EM-TECH

D6.3 – Report on e-motor sustainability assessment

EM-TECH - Innovative e-motor technologies covering e-axles and e-corners vehicle architectures for high-efficient and sustainable e-mobility

HORIZON-CL5-2022-D5-01-09

GA No. 101096083

Work package No.	**6**
Deliverable No.	D6.3
Expected delivery date	**31.12.2025**
Actual submission date	**13.01.2026**
Lead beneficiary	**POLITO**
Dissemination level	**PU**

Funded by the European Union

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History

Date	Version Number	Comment
3.11.2025	0.1	LCA/LCC of the IWM solution
15.11.2025	0.2	Revised LCA/LCC of the IWM solution
9.12.2025	0.3	LCA/LCC of the IWM and AFM solutions final draft
18.12.2025	0.4	Revised LCA/LCC of the IWM solution
22.12.2025	0.5	Final clean draft ready for PSB review
13.1.2026	1.0	Final version ready for submission

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Abbreviations

Abbreviation	Long Version
2DD	2-Dimensional Distributed Winding
3DD	3-Dimensional Distributed Winding

AFM	Axial Flux Motor
BoM	Bill of Materials
IWM	In Wheel Motor
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCI	Life Cycle Inventory
EF	Environmental Footprint
EoL	End-of-Life
EOL	End-Of-Line
EPR	Extended Producer Responsibility
EV	Electric Vehicle
IGBT	Insulated Gate Bipolar Transistor
IWM	In-wheel Motor
MEB	Modularer E-Antriebs-Baukasten
NdFeB	Neodymium-Iron-Boron
OBM	On-Board Motor
OEM	Original Equipment Manufacturer
OPEX	Operational Expenditures
PM	Permanent Magnet
PMSM	Permanent Magnet Synchronous Motor
RDE	Real Driving Emissions
REEs	Rare Earth Elements
REPM	Rare Earth Permanent Magnet
RFM	Radial Flux Motor
SiC	Silicon Carbide
SotA	State-of-the-Art
SUV	Sport Utility Vehicle
VAT	Value Added Tax
WLTC	Worldwide Harmonized Light Vehicles Test Cycle

Partners

Short name	Legal name
AVL	AVL LIST GMBH
TUIL	TECHNISCHE UNIVERSITAET ILMENAU
POLITO	POLITECNICO DI TORINO
ELA	ELAPHE POGONSKE TEHNOLOGIJE DOO
TRX	TRAXIAL
I&M	IDEAS & MOTION SRL
URBANGOLD	URBANGOLD GMBH
AIG	ARMENGAUD INNOVATE GMBH
USR	UNIVERSITY OF SURREY
UBATH	UNIVERSITY OF BATH

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1 Publishable Executive Summary

1.1 Overview of project

The Horizon Europe EM-TECH project will develop novel solutions to push the boundaries of electric machine technology for automotive traction, through: i) innovative direct and active cooling designs; ii) virtual sensing functionalities for the high-fidelity real-time estimation of the operating condition of the machine; iii) enhanced machine control, bringing reduced design and operating conservativeness enabled by ii); iv) electric gearing to provide enhanced operational flexibility and energy efficiency; v) digital twin based optimisation, embedding systematic consideration of Life Cycle Analysis and Life Cycle Costing aspects since the early design stages; and vi) adoption of recycled permanent magnets and circularity solutions.

The proposed innovations will be implemented in new series of radial flux direct drive in-wheel motors (IWMs) characterised by so far unexplored levels of torque density (>150 Nm/litre, >50 Nm/kg), and on-board single stator double rotor type ironless axial flux motors (AFMs) providing power density and specific power levels in excess of 30 kW/litre and 10 kW/ kg. The solutions will address both passenger car and van applications (continuous power levels of 50 kW - 120 kW), providing competitive costs (<6 Euro/kW for a production of 100000 units/year), and leading to significant reduction of motor energy loss during real vehicle operation (>25%), and to >60% decrease of the rare earth content, including implementation of magnet recycling solutions.

1.2 Deliverable Objective and Results

Deliverable D6.3 summarizes the outcomes regarding Life Cycle Assessment (LCA) and Life Cycle Costing (LCC). It is related to Task 6.3, which is concerned with the assessments in terms of environmental and economic impacts, namely LCA and LCC, of the proposed innovations in EM-TECH. The analysis is carried out on two electric drivetrains to which it will be referred to as “EM-TECH solutions”. To address the potential savings of the EM-TECH solutions, they have been compared with state-of-the-art (SotA) e-motors to which it will be referred to as “baseline solutions” afterwards. These baseline solutions are intended to be representative of the state-of-the-art in Europe. The identification and detailed LCA and LCC assessments of the baseline solutions were the objectives of Task 2.2 of WP2 and were included in deliverable D2.2.

2 Introduction

This paragraph is intended to give an overview of all the activities related to the LCA and LCC (Figure 1).

Figure 1 LCA overview

Task 6.3. has seen the investigation of potential environmental impacts (LCA) and economic evaluation (LCC) of EM-TECH IWMs and AFMs for identified applications. Two data request forms (one for the IWM and one for the AFM) have been prepared and shared among project partners to successfully collect the data for Life cycle Inventory (LCI) development. An analysis of the list of components and processes involved has been conducted. Any unavailable primary data have been substituted with secondary data taken from LCA databases (e.g., EcoInvent) and literature. In this manner, the LCA and LCC models of the baseline and proto solutions have been performed.

LCA models have been set up and parametrized, following the main steps of LCA (goal and scope definition, inventory analysis, impact assessment and interpretation), with all life cycle phases included (production, use phase, End-of-Life (EoL). Climate change and other most important environmental impact categories have been considered including circularity of considered solutions. Specific attention has been paid to the use of rare resources. The outcomes gave fundamental inputs for the identification of novel eco-design strategies.

LCC assessment of all demonstrators has been carried out. All the costs that occur during product's life cycle (such as costs of purchasing, costs of the use of energy, fuel and water, cost of maintenance, costs of EoL treatments) have been considered and unit costs of the EM-TECH e-motors have been estimated.

In accordance with project partners, the two baseline solutions have been identified in terms of components and technical specifications in deliverable D2.2. Based on deliverable D2.2, the two baseline solutions have been compared with the EM-TECH solutions to address the potential savings.

3 LCA and LCC of the proto solutions

The LCA has been conducted in compliance with the standards ISO 14040:2020 and ISO 14044:2021, which are the most relevant standards in this field. LCC is less standardized than LCA, however this work refers to Directive 2014/24/EU. In the absence of standardized guidelines, the LCC modelling approach is aligned with the structure defined for the LCA. Specifically:

- the same methodological framework used for the LCA was adopted for the LCC,
- the same system boundaries and functional unit ensured full comparability between assessments.

This alignment guarantees a coherent comparison between environmental and economic results.

3.1 Goal and scope definition

3.1.1 Products under study

The products under study are electric drivetrains suitable for automotive applications in passenger cars and small vans in Europe.

Regarding the baseline for the IWM solution, ELA has already developed a series of available direct-drive IWM products, which have been applied to micro or small electric vehicles (EVs), sport utility vehicles (SUVs), people movers, and light commercial vehicles. The baseline solution considered for comparison with the EM-TECH IWM solution is ELA L1600.

Table 1 reports the main performance parameters of the ELA L1600 (baseline solution) and the corresponding for the EM-TECH IWM solution mounting the IWM proto developed during the project. Inverter data are the same as in the baseline.

Table 1 Main performance parameters of the baseline and EM-TECH IWM solutions.

	BASELINE solution	EM-TECH solution
	Motor	
Nominal voltage (V)	370	730
Peak torque (Nm)	1500	1538
Continuous torque (Nm) @ 370 RPM	650	800
Top speed (rpm)	1480	1700
Peak power (kW)	110	72 / 128 [series winding / parallel winding]
Weight (kg)	34.8	34.6
Efficiency peak (%)	94	95 [series & parallel winding]
	Inverter	
Type	Si based 3-phase insulated gate bipolar transistors (IGBTs)	Si based 3-phase insulated gate bipolar transistors (IGBTs)
Weight (kg)	9	9
Efficiency peak (%)	91	91
Cost (€)	400	400
	E-gear	
	Gearless	Included
Efficiency peak (%)	-	99.9
Weight (kg)	-	1.8
Cost (€)	-	81.9

Regarding the baseline for the AFM solution, as explained in deliverable D2.2, radial flux motor (RFM) technology was selected as the baseline because it is mature, well-documented, widely deployed in industry, and already mass-produced at scale, making it representative of the current SotA for on board electric motors. In contrast, existing studies on AFMs, despite their long conceptual history, were not sufficient for developing an LCA or LCC model, making them unsuitable as a practical baseline for comparison. The baseline drivetrain is the Volkswagen ID.3 on their modular electric drive matrix (in German called “modularer E-Antriebs-Baukasten”, abbreviated with MEB) platform.

Table 2 reports the main performance parameters of the radial flux on-board motor (OBM) solution (baseline) and the corresponding parameters for the EM-TECH AFM solution mounting the AFM proto developed during the project. Inverter data are not representative of the inverter developed within EM-TECH, but they refer to an IGBT inverter assumed to be the same as in the baseline. This is because publicly available data on Silicon Carbide (SiC) inverters are currently insufficient to support a detailed LCA/LCC. Lastly, the table reports data of the virtual transmission developed within EM-TECH.

Table 2 Main performance parameters of the baseline and EM-TECH AFM solutions.

	BASELINE solution	EM-TECH solution
	Motor	
Peak torque (Nm)	310	321
Continuous torque (Nm)	150	237
Top speed (rpm)	16000	9000
Peak power (kW)	150	202
Continuous power (kW)	70	160
Weight (kg)	54.1	24.1
Efficiency WLTC (%)	-	95.3
	Inverter	
Type	Si based 3-phase insulated gate bipolar transistors (IGBTs)	Si based 3-phase insulated gate bipolar transistors (IGBTs)
Weight (kg)	5.5	5.5
Efficiency peak (%)	91	91
Cost (€)	400	400
	Mechanical gearbox	
	Included	Included
Weight (kg)	20	20
	Entire drivetrain	
Efficiency WLTC (%)	73	80.3
WLTC energy consumption (kWh/100 km)	15.4	13.66

3.1.2 Functional unit

The functional unit is one electric drive solution comprised of one or more of the following components: one or more electric motors, inverter, and gearbox or e-gear depending on the architecture.

3.1.3 System boundary

The system boundary is cradle-to-grave and it comprises the following life cycle stages: raw material acquisition and preprocessing, manufacturing, distribution, use, collection at EoL, and EoL. The study focuses on all the components of a drivetrain excluding the propulsion control unit and the battery pack. The exclusion of the propulsion control unit will not significantly impact the outcomes resulting from the comparison with the EM-TECH solution developed during the project since the difference solely stays in the applied control strategy. The battery pack is not included in the system boundary since it is not in the scope of the project.

As far as the IWM is concerned, the system boundary includes the LCA of the following components: electric motor, inverter, and e-gear (Figure 2).

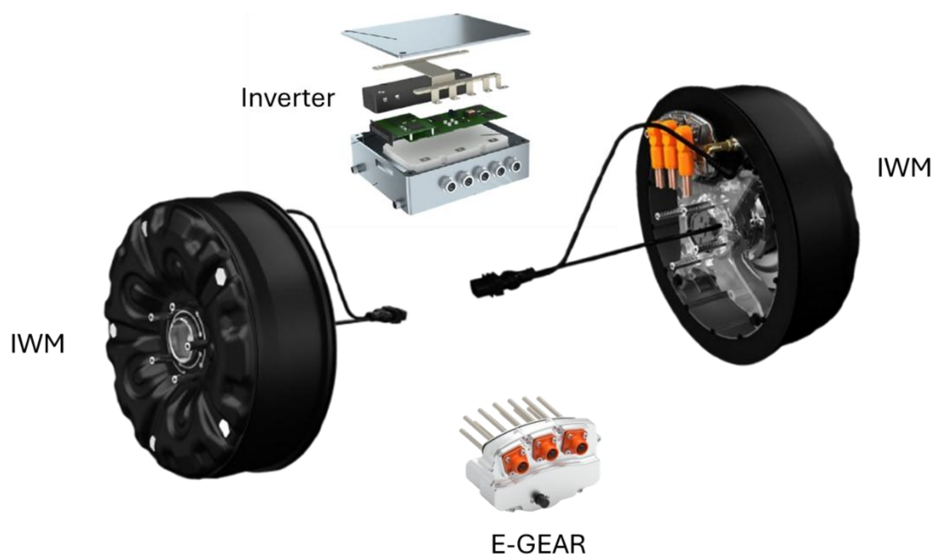


Figure 2 System boundary of the IWM solution in terms of components.

As far as the AFM is concerned, the system boundary includes the LCA of the following components: electric motor, inverter and mechanical gear (Figure 3).

