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IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received 22 September 2024, accepted 22 October 2024, date of publication 25 October 2024, date of current version 4 November 2024.

Digital Object Identifier 10.1109/ACCESS.2024.3486380

RESEARCH ARTICLE

A Novel Scenario Analysis Framework for the Life Cycle Assessment of Permanent Magnet Synchronous Motors for Electric Vehicles

SALVATORE MAFRICI[1,2], ANTONELLA ACCARDO[3], EZIO SPESSA[3], AND ALBERTO TENCONI[2], (Senior Member, IEEE)
[1]Advanced Engineering Group, Dumarey Automotive Italia S.p.A., 10129 Turin, Italy
[2]Dipartimento Energia "Galileo Ferraris," Politecnico di Torino, 10129 Turin, Italy
[3]Dipartimento Energia "Galileo Ferraris," CARS@Polito, Politecnico di Torino, 10129 Turin, Italy

Corresponding authors: Antonella Accardo (antonella.accardo@polito.it) and Salvatore Mafrici (salvatore.mafrici@polito.it)

ABSTRACT Nowadays, the application of Life Cycle Assessment (LCA) methodologies to vehicles and automotive components like electric motors is a cutting-edge research field. The goal of this paper is to gain a better understanding of how electric motors affect the environment and to shed light on the effects of certain assumptions on the LCA results. The LCA methodology was used to assess a wide range of environmental impacts in a cradle-to-use perspective and compare several electric motors designed for passenger cars. First, a baseline motor was identified and assessed. Then, a comparative LCA was conducted based on a novel scenario analysis framework. This framework ensures consistency in location settings, vehicle parameter settings, and scenario considerations so that all the comparisons are conducted on a like-to-like basis. The study examined two alternative scenarios to investigate the effect of geographical boundaries and vehicle applications. The methodological choices, including the specific modelling of environmental impacts, scenario modelling, and dataset selection are transparent and based on existing scientific literature or industrial publicly available data sources. The findings of this study provide indications on the relative life-cycle performance of the different scenarios considered and good evidence on how intended application and geographical factors influence life-cycle performance of electric motors. Moreover, while the use phase resulted as the main driver of the emissions in climate change and use of fossil resources, the other environmental categories resulted in a more balanced contribution between manufacturing and use phases, highlighting the importance of eco-design choices.

INDEX TERMS Electric motors, electric vehicles, LCA, life cycle assessment, transport.

I. INTRODUCTION

Nowadays, increasing emphasis is being placed on the environmental sustainability of commercial products. This trend can be attributed to government regulations aimed at reducing greenhouse gas (GHG) emissions, as well as market strategies in which product sustainability is increasingly becoming a qualification for companies [1]. In this context, significant interest is rising in the electric motor sector, estimated to consume 7200 TWh per year (46.2% of global end-use electricity consumption) in 2011 and expected to consume 13360 TWh per year by 2030 if comprehensive and effective energy–efficiency policy measures are not implemented [2]. In terms of GHG emissions, the electric motor sector was estimated to emit 6040 Mt of CO_2 per year in 2011, a value that is expected to rise to 8570 Mt CO_2 per year in 2030 [2]. Focusing on the transport sector, in 2022, [3] forecasted that the electricity usage would grow from 658 TWh in 2011 to 2859 TWh in 2030 in the net zero scenario. In terms of GHG emissions, the transport sector was estimated to emit 7171 Mt of CO_2 per year in 2011, a value that is expected to rise to 7465–8947 Mt of CO_2 per year in 2030 [3].

The associate editor coordinating the review of this manuscript and approving it for publication was Zhuang Xu.

In the European context, a number of policies have been implemented in the transportation sector to address sectoral environmental impacts and support the transition to a low-carbon, circular economy [4]. At the product level, the Life Cycle Assessment (LCA) approach is being increasingly used to evaluate products' environmental impacts. However, not so many life cycle studies exist in the literature in the field of electric motors, which are often treated as a subsystem within vehicle LCA studies. A literature search was conducted in Scopus adopting ''LCA'', ''life cycle assessment'' and ''electric motor'' as research keywords. The search was stopped in December 2023. To the best of our knowledge, for the LCA of electric motors, 17 papers have been published in the past [5], [6], [7], [8], [9], [10], [11], [12], [13], [14], [15], [16], [17], [18], [19], [20], [21], varying in terms of motor technology and market application considered. Among these, 9 papers are focused on electric motors for transportation. In all of them, the main scope is a comparison of environmental impacts in terms of motor technology, size, or end-of-life disposal. Technology comparison entails Permanent Magnet Synchronous Motors (PMSMs), Permanent Magnet Assisted Synchronous Reluctance Motor (PMaSynRM), Induction Motor (IM), Synchronous Reluctance Motor (SynRM) and Externally Exited Synchronous Motor (EEsynM).

In [13], different motor technologies (i.e., PMSM, ferrite-based PMSM, ferrite-based PMaSynRM and SynRM) are compared in terms of performance, weight and carbon footprint adopting a cradle-to-grave approach. In [14], a cradle-to-use LCA of six different electric motors is performed, varying both technologies (i.e., Nd(Dy)FeB PMSM, SmCo PMSM, Sr-ferrite PMaSynRM) and production and use countries (i.e., Sweden, USA). In [15] four different electric motors are compared (i.e., IM, PMSM, EEsynM and SynRM) in terms of mass and GHG emissions, and adopting a cradle-to-gate approach. In [16] and [17] a scalable life cycle inventory model for designing and manufacturing PMSMs is developed. In [18] three examples of circular economy loops (reclaim, recycle and reuse) for an electric motor and inverter are evaluated in terms of carbon footprint. In [19] and [20] the environmental impacts of magnet production for a PMSM compared with a SynRM are evaluated adopting a cradle-to-gate approach. In [21] the environmental impact of a high speed PMSM and the environmental saving associated to eco-design strategies are evaluated.

In terms of motor technology, this research does not entail a technology comparison, but it is focused on PMSMs, that currently represent the predominant technology in the transportation market. In terms of vehicle application, this research focuses on passenger cars.

The present paper presents a consistent LCA scenario analysis framework that considers two alternative scenarios, namely geographical and application scenarios. The aim is to investigate the effect of different geographical boundaries and vehicle applications on the environmental impacts of PMSMs. In the geographical scenario, four alternative countries are investigated for motor production and use to evaluate the extent to which each country's electricity mix affects environmental impacts. In the application scenario, four different vehicles were considered to investigate the effect of vehicle type on environmental impacts. An ad-hoc integrated vehicle simulation model was developed to ensure consistency. Lastly, this paper gives fundamental understanding on what are the main drivers that affect the environmental impacts of electric motors both in terms of components and life cycle phases.

The present paper presents novelty in the LCA field because, even though certain researchers worked on the LCA of electric motors, often conducting comparative studies, very few researchers were found to have discussed the comparability issue. The framework includes explicit consideration of the differences related to vehicle application and geographic location, with the aim to systematically evaluate the associated environmental impacts.

