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Environmental sustainability analysis of Formula-E electric motor

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Abstract

Demand for urban mobility continue to be on the rise and the changing landscape has profound repercussions on a varied range of issues as well as health, safety, water, transport and energy consumption. For this reason, to achieve sustainable urbanization, cities must generate better employment opportunities, expand the necessary infrastructure, ensure equal access to services, preserve the natural assets within the city and surrounding areas. In this context, even in motorsport (particularly in FIA) future trends are beginning to be oriented to sustainability issues and there is a growing interest in assessing the sustainability profile of racing vehicles. Environmental protection and eco-mobility represent the main challenge facing Formula-E by offering electric vehicles (EVs) designed to combine technology, innovation and sustainability, as well as to enable the transition towards low-carbon smart cities in the next future. Up today the sustainability issues in Formula-E have been treated exclusively at system level (i.e. logistics and management, travel, infrastructure and so on), but no studies exist at component level. Technological development related to racing performance field is also potentially boosting innovation, thus supporting continuous improvement of electrical powertrain in terms of efficiency, performance and optimal use of materials, such as rare earths for electric motors and active materials for batteries. The target of the paper is the development and implementation of a tailored methodological approach to assess the environmental impacts of the whole Life-Cycle (LC) of a Formula-E electric motor. The primary data collection is functional to enhance knowledge and inventory regarding the specific application. At the same time, the results provide useful indications to both improve product development under eco-design perspective and ensure technology transfer from racing high-performance cars to commercial vehicles.

Keywords

Eco-design, life cycle assessment, electric motor, Formula-E, environmental impact

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Introduction

The demand for urban mobility continue to be on the rise because 53% of the population currently lives in urban area and by 2050 this number is expected to reach 67%.[1] If we consider that transportation sector is already responsible for 23% of global CO_2 emissions from fossil fuel combustion, the key to lead a real transition towards low-carbon smart cities is getting the right balance between technology, innovation and sustainability. As a matter of fact, to achieve sustainable urbanization, cities must generate better employment opportunities, expand the necessary infrastructure, ensure equal access to services, preserve the natural assets within the city and surrounding areas.[2] This means that the changing landscape has profound repercussions on a varied range of issues as well as health, safety, water, transport and energy consumption.

Over the years, since more and more people developed a deeper environmental awareness, many different strategies for sustainable transportation have been used worldwide,[3] including: the development of alternative fuels (e.g. biofuels); the improving public transportation or its accessibility (e.g. car sharing programs); the implementing new design concepts (e.g. lightweight materials)[4] or modern production technologies (e.g. 3D printing); the development of alternative powertrains (e.g. electric vehicles, EVs).

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It is well-known that the development and promotion of EVs could contribute to decreasing of the tailpipe greenhouse gases (GHG) emissions; however, there are still different technological challenges to be overcome. The production of the battery system, for instance, is responsible for an amount estimated up to 40% to 50% of the total CO_2-eq. emissions of the vehicle's manufacturing stage.[3] Furthermore, several problems might arise within other life cycle stages (LC) in the case of additional requirements for metals (e.g. copper and aluminum for battery system) and rare earth metals (e.g. neodymium and dysprosium for the electric engine). The use of EVs does not mean having an absolute environmental gain, especially if we consider the source of energy used to power a vehicle during its use phase. Since the energy significantly effects the environmental impact, promoting the market of EVs in regions where electricity is produced mostly from fossil sources can be counterproductive and consequently it can further increase the global GHG emissions from transport.

In this context, many Life Cycle Assessment (LCA) studies applied to the EVs have been conducted in order to analyze the benefits and weaknesses of different design options in terms of environmental impact (e.g. the balance between resource extraction versus GHG emissions).[5–7] In particular, several works deals with various complete vehicles,[8–10] while others focus on the traction batteries,[11,12] since these are the largest contributors to the environmental load. On the other hand, many researchers put out aggregated data from published sources and investigate the production of BEV powertrain/battery with different levels of detail and transparency; moreover, some of them deal with only specific phases of car life cycle, such as use or vehicle production.[13]

However, few well-populated studies focus on traction motors for EVs and neither of these studies contemplate scrap loses during the production stage.[5,14–16] The main focus of such studies regards permanent magnets included in traction motors and related Rare Earth Elements they are made of (i.e. neodymium, dysprosium, iron, boron).[17–19]

Nowadays, environmental sustainability is a topical issue that receives plenty of attention also from motorsports of the Fédération Internationale de l'Automobile (FIA) group concerning the performance and design challenges of Formula-E racing vehicles. Up today, the sustainability issues in Formula-E have been treated at system level activities (e.g. logistics and management, travel, infrastructure) while specific studies at component level do not emerge yet. This is the framework for a joined research activity between Marelli Motorsport S.p.A. and the University of Florence. Since 2012 Marelli uses LCA to develop, compare and validate alternative design solutions in the context of lightweighting,[20,21] components disassembly and materials recycling according to 2000/53/EC directive.[22] The aim of the present research is demonstrating in a rigorous manner the environmental impacts related to Formula-E electric motor, which is certainly a critical component for design issues and materials selection. More specifically, the work strives to develop a tailored methodological approach to assess the sustainability profile of the Formula-E motor, which enables to identify the main sustainability hotspots within the product LC. Additionally, the paper is aimed at increasing transparency and sensitiveness about the implication of shifting to new technologies, as well as providing elements for strategy development with a view to the future application to mass-market vehicles. The paper is structured as follows: paragraph 2 provides a brief literature review on motors for EVs and on the role of motorsport in promoting innovation; paragraph 3 describes the materials and method adopted for the LCA; paragraph 4 reports results, including interpretation and discussion; finally, conclusions are presented in paragraph 5.

Literature review on motors for EVs and on the role of motorsport in promoting innovation

Development trends for EV electric motors

Various motor architectures can be adopted mass market EVs and are currently co-existing in production vehicles, such as induction, wound rotor, reluctance and PM synchronous machines[23]; PM synchronous ones adopting Rare Earths Elements emerge clearly as those able to conjugate good controllability with performances such as high energy torque and power density, compactness in size and mass, maximum efficiency not in terms of peak value but also in terms of average efficiency amongst various working points in comparison with other solutions.

The debate about the evolution and the adoption of these PM machines, usually adopting rare earths elements REE, has been increasing in the last decades due to environmental and economic costs[24] as well as strategic implications related to REE availability[25,26]; such factors, in fact, have to be taken into account in the light of potential demand increase due to the whole clear technology sector, including automotive one.[27,28]

Recent researches confirm the potential relevant impact not only in terms of environmental indicators[29] but also in terms of social impacts,[30] which means that the extraction of REEs can be related with distortions on living conditions for certain population and workers. Unsurprisingly, EU community defines REE and, in particular, certain metals (Heavy-REE) as CRM – critical raw materials.[31]

Research and technological improvement, however, can act in order to mitigate the impact of REE extraction and acquisition in several ways. On one hand, developing alternatives technologies, a challenging task due to the overall excellent performance characteristics of PM machines[32]; on the other hand, optimizing the use of materials and reducing the net consumption of CRM. Main interventions are:

- Increasing not only power density, but also the power developed per amount of CRM used (kW/kg_REE), a task useful also for renewable energy sector using REE for generators[33,34]
- Increasing the recycling rate of existing and newly produced CRM using machines both through[35–37]:
  - Improved machine design (a key factor in improving recyclability since the beginning)
  - Optimal material choice (e.g. sintered or bonded PM)
  - Improved recycling technologies.

In such context, motorsport applications are a potential opportunity for improvement especially for the reduction of REE used per kW due to optimization, accurate design and innovation.

Electric motorsport potential as technology improvement driver

The description of racing and motorsport application in technical literature often highlight the role of such activities not only in terms of enhancing visibility of new technologies through media communications or creating entertainment markets, but also documenting their ability to stimulate innovative technologies and organization models.[38]

In the field of electric mobility, different competitions have been defined in the last two decades, each one posing different technological challenges. Suitable examples are: the promotion of aerodynamic and lightweight structures while dealing with crash-safe regulations for solar competitions[39]; the promotion of high-power density energy storage systems[40] in Formula SAE, when battery technology seemed unsuitable for high performances; the increase of hybrid electric-ICE powertrain fuel economy in Formula 1[41]; the creation of state-of-the-art flywheel for endurance racing applications such as the one adopted by Porsche[42]; the maximization of the performances of innovative architectures (all wheel drive powertrains with independent control[43] on known race tracks adopting multi-objective optimization techniques.

When the Formula-E championship (a category dedicated to battery racing vehicle) started in 2014,[44] the electric racing cars adopted used standardized components amongst all teams due to the need to achieve sufficient competitiveness and reliability for the new formula while maintaining development cost under control. Progressively, rules have been modified letting constructors adopt their own powertrain, and in particular admitting new inverter, motors and transmission group, battery being the same for all teams.[45] As highlighted by literature studies,[46] developing new racing motors is usually performed adopting as targets:

- High torque density, almost at the limit achievable with known materials (e.g. for permanent magnets)
- Reduced weight and size, compactness implying very efficient cooling systems
- Wide RPM range usability both for traction and regeneration use, even if such range can vary with the transmission adopted (e.g. direct drive or 1 gear, more gears etc.), which also boosts the study of power electronics able to deal with a large number of harmonics.

Even if various types of motors are still used for competitions (e.g. DC ones[47]), PM synchronous machines emerged as most used technology due to their potential in terms for maximum performances; design optimization up to the limit of mechanical and thermal integrity being a research topic promoted by racing needs[48]; interesting, this latest article highlights the possibility to achieve 1000 h durability even for racing electric motor windings, which is a key need for technology transition from motorsport to industrial production.

Considering the above exposed criticalities potentially related to the adoption of high performance PM electrical machines in automotive applications, it is undoubted that electric motorsport competitions can act as drivers for the optimization of the performances of powertrain groups (including not only motors, but also power electronics, gearbox, transmission units and their management) under constraints of lightness and reduced volumes, therefore contributing to the development of solutions improving efficiency and power density while reducing the use of critical materials which can be translated to mass-market productions.

Materials and methods

The sustainability assessment is performed through the LCA methodology[49,50] that allows evaluating the environmental potential impacts of the entire product system LC on the basis of all material and energy flows exchanged with the ecosystem. The following paragraphs describes the methodological approach adopted for the study which is carried out according to ISO 14040 and 14044 standards.

Goal and scope

The paper is focused on the analysis of the environmental performances of a Formula-E electric motor (see Figure 1), a Permanent Magnet Synchronous Machine (PMSM) using interior magnets, NdFe type. The environmental impacts are expressed in terms of the Global Warming Potential (GWP) through the CML 2001 impact assessment method[51] and the Primary Energy Demand (PED) from renewable and non-renewable resources (gross cal. value).[52]

The considered Functional Unit (FU) is the propulsion of the Formula-E vehicle ensuring performance levels required by the FIA Formula E championship.

The system boundaries (Figure 1(b)) include the whole LC of the E-motor divided into three main

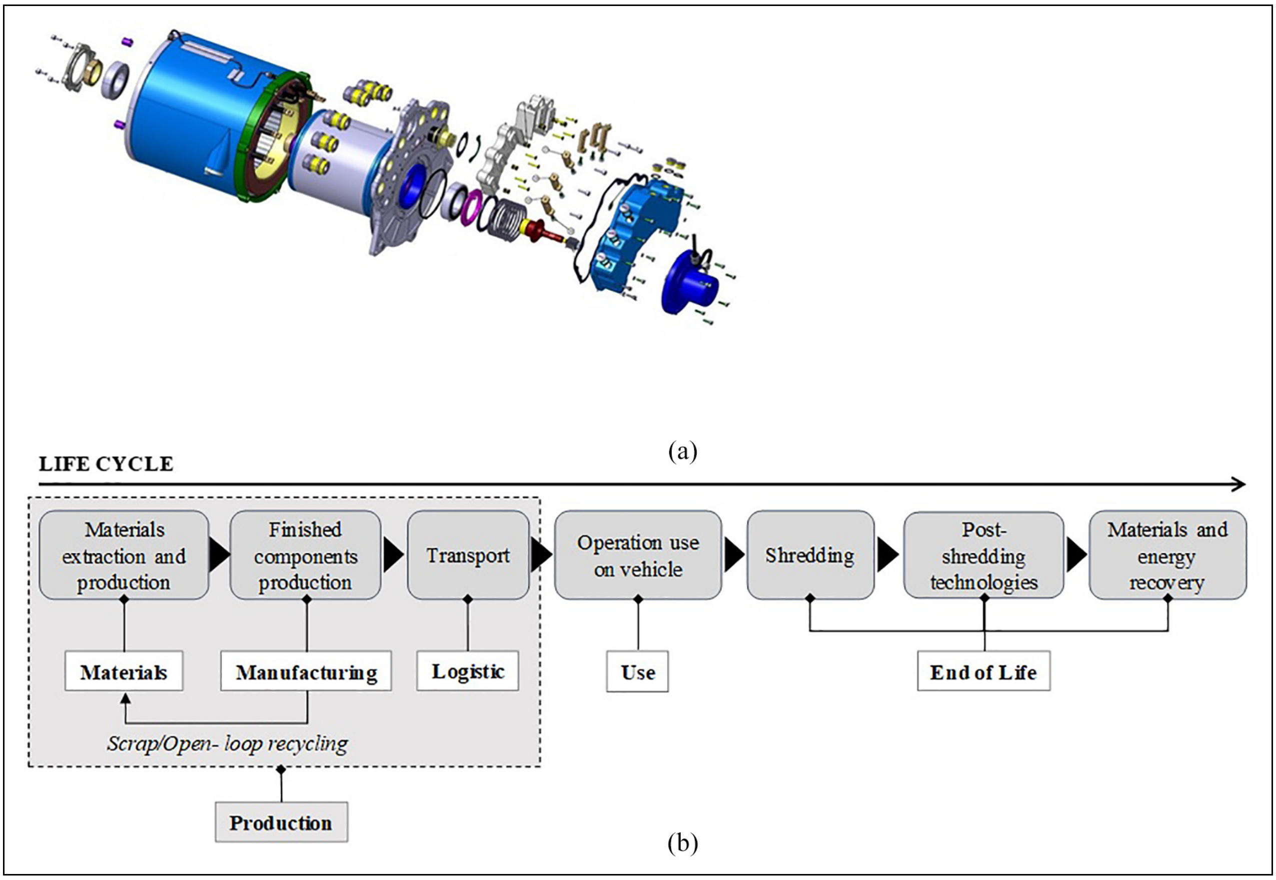

Figure 1. Exploded drawing of Marelli E-motor (a) and system boundaries for the LCA (b).