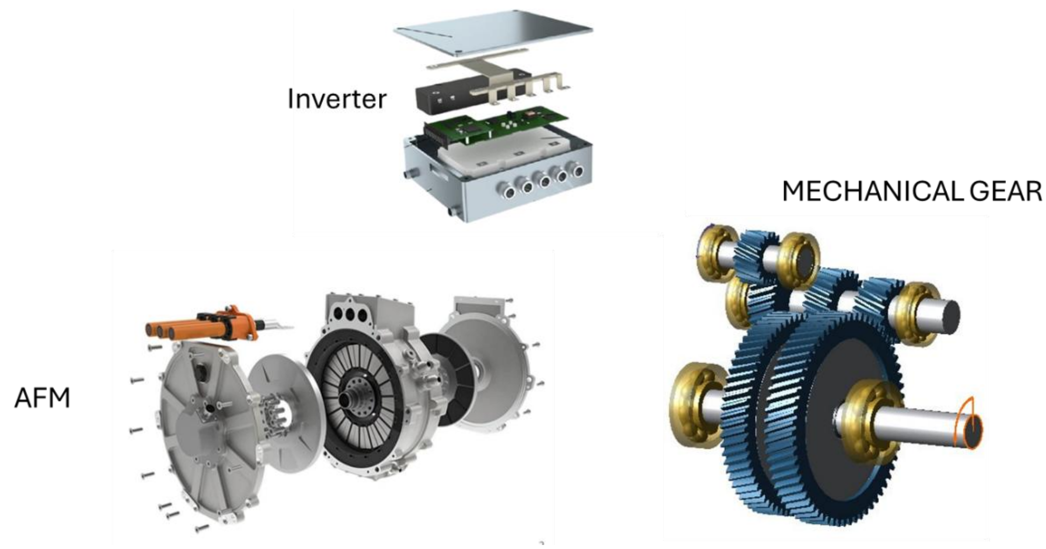
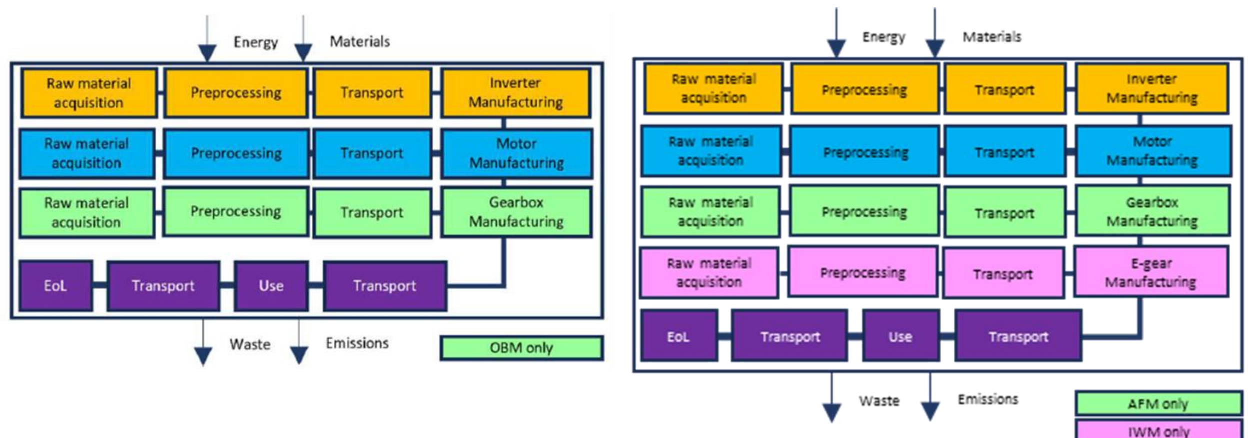


Figure 3 System boundary of the AFM solution in terms of components.



Baselines *Prototypes*

Figure 4 System boundary of both solutions (IWM and OBM) and scenarios (baselines and prototypes) in terms of life cycle phases and components.

3.1.4 Data sources

The Bill of Materials (BoM) for each of the two electric motors is based on primary data provided by project partners. For the IWM, data are retrieved from ELA, for the AFM, data are retrieved from TRX. The dismantling procedures and data have been provided by URBANGOLD. The background database is from EcoInvent version 3.8 as released in SimaPro version 9.4.0.3.

3.1.5 Environmental impact assessment method

The environmental impact assessment is the Environmental Footprint (EF) method version 3.0.

3.1.6 Fine tuning of the IWM baseline for comparability purposes

The following modifications of the IWM baseline assumptions and results have been applied to ensure comparability with the IWM prototype or to fix mistakes:

- Raw materials & manufacturing: Added components called "Other assembly needed components (bearing, connection box, knuckle, and sensors)" hereafter. These components are needed for mounting the motors on the vehicle. Now added both in the baseline and proto.
- Use phase: Reference driving cycle has been changed with respect to deliverable D2.2. We decided to move from real driving emissions (RDE) to Worldwide harmonized Light duty vehicles Test Cycles (WLTC) emissions. The assumption is consistent both in the baseline and proto.
- ERRATA CORRIGE: Transport costs of die cast aluminium, magnets and electrical steel sheet were not included in deliverable D2.2, but have been included now.

The following modifications of the OBM baseline assumptions and results have been applied:

- ERRATA CORRIGE: Baseline drivetrain efficiency is 0.73. Result obtained from simulations conducted by TRX.

3.2 Life Cycle Inventories

3.2.1 Raw material acquisition and pre-processing phase

Raw materials data are based on the BoM provided by the project partners. Default results refer to the production of the motor from virgin materials only, but the models allow for the estimation of the effects of the use of secondary permanent magnets, aluminium, copper and steel. The study takes also into account the emissions and costs of the transportation of raw materials from supplier locations to Europe.

The map in Figure 5 illustrates the geographical distribution and intensity of material transportation within the IWM supply chain. Countries are colour-coded based on the mass of materials transported, with darker shades representing higher volumes. China and Slovenia are respectively highlighted in red and orange, indicating they are the primary nodes in the supply chain with the highest volumes of transported materials.

Taiwan appears in light orange, suggesting a significant but secondary role in the flow of materials. Sweden and Japan, shown in yellow, contribute moderately to the supply chain.

Countries shaded in various tones of blue represent regions with lower volumes of transported materials. Spain, depicted in dark blue, is associated with the lightest material flow, while Germany and India also participate with relatively smaller volumes. Several other European countries are marked in light blue, indicating their inclusion in the broader European network supporting the supply chain.

This visualization offers a clear understanding of the relative importance of each country in IWM's logistic emissions and costs. Transport occurs via multimodal transport (container ship up to Trieste and road transport from Trieste to Ljubljana) in the case of China, Taiwan, Japan and India. Transport occurs via road transport in all other cases. All transport assumptions are reported in Table 3.

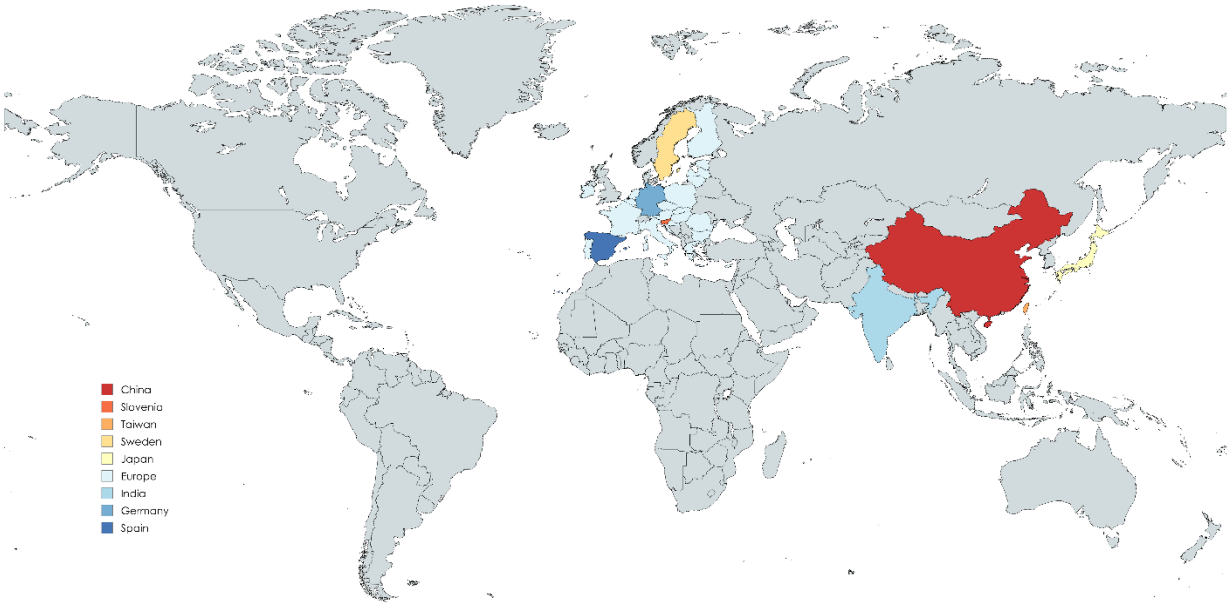


Figure 5 IWM proto supply chain. Colour code: heaviest transported materials (Red), lightest transported materials (Dark blue)

Table 3 List of source countries per material with assumed departure, arrival locations, distances and means of transport (proto IWM).

Material	Source country	Departure location	Arrival location	Means of transport	Distance (km)
Die cast Al; Electrical steel sheet; NdFeB magnets; Isolators	China	Tianjin	Trieste	Container ship	20106
		Trieste	Ljubljana	Euro 6 16-32 metric ton truck	96.6
Die cast Al	Taiwan	Taipei	Trieste	Container ship	17300
		Trieste	Ljubljana	Euro 6 16-32 metric ton truck	96.6
Electrical Steel sheet	India	Mumbai	Trieste	Container ship	9305
		Trieste	Ljubljana	Euro 6 16-32 metric ton truck	96.6
Rotor & stator seals; Resin	Germany	Monaco	Ljubljana	Euro 6 16-32 metric ton truck	400
Rotor & stator chemicals	Average EU	-	-	-	-
Rotor & stator other parts	Slovenia	Maribor	Ljubljana	Euro 6 16-32 metric ton truck	120
Windings, busbars	Japan	Tokyo	Trieste	Container ship	19670
		Trieste	Ljubljana	Euro 6 16-32 metric ton truck	96.6
Sensors	Spain	Madrid	Ljubljana	Euro 6 16-32 metric ton truck	2000

Bearing	Sweden	Stockholm	Ljubljana	Euro 6 16-32 metric ton truck	2000

For the AFM, the map is quite homogeneous since the majority of suppliers are based in Europe.

3.2.2 Manufacturing process

3.2.2.1 IWM manufacturing

The IWM assembly process follows a precise and structured flow to ensure optimal performance and reliability. It begins with wire preparation. Prior to describing the prototype IWM assembly process, it must be pointed out that these data reflect energy usage measured during the development and testing of the prototype unit, rather than scaled production. Both 2-Dimensional Distributed Winding (2DD) and 3-Dimensional Distributed Winding (3DD) configurations are used in the stator, laying the foundation for electrical connectivity. The stator housing is then coupled with the laminated stack of electrical steel sheets that make up the core of the stator (the bladestack), followed by wire insertion and brazing to secure electrical connections. The assembly undergoes a potting process to insulate and protect the windings, followed by curing in an oven. Stator bandaging adds mechanical reinforcement. Simultaneously, magnets are glued onto the rotor components. Key parts are cleaned, prepared, and glued as part of general assembly protocols. The rotor housing is then joined with the rotor yoke, and the bladestack/back-iron undergoes a bakeout process to remove moisture. A cathodic electrodeposition coating (KTL surface treatment) is applied for corrosion resistance to the rotor subassembly. Finally, the motor marriage step couples the stator and rotor sub-assemblies, culminating in End-Of-Line (EOL) testing to validate performance and quality.

Figure 6 illustrates the relative energy consumption associated with each stage of the IWM assembly process. The pie graph breaks down the total energy usage into specific assembly operations, highlighting which steps are the most energy-intensive (i.e., potting process and oven curing due to thermal processes and power-intensive machinery). Moderate energy use can be seen in wire brazing, bandaging, and magnet gluing, while lower energy demand is associated with mechanical coupling steps like stator and rotor housing assembly and general parts cleaning. This figure provides insights into potential areas for energy optimization in the manufacturing process.