The paper is organized as follows: the methodology is described in section II, the results are shown in section III and the conclusion is provided in section IV. Section II is divided into sub-sections A and B. In sub-section A, the vehicle model developed for the estimation of the energy consumption during operation is described. In sub-section B, the adopted scenarios are explained with the following sequence: paragraph 0 presents the baseline, paragraph II) discusses the geographical scenario and paragraph III) explains the application scenario. Section III is divided into three sub-sections that show the results obtained for each of the previously listed scenarios.

II. METHODOLOGY

Evaluating the environmental burdens associated with electric motors requires consideration of their complete life cycles, since substantial burdens can be generated not only in use, but also in their production and in energy supply chains. The distribution of these burdens will be very different depending on the powertrain architecture and electricity production pathways. A balanced comparison requires a consistent modelling framework for all parts of the life cycle of electric motors and boundary conditions appropriately reflecting realistic technological advancement.

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 (EoL) of a product and, based on these, quantifying the associated life cycle burdens [22]. The LCA methodology applied in this study follows the international standards [23], [24].

The goal of this study is to provide a methodology for conducting LCAs of electric motors designed for passenger cars. The results of this paper are supposed to answer the question, ''What are the environmental burdens of travelling one kilometre with a certain electric motor manufactured in a specific country for a specific vehicle application, and where do they come from?''. A better understanding of the

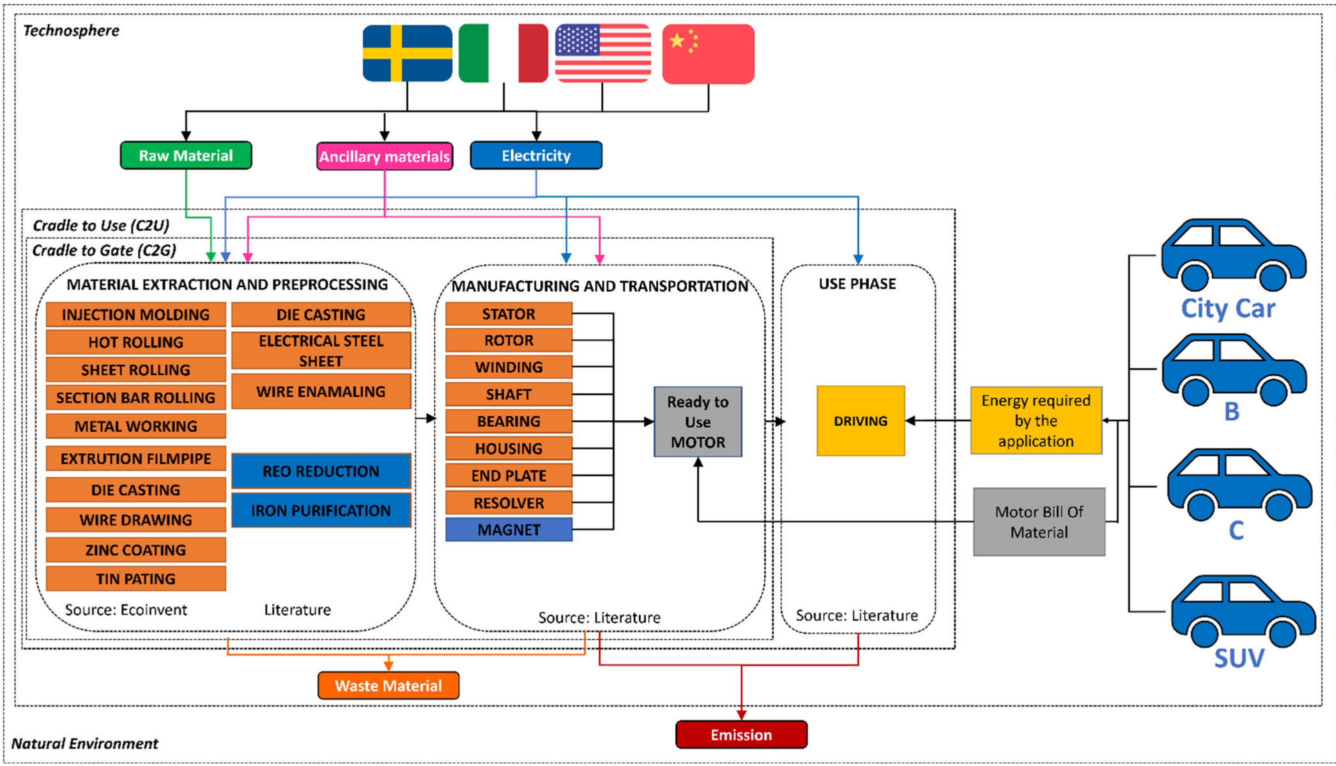

FIGURE 1. System boundary.

environmental impacts of electric motors is provided by investigating a wide range of scenarios. The scope of this analysis represents an attributional process-based cradle-to-use LCA, as shown in Fig. 1. The figure also shows interaction between the adopted scenarios and the system boundary. The system boundary includes the raw material acquisition and pre-processing, manufacturing, distribution, and use stages, grouped into two macro-phases. The first macro-phase is called cradle-to-gate (C2G), and contributions are divided between electric motor (in orange) and magnets (in blue), while the second phase is related to use stage. The use stage 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, i.e., cradle-to-use (C2U). The EoL phase is excluded and the reason for this assumption is reported hereafter. Despite electric motors are currently dismantled from vehicles, they are subsequently shredded. The shredding process causes the loss of the permanent magnets, that are currently not recovered [21]. Some research initiatives are currently in place in Europe to develop high technology readiness level dismantling procedures and novel permanent magnet recycling processes to enhance the recoverability of rare earth elements, but they are not commercialized yet [21]. Adding a hypothetical process for the EoL phase would significantly affect the results potentially conveying wrong/uncertain conclusions and decrease the quality of this study [14]. The functional unit is one kilometre (km) driven along the entire lifespan of the vehicle (i.e., 200,000 km) in compliance with [14].

The LCA database Ecoinvent v3.8 [25] was used as background database while the LCA model was carried out using the LCA software SimaPro [26]. Environmental burdens were calculated through midpoint Life Cycle Impact Assessment (LCIA) indicators of the EF3.0 method, in conformity with [27]. To identify the most relevant impact categories, the normalized and weighted results were used according to [28]. Regarding the LCA model of the electric motor that served as the baseline for all the scenarios, the LCI data of the processes involved in the motor's production (i.e., raw material acquisition, pre-processing, and motor assembly) are representative of an industrial scale motor production process occurring in 2019 based on [14]. To consider the different design features of the electric motors, the scaling approach described in [16] was used. All details related to LCI are reported in the Supplementary material in order to provide useful information for LCA practitioners aiming to build a model on electric motors. Referring to the supplementary material the Baseline Bill of Material (BOM) is reported in Table S1 while detailed inventory related to the same motor, including all material and energy input as well as emissions, is summarized in Table S2. Instead, the procedure for relevant impact categories selection is reported in Table S3. Results are reported for all the investigated scenarios in Table S4.1 and S4.2. Furthermore, a comparison of the obtained results against the literature is reported in Fig. S5. The factors contributing to the observed differences are highlighted.