Table 1. System boundaries: LC stages, sub-stages and unit processes (UPs).

System boundaries		
LC stage	Sub-stage	Unit processes (UPs)
Production	Materials	Raw materials extraction and production processes (materials and energy consumption, waste production, emissions to the environment) Manufacturing processes of semi-finished products (materials and energy consumption, waste production, emissions to the environment) Recovery processes of scrap materials from manufacturing activities
	Manufacturing	Manufacturing processes of finished part (materials and energy consumption, waste production, emissions to the environment)
	Logistic	Transportation of materials and components between Marelli and suppliers plants
Use	–	Operation of E-motor on Formula-E vehicle, assuming the distance covered by the Formula E vehicle over 1-year championship (1500 km)
EoL	–	Shredding, sorting and recovery processes

stages: production, use and end-of-Life (EoL). Production is divided into materials (raw materials extraction and production), manufacturing (manufacturing activities to convert semi-finished products into the final E-motor components) and logistic (transportations for provision of semi-finished products from suppliers to Marelli plant) sub-phases. Table 1 describes the LC of the E-motor in terms of unit processes (UPs) included within each LC stage.

Life cycle inventory

The inventory is carried out by means of the GaBi software[53] and it is modelled as materials/energy consumption, waste production and emissions to the environment by using processes and elementary flows from the GaBi life cycle inventory (LCI) dataset. The following paragraphs describe data collection and LCI modelling for each LC stage of the E-motor.

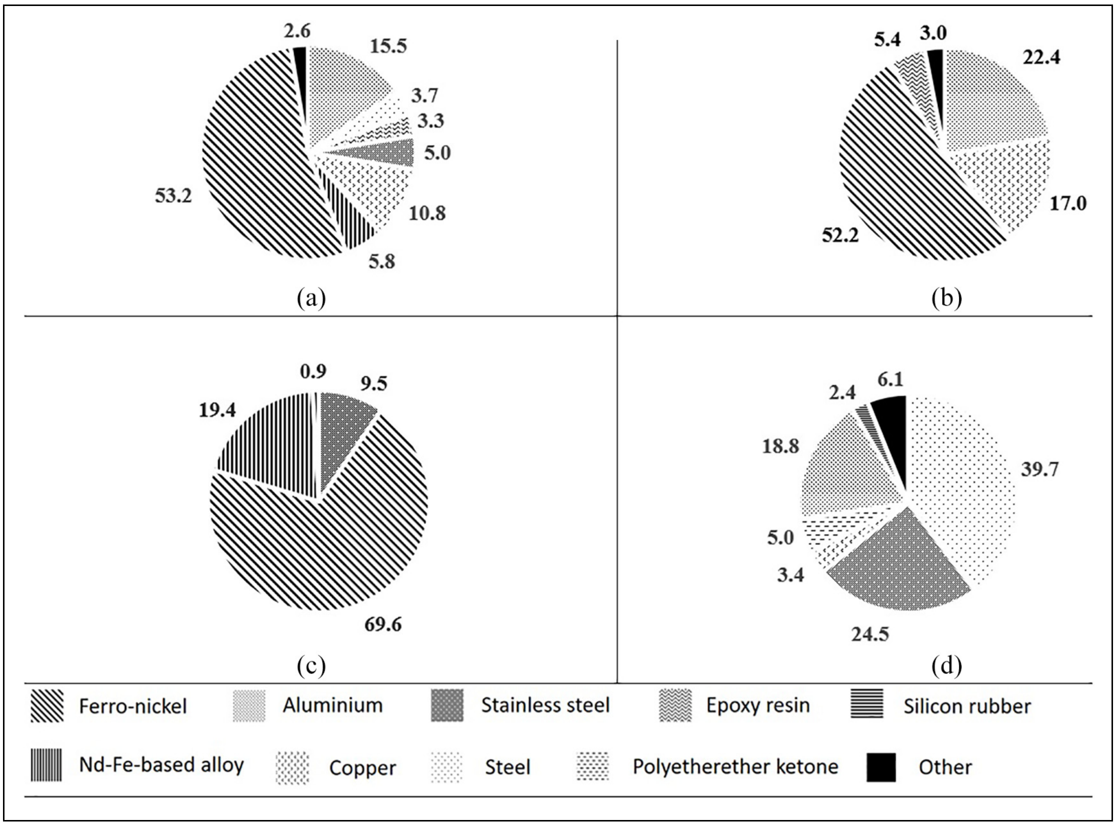

Figure 2. Material composition (%): total E-motor (a) and different modules: stator (b), rotor (c) and miscellaneous (d).

Table 2. Distribution of mass between E-motor modules.

Module	Mass	
	kg	% of total E-motor
Stator	14.72	61.70
Rotor	7.10	29.90
Miscellaneous	2.00	8.40
Total	23.82	100.00

Production. Data collection and LCI modelling are reported separately for the three sub-phases of production, (materials, manufacturing and logistic).

Concerning materials and manufacturing, the LCI modelling is conducted through the breakdown approach which provides that the production of each mono-material part of the E-motor is assessed separately.[20] As a consequence, the overall impact of these LC steps is obtained as the sum of contributions of the single mono-material parts. The assessment takes into account processes from raw materials extraction up to the manufacturing of finished mono-material parts, including the recovery of scrap materials from manufacturing. The modelling is based on primary data collection (materials, energy consumption and scrap rate of manufacturing processes) coming from direct measurements on Marelli machineries and plants. On the other hand, secondary data from the GaBi process dataset are used when no primary data regarding unit processes are available. Table A.1 in the Annex section reports LCI primary data provided by Marelli for all E-motor components subdivided into three levels: main modules, macro-components and single components. Columns 'Materials' report quantity and number of items for each component. Likewise, columns 'Manufacturing' include manufacturing processes, resources consumption (in terms of energy, oil and water consumptions) as well as scrap materials from production activities. Data about manufacturing materials and processes are provided directly by the constructor; due to the needs of small production for racing applications, the vast majority of components are produced with custom design and technologies which differ from typical manufacturing production for mass-market products.

Starting from primary data reported in Table A.1, E-motor components are grouped within three main modules (stator, rotor and miscellaneous) and on the basis of such a system structure the LCI modelling (as well as LCIA results presentation and discussion) is carried out. Table A.2 in the Annex section reports GaBi LCI dataset processes used for the modelling of sub-phases materials and manufacturing: data are provided individually for each component belonging to the three main modules. Table 2 shows the distribution of mass between E-motor modules while Figure 2 provides the material composition.

Table 3. LCI data for recovery/recycling of scrap from manufacturing for standard and best scenarios.

Scenario	Material	Material recycling		Incineration with energy recovery	
		Share of scrap material to recycling activities (%)	Substitution factor primary raw material ([%)	Share of scrap material to incineration (%)	Electricity generation (MJ/kg)
Standard	Turned steel (reference for substitution: steel plate)	100	2	–	–
	Milled steel (reference for substitution: steel plate)	100	2	–	–
	Rolled steel (reference for substitution: steel plate)	100	30	–	–
	Turned aluminium (reference for substitution: aluminium ingot)	100	15	–	–
	Milled aluminium (reference for substitution: aluminium ingot)	100	15	–	–
	Rolled aluminium (reference for substitution: aluminium ingot)	100	78	–	–
	Milled copper (reference for substitution: copper mix)	100	2	–	–
	Injection moulded polypropylene, PP	–	–	100	5.28
	Injection moulded polyurethane rigid foam, PU	100	–	–	–
	Injection moulded polyamide 6.6 fibres, PA 6.6	–	–	100	4.71
	Milled polyetherether ketone granulate, PEEK	–	–	100	4.71
	Turned polyethylene terephthalate granulate, PET	–	–	100	3.12
	Injection moulded polytetrafluoroethylene granulate, PTFE	–	–	–	–
	Injection moulded silicone rubber (RTV-2, 25% siliceous sand)	–	–	–	–
	Milled PEEK GF30	–	–	100	4.71
Best	Turned steel (reference for substitution: steel plate)	100	6	–	–
	Milled steel (reference for substitution: steel plate)	100	6	–	–
	Rolled steel (reference for substitution: steel plate)	100	60	–	–
	Turned aluminium (reference for substitution: aluminium ingot)	100	30		
	Milled aluminium (reference for substitution: aluminium ingot)	100	30		
	Rolled aluminium (reference for substitution: aluminium ingot)	100	98		
	Milled copper (reference for substitution: copper mix)	100	6		
	Injection moulded polypropylene, PP (reference for substitution: PP granulate)	100	80	–	–
	Injection moulded polyurethane rigid foam, PU	100	–	–	–
	Injection moulded polyamide 6.6 fibres, PA 6.6	100	–	–	–
	Milled polyetherether ketone granulate, PEEK	100	80	–	–
	Turned polyethylene terephthalate granulate, PET	100	80	–	–
	Injection moulding polytetrafluoroethylene granulate, PTFE	–	–	–	–
	Injection moulded silicone rubber (RTV-2, 25% siliceous sand)	–	–	–	–
	Milled PEEK GF30 (reference for substitution: PEEK GF30 granulate)	70 (plastic matrix)	50	30 (fiber)	4.71

The modelling takes into account also the environmental credits due to the recycling of scrap materials from manufacturing activities which are credited to materials sub-stage. In this regard, the main assumption is related to the environmental credits stemmed from recovery processes. As manufacturing processes produce a large amount of waste materials, the modelling of scraps EoL is performed considering two different scenarios (scenario standard and scenario best) in order to reflect the variability of environmental credits due to

- inherent properties and boundary conditions (availability, efficiency, technology level and quality of recycled materials) of recovery processes for the different material types
- allocation of materials between recycling (material recovery) and energy recovery processes.

As regards material recycling, the variability between the two scenarios is expressed in terms of parameter 'substitution factor' which represents the avoided production of semi-finished materials from virgin resources achieved through the open-loop recycling. Recycling is assessed as the sum of environmental burdens (material/energy consumption and emissions of recycling activities) and credits (avoided impacts) and the inventory is modelled as an avoided production of primary raw materials through specific substitution factors from the GaBi LCI database. For the two considered scenarios Table 3 reports:

- percentage allocation of materials on a mass basis between material and energy recovery processes (assumption based on GaBi dataset secondary data)
- substitution factor (assumption based on GaBi dataset secondary data)
- electricity generation from energy recovery (GaBi dataset secondary data).

Concerning logistic sub-phase, data collection consists of the determination of transportation type (truck or plane) and travelled distance for carrying materials between suppliers and Marelli plants (Table A.3 in the Annex section). The processes from GaBi LCI dataset are:

- 'Truck, Euro 5, 20–26t gross weight/17,3t payload capacity', for roadway transportations
- 'Cargo plane, 22 t payload', for airway transportations
- 'Container ship, 27,500 dwt payload capacity, ocean', for waterway transportations

Use. The use stage impacts are calculated basing on energy consumption of the Formula-E vehicle over 1 year championship. No allocation of energy demand to the specific e-motor is performed, the electricity of the entire car is associated with the operation of the component. The amount of electric energy consumed is determined through the

- average consumption of the Formula-E vehicle over all championship races (0.185 kWh/km)
- mileage covered over 1 year championship (1500 km)

Both average consumption and annual mileage are primary data directly provided by Formula-E racing team and they are related to the 2019 Formula-E championship; in particular, the consumption refers to the whole car and it represents the net electricity absorption of the Formula-E vehicle. As a worst-case scenario, it can be assumed that the electric energy consumption under intense use (i.e. with limited energy saving racing strategy) can be enhanced up to 0.520 Wh/km, that is the maximum energy usage according to Formula-E racing rules. The impacts associated with the production of electricity are determined considering the electricity grid mix of the country where the races take place. The modelling of electricity production is performed through secondary data from GaBi inventory dataset; where GaBi inventory data are not available, electricity grid mix is retrieved from literature. Table 4 summarizes the

Table 4. Inventory data for the modelling of electricity production.