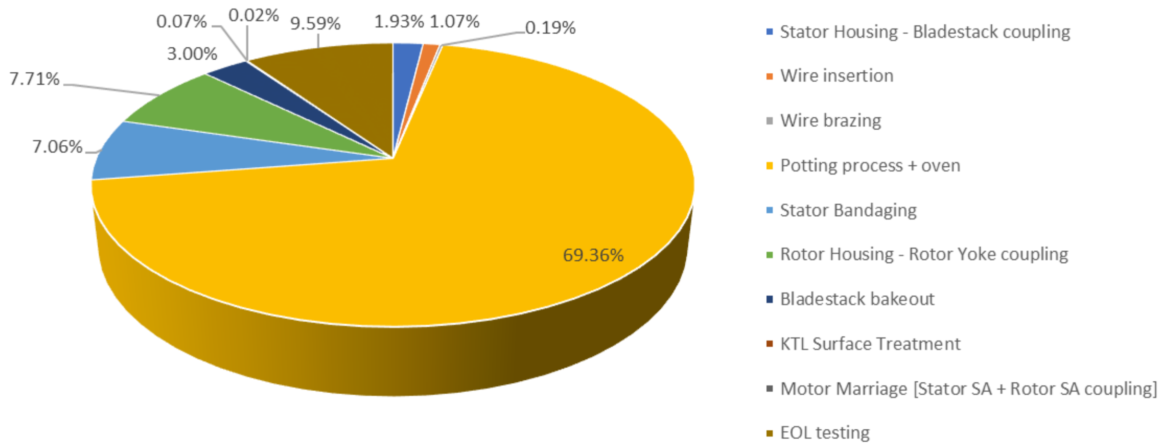


Figure 6 Energy demand share for the different assembly steps

The data collected from the real assembly process carried out by ELA do not include direct emissions that may potential occur during curing and bakeout.

The carbon footprint and LCA results of the prototype IWM assembly process have been compared with values obtained from literature on an industrial-scale production process of a permanent magnet synchronous motor (PMSM) (Figure 7). Although the collected data refer to a prototype, they offer significant value due to their direct relevance to the specific motor under study. This real-world, process-specific data ensures a high degree of accuracy in representing the environmental impact of the actual product, unlike generalized industrial data which may not fully capture the unique characteristics of this motor design and technology. As such, even at a smaller scale, the prototype-based results provide a critical reference point for evaluating and improving the sustainability of future industrial manufacturing.

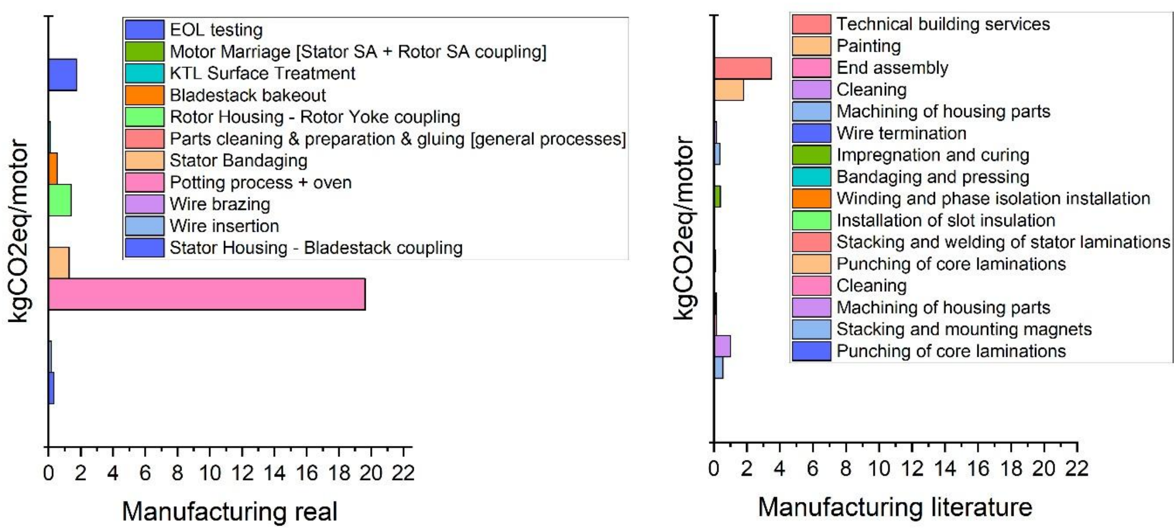


Figure 7 Carbon footprint emission breakdown of the manufacturing process assuming (left) real ELA process data; (right) literature data based on (Nordelof et. al, 2019).

3.2.2.2 AFM manufacturing

The production of the AFM consists of three main parallel manufacturing streams, namely stator, rotor, and housing productions, which converge during final assembly.

Stator production starts with punching the core laminations, after which the laminations are stacked. The stator then undergoes slot insulation, including the installation of plastic parts. Next, the windings are installed, together with phase isolation, and windings are welded.

Rotor production begins with slitting the electrical steel coil, followed by coiling to create the rotor core. This is followed by the hub and back-iron assembly, which includes welding operations, and the adhesive bonding of parts to the back-iron. Once this subassembly is prepared, the rotor proceeds to mounting magnets, after which a retaining ring is inserted to secure the magnets.

The housing is produced through machining, followed by cleaning, and finally mounting of the necessary elements to prepare the housing for integration.

The stator, rotor, and housing streams merge in the end assembly stage, where all components are integrated into the complete AFM. For this life cycle stage, data from (Nordelöf et al. 2017) has been used and adapted to the TRX case.

3.2.3 Use phase

Figure 8 illustrates the methodological framework used to assess the environmental and economic impacts associated with the use phase of an EV, based on its electricity consumption over a standardized driving cycle. The analysis begins with the selection of the electricity source: by default, the average EU electricity mix is used, while two alternative scenarios (offshore wind turbines in the Netherlands and hard-coal power plants in the Czech Republic) serve as optional comparisons. Each electricity scenario provides the corresponding emission factors (e.g., $kgCO_2eq/kWh$).

The vehicle's energy consumption is evaluated using the WLTC, which determines the energy demand per kilometre. This consumption is then integrated over a 150,000 km lifetime to obtain the total use-phase energy requirement. Combined with the motor or drivetrain efficiency, the total environmental and cost impacts are calculated. The results are allocated using the so-called delta approach. As already explained in deliverable D2.2, regarding the use phase modelling, no general methodological consensus exists for automotive products. Very often the related impacts and activities are modelled fully. The so-called delta approach has been assumed in this study for the use phase to allocate only a part of the environmental and economic impacts of the vehicle use to the drivetrain. Only the drivetrain losses during conversion of electrical energy to mechanical have been considered for the use phase, rather than the whole energy required by the vehicle.

In the IWM baseline, the use phase refers to a drivetrain efficiency of 85.54% as a result of the motor efficiency accounting for 94% (AUDI AG 2019) and the inverter efficiency accounting for 91% (I&M, 'Personal Contact', 30 May 2023). In the proto, the use phase refers to a drivetrain efficiency of 86.36% as a result of the motor efficiency achieved in the project and accounting for 95%, the inverter efficiency equal to the baseline and e-gear efficiency of 99.9%.

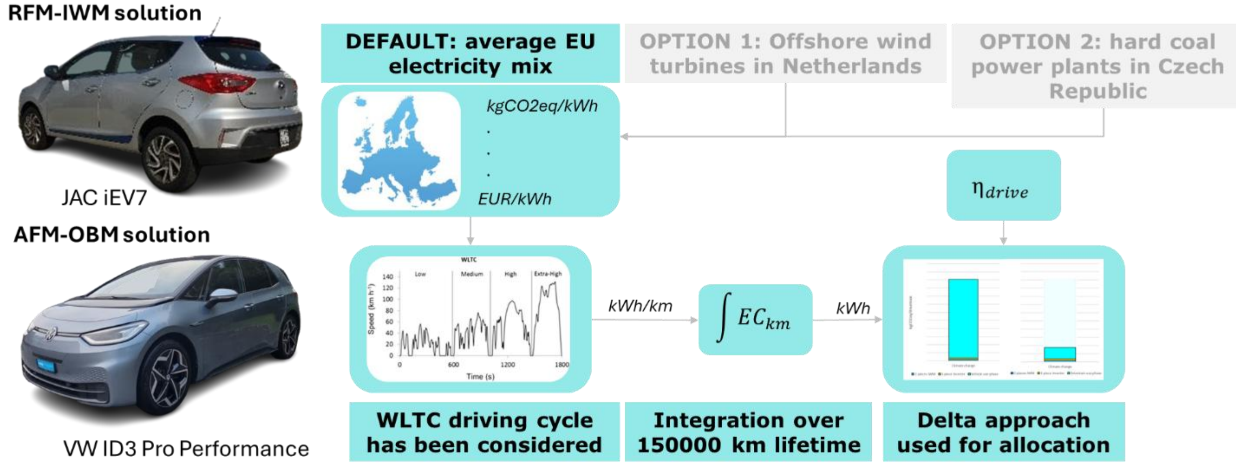


Figure 8 Scheme of the methodology applied for the estimation of the use phase emissions.

In the AFM baseline, the use phase refers to a drivetrain efficiency of 73% as a result of the simulations conducted by TRX. In the AFM proto, the use phase refers to a drivetrain efficiency of 80.3% as a result of the motor WLTC efficiency achieved in the project and accounting for 90.3%, the virtual transmission efficiency and the IGBT inverter efficiency equal to around 91%. Then, a scenario has been added (Table 6) for the use phase only, where the inverter is the one developed by I&M, so the drivetrain efficiency is 87.3% as a result of the motor WLTC efficiency achieved in the project and accounting for 90.3%, the efficiency of the inverter developed by I&M equal to around 99% and the efficiency of the virtual transmission.

3.2.4 EoL phase

Regarding the EoL phase, special attention was paid to the modelling of the EoL treatments both in terms of environmental impacts and costs. The partners were involved to share their feedback in order to have a multidisciplinary perspective on this topic and to set up an EoL scenario that takes into account an effective dismantling procedure aimed at enhancing the recoverability of materials, especially rare earth elements (REEs) in order to bypass the limitations of the current applicable Directive 2000/53/EC (EoL vehicle directive), which does not consider the particularities of electric vehicles compared to internal combustion engine vehicles. The aim is to give an impact also in terms of reliability/applicability of the procedure and suggest new potential eco-design strategies for electric drive motors beyond the so far approved eco-design strategies of EVs, which focus mainly on energy efficiency and do not consider circular solutions such as material reuse or improving recyclability.

Figure 9 shows the EoL treatment pathways for a PMSM that are alternatives to SotA shredding. The PMSM is separated into two main components:

- housing and stator
- rotor

For each part, additional steps are shown. For housing and stator, two major approaches exist: the manual disassembly path (eventually aided by separation tools and/or thermal and chemical treatments) and separation with an e-motor wrecker. For the rotor, once it has been separated, it can undergo three alternative magnet-removal or recovery processes: thermal treatment, mechanical removal, or manual removal.

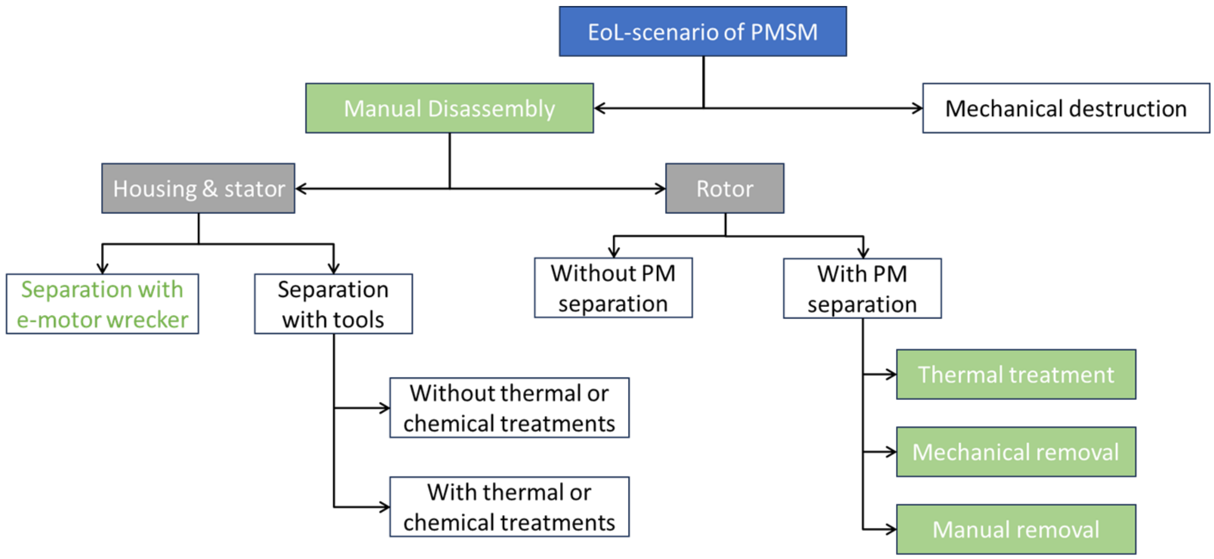


Figure 9 EoL-scenario to collect PM from PMSM

Because the IWM incorporates internally mounted permanent magnets (PMs) in the rotor, which are practically impossible to remove using hand tools without damaging the magnets and the rotor, an industrially applied mechanised separation route for e-motors was considered. In this scenario, an electric motor recycling system is employed, consisting of a metal cutting blade that breaks the case and splits the IWM in two parts and an e-wrecker that subsequently extracts the copper windings. Finally, splitting the rotor into two parts exposed the PMs, which are extracted using a hydraulic press. Both procedures require the assistance of trained operators. This is a destructive extractive process which limits the applicable recycling techniques for EoL PMs. Therefore, a smelting process was considered for recycling the PMs to obtain a rare-earth concentrate. Figure 10 illustrates the recycling of the drive motor through different treatment stages. The process model begins with the input of the whole e-drive motor thermally demagnetized.