A. VEHICLE MODELING AND SIMULATION

The use phase varies according to the mechanical energy demand of a specific type of vehicle, including its propulsion line and driving cycle. Therefore, an ad-hoc model was developed to take into account the longitudinal dynamics of the vehicles under study. The model is fed with vehicle and propulsion line characteristics and speed profiles. By means of dynamics equations, the use phase energy required for each vehicle under study is obtained. Each vehicle is defined by its mass m, frontal area A, aerodynamic drag c_x, and rolling resistance f_r coefficients, while the propulsion line is characterized by the efficiencies of the various components η and gear ratio k_{gear}. Regarding speed profiles, the Worldwide harmonized Light Duty vehicles Test Cycle (WLTC) is used as the reference driving cycle for the evaluation of energy request for motion.

In compliance with [14] and [21], not all the energy requested by the vehicle is 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.

The energy allocated to the electric motor, $E_{due\ to\ EM}$, is determined based on [14] as the difference between the net energy provided by the battery, including motor losses and motor mass, $E_{net\ with\ EM}$, and excluding them, $E_{net\ without\ EM}$ as shown in (1).

The net energy provided by the battery over the driving cycle is determined by subtraction of the energy recovered through regenerative braking E_{rec} from the energy required to drive the vehicle, E_{req}. These are respectively the energy at the wheels during braking, $E_{wheel(BR)}$ and during acceleration $E_{wheel(p)}$, increased of the powertrain losses during braking $E_{losses_{PT(BR)}}$ and acceleration $E_{losses_{PT(P)}}$(2). The energy required to drive the vehicle, E_{req}, is determined dividing the energy at the wheels during acceleration, $E_{wheel(p)}$, by powertrain efficiencies (2). The energy recovered through regenerative braking, E_{rec}, is determined multiplying the energy at the wheels during braking, $E_{wheel(BR)}$, by powertrain efficiencies (2).

Based on [29], the energy available at wheels is determined in (3) as time integral over the WLTC cycle of the power at wheels, which is the product of the vehicle speed and the force, required to overcome inertia, aerodynamic and rolling resistance. The first term related to inertia is of a conservative type (positive during acceleration and negative during braking with same absolute value) and in battery electric vehicle is equal to zero, considering that 100% of the energy due to inertia braking is recovered. Second and third terms instead are always resistant to motion, and so not recoverable during braking. For what concerns efficiencies of the driveline, fixed values have been considered, except for the electric motor for which an efficiency map function of motor speed and torque has been considered. The motor speed, and consequently motor torque to be used as input for the motor efficiency calculation, are determined according to (4), (5) and (6).

$$E_{due\ to\ EM} = E_{net\ with\ EM} - E_{net\ without\ EM} \tag{1}$$

where:
$E_{due\ to\ EM}$: energy allocated to the electric motor; $E_{net\ with\ EM}$: net energy including the motor; $E_{net\ without\ EM}$: net energy excluding the motor.

$$\begin{aligned} E_{net} &= E_{req} - E_{rec} = \\ &= E_{wheel(p)} + E_{losses_{PT(P)}} - E_{wheel(BR)} + E_{losses_{PT(BR)}} = \\ &= E_{wheel(P)} / \eta_{batt}\eta_{inv}\eta_{mot}\eta_{red} - E_{wheel(BR)}\left(\eta_{batt}\eta_{inv}\eta_{mot}\eta_{red}\right) \end{aligned} \tag{2}$$

where:
η_{batt}: battery efficiency; η_{inv}: inverter efficiency; η_{mot}: electric motor efficiency; η_{red}: transmission efficiency
E_{net}: net energy; E_{req}: energy required to drive the vehicle; E_{rec}: energy recovered through regenerative braking; $E_{wheel(p)}$: wheel energy over acceleration phase; $E_{losses_{PT(P)}}$: powertrain energy losses over acceleration phase; $E_{wheel(BR)}$: wheel energy over braking phase; $E_{losses_{PT(BR)}}$: Powertrain energy losses over braking phase.

$$\begin{aligned} E_{wheel} &= E_{inertia+} + E_{aero} + E_{rolling} = \\ &= \int_0^{cycle} P_{inertia}dt + \int_0^{cycle} P_{aero}dt \\ &\quad + \int_0^{cycle} P_{rolling}dt = \\ &= \int_0^{cycle} VF_{inertia}dt + \int_0^{cycle} VF_{aero}dt \\ &\quad + \int_0^{cycle} VF_{rolling}dt = \\ &= m\int_0^{cycle} V\frac{dV}{dt}dt + \frac{1}{2}c_x A\rho_{air}\int_0^{cycle} V^3dt \\ &\quad + mf_r g\int_0^{cycle} Vdt \end{aligned} \tag{3}$$

where:
E_{wheel}: wheel energy over cycle; $E_{inertia}, P_{inertia}, F_{inertia}$: energy, power, force request to oppose inertia resistance; $E_{aero}, P_{aero}, F_{aero}$: energy, power, force request to oppose aerodynamic resistance; $E_{rolling}, P_{rolling}, F_{rolling}$: energy, power, force request to oppose rolling resistance caused by the deformability of tires and road; m: vehicle mass; $cycle$: WLTC cycle test duration; V: vehicle speed; c_x: aerodynamic drag coefficient of the vehicle; A: projection of the transversal surface of the vehicle according to the motion direction; ρ_{air}: air density assumed as 1,225 kg/m^3; f_r: rolling resistance coefficient; g: gravitational force

$$n_{mot} = \frac{60 \cdot k_{gear} \cdot V}{\pi \cdot D_{tyre}} \tag{4}$$

where:
k_{gear}: gear ratio; D_{tyre}: wheel rim diameter; n_{mot}: motor angular speed expressed in rpm.

$$T_{mot} = \frac{P_{mot}}{n_{mot}\frac{\pi}{30}} \tag{5}$$

$$P_{mot} = \begin{cases} P_{wheel}\eta_{red}, & P_{wheel} < 0 \\ \dfrac{P_{wheel}}{\eta_{red}}, & P_{wheel} \geq 0 \end{cases} \quad (6)$$

where:

T_{mot}: Motor torque; P_{mot}: Motor power; P_{wheel}: Wheel power

B. SCENARIO SETTING

Once the baseline model of the electric motor has been setup basing on the literature, a scenario analysis framework has been developed aiming at providing useful indication for Original Equipment Manufacturers (OEMs) and electric motor's manufacturers. According to [30], during the LCA modelling of any system the appropriateness of the used background processes is checked in terms of geographical, and technological representativeness. Accordingly, two alternative scenarios in addition to baseline case study, were modelled named: geographical and application scenarios (Table 1).

TABLE 1. Scenario setting.

