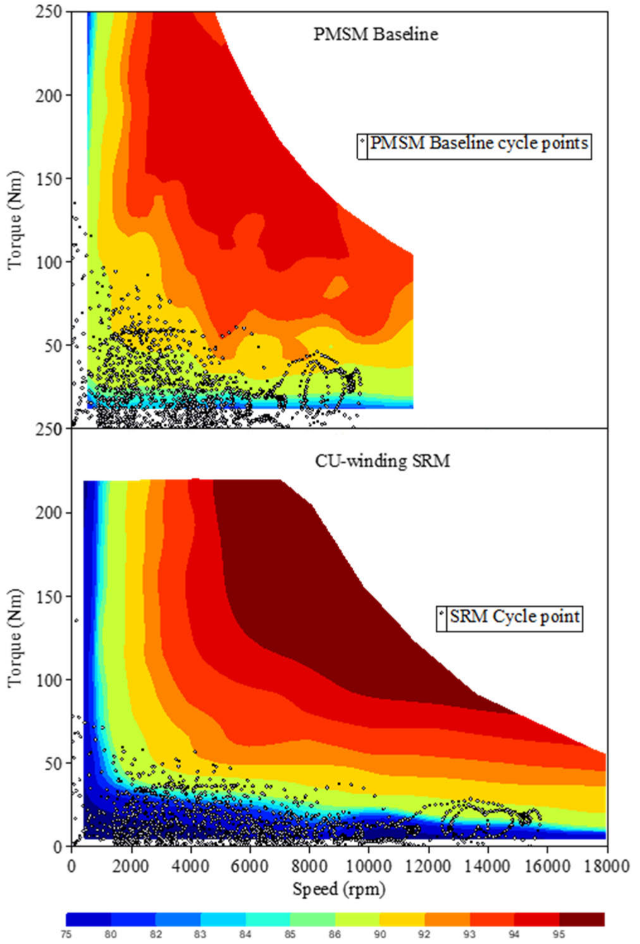

FIGURE 5. Efficiency maps of PMSM baseline and CU-winding SRM.

TABLE 5. Main differences between cu and al winding configuration.

Parameter	CU winding	AL winding
Winding mass	7.8 kg	2.1 kg
Power density	1.5kW/kg	1.6 kW/kg
Winding material cost	57.8 $/kg	5.25 $/kg
Overload time margin	60 s	20 s

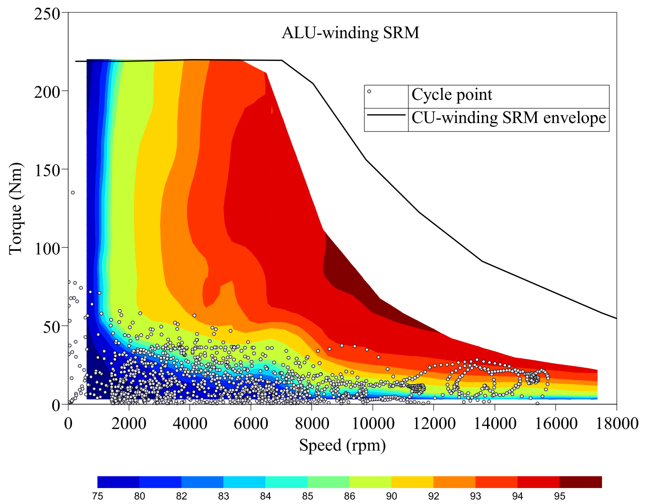

FIGURE 6. Efficiency maps SRM with aluminum windings.

circular economy are becoming topics of high interest as stated in [33] and [41]. Asynchronous motors with different efficiency levels, due to material change, have been studied evaluating trade-offs between various life cycle stages in [42]. Within this piece of research, the implementation of an eco-design strategy, considered appealing for its high cost-effectiveness, is evaluated, taking into account not only the materials, but also the different efficiency influence on environmental impact. The approach explained in [19] was not to scale the core, but to evaluate performance achieved in the new configuration, accepting a slightly decrease in the overload time margin from 60 to 20 seconds.