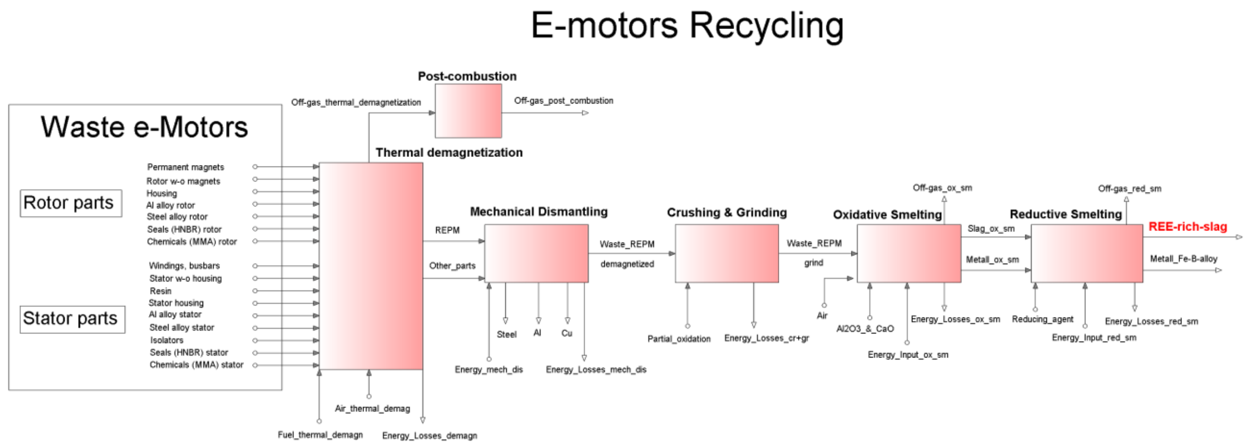


Figure 10 Material flow analysis of the EoL phase of the IWM proto.

During thermal demagnetization, energy is consumed mainly as fuel input. Off-gas produced during this stage is sent to post-combustion for further treatment, minimizing emissions. After demagnetization, the materials move to the mechanical dismantling step, where rotor and stator components are mechanically split and the magnets are physically extracted from the rotor. After the mechanical dismantling, the EoL e-drive motor are sorted into four different material streams i.e., steel, aluminium, copper and PM scrap. Some energy is consumed in the form of electricity.

The separated scrap containing rare earth permanent magnets (REPMs) then undergoes crushing and grinding to reduce its size, allowing for more efficient recovery before smelting. This step involves additional energy input and partial oxidation, generating fine REPM particles for further processing. The waste material proceeds to oxidative smelting, where oxidation reactions help separate metallic and non-metallic components. Slag and metallic oxides are produced with energy consumption.

Following oxidative smelting, the process continues with reductive smelting, where reducing agents are used to recover iron and boron in the metallic phase and REEs in the slag phase. This stage requires substantial energy input and results in the production of a REE-rich slag, which represents the key output of the recycling process. Metal fractions such as iron-boron alloys are also recovered.

Table 4 shows the material and energy flows calculated on a basis of 3 shifts of 8 hours-batch per day considering 300 annual working days.

Table 4 Material and energy flow of the EoL-scenario of the IWM proto.

Total Auxiliaries		
	Usage	Unit
Air	5 756 019	Nm³
Reducing agent	9 500	kg
Caustic soda 40%	30 000	kg
Demi water	5 000	kg
Aluminum oxide	2 250 000	kg
Limestone	2 250 000	kg

	Total Energy	
	Usage	Unit
Electricity	11 000 000	kWh
Gas	3 000 000	kWh

Figure 11 shows the resulting EoL sub-model implemented in the overall LCA-LCC model of the IWM solution. After thermal demagnetization, PMs are dismantled, crushed and grinded. Then, PMs are smelted through oxidative and reductive smelting. With a recovery efficiency of 99%, REE-rich slag and Fe-B alloy fractions are recovered. With a 95% recovery efficiency, steel, copper and aluminium fractions are dismantled and recovered as well at the mechanical dismantling stage. Lastly, iron, copper and aluminium are recycled from these dismantled fractions, assuming the same recycling efficiency and treatments considered in deliverable D2.2 for the baseline solution. Electronics is treated as in deliverable D2.2 for the baseline solution. Figure 11 shows in yellow the differences with respect to the baseline scenario.

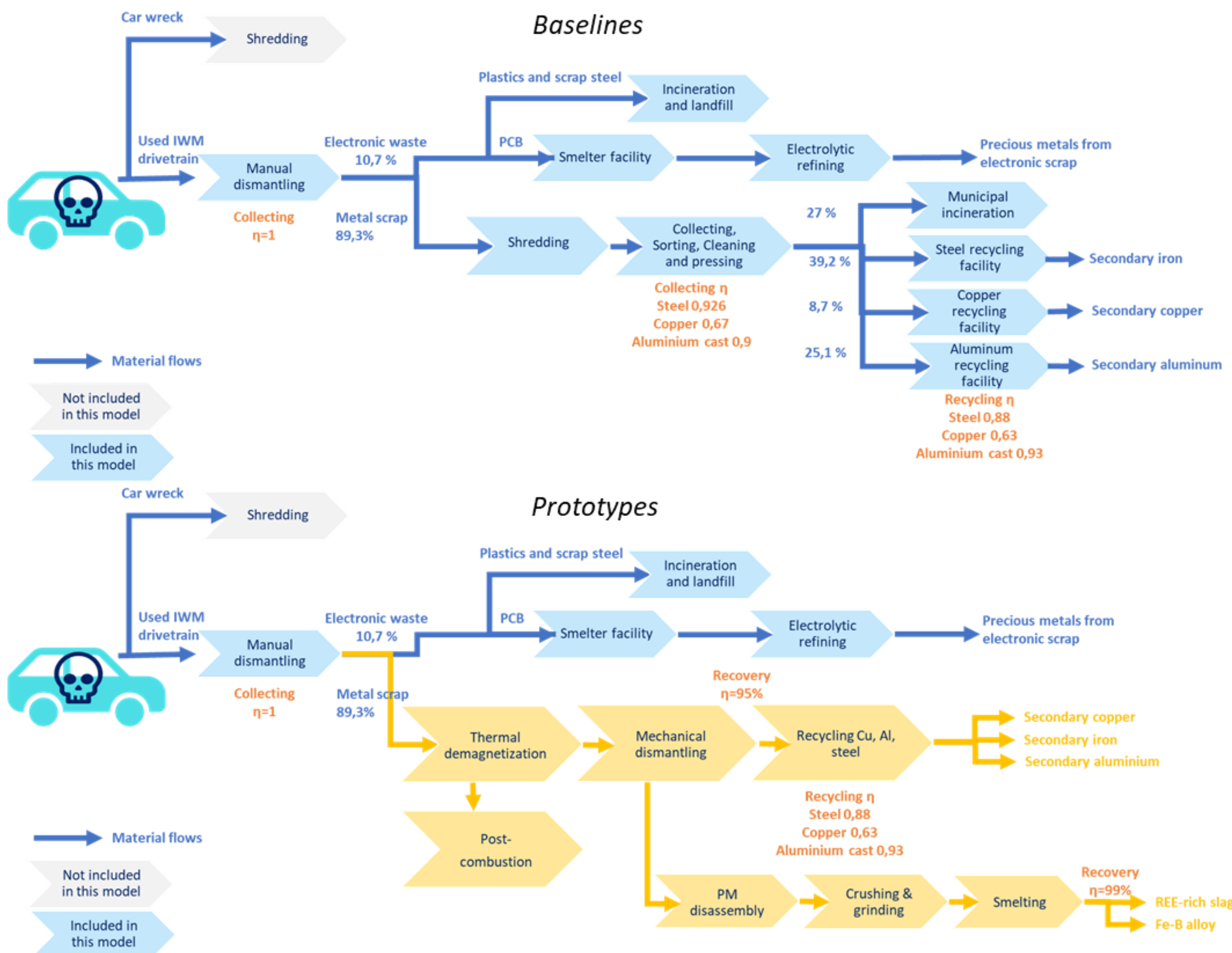


Figure 11 Resulting EoL sub-model implemented in the overall LCA model of the IWM solution (top) for the baseline, (bottom) for the prototype

In the case of the AFM, the motor undergoes a manual dismantling. Copper, iron, and aluminium are assumed to be recovered and recycled with the same efficiency of the IWM (Figure 11). Then, PMs are assumed to be recycled through a novel hydrogen-decrepitation-based recycling process. The experimental demonstration of this process was conducted on a laboratory scale in Slovenia as reported in (Accardo et al. 2024). The EoL magnets were first cleaned through sandblasting and then processed using standard steps applied to virgin alloys, including hydrogen decrepitation, milling, pressing, and sintering. After heat treatment and machining to achieve the required magnetic properties and final shape, the magnets were magnetized, and an epoxy coating was applied.

3.2.5 Final LCA model of the IWM

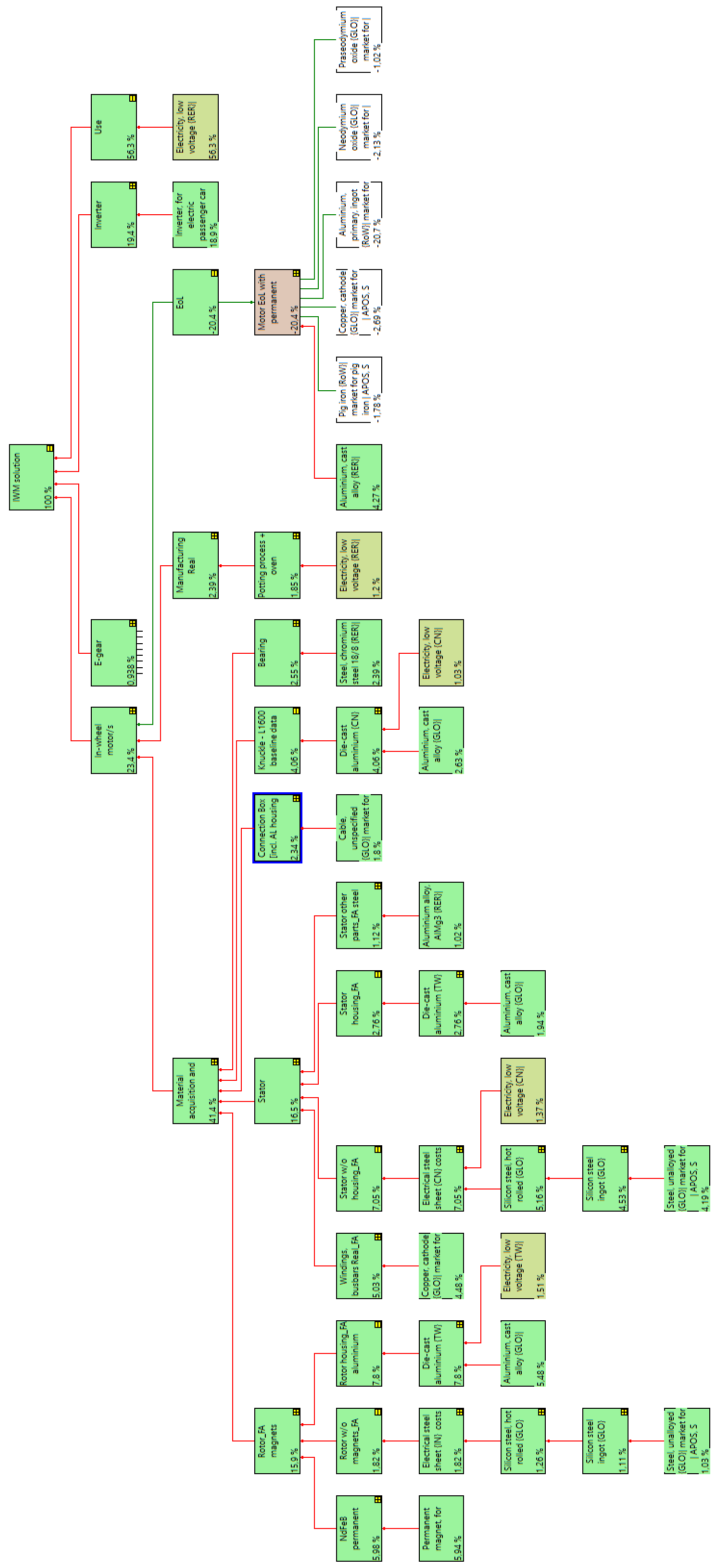


Figure 12 LCA model of the IWM drivetrain with carbon footprint flow results, considering real manufacturing emissions. Cut-off of material and energy flows at 0.93% to ensure visibility.