	Production and use locations	Vehicle application
Baseline	Italy	Segment C
Geographical scenario	1. Sweden 2. Italy 3. US 4. China	Segment C
Application scenario	Italy	1. City car 2. Segment B 3. Segment C 4. SUV

1) BASELINE

The motor equipped in the 2013 Nissan Leaf was identified as the baseline motor. This was widely analysed by the Oak Ridge National Laboratory, for the U.S. Department of Energy in 2013 and from the available reports both BOM and efficiency map have been retrieved [31], [32], in order to perform the LCA. All vehicle data for the calculation of the energy consumed in the use phase have been derived from [33], [34], and [35] and are the same used in the Segment C application considered in the application scenario (Table 1). Because of lack of data, the vehicle considered for the baseline analysis is not the original Leaf on which the motor was installed, but it is representative of the same vehicle segment. Lastly, for motor manufacturing, this work based on data from [14]. To validate and give consistency to the model developed by the authors, the results obtained have been compared with results obtained in the literature. Although the comparison is affected by time-related shift and potential different choices in terms of datasets, the model revealed to be robust. The results of this comparison are reported in the supplementary material (Fig. S5).

2) GEOGRAPHICAL SCENARIO

The geographical scenario gives indications for OEMs and companies interested in the production and commercialization of electric vehicles and motors, providing hints related to geographical boundaries and showing also influence of each life cycle phase in all the relevant impact categories, suggesting different conclusions depending on the considered country. To evaluate the effect of geographical boundaries, the baseline model was retrofitted to different production and use countries. Four different countries (i.e., Sweden, Italy, USA, and China) were investigated in this scenario, varying the electricity mixes of production and use, as well as the transport distances during acquisition of raw materials and the raw materials, ancillaries and processes considered in the manufacturing stage. These variations affect the entire life cycle including, raw material acquisition and preprocessing, production, and use stages. Sweden was selected because characterized by a green energy mix and huge penetration of electric vehicles, being the second for sales share of electric car in 2022 [36]. Italy, instead, was considered because more representative of an average European scenario for what concerns the share of fossil resources, despite the absence of nuclear sources in the electricity mix [37]. China and USA were chosen because are two largest economies and two of the most influential and powerful countries in the world representing also largest polluters. China has also a relevant role in the electric motor sector and, more in general, in electric vehicle field accounting for half of the world's electric cars on its roads [36] thanks both to the rare earth availability on its territory and consequent technological leadership on manufacturing. According to [38], China is dominating all the supply chain stages of the NdFeB magnets accounting for the 58% share of annual global rare earth mining in 2020 and for the 92% share of annual global magnet production. In Fig. 2 the electricity mixes of the four selected countries are represented considering the 2012-2022 timeframe. Fig. 2 shows the trend in reducing fossil sources in favour of renewable sources in the last decade. The figure also highlights the difference between the countries, showing how Sweden is already independent from fossil sources with a contribution lower than 1%, while the other countries are accounting for a 65% of electricity production from fossil sources.

3) APPLICATION SCENARIO

This study aims at providing indications on the environmental impacts of electric motors varying vehicular application. Vehicle features and desired performance level, in fact, determine motor selection. After an extensive benchmark analysis of the European battery electric vehicle market based on publicly available data [33], [34], [35], four different vehicles, including the baseline one, known to mount PMSMs were chosen for this scenario and their environmental impacts were assessed. The four vehicles differ in terms of vehicle segment, peculiar road load and performance. Because both the use and manufacturing phases are entailed by the vehicular

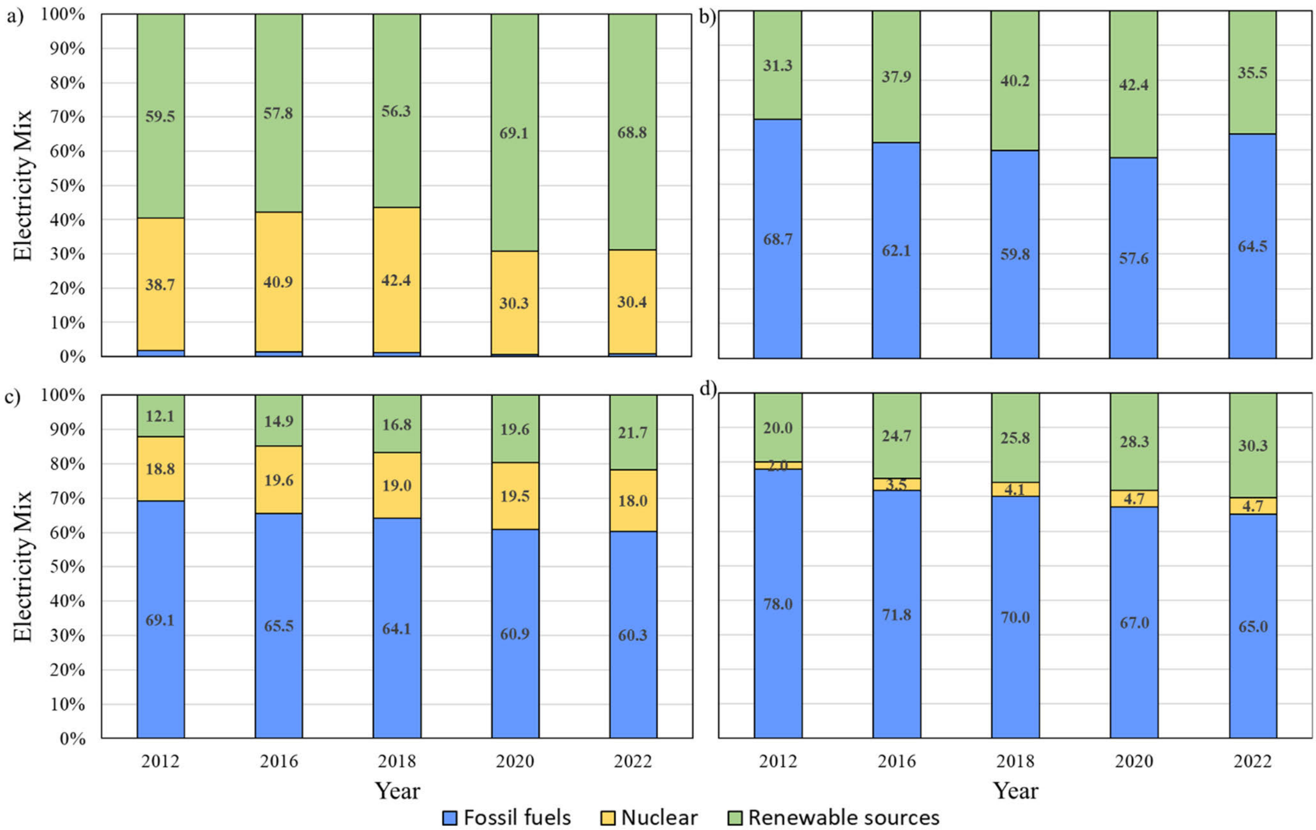

FIGURE 2. Country energy mix a) Sweden b) Italy c) USA d) China.