Lower performances of the ALU-winding SRM configuration are associated both to winding material change and to the fact that the structure of the machine is identical in the two configurations, including cooling circuit architecture and the winding fill factor. Concerning the first, a temperature limit is reached earlier in the ALU-winding SRM case than in the CU-winding case, however, the performance reduction is considered acceptable as other products on the market are featuring similar behavior [43], [44] in alignment to what indicated by US Department of Energy in the 2020 targets selection [45]. As known, the electrical resistivity of aluminum is 60% higher than that of copper, while the mass density of aluminum is about 30% that of copper, leading to higher peak power density and to lower peak efficiency at a given electrical loading. Current density is different consistently with the different resistivity and in particular the CU-winding SRM can withstand 20% higher continuous current density, up-to base speed (6 krpm). The current density withstand-ability difference between the two machines tends to decrease at higher speeds (i.e., within the range 6 to 18krpm), as in this operating range core losses tend to prevail over Joule losses. Based on these assumptions, to achieve one of the objectives of this research, a specific material and energy input were provided configuration. In Table 5 are summarized the most for the ALU-winding SRM significative differences between CU-winding SRM and ALU-winding SRM configurations.

The usage of aluminum winding represents a further mean for lowering cost of a machine that is intrinsically cheaper than other technologies as demonstrated in [2] where the total cost of the SRM is respectively 50% and 44% lower compared to a PMSM and to an IM. Indeed, cost per mass unit of aluminum is almost 3 times lower than copper. Referring to cost, the whole system including motor and inverter should be analyzed in order to have a holistic technologies comparison, considering potential indirect drawbacks of the SRM adoption, that requires a higher voltampere rating inverter.

Inverter cost represents less than 40% of the overall system cost [46], [47] and in case of SRM drives could present both a penalty associated to the lower power factor [48], [49], [50] and a potential advantage due to the possible usage of a Miller converter, with respect to a conventional PMSM three-phase inverter. All the above is leading to an overall SRM drive cost advantage related mainly to the lower cost of the electrical machine. In FIGURE 6 the efficiency map of the ALU-winding SRM and the cycle operative point are reported. Again, it is possible to note that the machine's torque capability exceeds the application requirement, implying a wide margin for mass/volume reduction, and cycle efficiency increment. However, it is also noticeable the torque-speed envelope reduction at higher speed, with respect to CU-winding SRM envelope, due to the aluminum's lower thermal limit. The above-mentioned derating for speeds higher than the base motor speed, leads to lower losses in the ALU-winding SRM in the operating cycle points. This is mainly due to a better combination of winding resistance (i.e., turns per phase) and control strategy to limit thermal overload in the mid-high-speed region. ALU-winding SRM is virtually running the considered driving cycle at higher torque level than CU-winding SRM with respect to their own maximum capabilities, working at favorable efficiency. This is reflected in lower energy losses with respect to both PMSM and CU-winding SRM with a value of 25 [Wh/km]. Substitution of copper winding with aluminum impacts all the phases of the life cycle due to differences in the raw material extraction, manufacturing process, use phase due to different efficiency and recycling process. This also considering the fact that winding mass is reduced from 7.8kg of the copper configuration to 2.1kg of the aluminum configuration, with a secondary effect related to motor mass in use phase. Concerning the manufacturing stage, due to lack of data related to the aluminum wiring process in the background dataset, for the purpose of this research, it has been conservatively assumed to not modify the copper's winding wire manufacturing process as it was considered more energy intense with respect to aluminum counterpart, due to the higher melting temperature of copper.

E. LIFE CYCLE IMPACT ASSESSMENT

The LCIA was conducted through the most updated version of the Environmental Footprint (EF) method, in conformity with [51] and midpoint impact categories were considered for the assessment. To identify the most relevant impact categories, the normalized and weighted results were used according to [52]. The most relevant impact categories are those that cumulatively contribute at least to 80% of the total environmental impact. The assessment results, in the identification of the categories with higher impact, are reported in Table 6 in descending order, with their percentage contribution. The first six are contributing 81% of the overall environmental impact and have been consequently considered for the comparison in the results section. It is clear that more than half of the contribution is represented by Climate change and Resource usage both fossil and minerals and metals.

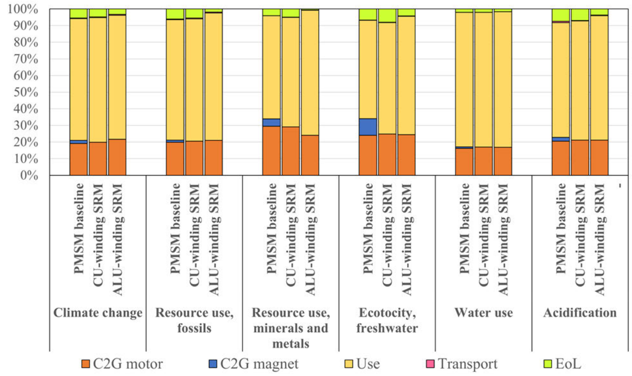

FIGURE 7. LCA results for PMSM baseline, CU and ALU-winding SRM.