3.2.6 Final LCA model of the AFM

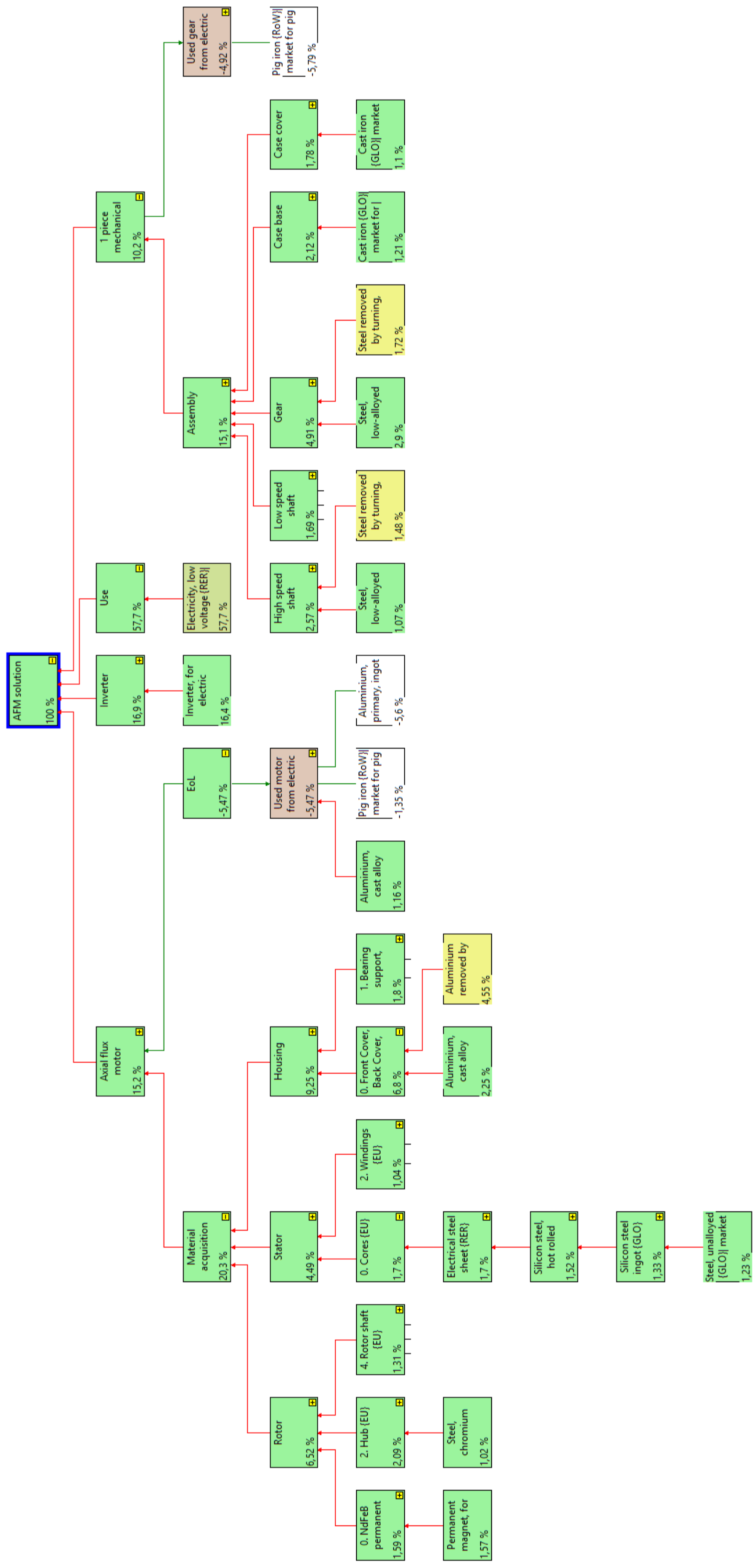


Figure 13 LCA model of the AFM drivetrain with carbon footprint flow results. Cut-off of material and energy flows at 0.93% to ensure visibility.

3.3 LCA and LCC results for the IWM proto solution

3.3.1 E-gear

This bar chart (Figure 14) shows the LCA results of the production of the e-gear, broken down by environmental impact category and component contribution. The impacts are shown in percentages, normalized per category to 100%, which allows easy comparison of which components dominate each impact. Each bar represents a specific impact category, while the coloured segments indicate the share of each component, such as the main assembly, main housing, bulkhead connectors, and sealing elements, within that category.

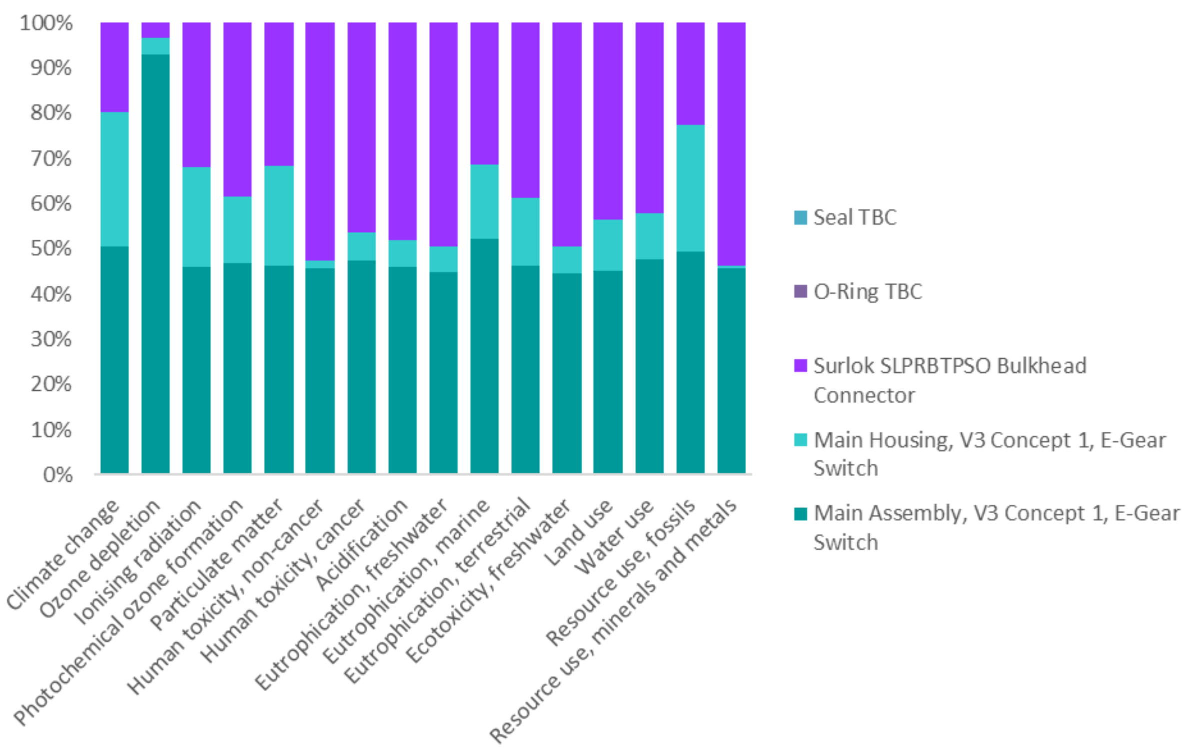


Figure 14 Environmental impacts of e-gear production.

Overall, the results indicate that the main assembly is the dominant contributor across most environmental indicators. For the climate change, the main assembly and housing are clearly responsible for most of the impact (Figure 14), and this is especially true when accounting for the fact that if the e-gear were not present then the Surlok bulkhead connectors (or an equivalent) would be used within the motor assembly instead, and so these do not present an additional environment impact. The selector assembly and inner housing assembly drive the carbon footprint on the main assembly side (Figure 15) and milling process of aluminium parts on the housing side (Figure 16). The main assembly still accounts for most of the ozone depletion impact, likely due to specific chemical processes or materials used in selector assembly. Ionising radiation shows substantial share from the main assembly (Figure 14), mainly due to the selector assembly (Figure 15). Photochemical ozone formation, particulate matter, marine eutrophication, and fossil resource use also show substantial shares from the main assembly and main housing (Figure 14), which are mainly related to the selector assembly (Figure 15). Acidification and eutrophication impacts are again largely dominated by the main assembly, again mainly due to the selector assembly (Figure 15). Freshwater ecotoxicity and use of mineral and metal resources appear more evenly distributed among the main assembly and bulkhead connectors.

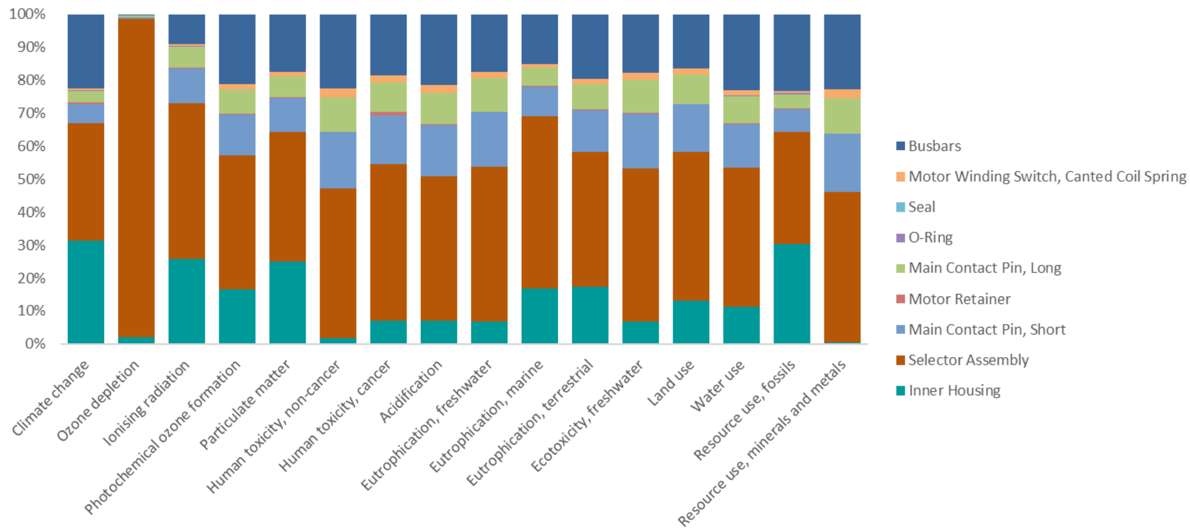


Figure 15 Environmental impacts of the main assembly of the e-gear.

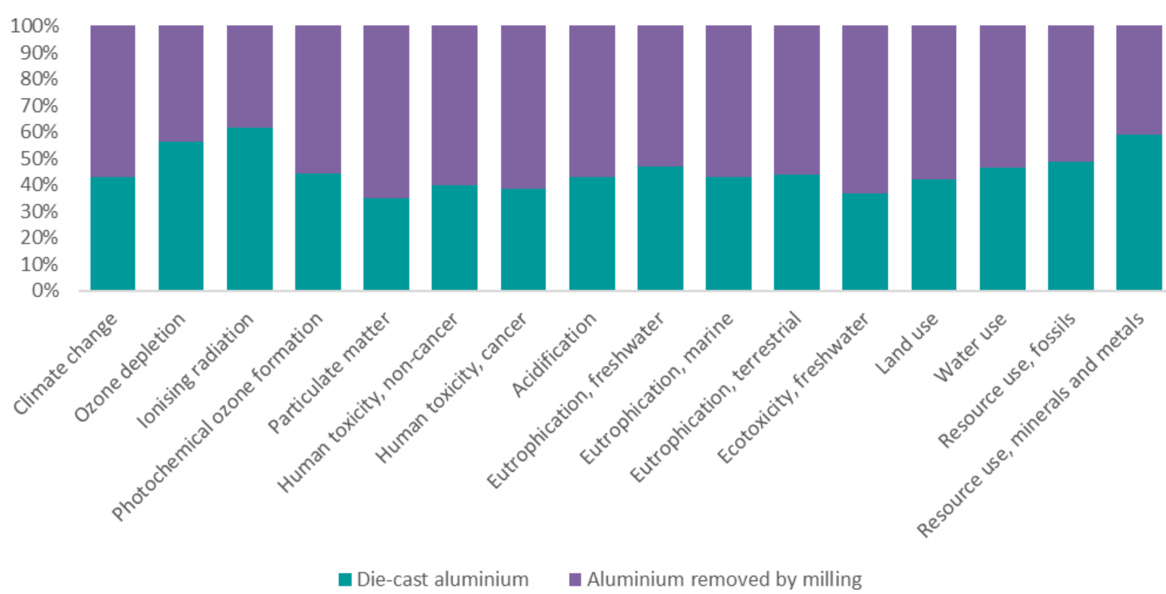


Figure 16 Environmental impacts of the main housing of the e-gear.