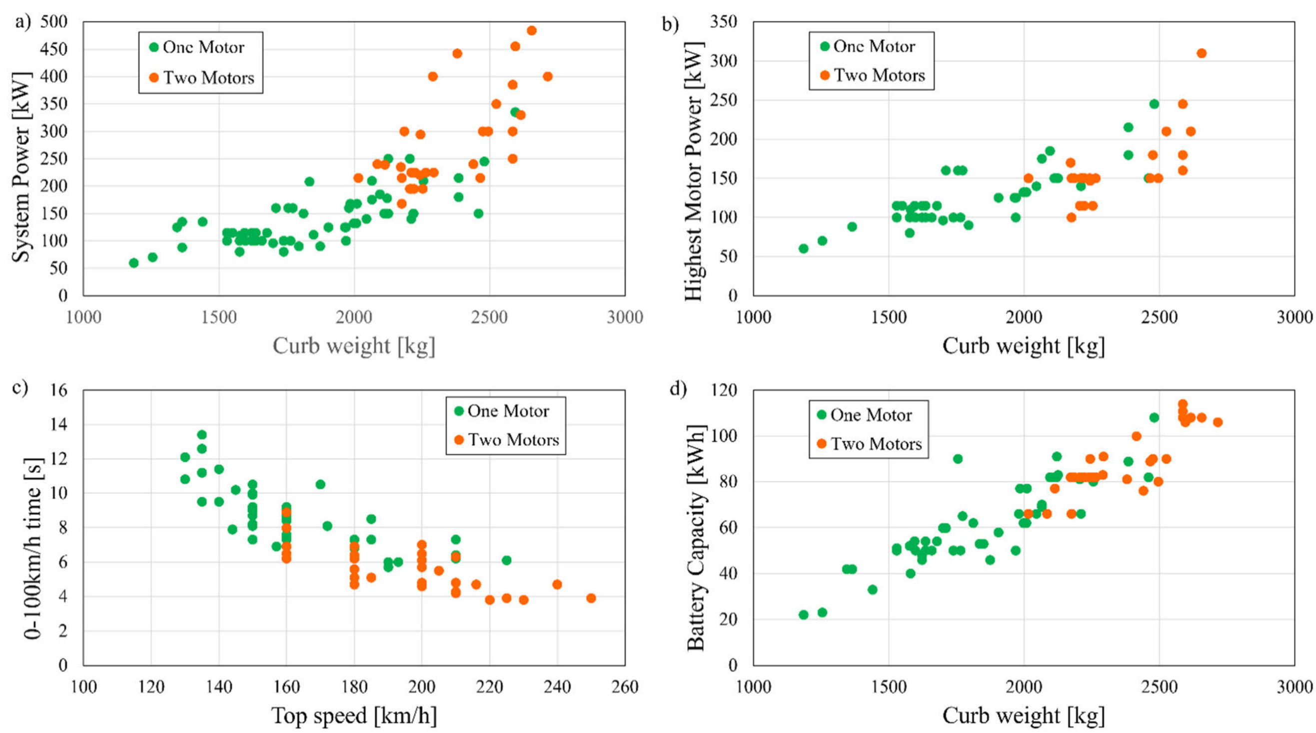

FIGURE 3. Electric motors sold in the European BEV market classified by a) system power as a function of the vehicle's curb weight, b) highest motor power as a function of the vehicle's curb weight, c) vehicle acceleration as a function of vehicle top speed d) battery capacity as a function of vehicle's curb weight.

application, for each vehicle, a dedicated BOM of the electric motor has been derived as a function of the power and torque level based on [17]. Rolling resistance coefficient is the sole vehicle parameter not retrieved by above mentioned reference but assumed on the base of vehicle segment as in [39]. Fig. 3 shows the results of the benchmark analysis. Fig. 3a shows the system power (i.e., equivalent to the motor power in the case of a single motor or to the sum of two motor powers in the case of two motor architectures) as a function of vehicle's curb weight. The vehicle's curb weight ranges from 1.2 to 2.7 tons, while system power ranges from 60 to 484 kW. Furthermore, the single motor cluster (green dots) has its highest values at 2.6 tons and 335 kW suggesting that the single motor cluster may be representative of almost all motor variants available on the market. Fig. 3b shows the highest motor power (i.e., equivalent to the peak power in the case of a single motor architecture or to the highest peak power in the case of two motors architecture) as a function of vehicle's curb weight.

The single motor cluster (green dots) has its highest values at 2.5 tons and 245 kW suggesting, also in this case, that the single motor cluster may be representative of almost all motor variants available on the market. For this reason, the single motor cluster was considered in this study and four applications segments were chosen, i.e., City car, B, C and Sport Utility Vehicle (SUV). Figures 3c and 3d show vehicle acceleration as a function of vehicle maximum speed and battery capacity as a function of the vehicle weight. Figures 3c and 3d confirm that also in terms of maximum vehicle performances and available energy, the single motor cluster may be considered as representative of the whole market. Data related to the selected vehicles and main parameters of their scaled motors are reported in Table 2. The selected vehicles are characterized by different road load, leading to a different electric motor operating point, and by different power and torque levels, leading to different electric motor weights. Both these aspects are shown in Fig. 4, where energy adsorption during WLTC is evaluated. The Baseline motor efficiency map has been considered for all four scenarios assuming that differences in the considered performance ranges are not significant in terms of efficiency.

TABLE 2. Vehicle and motor data used in the application scenario.

Product system	City Car	Segment B	Segment C	SUV
Curb Weight [kg]	1365	1530	1780	2125
Rolling resistance coefficient [-]	0.0065	0.00715	0.0084	0.0121
Reducer ratio [-]	9.59	9.3	8.19	12.98
Wheel diameter [m]	0.6099	0.6209	0.6319	0.7411
Frontal Area [m2]	2.14	2.18	2.38	2.62
Aerodynamic drag coefficient [-]	0.311	0.29	0.28	0.28
System Power	87	100	160	150
System Torque	225	260	340	310
Homologated Power	43	57	90	70
Motor mass [kg]	41.5	47.2	64.5	59.7

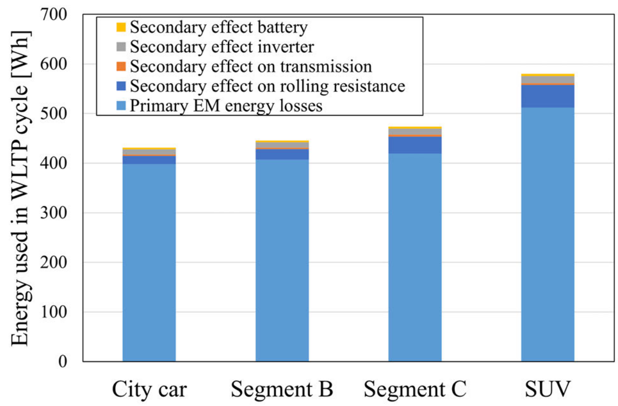

FIGURE 4. Energy used in WLTC for selected applications.

TABLE 3. Life cycle assessment results.