TABLE 6. Impact categories.

Impact Categories	Percentage contribution
Climate change	26.6 %
Resource use, fossils	20.2 %
Resource use, minerals and metals	12.7 %
Ecotoxicity, freshwater	9.2 %
Water use	6.8 %
Acidification	5.7 %
Eutrophication, freshwater	5.6 %
Particulate matter	3.5 %
Photochemical ozone formation	2.8 %
Eutrophication, marine	1.8 %
Ionising radiation	1.7 %
Eutrophication, terrestrial	1.2 %
Human toxicity, non-cancer	0.9 %
Human toxicity, cancer	0.7 %
Land use	0.6 %
Ozone depletion	0.2 %

III. RESULTS

To provide a first screening of the results, FIGURE 7 presents the percentage influence of the six most relevant impact categories on the overall life cycle environmental impact for the three motors analyzed. It is clear that the motors life cycle phases have almost identical percentage distribution for the three motors, referring to climate change, use of fossil resources, water use and acidification categories. These four categories are highly impacted by the use phase with values from 70% to 80%. For the above-mentioned categories C2G Magnet, has low influence, accounting for only 2% of the overall impact.

For what concerns the use of mineral and metals resources and ecotoxicity freshwater in the PMSM baseline, although the use phase is still the main contributor, both G2G motor and magnet have higher influence in comparison to previous cluster of categories. Transportation phase is instead negligible while EoL has a beneficial impact, estimated between 3% and 10% considering all categories.

The use phase is clearly determined by energy required over life cycle, and so it is highly dependent from the motor efficiency itself and from the considered vehicle, which determines the cycle operating point. Another key aspect is the geographical location considered for the study (i.e., Italy), and its electricity mix, today constituted by fossil fuel and renewable sources respectively contributing for the 60% and 40% of total electricity production at the year considered in Ecoinvent [53]. Processes and materials involved in the production of the high voltage electrical energy are main contributors to the use phase, and more in general to the overall impact for all the categories. Nevertheless, discussing the influence of these scenarios on electric motor environmental impact is not in scope for this paper, where the main differences between the considered motors are investigated.

Carbon dioxide emissions, representing climate change category, are produced mainly during high voltage electricity production at coal power plants and at combined cycle power plant. For what concerns use of fossil resource, the main contributors are the operations required to import the natural gas involved in the high voltage electricity production to Italy. The metals and minerals resource use category is also mainly influenced by the use phase, as the main driver is the copper adoption in the infrastructure of the electricity distribution network, that however assumes importance also in the manufacturing phase for the configurations with copper winding. Emissions affecting the ecotoxicity freshwater category are mainly coming from production of biogas from sewage sludge employed in the high voltage electricity production and by blasting process; in the PMSM baseline configuration the production of rare earth carbonate concentrate is a relevant contributor. Water use main contributor is the production of high voltage electricity at grid-connected reservoir hydropower plant, while acidification emissions are mainly coming from production of high voltage electricity in the coal power plant. A detailed comparison of the three motors considering impact with respect to the FU is provided in FIGURE 8 where are reported respectively climate change (8a), and use of mineral and metal resources (8b). In this paper the two most relevant categories, characterized by a different breakdown trend of life cycle stages, have been reported.

Concerning the climate change, the analysis shows a disadvantage of the CU-winding SRM with respect to PMSM baseline, mainly due to the use phase, caused by lower efficiency over the considered cycle. Indeed, even if TR was adapted to ensure a fair trade-off between performance and efficiency, the CU-winding SRM was not specifically sized for the selected vehicle. In addition to that, the higher CU-winding SRM mass with respect to PMSM baseline, indirectly affects rolling resistance and the energy losses of the other propulsion unit components, working at higher power. SRM configurations are characterized by the absence of the