In the human toxicity categories (both cancer and non-cancer), acidification and eutrophication, the bulkhead connectors begin to have a visible contribution, due to the use of copper and brass scrap generated during turning (Figure 17). Use of fossil resources appears more evenly distributed among the main assembly, housing, and bulkhead connectors, showing that multiple materials contribute to this impact.

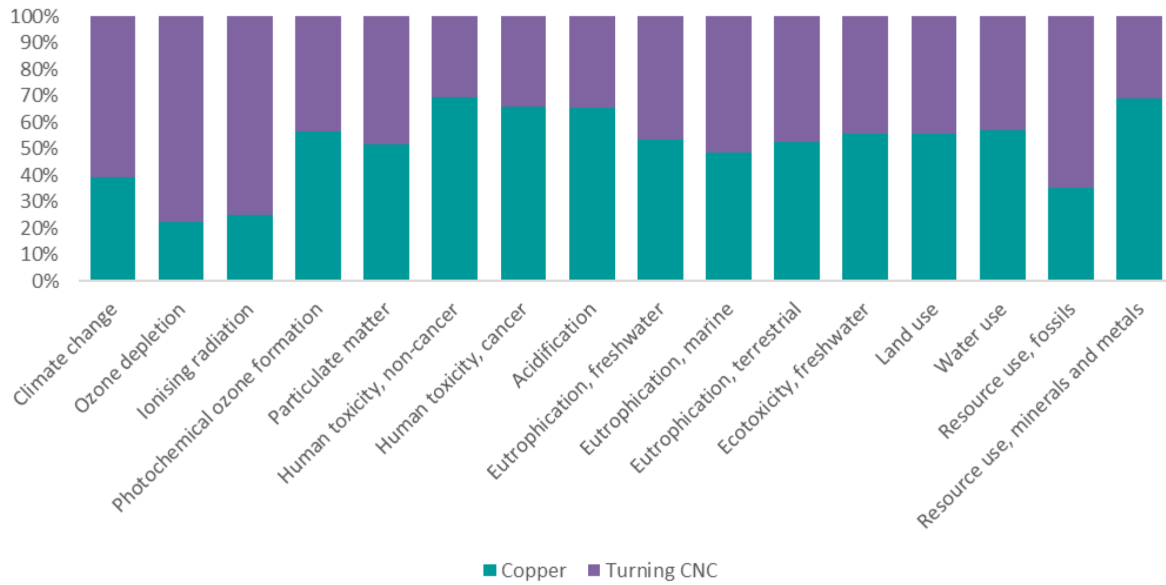


Figure 17 Environmental impacts of bulkhead connector

Land use and water use are also mainly driven by the main assembly. In summary, the main assembly is the environmental hotspot of the product, as it contributes most significantly across nearly all impact categories. Reducing its environmental burden, through material optimization, improved manufacturing efficiency, or recycling strategies, could therefore yield the greatest overall improvements in the sustainability performance of the e-gear system.

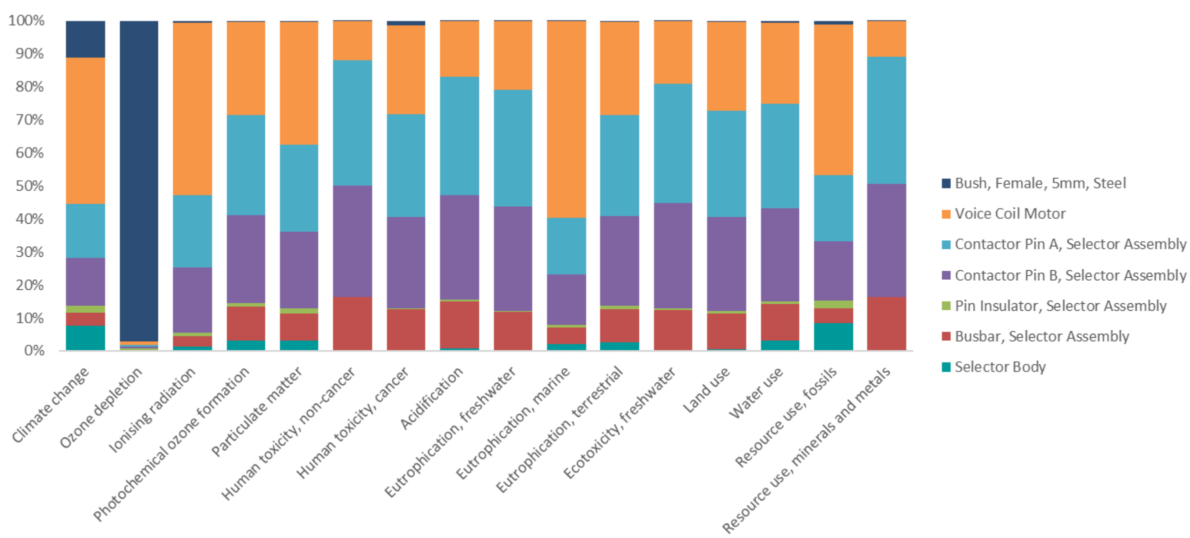


Figure 18 Insight into the environmental impacts of selector assembly.

3.3.2 Proto IWM LCA

Figure 19 shows the LCA emission profile of the IWM drivetrain. It compares how the different drivetrain components contribute to a wide range of environmental impact categories. Each bar adds up to 100%, showing the relative share of four contributors: IWMs, the inverter, the e-gear, and the drivetrain use phase.

A clear pattern emerges across most categories: the drivetrain use phase (represented in light blue) is the dominant contributor in 6 out of 16 indicators, especially for climate change, ozone depletion, acidification, eutrophication, and fossil resource use. This indicates that the environmental burden of operating the drivetrain over its lifetime outweighs that of manufacturing its components in these impact areas.

IWMs (shown in dark blue) frequently appear as the main or second-largest contributors. They particularly influence the:

- ionizing radiation due to material acquisition and preprocessing, especially NdFeB magnets in the rotor,
- photochemical ozone formation due to EoL recycling,
- ozone depletion, particulate matter formation, human toxicity, freshwater ecotoxicity and use of mineral and metal resources due to material acquisition and preprocessing, especially the copper windings in the stator,
- acidification due to both material acquisition and preprocessing (especially the copper windings in the stator) and EoL recycling,
- terrestrial and marine eutrophication due to EoL recycling, and
- land and water use due to material acquisition and preprocessing, especially the copper windings in the stator and especially NdFeB magnets in the rotor.

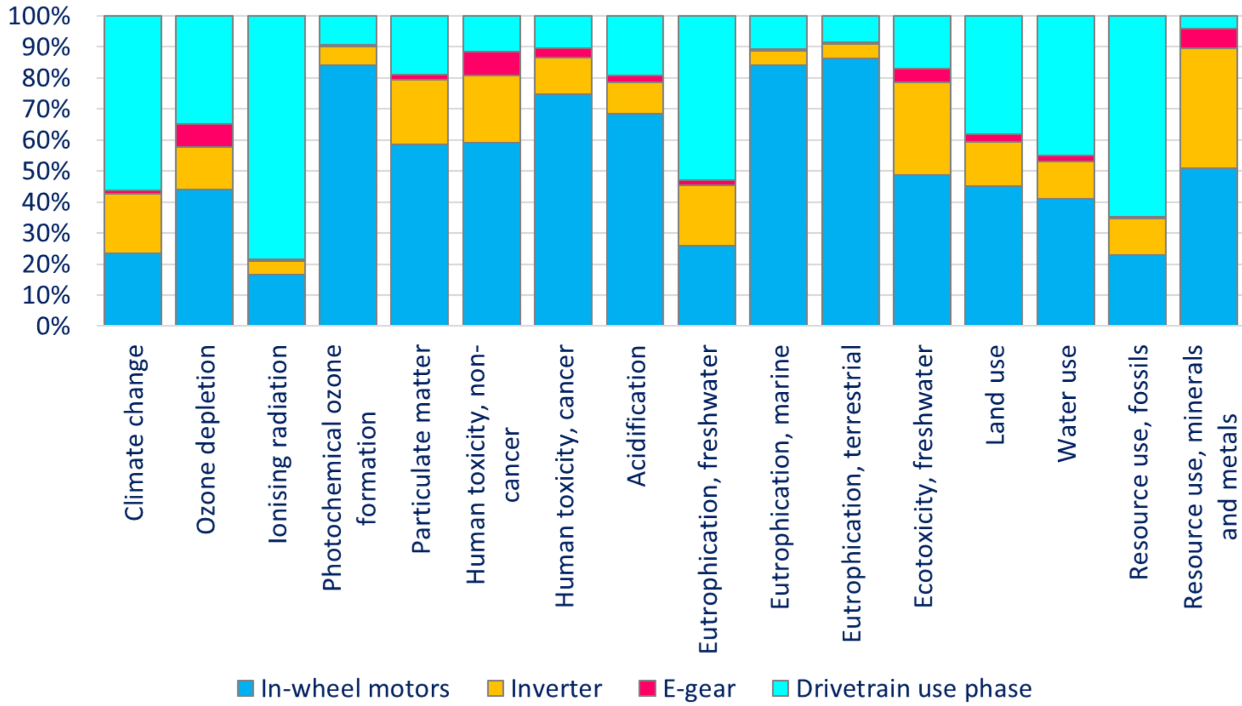


Figure 19 LCA emission profile of EM-TECH IWM solution, considering two IWMs on the rear axle mounted on a JACiEV7 and real manufacturing emissions. The delta approach is used to estimate the drivetrain use phase emissions. EoL is included and PMs are assumed to be recovered.

Figure 20 shows the detailed carbon footprint of the IWM prototype life cycle (use phase excluded). As in the baseline IWM, the raw material acquisition and pre-processing phase is the major driver of the carbon footprint (first bar chart from the left). Motor recycling allows for a carbon footprint reduction of 59%. Also, rotor and stator almost equally contribute to raw material acquisition and pre-processing (second chart from the left). The two pie charts show the emission breakdown of the rotor (top) and stator (bottom). The carbon footprint of the **rotor is mainly driven by the aluminium housing and NdFeB magnets**. Instead, the carbon footprint of the **stator is mainly driven by the stator lamination cores and copper windings and busbars**.

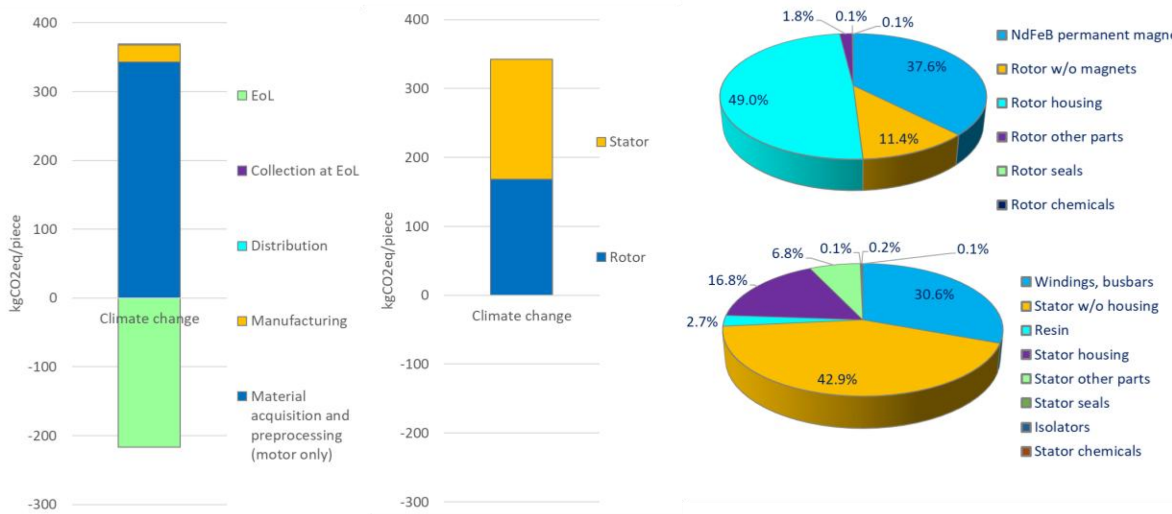


Figure 20 Detailed carbon footprint emissions of the IWM only (use phase excluded), considering real manufacturing emissions. EoL is included and PMs are assumed to be recovered.

3.3.3 Effects of recycling

Figure 21 shows the LCA results for one piece of IWM, showing the contribution of different life cycle stages to various environmental impact categories. The vertical bars are normalized to 100%, with positive and negative values indicating environmental burdens and benefits, respectively. Each colour represents a distinct life cycle phase: material acquisition and pre-processing, manufacturing, distribution, collection at EoL, and EoL treatment (light blue).