Impact Categories	C2G motor	C2G magnet	Use
Climate change [g CO_2eq/km]	2.88	0.37	8.44
Resource use, fossils [MJ/km]	0.04	0.004	0.13
Resource use, minerals and metals [mg Sbeq/km]	0.06	0.004	0.08
Ecotoxicity, freshwater [CTUe/km]	0.11	0.012	0.16
Eutrophication, freshwater [mg Peq/km]	1.44	0.1	2.55
Particulate matter [10^{-9} disease inc./km]	0.15	0.04	0.18

III. RESULTS

A. BASELINE

In this section, the LCA results related to the baseline motor are presented, highlighting both the influence of the life cycle phases on the overall environmental impact and the contribution deriving from the production of each component.

The first portion of results is reported in Table 3 where absolute values of the life cycle phases for the six most relevant categories are summarized, according to the calculation procedure mentioned in section II and more accurately described in the Supplementary Material.

The use phase is predominant in all the considered categories, accounting at minimum for 50% of the overall impact. Magnet manufacturing within the considered scenario has maximum influence, reaching 10% of total burden in the particulate matter category. Moreover, considering the evolution of the energy mix towards renewable sources, the manufacturing phase will be even more relevant on the overall environmental burden. This reason drove the analysis of the motor focusing on the C2G boundary, dividing the results by subsystems as shown in Fig. 5.

Indeed, the exclusion of the use phase provides useful information on the most impacting components, suggesting priority for environmental design interventions. Each bar represents the impact deriving from material extraction,

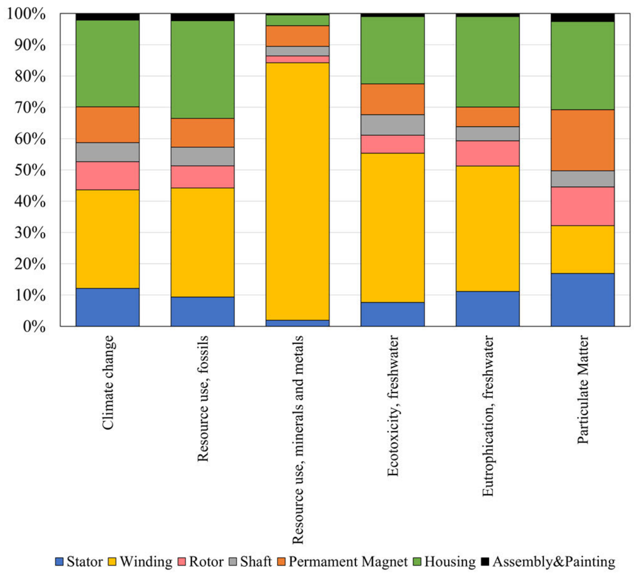

FIGURE 5. C2G phase breakdown by subsystems.

preprocessing, manufacturing, and assembly necessary to arrive at the final component production. The blue bar represents the stator contribution, the yellow bar represents the winding contribution, the pink bar represents the rotor contribution, the grey bar represents the shaft contribution, the orange bar represents the magnet contribution, the green bar represents the housing contribution, and the black bar represents the final assembly and painting, including the bearings contribution. The windings (yellow bars) resulted in the highest contribution in all the categories except for particulate matter. Windings portion accounts for approximately 30-35% in climate change and fossil resource use, 40-47% in ecotoxicity and eutrophication of freshwater and 82% in mineral and metal resource use, due to the extraction and preprocessing of copper. The second major contributor to the environmental impacts is the housing (green bars) which ranges between 20 and 30% in all categories except for mineral and metal resource use. This is mainly due to the extraction and preprocessing of aluminum and manufacturing of aluminum parts. The stator (blue bars) and rotor (pink bars), constituted by electrical steel, range between 6% and 17% in all categories with exception of mineral and metal resource use, where electrical steel extraction, preprocessing and manufacturing has a non-significant influence. Permanent magnets (orange bars) account for 20% of the overall impact in particulate matter, where they are the second contributor, following the housing. In the other categories, permanent magnets contribute between 6 and 11%. Lastly, results related to final assembly and painting, including bearing (black bars) are below 3% in all categories.

B. GEOGRAPHICAL SCENARIO

Geographical scenario analysis aims at evaluating the effect of the geographical area where an electric motor is produced and used on the environmental impacts. Direct correlation with country electricity mix and material availability and process used on the base of selected countries is shown. In Fig. 6 the results for the six most relevant impact categories are shown in order of relevance, highlighting influence of the life cycle phases.

Climate change is driven by the use phase and differences between countries are mainly due to the electricity mix. As shown in Fig. 6, in those countries (i.e., Sweden) where the electricity mix is not dominated by fossil sources, the production phase, including magnet manufacturing, significantly contribute to the overall impact. For example, the magnet production phase in Sweden accounts for 10% of the overall climate change. The overall climate change impact calculated in the Sweden scenario constitutes 10% of the emission found in the China scenario.

Similarly, fossil resource use is mainly driven by the use phase and consequently by the country electricity mix. With respect to this category, a gradual increase is visible going from Sweden to China scenarios, where the hard coal mine operation and preparation have strong influence on the Chinese electricity mix. In this category, the Sweden scenario has a slightly higher result than in Italy scenario, that revealed to be the best because there is no nuclear share of electricity production in the Italian electricity mix. In the Italy scenario, fossil resource use is 36% less than in the China scenario.

Concerning the use of mineral and metal resources, the contribution of the manufacturing phase to the overall impact resulted almost constant in all countries except for China where a step increase is noticeable. This is due to copper mine operations, which are more impactful on this category with respect to Europe or US, resulting in a 70% higher usage of mineral resources.

Similarly, particulate matter presents a flat trend except for China where the electricity production for usage in coal mines has a huge impact with values that are between 78% and 87% higher in comparison with the other scenarios.

Freshwater ecotoxicity has an increasing trend going from Sweden to China with an 80% difference between the two scenarios. This category is driven by blasting processes in all scenarios, but the main difference noticeable in the Chinese scenario is due to the impact of the hard coal mine operation.

Lastly, freshwater eutrophication is the sole category presenting a peak in the US scenario and not in China, mainly due to the spoil from lignite mining treatment in surface landfill. In this case, the best country, Sweden, has an impact approximately 87% lower in comparison to the US scenario.

C. APPLICATION SCENARIO

Fig. 7 illustrates the results of the application scenario analysis. It is shown that varying the vehicle, affects both use and manufacturing phases.

In the application scenario, the two extreme scenarios for all categories resulted to always be city car and SUV, resulting in approximately 25% difference in all categories.