Race	Source	Data quality
Saudi Arabia	Electricity grid mix: International Energy Agency[54]	Secondary
Morocco	GaBi modelling: Sphera LCI database[53]	
Chile		
Mexico		
Hong-Kong		
China		
Italy	Electricity grid mix and GaBi modelling:	
France	Sphera LCI database[53]	
Monaco		
Germany		
Switzerland		
United States_1		
United States_2		

list of championship races as well as the inventory data quality and sources for the modelling of electricity consumption. Even in the worst-case scenario, the use phase consumption impact remains significantly lower than the production phase, use GWP being 9.8% of total impact (average consumption) or 23.4% (peak consumption).

End-of-Life. Similar to production, EoL stage is modelled at component level. The considered EoL scenarios are consistent with 2000/53/EC directive[22] and ISO 22628 standard[55] and they are representative of the current European technology level. Dismantling time and component mass are crucial factors in order to determine whether a component is removed from the vehicle at the dismantling phase. In the light of the current technological level of End-of-Life of Vehicle (ELV) treatment processes, it is assumed that E-motor is not dismantled from the car and it is forwarded to the shredding process. After the shredding, materials are sorted and forwarded to recovery activities (both recycling and energy recovery). Recycling is assessed as the sum of environmental burdens (material/energy consumption and emissions of recycling activities) and credits due to the substitution of primary raw resources with recycled materials and the modelling is carried out by means of specific substitution factors from the GaBi LCI database. Similar to manufacturing sub-phase, EoL is modelled for the two scenarios standard and best in order to reflect the variability of environmental credits due to the inherent properties and boundary conditions of recovery processes as well as the allocation of materials between material and energy recovery. For the two considered scenarios Table 5 reports

- energy consumption of the shredding process (assumption based on GaBi dataset secondary data)
- percentage efficiency on mass basis and energy consumption of sorting processes of post-shredding materials (assumption based on GaBi dataset secondary data)
- percentage allocation of materials on mass basis between material and energy recovery processes (assumption based on GaBi dataset secondary data)
- substitution factor (assumption based on GaBi dataset secondary data)
- electricity generation from energy recovery (GaBi dataset secondary data).

Concerning LCI data quality, three types of data are distinguished:

- primary data: data obtained through direct measurements on Marelli process site;
- secondary data: data from literature and GaBi datasets;
- assumptions (e.g. analogous processes included in GaBi database).

An overview of LCI data quality is reported in Table 6.

Results and discussion

Table 7 reports LCIA potential impacts for both entire LC and single LC stages while Table 8 shows results for the mileage-independent LC stages (production and EoL) divided between E-motor modules.

The discussions are reported separately for each impact category according to the following structure:

- Contribution analysis of impacts by LC stage;
- Allocation of impacts in Production and EoL stages between E-motor modules and module components;
- Comparative analysis of scenarios assumed for the recycling of scraps from manufacturing and EoL materials.

Global warming potential

GWP: contribution analysis by LC stage. Figure 3 reports the contribution analysis of impact by LC stage as well as the distribution of GWP between E-motor modules for the mileage-independent LC stages (production and EoL). The highest contribution to total LC GWP is associated with production phase (about 85% of total absolute LC impact), followed by use (about 9%) and EoL (about 6%). The strong relevance of production is mainly associated with GHG emissions involved by raw materials acquisition and manufacturing (which account for respectively around 71% and 29% of total production GWP) while the contribution of logistic is negligible (about 0.1%). Concerning materials sub-stage, it has to be taken into account that the value of GWP is net of environmental credits achieved through the recycling of scraps from manufacturing. On the other hand, the relatively low contribution of use can be explained through the short mileage assumed for the operation phase, which limits the electricity consumption and consequently the GHG emissions for energy supply chain. Finally, EoL involves a negative GWP (environmental credit) thanks to both recycling (material recovery) and energy recovery (incineration with electricity production) of EoL materials.

GWP: allocation of production impact between E-motor modules and components. Figure 4 shows the contribution analysis of GWP in mileage-independent LC stages (Production and EoL) by module and module component, respectively for entire E-motor (Figure 4(a)) and single E-motor modules (Figure 4(b)–(d)). Use stage is not taken into account since operation impact is determined by the overall electricity consumption of the car, and therefore the GWP cannot be associated with the different E-motor modules.

Figure 4(a) reveals that most of production impact is associated with stator (76%), with rotor and miscellaneous modules having more or less the same influence

Table 5. LCI data for recovery/landfilling of EoL materials for standard and best scenarios.

Scenario	Material	Shredding		Recycling			Incineration with energy recovery	
		Share of EoL material to shredding process (%)	Electricity for shredding process (MJ/kg)	Sorted post-shredding material to recycling activities (%)	Electricity for sorting of post-shredding material (MJ/kg)	Substitution factor primary raw material – recycling (%)	Share of EoL material to incineration (%)	Electricity generation (MJ/kg)
Standard	Steel (reference for substitution: steel plate)	100	0.18	98	0.12	25	–	
	Aluminium (reference for substitution: aluminium ingot)	100	0.18	98	0.12	15	–	
	Copper (reference for substitution: copper mix)	100	0.18	98	0.12	25	–	
	Epoxy resin (reference for substitution: epoxy resin)	100	0.18	–	0.12	–	100	4.71
	Glass fibre, GF	100	0.18	–	0.12	–	100	1.15
	Polypropylene, PP	100	0.18	–	0.12	–	100	5.28
	Polyurethane rigid foam, PU	100	0.18	–	0.12	–	100	3.81
	Polyamide 6.6 fibres, PA6.6	100	0.18	–	0.12	–	100	4.70
	Polyetherether ketone granulate, PEEK	100	0.18	–	0.12	–	100	4.71
	Polyethylene terephthalate granulate, PET	100	0.18	–	0.12	–	100	3.12
	Polytetrafluoroethylene granulate, PTFE	100	0.18	–	0.12	–	100	4.71
	Silicone rubber (RTV-2, 25% siliceous sand)	100	0.18	–	0.12	–	100	4.71
	PEEK GF30	100	0.18	–	0.12	–	100	4.71
Best	Steel (reference for substitution: steel plate)	100	0.18	98	0.12	40	–	–
	Aluminium (reference for substitution: aluminium ingot)	100	0.18	98	0.12	25	–	–
	Copper (reference for substitution: copper mix)	100	0.18	98	0.12	40	–	–
	Epoxy resin (reference for substitution: epoxy resin)	100	0.18	33	0.12	50	67	4.71
	Glass fibre, GF	100	0.18	–	0.12	–	100	1.15
	Polypropylene, PP	100	0.18	33	0.12	50	67	5.28
	Polyurethane rigid foam, PU	100	0.18	33	0.12	50	67	3.81
	Polyamide 6.6 fibres, PA6.6	100	0.18	33	0.12	50	67	4.70
	Polyetherether ketone granulate, PEEK	100	0.18	–	0.12	–	100	4.71
	Polyethylene terephthalate granulate, PET	100	0.18	33	0.12	50	67	3.12
	Polytetrafluoroethylene granulate, PTFE	100	0.18	33	0.12	50	67	4.71
	Silicone rubber (RTV-2, 25% siliceous sand)	100	0.18	33	0.12	50	67	4.71
	PEEK GF30	100	0.18	–	0.12	–	100	4.71

(around 12%). Looking at mass-specific impact, stator and miscellaneous present values of about 1.0–1.5 kg CO_{2_eq}/kg, while the impact ascribable to the rotor is notably lower (about 0.4 kg CO_{2_eq}/kg). The explanation for this lies in the material composition of the modules:

Table 6. Overview of LCI data quality.

LC stage	Sub-stage	LCI data	
		Collected data	Data quality
Production	Materials	LCI data regarding raw materials extraction and production processes (materials and energy consumption, waste production, emissions to the environment)	Secondary[a]
		LCI data regarding production processes of semi-finished product (materials and energy consumption, waste production, emissions to the environment)	Primary/secondary[a]
	Manufacturing	LCI data regarding production processes of finished part (materials and energy consumption, waste production, emissions to the environment)	Primary/secondary [a]
		Scrap rate	Primary
		Allocation of scrap materials between recovery material and energy processes; substitution factor for virgin raw materials (environmental credits from recycling); energy generation from energy recovery processes	Secondary [a]
	Logistic	Vehicle type and travelled distance for carrying materials between suppliers and Marelli plants	
Use	–	Formula E vehicle consumption	Primary
		Electricity production	Secondary [a]
EoL	–	Energy consumption of shredding and sorting processes; allocation of EoL materials between material and energy recovery processes; substitution factor for virgin raw materials (environmental credits from recycling); energy generation from energy recovery processes	Secondary [a]

[a]GaBi dataset processes used for modelling secondary data have a temporal validity up to year 2021.

Table 7. LCIA results by total LC and single LC stage (scenario standard).

	Impact category	Production			Use	EoL	LC
		Materials	Manufacturing	Logistic			
Scenario standard	Global Warming Potential (GWP) [kg CO_2 eq]	9.40E + 02	3.84E + 02	1.18E + 00	1.35E + 02	−8.70E + 01	1.38E + 03
	Primary energy demand (PED) [MJ]	1.63E + 04	9.72E + 03	1.71E + 01	2.89E + 03	−1.42E + 03	2.75E + 04
Scenario best	Global Warming Potential (GWP) [kg CO_2 eq]	8.49E + 02	3.85E + 02	1.18E + 00	1.35E + 02	−1.32E + 02	1.21E + 03
	Primary energy demand (PED) [MJ]	1.46E + 04	9.72E + 03	1.74E + 01	2.89E + 03	−2.18E + 03	2.46E + 04

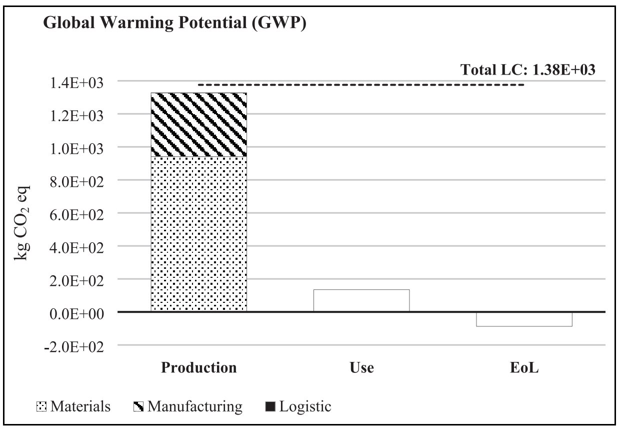

Figure 3. Global Warming Potential (GWP): contribution analysis by LC stage (standard scenario).

- rotor is almost completely made of ferro-alloys, against a more varied composition of stator and miscellaneous, which include both aluminium alloys, copper and polymeric materials (epoxy resin, polyetherether ketone, silicon rubber);
- the impact in materials acquisition stage of plastic materials is notable higher with respect to steel;
- the EoL scenario assumed for polymeric materials (incineration with energy recovery) involves GWP credits (or even positive impacts in case of miscellaneous module) which are notably lower than the open-loop recycling considered for the rotor ferro-alloys. This is determined by the air emissions produced by the incineration process, which are not counterbalanced by beneficial effects of energy generation.

Table 8. LCIA results of production and EoL stages by E-motor module.