Overall, the dark blue sections dominate most categories, showing that material acquisition and pre-processing are the main contributors to environmental impacts. This indicates that the extraction and preparation of raw materials are the most resource- and energy-intensive stages in the product's life cycle. In contrast, the EoL phase often shows negative contributions, meaning that recycling or recovery processes provide environmental benefits that offset some of the upstream impacts. This is particularly visible in categories such as climate change, ozone depletion, ionising radiation, land use, and resource use, where the blue bars extend below zero, signifying net savings due to avoided burdens from material recovery. **It is important to notice that recycling allows for a reduction in climate change that is 59% in life cycle perspective.**

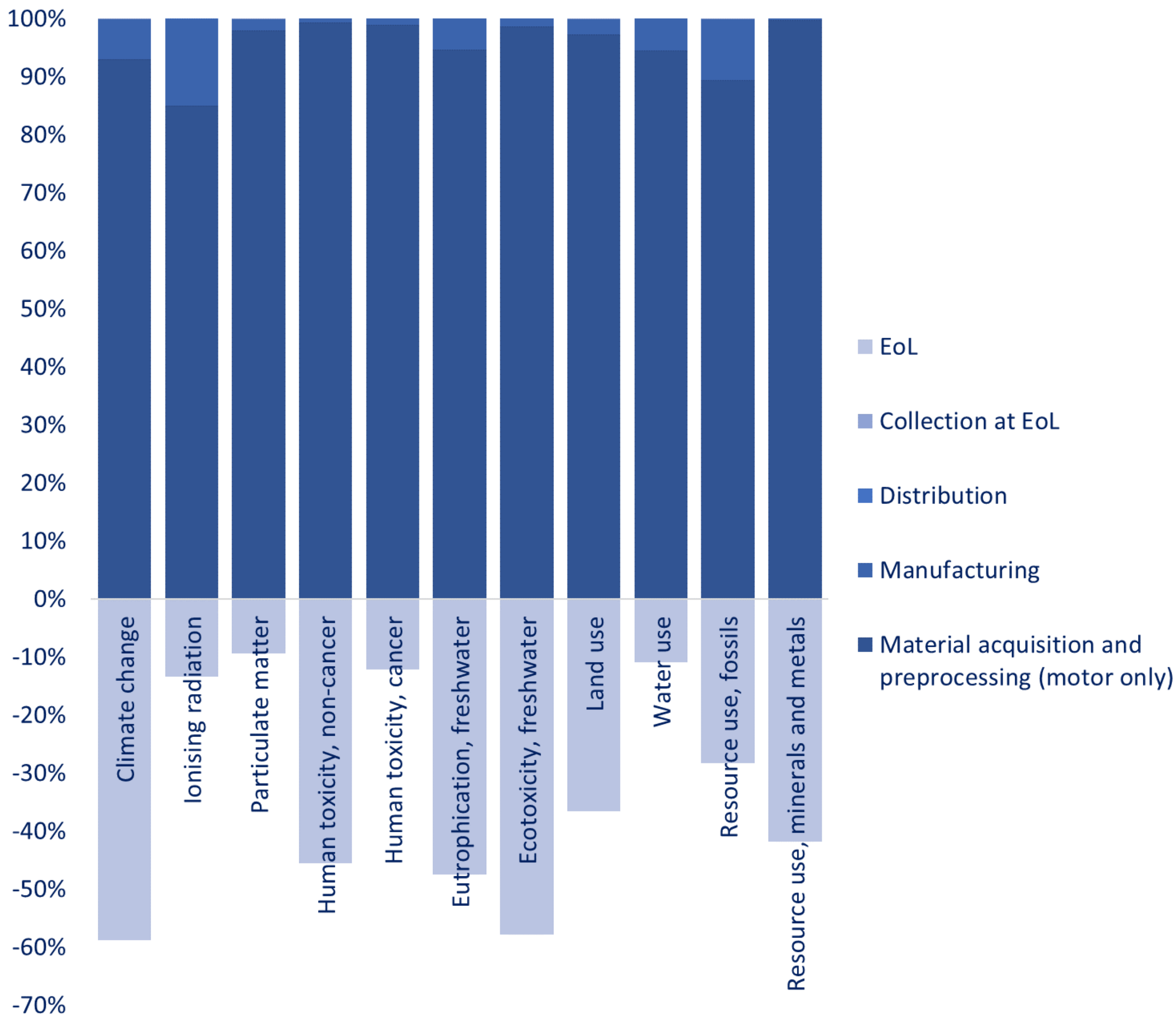


Figure 21 Results of the LCA of the IWM proto, including benefits of recycling in light blue.

Significant increases have been found in photochemical ozone formation, ozone depletion, acidification, marine and terrestrial eutrophication due to the recycling process (i.e., off gas released during demagnetization, oxidative smelting, and reductive smelting).

3.3.4 Proto IWM LCC

Figure 22 shows the detailed cost breakdown of the IWM drivetrain life cycle without revenues while Figure 23 shows the detailed cost breakdown of the IWM drivetrain life cycle with revenues from sold secondary materials. The assumed indirect costs for the IWM are shown in Table 5.

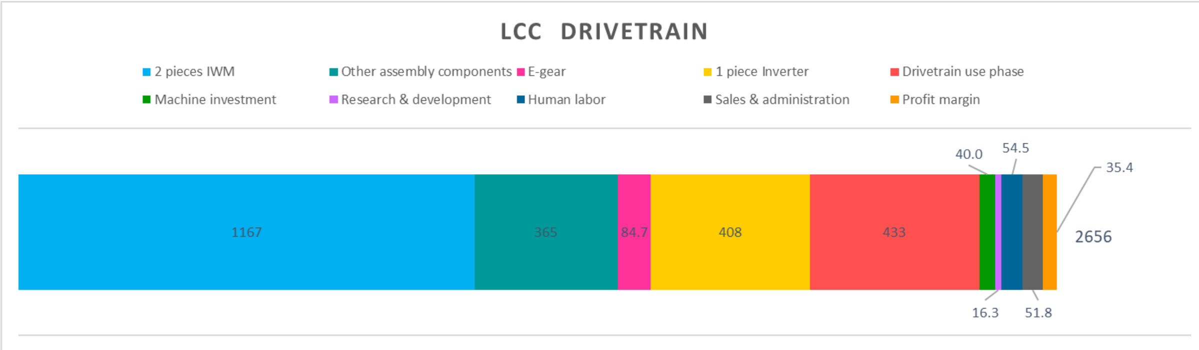


Figure 22 LCC of EM-TECH IWM solution, considering two IWMs on the rear axle mounted on a JACiEV7. The delta approach is used to estimate the drivetrain-related use costs. EoL is included and PMs are assumed to be recovered. Indirect costs are included. Revenues are not considered.

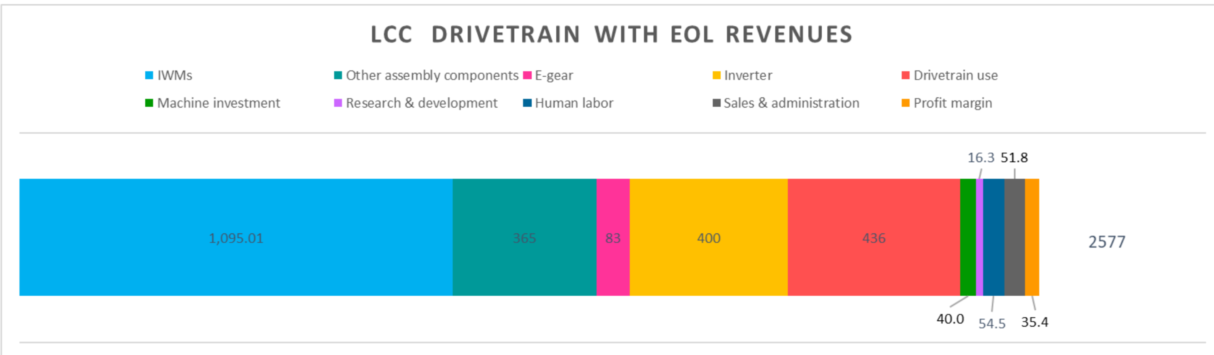


Figure 23 LCC of EM-TECH IWM solution, considering two IWMs on the rear axle mounted on a JACiEV7. The delta approach is used to estimate the drivetrain-related use costs. EoL is included and PMs are assumed to be recovered. Indirect costs are included. Revenues are considered

Table 5 Indirect costs of the IWM prototype.

Indirect costs			
Machine investment	28 million € over 7 years, with a production volume of 100000 pieces/year	40	EUR/motor
Research & development	3% of the motor cost	16.3	EUR/motor
Human labor	10% of the motor cost	54.5	EUR/motor
Sales & administration	9,5% of the motor cost	51.8	EUR/motor
Total indirect costs (motor manufacturer perspective)		**162.6**	**EUR/motor**
Profit margin	6,5% of the motor cost	35.4	EUR/motor
Total indirect costs (OEM perspective)		**198.0**	**EUR/motor**

Figure 24 shows the detailed cost breakdown of one IWM prototype (use phase excluded), where the raw material acquisition and pre-processing phase (first bar on the left) accounts for 530.5 €/motor. As in the baseline IWM, the raw material acquisition and pre-processing phase is the major cost driver.

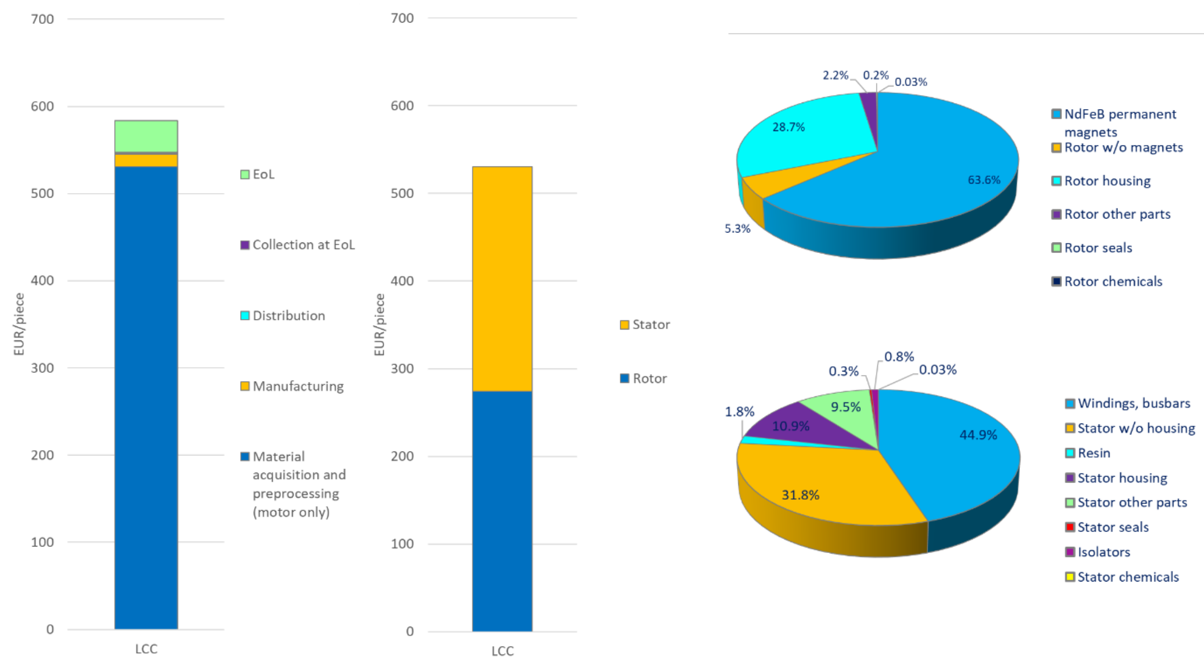


Figure 24 Detailed life cycle costs of the IWM only (use phase excluded), considering real manufacturing data. EoL is included and PMs are assumed to be recovered. However, no revenues are considered for sold recovered materials.

3.3.5 LCC at EoL-stage

The costs at the EoL stage for the IWM were calculated considering both the process costs and the total operating costs of the recycling sub-plants (thermal demagnetisation, mechanical dismantling and smelting operations). In the modelling, a favourable regulatory scenario is assumed in which Extended Producer Responsibility (EPR) is applied at the level of the electric drive motor. Under this assumption, manufacturers of e-drive motors bear the costs of collection and delivery, so EoL e-drive motors enter the recycling plant as a free of charge feedstock material, resulting in a positive EBITDA for the entire end-of-life treatment chain.