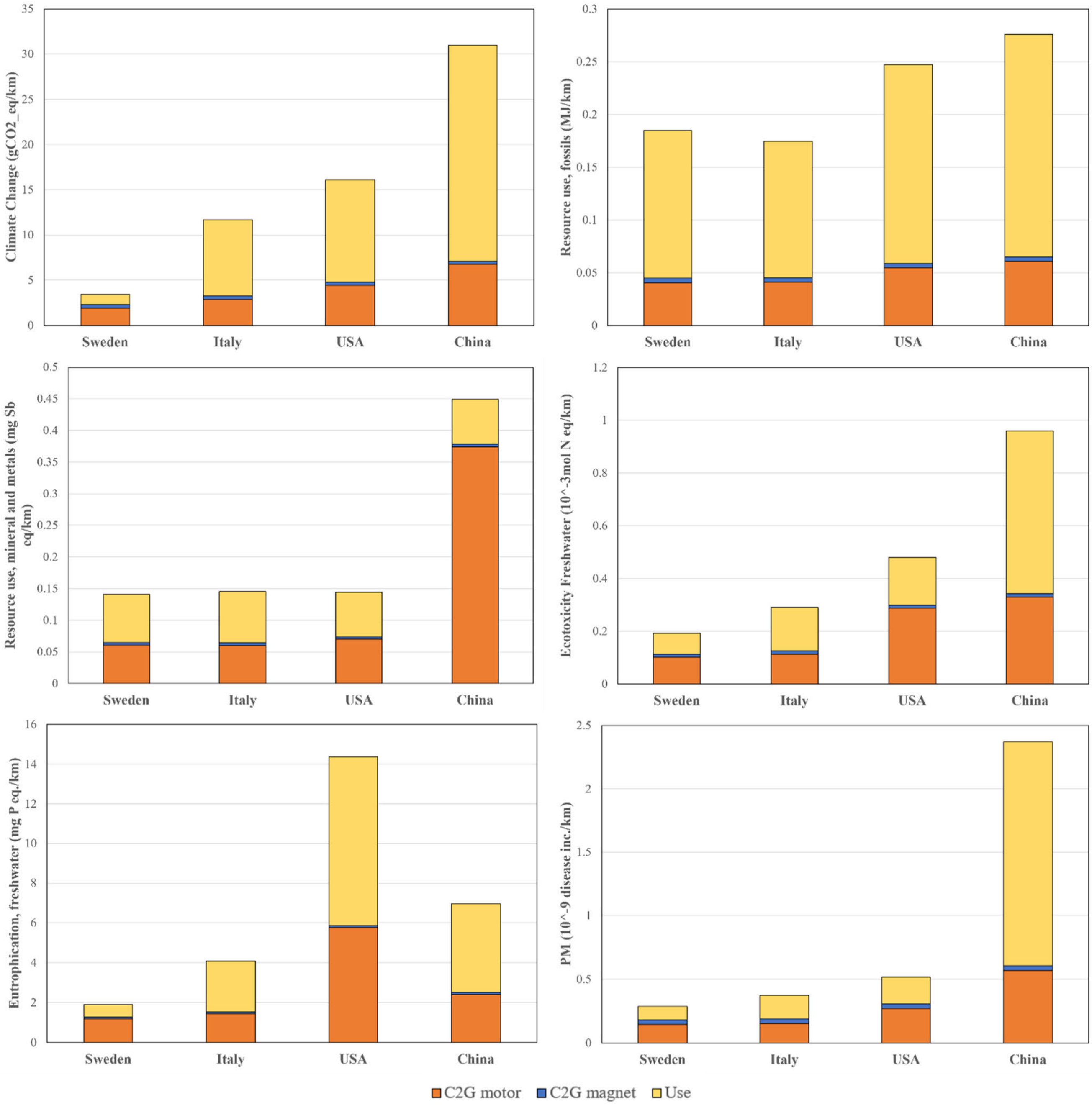

FIGURE 6. Results of the geographical scenario.

Focusing on the contribution of the different life cycle stages, all have comparable influence on the total environmental impact of each application scenario.

For the manufacturing phase, the BOM varies on the base of the required performances. The contribution of the manufacturing stage increases linearly with the required power, as the BOMs have been scaled accordingly. All categories are characterized by an increase of the manufacturing impacts passing from the city car to segment C scenario, with a slight reduction of the SUV scenario, with respect to segment C scenario, due to its lower power and torque. Instead, for the use phase, the energy required for operation is a function of the vehicle type that leads to a different efficiency map usage as shown in Fig. 4.The SUV scenario is characterized by an increase in all impact categories due to the higher energy absorbed over the use, given as the combination of efficiency and motor mass increase. For the other vehicles the trend is flatter because the motor mass increase from segment A to segment C is compensated by the higher efficiency of the latest, both thanks to the longer gear ratio and higher road load, that make the operating points shift towards higher iso-efficiency areas of the map.