	Impact category	Production			EoL		
		Stator	Rotor	Miscellaneous	Stator	Rotor	Miscellaneous
Scenario standard	Global Warming Potential (GWP) [kg CO_2 eq]	9.82E + 02	1.93E + 02	1.52E + 02	−3.97E + 01	−4.62E + 01	−1.14E + 00
	Primary energy demand (PED) [MJ]	1.95E + 04	3.24E + 03	3.36E + 03	−6.15E + 02	−7.76E + 02	−2.48E + 01
Scenario best	Global Warming Potential (GWP) [kg CO_2 eq]	9.14E + 02	1.93E + 02	1.20E + 02	−4.75E + 01	−7.42E + 01	−2.02E + 00
	Primary energy demand (PED) [MJ]	1.83E + 04	3.24E + 03	2.71E + 03	−7.38E + 02	−1.25E + 03	−4.98E + 01

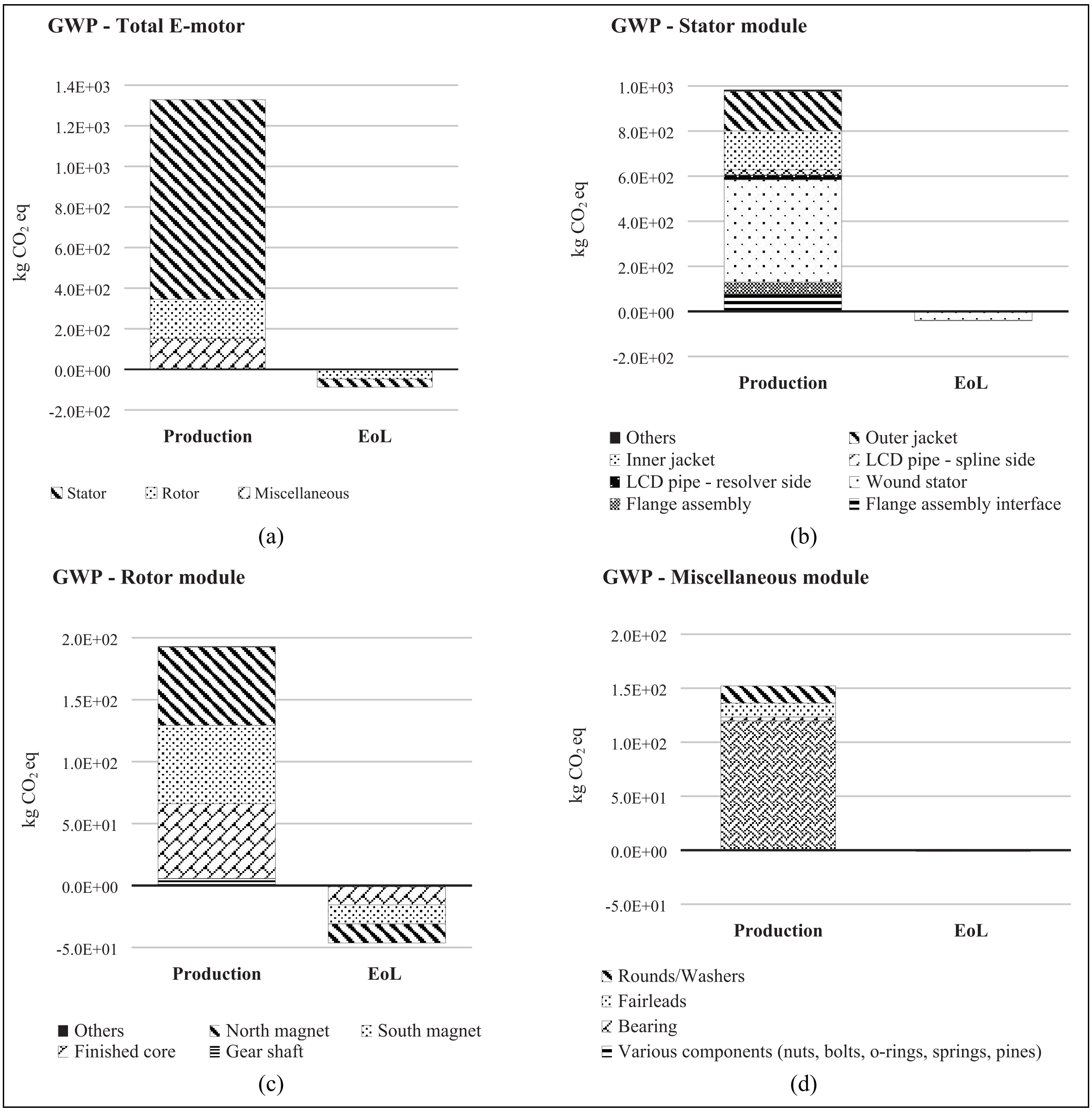

Figure 4. Contribution analysis of GWP by E-motor module (a) and module component: stator (b), rotor (c), and miscellaneous (d).

Concerning the analysis of different E-motor modules, about 61% of production impact of stator is ascribed to components wound stator, outer jacket and inner jacket (Figure 4(b)). This result is mainly associated with:

- the relevant amount of materials used for the production of stator due to the high scrap rate of manufacturing processes;
- the strong mass-specific impact for raw materials (kg $CO_{2\ eq}$/kg material): in particular, the supply

chain of ferro-nickel (wound stator) and aluminium (outer jacket and inner jacket) produces respectively about 11.9 and 8.3 kg $CO_{2\text{-eq}}$ per kilogram of material, due to the relevant energy demand for raw materials extraction and production of semi-finished products;
- the high electricity consumption of manufacturing processes: electroerosion cutting used for wound stator absorbs 58 kWh/kg, while turning consumes 86 and 103 kWh/kg respectively for components outer jacket and inner jacket.

The most relevant contribution to GWP credit from materials recycling at EoL (about 75% of total absolute EoL impact) is associated with component wound stator. It is worthy to note that the net environmental saving achieved through recovery processes at EoL is limited if compared with total production impact (about 4%). The main reason for this is the high scrap rate of manufacturing processes, which makes that the amount of semi-finished materials used for the production is definitely higher with respect to the mass of finished E-motor components.

The impact in both production and EoL (Figure 4(c)) of rotor module is mainly associated with components north magnet, south magnet and finished core (which account for around 90% of total module mass). Considering EoL, the net environmental saving achieved through recovery processes is notable if compared with total production impact (about 24%): the main explanation is the very low scrap rates of manufacturing processes with respect to stator and miscellaneous modules which make that the mass of finished components is similar to the one of semi-finished products, thus allowing a remarkable impact saving.

The GWP of miscellaneous module (Figure 4(d)) in mileage-independent phases is primarily involved by production and more specifically by raw materials provision of small metal parts (various components) that accounts for about 80% of total module production impact. The most influential component within various components is the electric box cover whose GWP is distributed between materials (around 42%) and manufacturing (around 58%) sub-stages. The strong contribution of manufacturing is acsribable to the high energy consumption required by processing of final components. The net environmental saving achieved through recovery processes at EoL is very low if compared with production impact; similar to stator, the explanation is the reduced mass of components if compared with the relevant amount of semi-finished materials processed, due to the high scrap rate of manufacturing processes.

GWP: comparative analysis of scenarios. The following figures show the comparison of GWP results between standard and best scenarios assumed for the modelling of recovery processes (scraps from manufacturing and EoL materials): the bars report the impact variation for

- both total LC and single LC stages (Figure 5)
- different E-motor modules (Figure 6).

Data highlight that optimistic assumptions made for the best scenario (higher efficiency of materials separation, higher substitution factors for recycling activities and higher amount of materials to recycling rather than to incineration) allow achieving an absolute LC GWP saving of around 150 kg CO_2eq, which translates into 11.7% decrease with respect to the standard scenario. The impact lowering is distributed between production (−120 kg CO_2eq, due to the higher amount of scraps from manufacturing which is effectively recycled) and EoL (−45 kg CO_2eq, due to the greater quantity of EoL materials forwarded to recycling activities). Looking at single E-motor modules, the lowest percent decrease occurs for stator (8.0% against about 19% and 22% respectively for rotor and miscellaneous modules),

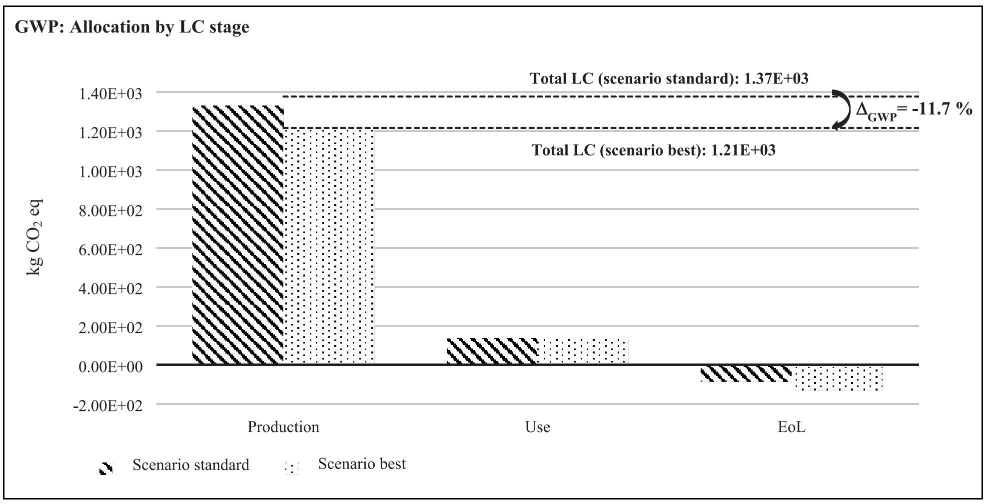

Figure 5. GWP: comparison between standard and best scenario for total LC and single LC stages.

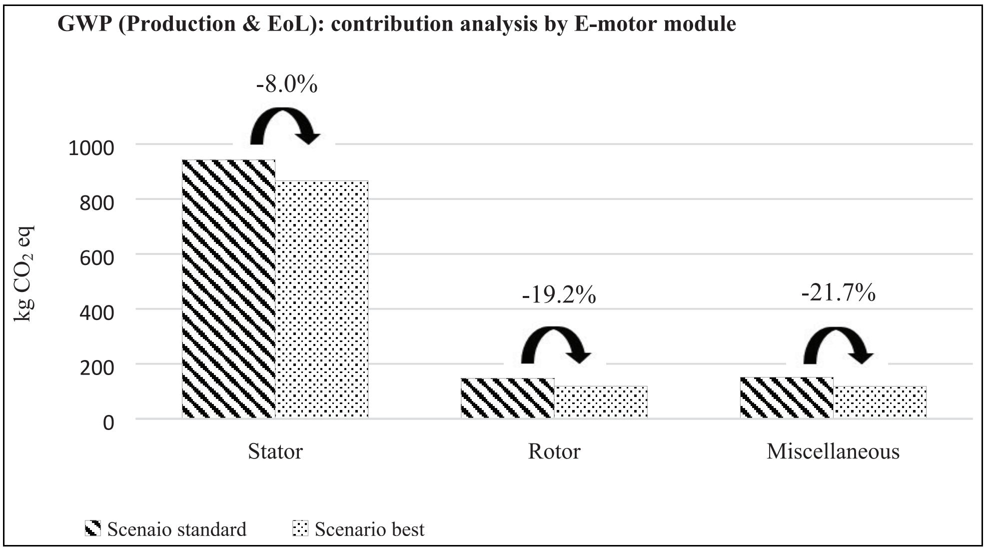

Figure 6. GWP: comparison between standard and best scenario for stator, rotor and miscellaneous modules.

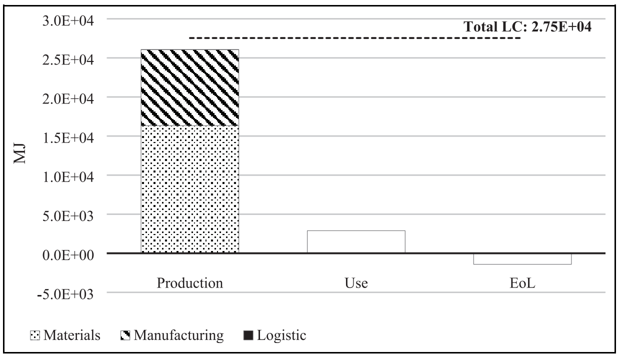

Figure 7. Primary Energy Demand (PED): contribution analysis by LC stage (standard scenario).

which however represents the highest absolute GWP saving (around 75 CO_2 eq). The reason for this is two-fold: on the one hand the greater mass of stator with respect to the other modules (more than 60% of total E-motor weight) and on the other hand the massive presence of materials characterized by high embodied GWP (such as aluminum, copper and epoxy resin).

Primary energy demand

PED: contribution analysis by LC stage. The diagram in Figure 7 reveals that the highest contribution to total LC PED is from production stage (about 86% of total absolute LC impact), followed by use and EoL (respectively 10 and 4%). Concerning production sub-phases, the main contributors are materials (impact primarily ascribable to high energy intensity of raw materials acquisition) and manufacturing (respectively 63% and 37% of total production impact). The share of total LC PED associated with logistic is negligible (around 0.1%). Regarding materials sub-stage, the impact is mostly associated with consumption of hard coal, crude oil and energy from hydropower (respectively about 11%, 9% and 8% of total LC PED), while the environmental burden of manufacturing is mainly caused by natural gas, hard coal and energy from solar (respectively around 17%, 8% and 14% of total LC impact). The relatively low contribution of use can be explained through the short mileage assumed for the operation life-time, which limits also the energy demand for electricity production. Similar to GWP, material recycling and energy recovery provide environmental credits at EoL.