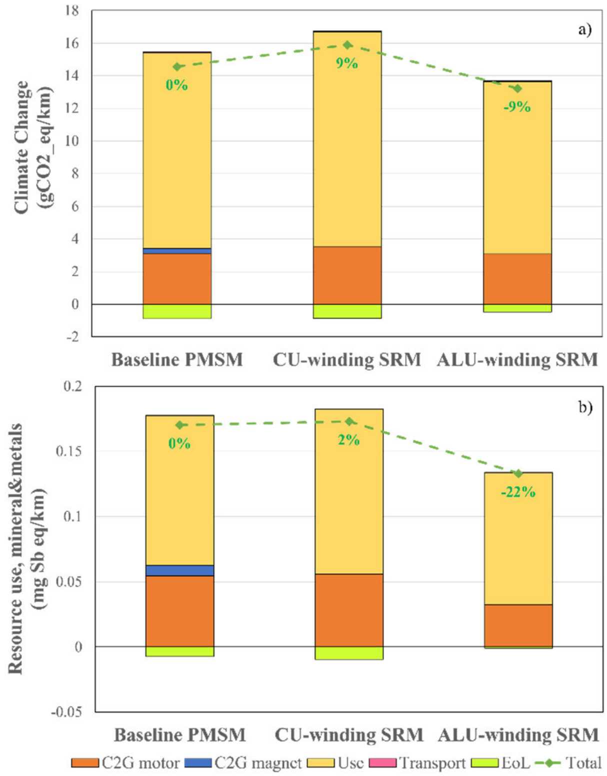

FIGURE 8. a) Climate change b) Resource use, mineral and metal for baseline PMSM, CU and ALU-winding SRM.

C2G magnet phase, that however is compensated in terms of impact on climate change by the higher electrical steel mass, due to bigger core dimensions. ALU-winding SRM configuration shows reduced impact in all the relevant life cycle stages both due to the high overall efficiency over the cycle and to the lightweight design; additionally, the manufacturing phase is characterized by the adoption of a less energy intense material for the winding. Even if it is reasonable to expect a lower peak efficiency for aluminum winding SRM with respect to copper winding configuration in absolute terms, in this case the more favorable efficiency map utilization is enabled by the better matching with the selected vehicle. For what concerns mineral and metal resource use, the manufacturing phase assumes higher importance with respect to climate change category, and moreover, activities for copper production are representing the most influent processes, with reflection in a noticeable reduction of the ALU-winding SRM compared to the others. Magnet manufacturing absence in the SRM configurations is another contribution to lower resource use impact. Considering overall impacts, CU-winding SRM shows a 9% deterioration in climate change with comparable values in terms of metals and minerals resource usage, while the ALU-winding configuration improves both CO2 emission and resource usage of 9% and 22% respectively.

IV. CONCLUSION

This paper provides a comparison in terms of environmental impact of electrical motors characterized by different technologies, designed with different targets, but intended to be used in similar applications. In particular, this research shows the environmental impact of an SRM, that represents a novelty in the transportation field, compared with a baseline PMSM, representing instead the mainstream technology for the considered market. The LCA results lead to the conclusion that the use phase is highly dependent from the efficiency over considered cycle, in this case determined mainly by matching between motor and vehicle. It is demonstrated that CU-winding SRM has comparable impacts in terms of resource use and has a slight disadvantage for what concern climate change, although it is virtually installed on a vehicle for which it is oversized. In addition to this base comparison, an eco-design strategy featuring substitution of copper with aluminum in the stator winding is described, showing potential advantages in terms of environmental impact. Indeed, for the ALU-winding SRM, the advantages related to both low energy requirement over use phase and employment of a less energy intense material for the winding have been explained. In addition, copper production is the main contributor to mineral and metal resource use. These findings have to be considered keeping in mind that SRM is a cheaper machine, featuring high durability and that doesn't employ rare earths, allowing geopolitical independency. Moreover, the future trend is to increase electricity production from renewable sources, leading to the conclusion that the use phase will assume lower importance, justifying increasing interest in magnet free motors and implementation of design strategies to improve products sustainability towards the two branches of the cost and environment. Apart from specific advantages related to the technology and material adopted, ALU-winding SRM configuration is demonstrating that a properly sized machine, even if intrinsically less efficient, could lead to better results coming from a favorable coupling with the application. However, this conclusion is determined by the approach followed in this study, where for the machine with aluminum winding, same core has been considered, accepting a deterioration of the performances at mid-high speed and a reduction of the overload time margin. In future work one could consider further opportunities and performance targets to compare a design of the SRM for a baseline PMSM application and potentially to experimentally verify performances of various SRM configurations. All results and conclusions are referred to the considered geographical scenario, that strongly influences the analysis, on the base of the dependance of a specific country's electricity production mix, by fossil and renewable resources. A deep investigation of the influence of geographical scenario will be provided in a dedicated future work as well as a comparison of the model results with relevant literature.

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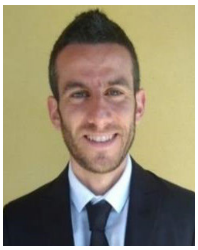

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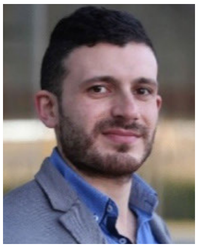

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