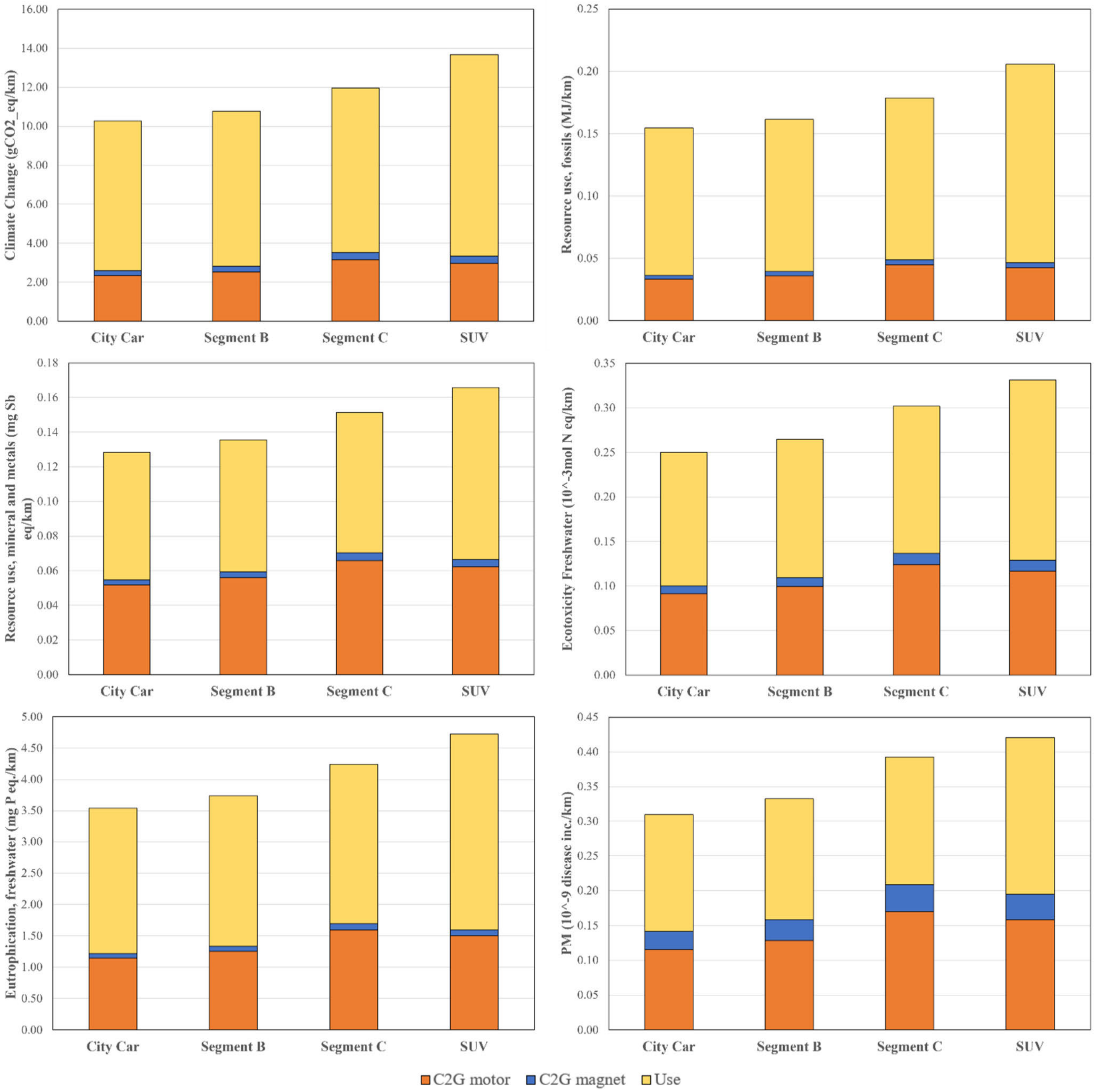

FIGURE 7. Results of the application scenario.

However, it is important to state that efficiency over the considered cycle is also due to the matching between motor and vehicle and so strongly impacted by transmission ratio. In this perspective the segment C that is also correspondent to the considered baseline is favourite as it takes advantage of a transmission ratio and motor size, properly sized for the vehicle.

IV. CONCLUSION

Despite they are more and more important, considered as relevant as performance and cost studies, LCA studies are affected by numerous assumptions. This paper can be regarded as a benchmark LCA study for permanent magnet electric motors suitable for passenger cars. It demonstrates the relevance of consistent geographical boundary setting. Moreover, it presents a step forward with respect to the literature in terms of consistency concerning comparative LCA studies, especially when different vehicle applications are considered. The proposed scenario analysis framework focuses on crucial key aspects influencing all the relevant phases of the electric motor life cycle, aiming at ensuring comparability.

First, a reference motor was identified as representative of the baseline. Results revealed that, in climate change and use of fossil resources, the use phase is predominant, confirming importance of both motor efficiency and electricity mix. The other categories resulted in a more balanced contribution of the manufacturing and use phases to the total. This will be even more true from now onwards if we look at the electricity mix trends, already showing reduction of fossil sources in all considered countries in the timeframe 2012-2022. Considering the baseline and excluding the use phase, copper windings resulted in the highest contribution in almost all categories, followed by the aluminium parts comprised in the housing, electrical steel in the stator, and permanent magnets.

In the geographical scenario, differences are mainly due to different electricity mixes in almost all impact categories and copper mine operations in resource use of minerals and metals. Moreover, in those countries (i.e., Sweden) where the electricity mix is not dominated by fossil sources, the production phase, including magnet manufacturing, not only resulted in a significant contribution to the overall climate change impact but it also gained relevance against the other life cycle phases. This highlights the importance of research focused on motor sustainable design and production.

In the application scenario, the environmental impacts are investigated for four vehicle applications, selected basing on the European BEV market. It is shown that, as the vehicle varies, both use and manufacturing phases are affected. Vehicle performance requirements and characteristics (e.g., weight, aerodynamic and rolling resistance) influence motor design and operating points and consequently manufacturing and use contributions, respectively. The contribution of the manufacturing stage resulted in growing linearly with the required power. All categories are characterized by an increase of the manufacturing impacts passing from city car to segment C, with a slight reduction for the SUV scenario against segment C scenario, due to its lower power. The SUV scenario resulted as the worst in all impact categories due to the higher energy consumption over use, given as the combination of efficiency and motor mass increase.

In the application scenario, the chosen case studies all fall into the passenger car category. It should be pointed out that, major differences are to be expected if the assessment is extended to 2-wheelers and/or medium- and heavy-duty vehicles.

Future work will extend the scenario analysis framework to other vehicle applications and motor technologies. Lastly, estimation of the impact of alternative design strategies on sustainability both from an environmental and economic standpoint will be provided in dedicated future works.

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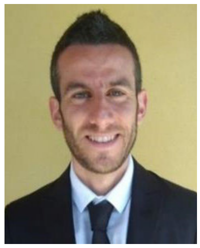

SALVATORE MAFRICI was born in Asti, Italy, in 1981. He received the degree in mechanical engineering from Politecnico di Torino, Turin, Italy, in 2006, where he is currently pursuing the Ph.D. degree.

From 2006 to 2020, he was with General Motors, where he was engaged in the development of new diesel engine families. He then joined Dumarey Automotive Italia S.p.A., where he is currently the Technology Area Leader for fuel cell system and hydrogen storage of the Innovation Team. His research interests include the design of electric motors for circular economy and life cycle assessment.

ANTONELLA ACCARDO was born in Palermo, Italy, in 1993. She received the B.S. and M.S. degrees in mechanical engineering from Politecnico di Torino, Italy, in 2019. She is currently pursuing the Ph.D. degree with the Department of Energy.

After graduating, she worked for two years as a Research Fellow with the Department of Energy, Politecnico di Torino. She is a member with the Interdepartmental Center for Automotive Research and Sustainable Mobility (CARS), Politecnico di Torino. Her research interests include the sustainability of the transport sector, including the application of life cycle assessment and life cycle costing to light- and heavy-duty commercial vehicles, and their main components (i.e., batteries, electric motors, hydrogen and internal combustion engines, and fuel cells).

EZIO SPESSA received the M.S. degree in mechanical engineering and the Ph.D. degree in energetics from Politecnico di Torino, Italy, in 1991 and 1995, respectively.

He is currently a Full Professor of fluid machinery with the Department of Energy ''G. Ferraris,'' Politecnico di Torino, and a member with the Interdepartmental Center for Automotive Research and Sustainable Mobility (CARS), Politecnico di Torino. His research interests include innovative vehicle technologies and powertrain solutions for the zero-tailpipe emission mobility of people and goods, including LCA approaches and circular economy aspects for sustainable and innovative road mobility solutions.

ALBERTO TENCONI (Senior Member, IEEE) received the M.Sc. and Ph.D. degrees in electrical engineering from Politecnico di Torino, Turin, Italy, in 1986 and 1990, respectively.

From 1988 to 1993, he was with the Electronic System Division, FIAT Research Center, where he was engaged in the development of electrical vehicle drive systems. He then joined the Department of Electrical Engineering (now the Energy Department), Politecnico di Torino, where he is currently the Head of the Department. His research activity is documented by more than 200 papers published in international journals and international conferences. He has participated, both as a Designer and as Scientific Responsible, in many National and European Research Programs. His current research interests include electric machines, power converters, and drives for transportation electrification. He is a reviewer of international journals and has been an Associate Editor of IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS.

Open Access funding provided by 'Politecnico di Torino' within the CRUI CARE Agreement