PED: allocation of production impact between E-motor modules and components. Figure 8(a) shows the contribution of different modules to PED impact in production and EoL stages: about 77% for stator, 10% for rotor and 13% for miscellaneous. Components wound stator, outer jacket and inner jacket (stator module) cover about 80% of stator production impact, which in turn represents around 55% of total E-motor production PED (Figure 8(a) and (b)). The high influence of these components is mainly attributable to:

- the relevant amount of materials used for their production (high scrap rate of manufacturing processes –Table A.1 of the Annex section) and consequently the notable amount of energy demand for raw materials extraction and production. In this regard, the major LCI flows that contribute to PED in materials sub-stage of components wound stator, outer jacket and inner jacket are natural gas, crude oil, hard coal, energy from solar and energy from hydropower;
- the high mass-specific energy demand (MJ/kg material) in raw materials provision (ferro-nickel for wound stator and aluminum for outer jacket and inner jacket). In this regard it has to be considered that that ferro-nickel and aluminum have a PED respectively of around 166 and 160 MJ/kg, due to

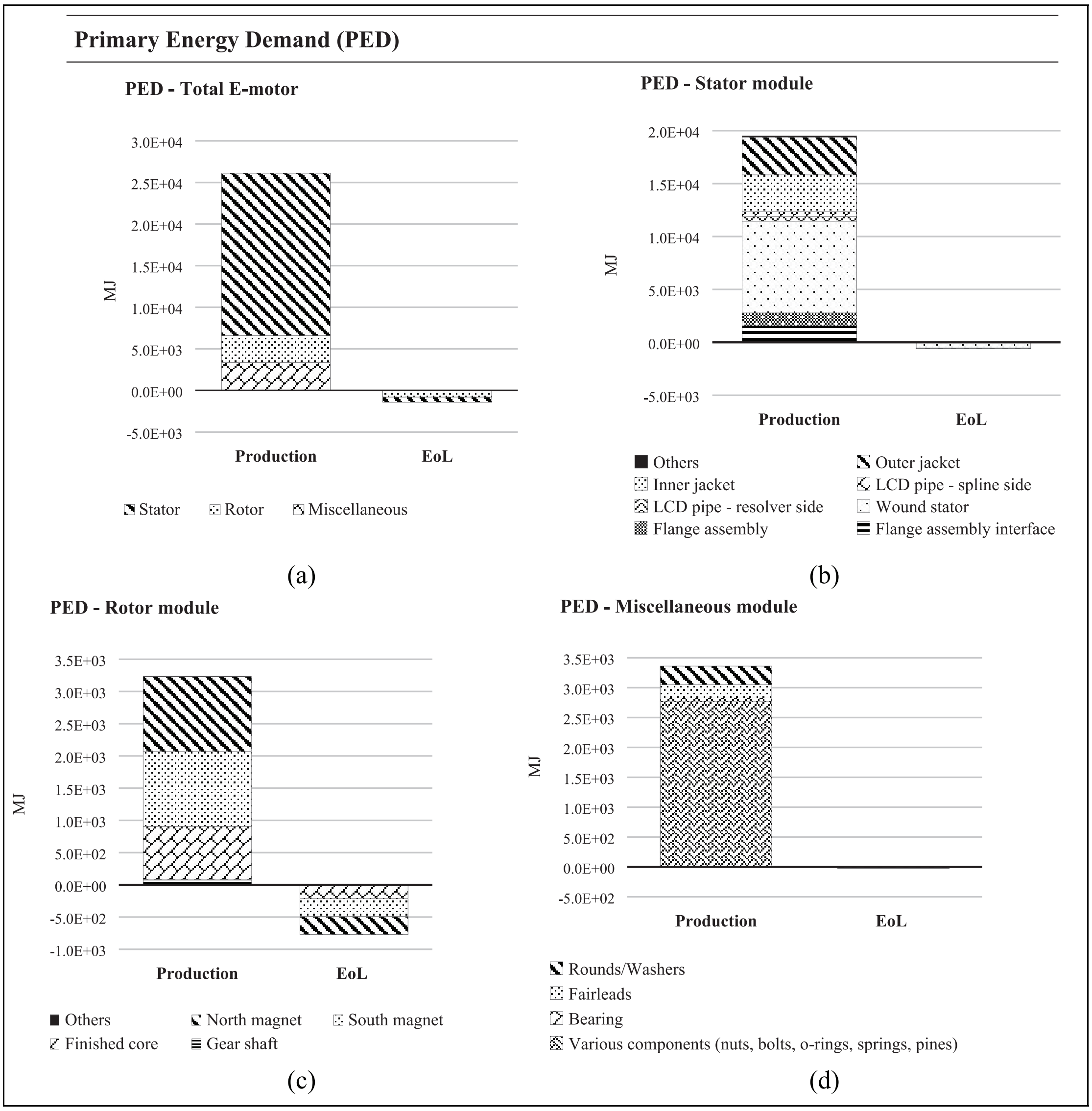

Figure 8. Contribution analysis of PED by E-motor module (a) and module component: stator (b), rotor (c) and miscellaneous (d).

the high energy intensity of the supply chain of semi-finished products;
- relevant electricity consumption of manufacturing processes (Table 2) that involves high energy resources depletion (mainly natural gas, hard coal and energy from solar).

Similar to GWP, the net environmental saving achieved at EoL is very low if compared to the overall production impact (about 3%), the major explanation for this being the high amount of material which is lost in the conversion of semi-finished products into finished E-motor components. The most relevant contribution to PED credit is associated with the recycling of material content of component wound stator (around 60% of total absolute EoL impact).

Considering rotor (Figure 8(c)), PED is more or less equally distributed between components north magnet, south magnet and finished core (both production and EoL), which represent about 90% of total module mass. The environmental burden in production is mostly caused by material acquisition (about 80%), while the net impact saving achieved through recovery processes at EoL is remarkable with respect to production PED (very low scrap rates in manufacturing with respect to components of stator and miscellaneous modules).

PED associated with production of miscellaneous module is almost exclusively concentrated in small metal parts (various components in Figure 8(d)): the most influential component is the electric box cover (about 38% of total module), whose PED is mainly ascribable to manufacturing (about 65% against 35% of materials sub-phase). By analogy with GWP, the net environmental credit achieved at EoL is negligible, the reason being the high scrap rate of manufacturing processes that significantly increases the amount of materials required by production.

PED: comparative analysis of scenarios. Results stress that total LC PED decreases by almost 11% (around

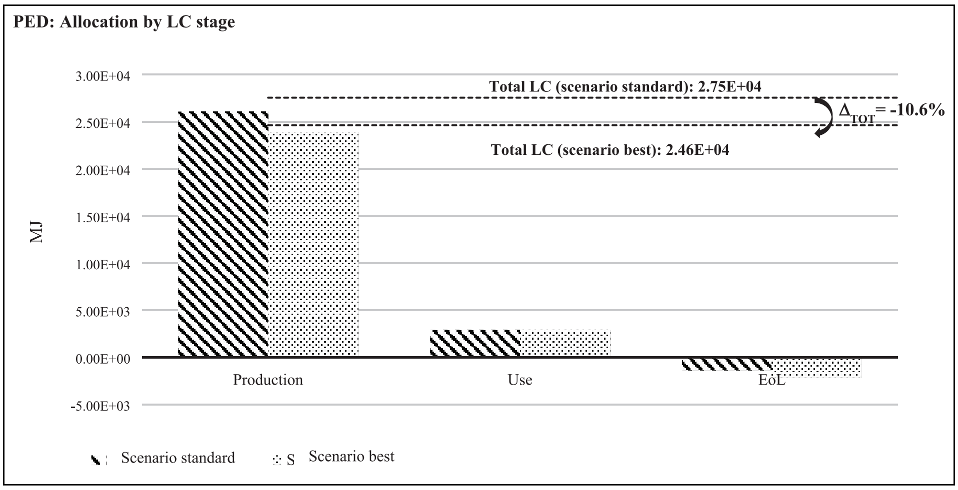

Figure 9. PED: comparison between standard and best scenario for total LC and single LC stages.

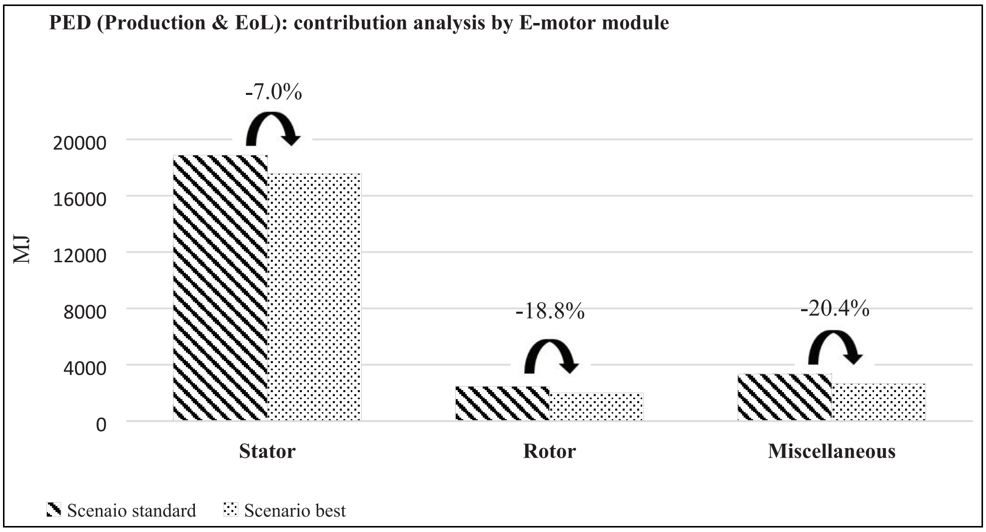

Figure 10. PED: comparison between standard and best scenario for stator, rotor and miscellaneous modules.

2700 MJ absolute saving) when considering the assumptions of the best scenario with respect to the standard one (Figure 9). Similar to GWP, the benefit is mainly concentrated in production (about −2200 MJ), thanks to the higher amount of primary materials saved through the recycling of scrap materials from manufacturing; lower energy saving is achieved at EoL (around −700 MJ) and it is associated with higher credit because of greater quantity of recycled materials. Once again most of absolute PED decrease (about 1400 MJ) comes from stator, since the higher mass and the greater embodied energy of constituent components and materials maximize the benefit with respect to the other modules (Figure 10).

The analysis of GWP and PED results stresses that the environmental impact due to the LC of the Formula-E motor can strongly benefit from the improvement and optimization of manufacturing processes, both in view of material and energy resources saving. The main example for this is that certain manufacturing processes (e.g. milling from raw blocks) are responsible for a quite relevant impact (e.g. due to the large amount of scraps deriving), and therefore such phases should be proposed as priority for optimization in case of mass-market products. These measures would lead to a strong decrease in the impacts due to raw materials acquisition and energy supply chain, which appear necessary to enable technology transfer from high performance racing vehicles to commercial road cars. Lesson learned from the sustainability analysis of the Formula-E motor could be surely useful to improve the eco-profile of the product as well as to transfer and scale up advanced design solutions from high-performance to conventional commercial vehicles.

Conclusion

The paper focuses on the sustainability assessment of the Formula-E motor, which is carried through the Life Cycle Assessment (LCA) methodology, as part of the Life Cycle Sustainability Assessment (LCSA) framework. The system boundaries of the study include production (raw materials acquisition and manufacturing), use (electricity consumption during operation) and End-of-Life (disposal of EoL materials/components) while the functional unit is defined as the propulsion of the Formula-E vehicle ensuring performance levels required by the FIA Formula-E championship over 1500 km operation mileage (distance covered by the Formula-E vehicle over 1 year championship).

The results are expressed in terms of Global Warming Potential (GWP) and Primary Energy Demand (PED) impact categories and the LCI modelling is performed through the GaBi software. The environmental benefits achieved through the recovery of scrap materials from manufacturing as well as EoL materials is modelled according to two different scenarios: such scenarios enable to consider the variability of environmental credits associated with both inherent properties/boundary conditions (availability, efficiency, technology level and quality of recycled materials) of recovery processes for the different material types and the allocation of materials between recycling/energy recovery processes.

LCIA results reveal that the most relevant LC stage is production (about 85% of total LC impact for both GWP and PED indicators), followed by use and EoL (respectively around 10% and 5%). Concerning production stage, the highest contribution comes from raw materials provision, (about 71% and 63% of total production impact respectively for GWP and PED) while manufacturing accounts for almost the entirety of the remaining share (around 29% and 37% respectively for GWP and PED); the contribution of logistic sub-phase is negligible. Despite the relevant energy consumption required by the manufacturing of some E-motor components, the greater influence of materials acquisition is mainly due to the high scrap rates in manufacturing, which involve a relevant increase in raw materials amount. The contribution analysis of mileage-independent LC stages (production and EoL) shows that the allocation of impacts between E-motor modules is very similar for both indicators: most of environmental load is associated with stator (about 76% of total production and EoL impact), with lower quotas ascribed to rotor and miscellaneous (around 11–13% for both modules). The comparative analysis between the two scenarios for materials recovery highlights that the optimistic hypothesis allows achieving a notable saving in environmental burdens with respect to the standard scenario (about 11%–12% for both GWP and PED). From the above it is clear that the environmental profile of the Formula-E motor can be notably improved by enhancing the efficiency in materials and energy use of the current manufacturing processes. At the same time, reduction and optimization in material and energy consumption represent necessary measures so that in future racing-derived technologies can be effectively transferred from motorsport to commercial automotive field. In conclusion, the main advancements provided by the study with respect to the current state of the art can be summarized in the following points:

- refining a tailored methodological approach to model the environmental profile of specific components of Formula-E vehicle, since to date sustainability issues in the motorsport field have been treated exclusively at system level;
- developing knowledge and data collection regarding the environmental sustainability of Formula-E motors, both in terms of magnitude of impacts and identification of main environmental LC hotspots;
- providing indications to improve product development under eco-design and energy sustainability perspectives;
- supporting designers, decision makers and supply chain managers in the application of high-performance components, materials and technologies to large mass production. Indeed, even if advanced solutions for the moment are not reasonably transferable to high-volume production both in sustainability and affordability perspective, the methodological approach, the choice of lightweight/performing materials and the issues related to the recycling of scraps/end-of-life materials represent common challenges also for the automotive sector.

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Annex A

LCI modelling is conducted through a *break-down* approach which provides that the production of each mono-material part of the E-motor is assessed separately. The inventory of each mono-material part is modelled as materials/energy consumption, waste production and emissions to the environment. The modelling is based on primary data collection (materials, energy consumption and scrap rate of manufacturing processes) coming from direct measurements on Marelli Europe S.p.A. machineries. Resources consumption, waste production and emissions to the environment are modelled through LCI processes and elementary flows from the GaBi dataset. On the other hand, secondary data from the GaBi process dataset are used when no primary data regarding unit processes are available.

Table A.1 reports LCI primary data regarding materials and manufacturing sub-phases (production) provided by Marelli S.p.A. for all E-motor components subdivided into three levels:

-Level 1: main modules;
-Level 2: macro-components;
-Level 3: single components.

Columns *Materials* report quantity and number of pieces for each component; similarly, columns *Manufacturing* include manufacturing processes, resources consumption (in terms of energy, oil and water consumptions) as well as scrap materials from production activities.

Table A.2 reports LCI dataset processes used for the module components modeling relating to Materials and Manufacturing sub-stages; moreover, column Materials describes also specifics on quantity and percentage mass of total E-motor for each component.

Table A.3 reports LCI primary data for logistic stage (source: Marelli Sp.A.).

Table A.1. LCI primary data for materials and manufacturing sub-phases.

Level 1	Level 2	Level 3	Materials			Manufacturing				
			Name	Quantity [kg]	Amount (number of components)	Process	Energy consumption [kwh/item]	Oil [l/item]	Process water [l/item]	Scrap [kg/item]
Stator assembly	Stator spacer (ST177)		Aluminium profile EN AW 2024 [AlCu4Mg1]	0.0234	1	Turning	3.6	0.005	0.105	1.33
	Outer jacket		Aluminium profile EN AW 2024 [AlCu4Mg1]	0.64	1	Turning	55.69	0.0811	1.623	23.88
	O-ring (Viton – ORMV 1820-30)		Silicone rubber	2.33 E-05	6	Injection Moulding				
	O-ring (Viton – ORMV 1840-30)		Silicone rubber	0.001	1	Injection moulding				
	O-ring (ORMV 1450-30)		Silicone rubber	0.001	1	Injection moulding				
	Screw (TCBEI_ISO9327-M5X0.8-10.9 L = 10)		Steel electrogalvanized	0.0090	44	Cold rolled				
	Rosette (EN-ISO7089-CT.A INOX-D10-d5.3-s1)		Steel	0.00113	44	Cold rolled				
	Helicoil (M5X1.5D-FR)		Steel wire rod	0.00034	8	Cold rolled				
	O-ring (Viton – ORV 3700)		Silicone rubber	0.001	1	Injection moulding				
	Helicoil (M8X1X1D-FR)		Steel wire rod	0.001	6	Cold rolled				
	LCD pipe – resolver side		PEEK GF30	0.0281	1	Milling	4.6	0.006	0.114	1.242
	LCD pipe – spline side		PEEK GF30	0.0346	1	Milling	5.3	0.007	0.131	1.235
	Resin (CW 5742)		Epoxy resin	0.01	1					
	Hardener resin (HY 5726)		Epoxy resin	0.01	1					
	Pine (3x22-M6-2.3x6)		Steel billet		2	Turning	0.73	0.00	0.00	
	Inner jacket		Aluminium profile EN AW 2024 [AlCu4Mg1]	1.351	1	Turning	46.4	0.068	1.352	19.899
	Flange assembly	Flange	Aluminium profile	0.594	1	Turning	61.9	0.077	1.534	2.926
		Helicoil (M5X1.5D-FR)	Steel wire rod	0.002	8	Cold rolled				
		Helicoil (M3X1.5D-FR)	Steel wire rod	0.001	20	Cold rolled				
		Helicoil (M3X1D-FR)	Steel wire rod	0.001	8	Cold rolled				
		Bearing cartridge_LR	Stainless steel plate 30NiMo16-6 EN 10083-3	0.109	1	Turning	6.3	0.015	0.292	0.998
		Helicoil (M3X1.5D-FR)	Steel wire rod	0.001	20	Cold rolled				
		Helicoil (M3X1D-FR)	Steel wire rod	0.001	8	Cold rolled				
	Flange assembly interface	Flange interface	Aluminium profile EN AW 2024 [AlCu4Mg1]	0.72	1	Turning	23.4	0.034	0.682	8.580
		Bearing cartridge – LS	Stainless steel plate	0.112	1	Turning	6.3	0.015	0.292	1.207
		Helicoil (M4x0.7X 1.5D-FR)	Steel wire rod	0.00275	4	Cold rolled				
	Straight pin (UNI-EN 28734-2H6X8)		Steel billet (100Cr6)	0.001	2	Cold rolled				
	Straight pin (UNI-EN 22338-A-3X8)		Steel billet (100Cr6)	0.001	1	Cold rolled				
	Wound stator	Sample (GPHC5.0-0.100-02-0404)	Silicon rubber + fibre glass	0.001	1	Injection moulding				

(continued)

Table A.1. Continued

Level 1	Level 2	Level 3	Materials			Manufacturing				
			Name	Quantity [kg]	Amount (number of components)	Process	Energy consumption [kwh/item]	Oil [l/item]	Process water [l/item]	Scrap [kg/item]
		Brazing rod (FRO-AG 40 SN RIV)	Solder paste (SnAg3Cu0.5)	0.015	1					
		Glass fiber braided sleeving (SS-ID.2.5)	Glass fiber	0.005	1					
		Sheathing (Viton - RW-200-E-1/8-0-SP)	Polypropylene, PP	0.001	4	Injection moulding				
		Slot insulator	Polyurethane, PU	0.002	3	Injection moulding				
		Outer insulator	Polyurethane, PU	0.002	48	Injection moulding				
		Wadge (3.5x0.35X106-Vetronit-G11)	Glass-polymer insulator	0.002	1					
		Inner insulator	Polyurethane, PU	0.002	48	Injection moulding				
		Sheathing (Viton_RW-200-E-1/4-0-SP)	Polypropylene, PP	0.002	0.13	Injection moulding				
		Tape (Kapton-0.13mm)	Polyamide 6.6 fibres, PA 6.6	0.002	1					
		Stator coil lacing cord	Polyamide 6.6 fibres, PA 6.6	0.002	2					
		Flux (EASYFLUX)	Alccol isopropanol	0.001	1					
		Copper wire (ML240 G2/0.5)	Copper wire	2.5	1					
		Coil terminal gasket	Silicone rubber	0.001	1	Injection moulding				
		Sensor (PT1000 CO.S10 0820PFYK60B)	Thermistor THT PTC	0.003	1	Injection moulding				
		Coil terminal	Copper	0.004	1	Milling				
		Stator stack	Ferro nickel &	7.702	1	Electroerosion cutting	446.4	0	0	13.958
	Water plug		Polyethylene terephthalate, PET	0.006	2	Turning	1.6	0.004	0.076	0.024
	Screw (TCEI ISO 4762 M5X0.8-12.9 L = 10)		Steel electrogalvanized	0.002	2	Cold rolled				
	Washer (S75190-DE.10XDI.5XT.0.5)		Steel electrogalvanized	0.001	2	Cold rolled				
	O-ring (ORMV 0100-15)		Silicone rubber	0.0005	2	Injection moulding				
	Sheet (GAP-PAD-GP5000S35-0.02-02-0816)		Fiberglass-reinforced filler and polymer	0.02	0.25					
	Fairlead (CD06MW-RV)		Brass	0.015	2	Turning				
	Sheathing (Viton – RW-200-E-1/8-0-SP)		Polypropylene, PP	0.001	4	Injection moulding				
	Sensor (PT1000-S101910PF2F60)		Thermistor THT	0.003	1	Injection moulding				
Rotor assembly	Rotor mounting	Mounting	Round bar TI6AL4V		1	Turning				
		Core locking ring	Stainless steel plate 30NiMo16-6 EN 10083-3	0.046	1	Turning	5.5	0.000	0.000	0.514
		Release agent – dry film	Polytetrafluoroethylene, PTFE	0.02	1					
		Adhesive (LOCTITE 270)	EPOXY Adhesive	0.02	1					
		Isopropyl alcohol	Isopropanol	0.02	1					
		Solvent (LOCTITE-	Silicon rubber	0.002	1					

(continued)

Table A.1. Continued

Level 1	Level 2	Level 3	Materials			Manufacturing				
			Name	Quantity [kg]	Amount (number of components)	Process	Energy consumption [kwh/item]	Oil [l/item]	Process water [l/item]	Scrap [kg/item]
		7063)								
		Finished core	Coating electrodeposition	0.002	1					0
		Rotor shaft	Stainless steel plate 30NiMo16-6 EN 10083-3	0.68	1	turning				2.42
		Adhesive (HYSOL EA 9394 C2_KIT A + B)	EPOXY Adhesive	0.005	1					
		North magnet	SmCo	0.029	24	Magnetization	0.2	0	0	
		Rotor stack		0.444	6					
		South magnet	SmCo	0.029	24	Magnetization	0.2	0	0	
Bearing (SKF_BY-6006-2Z/HT-Anti-rotation)	Bearing (SKF_BY-6006-2Z/HT)		Steel billet (100Cr6)	0.120	1	Cold rolled	2.800	0.000	0.000	0.001
Anti-rotation lock	Hardened Round bar (30NiCrMo16-_FDMA-D.85)		Stainless steel plate 30NiMo16-6 EN 10083-3	0.034	1	Milling	15.405	0.0085	0.1705	0.696
Bearing locking ring	Round bar (36NiCrMo16 819BTT1250/1370Mpa D.65)		Stainless steel plate 30NiMo16-6 EN 10083-3	0.035	1	Turning	3.675	0.0150	0.2992	0.394
Wave spring_(SSB-D55xD46.11xH3.81)			Harmonic wire steel	0.01	1	Cold rolled				
Bearing cover	Hardened Round bar (30NiCrMo16 – FDMA-D.85		Stainless steel plate 30NiMo16-6 EN 10083-3	0.068	1	Turning	10.27	0	0	1.662
Cable gland (M20x1.5-20M3M2061)	Strain relief (M20×1.5-20M3M2061N)		Polyamide 6.6, PA 6.6	0.01	1	Manual turning	0.67	0.01	0.28	
Screw (TCEI ISO 4762 M4X0.7-12.9 L = 8)			Steel electrogalvanized	0.0015	6	Cold rolled				
Plug (M20x1.5-2053M12N)			Steel electro-galvanised	0.021	1	Turning				
Phase bridge – U1 W2	Unfinished phase bridge -U1 W2		Copper wire	0.02	1	Milling	9.854	0.014	0.273	0.133
Phase terminal block – UB VB WB	Sheet (TECAPEEK GF30-40×110)		Polyetherether ketone, PEEK	0.073	1	Milling	17.417	0.000	0.000	0.487
Terminal block cover	Unfinished phase cover		Aluminium AlSI1MgMn 6082-t651	0.191	1	Milling	70.813	0.012	0.244	3.009
Screw (TCEI ISO 4762 M3X0.5 – 12.9 L = 10)			Steel electrogalvanized	0.0013	14	Cold rolled				
Phase bridge – V1 V2	Unfinished phase bridge – V1 V2		Copper wire	0.028	1	Milling	9.854	0.012	0.244	0.137
Phase bridge – U2 W1	Unfinished phase bridge – U2 W1		Copper wire	0.024	1	Milling	11.000	0.014	0.273	0.131
Shim washer (PCIMRS-D55-V45-T0.05)			Steel C40	0.006	4	Cold rolled				
Screw (TCEI ISO 4762-M4X0.7-12.9 L = 10)			Steel electrogalvanized	0.0015	4	Cold rolled				
Terminal block cover gasket			Silicon rubber	0.02	1	Injection moulding				
Gasket (GV-14) connector AS			Silicon rubber	0.02	1	Injection moulding				
Nut plate (ATM396-14)			Steel tinplated	0.0015	1	Cold rolled				
Screw (TSEI_ISO10642-M3x0.5 – 10.9 L = 15)			Steel electrogalvanized	0.0013	8	Cold rolled				
Thread insert (M4)			Stainless steel plate 30NiMo16-6 EN 10083-3	0.001	3	Turning				
Screw (TCEI ISO 4762 M4X0.7-12.9 L = 12)			Steel electrogalvanized	0.0015	4	Cold rolled				

(continued)

Table A.1. Continued

Level 1	Level 2	Level 3	Materials			Manufacturing				
			Name	Quantity [kg]	Amount (number of components)	Process	Energy consumption [kwh/item]	Oil [l/item]	Process water [l/item]	Scrap [kg/item]
Screw (TCEI_ISO 762-M3X0.5-12.9 L = 8)			Steel electrogalvanized	0.0013	4	Cold rolled				
Phase base –UA VA WA	Sheet (TECAPEEK GF30 40x110)		Polyetherether ketone granulate, PEEK	0.073	0.45	Milling	17.417	0.022	0.432	0.377
	Thread insert (M4)		Stainless steel plate 30NiMo16-6 EN 10083-3	0.0005	3	Turning	N.A.	N.A.	N.A.	N.A.
O-ring (Viton – ORMV 2037)			Silicon rubber	0.001	6	Injection moulding				
Screw (TSEI UNI5933 M3X0.5-10.9 L = 8			Steel electrogalvanized	0.0013	2	Cold rolled				
Resolver assembly	Inner spacer		Aluminium profile EN AW 2024	0.006	1	Turning	0.417	0.000	0.000	0.044
	Cable bushing (M8)		Aluminium profile EN AW 2024	0.002	1	Turning	1.062	0.002	0.049	0.009
	Outer spacer		Aluminium profile EN AW 2024	0.007	1	Turning	1.820	0.001	0.027	0.043
	Tamagawa (TS2224N14E102)		50% Acciaio al silicio per magnete; 50% copper	0.05	1	Cold rolled				
	Resolver cover		Aluminium profile EN AW 2024	0.163	1	Milling	16.940	0.022	0.432	1.667
	Connector (AS014-35SN-37PIN)		Zamak	0.04	1	Pressofusione + nickel plated				
	Fairlead (CD08MW-RV)		Brass	0.02	1	Pressofusione				
	Sheathing (Viton-RW-200-E-3/16-0-SP)		Silicon rubber	0.002	0.13	Injection moulding				
Slot screw (TCF_DIN 404_M3X10-AVP-ZINC)			Steel electrogalvanized	0.0013	2	Cold rolled				
Washer (PWF3 D3.2D6.0H0.5)			Steel electrogalvanized	0.00065	14	Cold rolled				
Shim washer (PCIMRS-D55-V45-T0.1)			Steel C40	0.006	3	Cold rolled				
Resolver shaft (R1)	Round bar (36NiCrMo16 819BTT1250/1370MpaD.50)		Stainless steel plate 30NiMo16-6 EN 10083-3	0.093	1	Turning	9.31	0	0	1.017
Flanged hexagon nut (DIN 6923 M6X6)			Stainless steel	0.012	1	Cold rolled				
Tang (0.93x1.1x4.4)	Round bar (36NiCrMo16 819BTT1250/1370MpaD.50)		Stainless steel plate 30NiMo16-6 EN 10083-3	0.0003	2	Electroerosion cutting	0.465	0	0	0.002
Shim washer (PCIMRS-D16-V10-T0.05)			Steel C40	0.002	3	Cold rolled				
Shim washer (PCIMRS-D16-V10-T0.1)			Steel C40	0.002	4	Cold rolled				
O-ring (VITON-ORV 3275)			Silicone rubber	0.001	1	Injection moulding				
Adhesive valve (GORE-AVS-43)			Polytetrafluoroethylene granulate, PTFE	0.003	1	Injection moulding				
Bush (8x12BK-DB100(Metric)			Aluminium AlSi1MgMn 6082-t651	0.0016	1	Turning	1.062	0.001	0.027	0.0094

Source: Marelli.

Table A.2. LCI modelling – GaBi LCI dataset processes for raw materials extraction/production of semi-finished components and manufacturing processes.

Module	Component		Materials			Manufacturing
			Name	Quantity [kg]	% of total E-motor mass	Process
Stator	Outer jacket		EU28: aluminium Ingot mix ts	640	2.678	User UNIFI process (component-specific): aluminium turning
	LCD pipe – resolver side		DE: PEEK ts	28	0.118	User UNIFI process (component-specific): PEEK milling
	LCD pipe – spline side		DE: PEEK GF30 ts	35	0.145	User UNIFI process (component-specific): PEEK milling
	Resin (CW 5742)		Epoxy resin [Plastics] ts	600	2.51	-
	Hardener resin (HY 5726)		Epoxy resin [Plastics]	200	0.837	-
	Outer jacket		EU28: aluminium ingot mix ts	1351	5.653	User UNIFI process (component-specific): aluminium turnings
	Flange		EU28: aluminium ingot mix ts	594	2.485	User UNIFI process (component-specific): aluminium turnings
	Flange interface_		EU28: aluminium ingot mix ts	720	3.013	User UNIFI process (component-specific): aluminium turnings
	Sensor (PT1000 CO.S100820PFYK60B)		Thermistor THT PTC temp sensor, leaded disk (250 mg) D4x42	3	0.013	DE: plastic injection moulding part (unspecific) ts
	Resolver shaft_R1		Stainless steel plate 30NiMo16-6 EN 10083-3 MM	93	0.389	GLO: steel turning ts
	Tamagawa (TS2224N14E102)		EU: steel cold rolled coil worldsteel	50	0.209	–
	Wound stator	Sample (GPHC5.0-0,100-02-0404)	Silicone rubber (RTV-2, condensation) ts	1	0.004	–
		Brazing rod (FRO-AG 40 SN RIV)	Solder paste SnAg3Cu0.5 (SAC-Lot) ts	15	0.063	–
		Glass fiber braided sheathing (SS-ID.2.5)	DE: glass fibres ts	5	0.021	–
		Slot insulator	Polyurethane rigid foam (PU) PE	6	0.025	DE: plastic injection moulding part (unspecific) ts
		Outer insulator	Polyurethane rigid foam (PU) PE	96	0.402	DE: plastic injection moulding part (unspecific) ts
		Wadge (3.5x0.35X106-Vetronit-G11)	Isolante elettrico (GF)	2	0.008	DE: glass fibres ts
		Inner insulator	Polyurethane rigid foam (PU) PE	96	0.402	DE: plastic injection moulding part (unspecific) ts
		Tape (Kapton 0.13 mm)	Polyamide 6.6 fibres (PA 6.6) ts	2	0.008	–

(continued)

Table A.2. Continued

Module	Component		Materials: Name	Quantity [kg]	% of total E-motor mass	Manufacturing: Process
		Stator coil lacing cord	Polyamide 6.6 fibres (PA 6.6) ts	4	0.017	–
		Flux (EASYFLUX)	Alccol isopropanol ts	1	0.004	–
		Copper wire (ML240 G2/0.5)	EU-15: copper wire ELCD/ECI	2500	10.46	–
		Coil Terminal gasket	Silicone rubber (RTV-2, 25% siliceous sand) [plastics] ts	1	0.004	–
		Coil terminal	Copper mix ts	4	0.017	User UNIFI process (component-specific): copper milling
		Stator stack	Ferro nickel PE & RER: epoxy resin PE	7702	32.226	User UNIFI process (component-specific): electroerosion
		Sensor (PT1000-S101910PF2F60)	DE: plastic injection moulding part (unspecific) ts	3	0.013	–
Rotor	Release agent – dry film		Polytetrafluoroethylene granulate (PTFE) Mix ts	20	0.084	–
	Adhesive (LOCTITE 270)		EPOXY resin PE	20	0.084	–
	Isopropyl alcohol		Isopropanol (iso-propanol; 2-propanol) [Organic intermediate products] ts	20	0.084	–
	Solvent (LOCTITE-7063)		Propene (propylene) ts	2	0.008	–
	Finished core		DE:FerroNickel PE & DE: coating electrodeposition mix PE	5002	20.929	–
	Rotor shaft		Stainless steel plate 30NiMo16-6 ts	680	2.845	GLO: steel turning ts
	Adhesive (HYSOL EA 9394 C2-KIT A + B)		EPOXY adhesive PE	5	0.021	–
	North magnet		DE: magnet Nd-Fe-Dy-B ts	696	2.912	–
	South magnet		DE: magnet Nd-Fe-Dy-B ts	696	2.912	–
Miscellaneous	Various components	Plug (M20x1.5-2053M12N)	GLO: steelelectro-galvanised worldsteel	21	0.088	GLO: steel turning ts
		Phase bridge – U1 W2	DE: copper mix ts	20	0.084	User UNIFI process (component-specific): copper milling
		Sheet (TECAPEEK GF30-40x110)	Polyetherether ketone granulate (PEEK)	73	0.304	User UNIFI process (component-specific): PEEK milling
		Terminal block cover	EU28: aluminium ingot mix ts	191	0.799	User UNIFI process (component-specific): aluminium milling
		Phase bridge – V1 V2	DE: copper mix ts	28	0.117	User UNIFI process (component-specific): copper milling

(continued)

Table A.2. Continued

Module	Component		Materials: Name	Quantity [kg]	% of total E-motor mass	Manufacturing: Process
		Phase bridge – U2 W1	DE: copper mix ts	24	0.1	User UNIFI process (component-specific): copper milling
		Nut plate (ATM396-14)	Steel tinplated steel [metals] ts	2	0.006	EU: steel cold rolled coil worldsteel
		Thread insert (M4)	Stainless steel plate 30NiMo16-6 ts	3	0.013	GLO: steel turning ts
		Sheet (TECAPEEK GF30 – 40x110)	Polyetherether ketone granulate (PEEK) ts	33	0.137	User UNIFI process (component-specific): PEEK milling
		Resolver cover	EU28: aluminium ingot mix ts	163	0.682	User UNIFI process (component-specific): aluminium turnings
		Connector (AS014-35SN-37PIN)	EU28: aluminium ingot mix ts	40	0.167	–
		Adhesive valve (GORE-AVS-43)	Polytetrafluoroethylene granulate (PTFE) ts	3	0.013	DE: plastic injection moulding part (unspecific) ts
		Water plug	Polyethylene terephthalate granulate (PET, amorph) ts	12	0.05	User UNIFI process (component-specific): plastic part turning
		Sheet (GAP-PAD-GP5000S35-0.02-02-0816)	DE: glass fibres ts	5	0.021	–
		Thread insert (M4)	Stainless steel plate 30NiMo16-6 ts	2	0.006	GLO: steel turning ts
		Tang (0.93x1.1x4.4)	Stainless steel plate 30NiMo16-6 ts	1	0.003	User UNIFI process (component-specific): electroerosion
	Bearings	Bearing (SKF-BY-6006-2Z/HT)	Steel plate worldsteel	120	0.502	User UNIFI process (component-specific): steel milling
		Cable bushing (M8)	EU28: aluminium Ingot mix ts	2	0.007	User UNIFI process (component-specific): aluminium turning
		Bush (8x12BK-DB100 Metric)	EU28: aluminium Ingot mix ts	2	0.007	User UNIFI process (component-specific): aluminium turning
		Bearing cartridge – LR	Stainless steel plate 30NiMo16-6 ts	109	0.456	GLO: steel turning ts
		Bearing cartridge – LS	Stainless steel plate 30NiMo16-6 ts	112	0.469	GLO: steel turning ts
	Nuts	Flanged hexagon nut (DIN 6923 M6X6)	Stainless steel plate 30NiMo16-6 ts	12	0.05	EU: steel cold rolled coil worldsteel
	Sheathings/O-rings	Phase cover gasket	Silicone rubber (RTV-2, 25% siliceous sand) [Plastics] ts	20	0.084	DE: plastic injection moulding part (unspecific) ts
		Gasket (GV-14) connector AS	Silicone rubber (RTV-2, 25% siliceous sand) [Plastics] ts	20	0.084	DE: plastic injection moulding part (unspecific) ts
		O-ring (VITON-ORMV 2037)	Silicone rubber (RTV-2, condensation) ts	6	0.025	DE: plastic injection moulding part (unspecific) ts

(continued)

Table A.2. Continued

Module	Component		Materials			Manufacturing
			Name	Quantity [kg]	% of total E-motor mass	Process
		Sheathing (VITON-RW-200-E-3/16-0-SP)	Silicone rubber (RTV-2, condensation) ts	0	0.001	DE: plastic injection moulding part (unspecific) ts
		O-ring (VITON-ORV 3275)	Silicone rubber (RTV-2, condensation) ts	1	0.004	DE: plastic injection moulding part (unspecific) ts
		O-ring (VITON-ORMV 1820-30)	Silicone rubber (RTV-2,condensation) ts	0	0.001	DE: plastic injection moulding part (unspecific) ts
		O-ring (VITON-ORMV 1840-30)	Silicone rubber (RTV-2,condensation) ts	1	0.004	DE: plastic injection moulding part (unspecific) ts
		O-ring (ORMV 1450-30)	Silicone rubber (RTV-2,condensation) ts	1	0.004	DE: plastic injection moulding part (unspecific) ts
		O-ring (VITON-ORV 3700)	Silicone rubber (RTV-2,condensation) ts	1	0.004	DE: plastic injection moulding part (unspecific) ts
		Sheathing (VITON-RW-200-E-1/8-0-SP)	Polypropylene/ethylene propylene diene elastomer granulate (PP/EPDM, TPE-O) Mix ts	4	0.017	DE: plastic injection moulding part (unspecific) ts
		Sheathing (VITON-RW-200-E-1/4-0-SP)	Polypropylene/ethylene propylene diene elastomer granulate (PP/EPDM, TPE-O) Mix ts	0	0.001	DE: plastic injection moulding part (unspecific) ts
		O-ring (ORMV 0100-15)	Silicone rubber (RTV-2,condensation) ts	1	0.004	DE: plastic injection moulding part (unspecific) ts
		Sheathing (VITON-RW-200-E-1/8-0-SP)	Polypropylene/ethylene propylene diene elastomer granulate (PP/EPDM, TPE-O) Mix ts	4	0.017	DE: plastic injection moulding part (unspecific) ts
	Springs	Wave spring (SSB-D55xD46.11xH3.81)	EU: steel cold rolled coil worldsteel	10	0.042	–
		Helicoil (M5X1.5D-FR)	EU: steel cold rolled coil worldsteel	3	0.011	–
		Helicoil (M8X1X1D-FR)	EU: steel cold rolled coil worldsteel	6	0.025	–
		Helicoil (M5X1.5D-FR)	EU: steel cold rolled coil worldsteel	16	0.067	–
		Helicoil (M3X1.5D-FR)	EU: steel cold rolled coil worldsteel	20	0.084	–
		Helicoil (M3X1D-FR)	EU: steel cold rolled coil worldsteel	8	0.033	–
		Helicoil (M3X1.5D-FR)	EU: steel cold rolled coil worldsteel	20	0.084	–

(continued)

Table A.2. Continued

Module	Component		Materials			Manufacturing
			Name	Quantity [kg]	% of total E-motor mass	Process
		Helicoil (M3X1D-FR)	EU: steel cold rolled coil worldsteel	8	0.033	–
		Helicoil (M4x0.7X1.5D-FR)	EU: steel cold rolled coil worldsteel	11	0.046	–
	Fairleads	Cable grand_(M20x1.5-20M3M2061N)	Brass (CuZn39Pb 3) ts	10	0.042	User UNIFI process (component-specific): brass turning
		Fairlead (CD06MW-RV)	Brass (CuZn39Pb 3) ts	30	0.126	User UNIFI process (component-specific): brass turning
		Fairlead (CD08MW-RV)	Brass (CuZn39Pb 3) ts	20	0.084	User UNIFI process (component-specific): brass turning
	Rounds/washers	Hardened round bar(30NiCrMo16-FDMA-D.85)	Stainless steel plate 30NiMo16-6 ts	34	0.142	User UNIFI process (component-specific): steel milling
		Round bar (36NiCrMo16 819BTT1250/1370Mpa D.65)	Stainless steel plate 30NiMo16-6 ts	35	0.146	GLO: steel turning ts
		Hardened round bar(30NiCrMo16-FDMA_D.85	Stainless steel plate 30NiMo16-6 ts	68	0.285	User UNIFI process (component-specific): steel milling
		Shim washer_(PCIMRS-D55-V45-T0.05)	EU: steel cold rolled coil worldsteel	24	0.1	EU: steel cold rolled coil worldsteel
		Inner spacer – Resolver	EU28: aluminium ingot mix ts	6	0.025	User UNIFI process (component-specific): aluminium turning
		Outer spacer – Resolver	EU28: aluminium ingot mix ts	7	0.029	User UNIFI process (component-specific): aluminium turning
		Washer (PWF3 D3.2D6.0H0.5)	EU: steel cold rolled coil worldsteel	9	0.038	–
		Shim washer (PCIMRS-D55-V45-T0.1)	EU: steel cold rolled coil worldsteel	18	0.075	–
		Shim washer (PCIMRS-D16-V10-T0.05)	EU: steel cold rolled coil worldsteel	6	0.025	–
		Shim washer (PCIMRS-D16-V10-T0.1)	EU: steel cold rolled coil worldsteel	8	0.033	–
		Core locking ring	Stainless steel plate 30NiMo16-6 ts	46	0.192	GLO: steel turning ts
		Stator spacer (ST177)	EU28: aluminium ingot mix ts	23	0.098	User UNIFI process (component-specific): aluminium turning
		Washer (S75190-DE.10XDI.5XT.0.5)	Steel cold rolled coil worldsteel	2	0.008	–
		Rosette (EN-ISO7089-CT.A INOX-D10-d5.3-s1)	Steel cold rolled coil worldsteel	50	0.209	–

(continued)

Table A.2. Continued

Module	Component		Materials			Manufacturing
			Name	Quantity [kg]	% of total E-motor mass	Process
	Screws/pines	Screw (TCEI ISO 4762 M4X0.7-12.9 L = 8)	EU: steel cold rolled coil worldsteel	9	0.038	–
		Screw (TCEI ISO 4762 M3X0.5 -12.9 L = 10)	EU: steel cold rolled coil worldsteel	18	0.076	–
		Screw (TCEI ISO 4762_M4X0.7-12.9 L = 10)	EU: steel cold rolled coil worldsteel	6	0.025	–
		Screw (TSEI_ISO10642_M3x0.5 – 10.9 L = 15)	EU: steel cold rolled coil worldsteel	10	0.044	–
		Screw (TCEI ISO 4762 M4X0.7-12.9 L = 12)	EU: steel cold rolled coil worldsteel	6	0.025	–
		Screw (TCEI_ISO 4762_M3X0.5-12.9 L = 8)	EU: steel cold rolled coil worldsteel	5	0.022	–
		Screw_TSEI UNI5933 M3X0.5-10.9 L = 8	EU: steel cold rolled coil worldsteel	3	0.011	–
		Slot screw (TCF-DIN 404-M3X10-AVP-ZINC)	EU: steel cold rolled coil worldsteel	3	0.011	–
		Screw (TCBEI-ISO9327-M5X0.8 -10.9 L = 10)	EU: steel cold rolled coil worldsteel	400	1.674	–
		Straight pin (UNI-EN 28734-2H6X8)	DE: steel plate worldsteel	4	0.017	GLO: steel turning ts
		Straight pin (UNI-EN 22338-A-3X8)	DE: steel plate worldsteel	1	0.004	GLO: steel turning ts
		Screw (TCEI – ISO 4762 M5X0.8 -12.9 L = 10)	EU: steel cold rolled coil worldsteel	4	0.017	–
		Pin (3x22-M6-2.3x6)	DE: steel plate worldsteel	0	0.001	GLO: steel turning ts

Table A.3. LCI primary data for logistic stage.

Part	Means	Distance [km]
Magnet (SmCo-R32HS)	Waterway	28,473 [waterway]
		1097 [roadway]
	Roadway	657
O-ring (Viton – ORMV 1820-30)	Airway	1540
O-ring (Viton – ORMV 1840-30)	Airway	1540
O-ring (ORMV 1450-30)	Airway	1540
Screw (TCBEI – ISO9327 – M5X0.8 –10.9 L = 10)	Airway	1540
Rosette (EN-ISO7089 – CT.A INOX D10 d5.3 – s1)	Airway	1540
Helicoil (M5X1.5D-FR)	Airway	1540
O-ring (Viton – ORV 3700)	Airway	1540
Straight pin (DIN6325 – 3×22 M6)	Airway	1540
Helicoil (M5X1.5D-FR)	Airway	1540
Helicoil (M5X1.5D-FR)	Airway	1540
Straight pine (UNI-EN 22338-A 3X8)	Airway	1540
Sensor (PT1000 CO.S100820PFYK60B)	Airway	1540
Screw (TCEI ISO 4762 M5X0.8 -12.9 L = 10)	Airway	1540
Washer (S75190_DE.10XDI.5XT.0.5)	Airway	1540
O-ring (ORMV 0100-15)	Airway	1540
Fairlead (CD06MW-RV)	Airway	1540
Sensor (PT1000_S101910PF2F60)	Airway	1540
Screw (TCEI ISO 4762 M4X0.7-12.9 L = 8)	Airway	1540
Screw (TCEI ISO 4762 M3X0.5 -12.9 L = 10)	Airway	1540
Shim washer (PCIMRS-D55-V45-T0.05)	Airway	1540
Screw (TCEI ISO 4762_M4X0.7-12.9_L = 10)	Airway	1540
Screw (TSEI_ISO10642_M3x0.5 – 10.9 L = 15)	Airway	1540
Screw (TCEI ISO 4762 M4X0.7-12.9 L = 12)	Airway	1540
Screw_TCEI_ISO 4762_M3X0.5-12.9_L = 8	Airway	1540
O-ring (Viton – ORMV 2037)	Airway	1540
Screw (TSEI UNI5933 M3X0.5-10.9 L = 8)	Airway	1540
Fairlead (CD08MW-RV)	Airway	1540
Washer (PWF3 D3.2D6.0H0.5)	Airway	1540
Shim washer (PCIMRS-D55-V45-T0.1)	Airway	1540
Shim washer (PCIMRS-D16-V10-T0.05)	Airway	1540
Shim washer (PCIMRS-D16-V10-T0.1)	Airway	1540
O-ring (Viton – ORV 3275)	Airway	1540
Helicoil (M8X1X1D-FR)	Roadway	25
Helicoil (M3X1.5D-FR)	Roadway	25
Helicoil (M3X1D-FR)	Roadway	25
Helicoil (M3X1.5D-FR)	Roadway	25
Helicoil (M3X1D-FR)	Roadway	25

(continued)

Table A.3. Continued

Part	Means	Distance [km]
Magnet (SmCo-R32HS)	Waterway	28,473 [waterway]
		1097 [roadway]
	Roadway	657
Thread insert (M4)	Roadway	25
Thread insert (M4)	Roadway	25
Thread insert (M4)	Roadway	25
Sample (GPHC5.0-0.100-02-0404	Roadway	316
Sheet (GAP – PAD_GP5000S35-0.02-02-0816)	Roadway	316
Strain relief (M20x1.5_20M3M2061N)	Roadway	34
Plug (M20x1.5 – 2053M12N)	Roadway	34
Adhesive valve (GORE-AVS-43)	Roadway	516
Bearing (SKF-BY-6006-2Z/HT)	Roadway	516
Bearing (SKF-BY-6006-2Z/HT)	Roadway	516
Bearing (SKF-BY-6006-2Z/HT)	Roadway	122
Bearing (SKF_BY-6006-2Z/HT)	Roadway	122
Copper wire (ML240 G2/0.5)	Roadway	383
Resin (CW 5742)	Roadway	30
Release agent – dry film	Roadway	30
Wave spring (SSB-D55xD46.11xH3.81)	Roadway	30
Wound stator	Roadway	40
Wound stator	Roadway	40
Annealed ferromagnetic sheet	Roadway	689
Annealed ferromagnetic sheet	Roadway	689
Adhesive (LOCTITE 270)	Roadway	32
Tamagava – resolver (TS2224N14E102)	Roadway	43
Balancing ring – resolver	Roadway	230
Coil terminal gasket	Roadway	30
Terminal block cover gasket	Roadway	30
Flat (AVIONAL -2024 T3-250X250X20)	Roadway	35
Round bar (AVIONAL 2024 T3-D.110)	Roadway	35
Hardened round bar (30NiCrMo16-FDMA-D.85)	Roadway	5
Hardened round bar (30NiCrMo16-FDMA-D.85)	Roadway	5
Round bar (36NiCrMo16 819BTT1250/1370Mpa D.6)5	Roadway	5
Round bar (36NiCrMo16 819BTT1250/1370Mpa D.65)	Roadway	5
Hardened round bar (30NiCrMo16-FDMA-D.85)	Roadway	5
Round bar (36NiCrMo16 819BTT1250/1370Mpa D.65)	Roadway	5
Hardened round bar (30NiCrMo16-FDMA-D.85)	Roadway	5
Hardened round bar (30NiCrMo16 –FDMA-D.85)	Roadway	5
Hardened round bar (30NiCrMo16-FDMA-D.85)	Roadway	5
Round bar (36NiCrMo16 819BTT1250/1370Mpa D.65)	Roadway	5
Round bar (36NiCrMo16 819BTT1250/1370Mpa D.65)	Roadway	5
Hardened round bar (30NICRMO16-FDMA-D.85)	Roadway	5

(continued)

Table A.3. Continued

Part	Means	Distance [km]
Magnet (SmCo-R32HS)	Waterway	28,473 [waterway]
		1097 [roadway]
	Roadway	657
Round bar (36NiCrMo16 819BTT1250/1370Mpa D.65)	Roadway	5
Hardened round bar (30NiCrMo16-FDMA-D.85)	Roadway	5
Round bar (TI6AL4V AMS4928-D.130)	Roadway	30
Round bar (TI6AL4V AMS4928-D.130)	Roadway	30
Gear shaft	Roadway	5
Electro-erosion block	Roadway	5
Electro-erosion block	Roadway	5
Gear shaft	Roadway	5
Electro-erosion block	Roadway	5
Electro-erosion block	Roadway	5
Terminal rod end	Roadway	35
Phase bridge – U1 W2	Roadway	35
Phase bridge – V1 V2	Roadway	35
Phase bridge – U2 W1	Roadway	35
Coil terminal	Roadway	35
Phase bridge – U1 W2	Roadway	35
Phase bridge – V1 V2	Roadway	35
Phase bridge – U2 W1	Roadway	35
Gasket (GV-14) connector AS	Roadway	220
Nut-plate (ATM396-14)	Roadway	220
Connector (AS014-35SN-37PIN)	Roadway	220
Round bar (36NiCrMo16 819BTT900/1050 Mpa D.65)	Roadway	279
Round bar (36NiCrMo16 819BTT900/1050 Mpa D.65)	Roadway	279
Round bar (36NiCrMo16 819BTT900/1050 Mpa D.65)	Roadway	279
Round bar (36NiCrMo16 819BTT1250/1370MpaD.50)	Roadway	279
Round bar (36NiCrMo16 819BTT1250/1370MpaD.50)	Roadway	279
Inner jacket	Roadway	115
Flange	Roadway	115
Flange interface	Roadway	115
Terminal block cover	Roadway	115
Resolver cover	Roadway	115
Inner jacket	Roadway	115
Flange	Roadway	115
Flange interface	Roadway	115
Resolver cover	Roadway	115
Sheet (TECAPEEK GF30 – 40×140)	Roadway	14
Sheet (TECAPEEK GF30 – 40×140)	Roadway	14
Round bar (ERTALYTE-NERA D.40)	Roadway	14
Sheet (TECAPEEK GF30_40×110)	Roadway	14

Source: Marelli Sp.A.