In this scenario, REEs are sold as a rare-earth concentrate to rare earths refineries, with low payability for the raw material. Figure 25 shows a percentual estimation of the operational expenditures (OPEX) breakdown. Figure 26 presents the estimated revenue breakdown of the IWM recycling operations, with 74% derived from copper sales (profit driver) and only 3% from rare earth sales (cost driver). Figure 25

EM-TECH

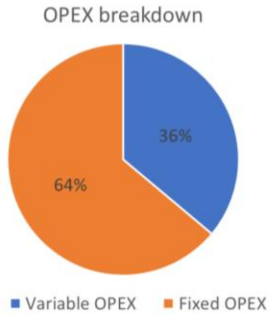


Figure 25 OPEX breakdown IWM recycling

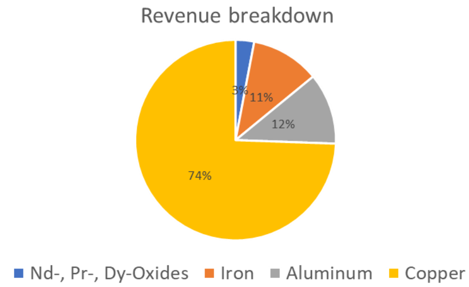


Figure 26 Revenue breakdown IWM recycling

The AFM EoL costs were calculated using the dismantling costs provided by TRX and the facility operating costs provided by URBANGOLD. In the modelling, a favourable regulatory scenario is assumed in which Extended Producer Responsibility (EPR) is applied at the level of the electric drive motor. Under this assumption, manufacturers are directly involved in the EoL treatment as an authorized dismantling facility, and bear the costs of collection and delivery, so EoL e-drive motors enter the recycling plant as a free of charge feedstock material, resulting in a very high EBITDA for the dismantling operator.

In this scenario, REEs are sold as an EoL PM to magnet recycling plants, with a high payability for the raw material. Figure 27 presents the estimated revenue breakdown of the IWM recycling operations, with 54% derived from copper sales and 30% from REE sales as an EoL PM. Figure 28 shows a percentual estimation of the OPEX breakdown.

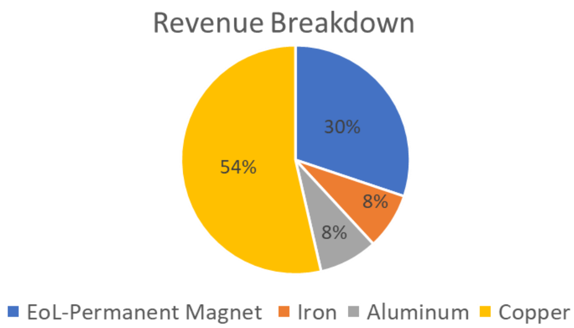


Figure 27 Revenue breakdown AFM recycling

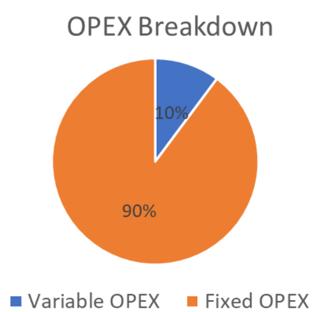


Figure 28 OPEX breakdown AFM recycling

3.3.6 Comparison with the baseline IWM

Figure 29 shows the comparison of the carbon footprint (left) and LCC (right) related to the entire life cycles of the baseline and proto motors. This project has no objective in terms of carbon footprint reduction, but we wanted to be sure to not increase the carbon footprint in the effort of increasing the performance and reducing costs.

In both charts, the first bar is the baseline motor with SotA EoL disposals.

The second bar is the proto IWM with the recycling procedure developed by URBANGOLD, that demonstrated the recoverability of Neodymium, Praseodymium, Dysprosium with a recover efficiency of 99% as well as iron, aluminium, and copper with a recover efficiency of 95%.

Moreover, an additional scenario (the third bar) has been included in the comparison to evaluate the effect of circularity, by assuming 60% reuse of PMs. Target for IWM is >60% reduction of the use of REEs in the EM-TECH motors with respect to the current SotA designs, and adoption of recycled PMs as a viable circularity solution based on a recycling circuit proposal.

The proto has no significant increase in the carbon footprint with respect to the baseline. **Against the SotA**, EM-TECH advancements comprised of dismantling of motor and PMs and their recycling, allowed to obtain **23% carbon footprint reduction as well as 11% LCC reduction**. Assuming **circular recycling** with a 60% reuse of PM allowed to obtain **24% carbon footprint reduction and 28% LCC reduction**.

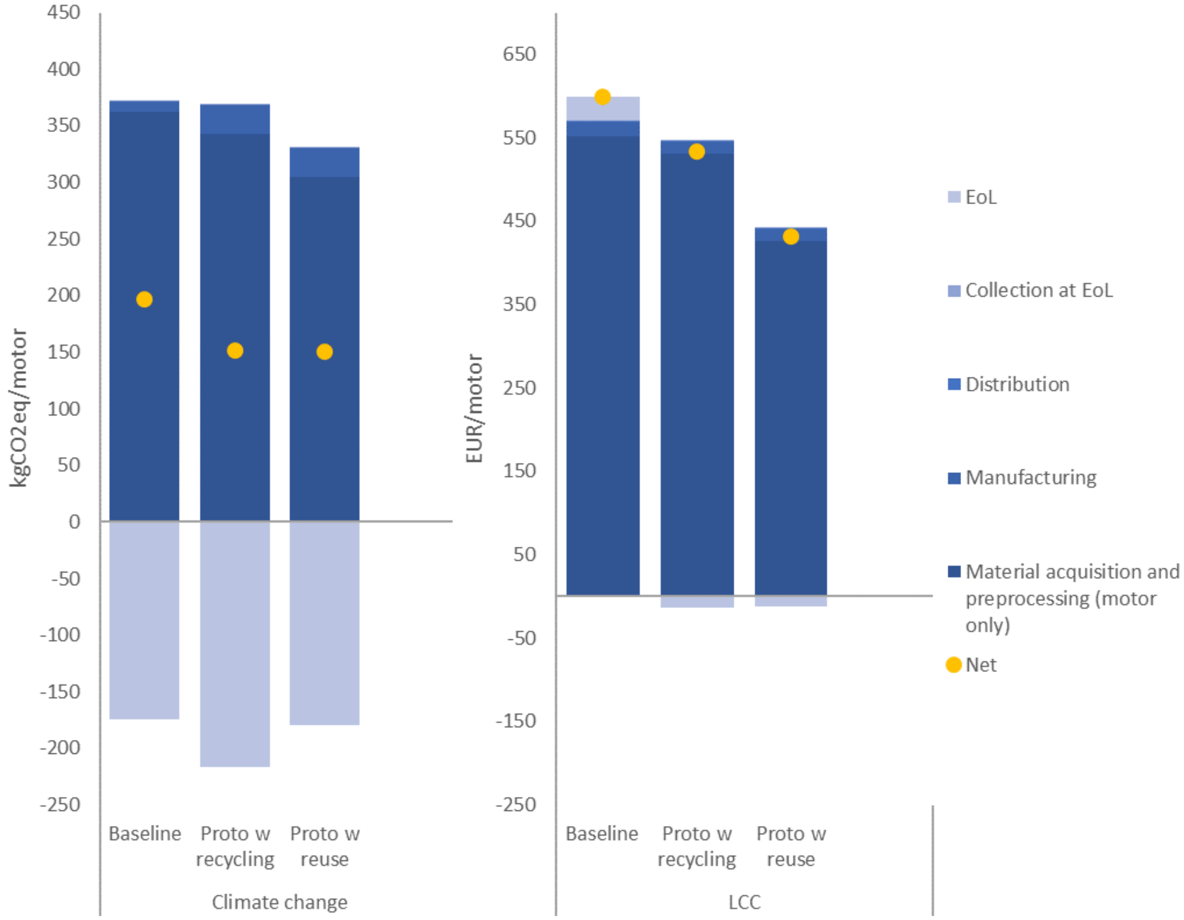


Figure 29 Comparison of carbon footprint and LCC of the baseline and proto IWM assuming recycling and reuse (revenues for sold secondary materials included).

3.4 LCA and LCC results for the AFM proto solution

3.4.1 Proto AFM LCA

Figure 30 shows the LCA emission profile of the AFM drivetrain. It compares how the different drivetrain components contribute to a wide range of environmental impact categories. Each bar adds up to 100%, showing the relative share of four contributors: AFM, inverter, mechanical gear, and the drivetrain use phase.

A clear pattern emerges across most categories: the drivetrain use phase (represented in light blue) is the dominant contributor in 13 out of 16 indicators, especially for climate change, ozone depletion, ionising radiation, eutrophication, and fossil resource use. This indicates that the environmental burden of operating the drivetrain over its lifetime outweighs that of manufacturing its components in these impact areas.

The AFM (shown in dark blue) appears as the main or second-largest contributor in the:

- human toxicity, due to rotor hub and copper in stator windings, and

- use of mineral and metal resources due to material acquisition and preprocessing, especially the copper windings in the stator.

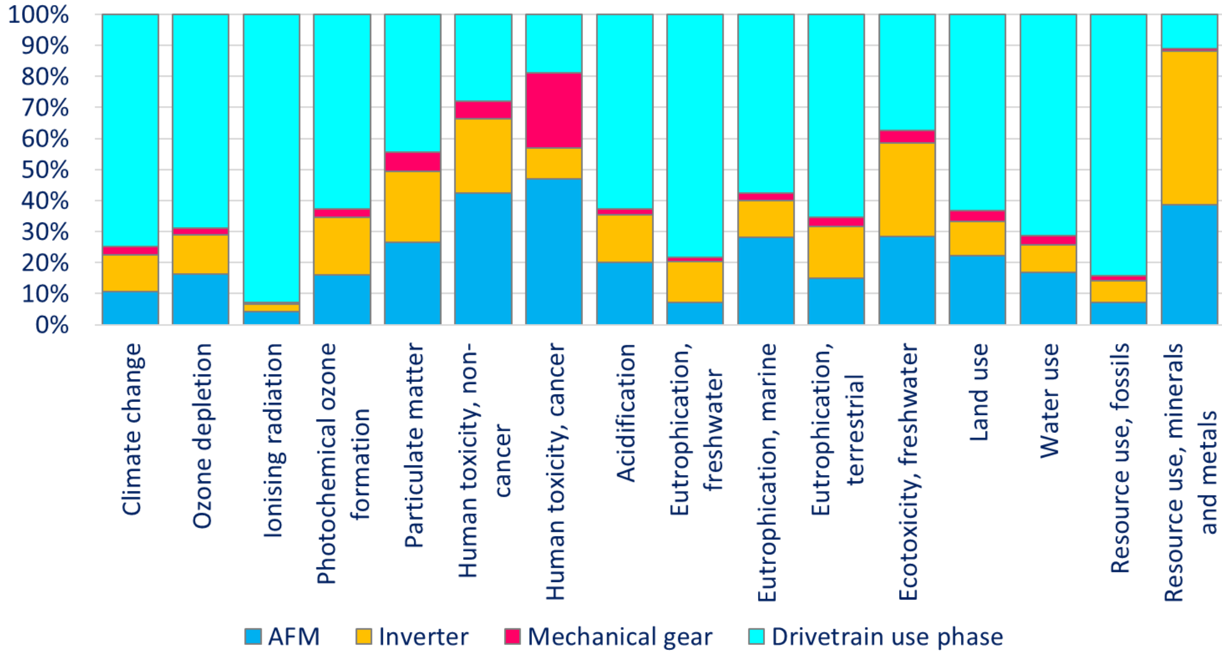


Figure 30 LCA emission profile of EM-TECH AFM solution, considering the Volkswagen ID.3 Pro Performance as the reference vehicle and IGBT inverter. The delta approach is used to estimate the drivetrain use phase emissions. EoL is included and PMs are assumed to be recovered.

Figure 31 shows the detailed carbon footprint of the AFM prototype life cycle (use phase excluded). As in the baseline, the raw material acquisition and pre-processing phase is the major driver of the carbon footprint (first bar chart from the left). Motor recycling allows for a carbon footprint reduction of 25%. In terms of motor components, the main driver of the carbon footprint is the housing (43.4%), while the rotor (35.5%) and stator (21.0%) follow behind (second chart from the left). The three pie charts show the emission breakdown of the rotor (top), stator (bottom-left) and housing (bottom-right). The carbon footprint of the **housing is mainly driven by the aluminium in the front cover, back cover, and centre-section**. The carbon footprint of the **rotor is mainly driven by NdFeB magnets and steel in hub and rotor shaft**. Instead, the carbon footprint of the **stator is mainly driven by the stator lamination cores and copper windings**.

Because the inverter was not the focus of the LCA/LCC in this project (but the electric motor was) and due to the lack of publicly available data on material composition and production processes of SiC-based power modules, we decided to use as a default the same IGBT inverter in both the baseline and the prototype drivetrains. However, we decided to exclude for a moment those life cycle phase emissions that are dependent on the chemical composition and production processes, namely production and EoL phases, and show some results in Table 6. Table 6 reports the difference between the use phase carbon footprint of the AFM solution when different inverters are considered, namely the IGBT inverter (91% efficiency) used in the baseline, and the SiC inverter (99% efficiency) developed by I&M within EM-TECH.

Table 6 Comparison of the carbon footprint results of the use phase only, assuming the same AFM and gearbox but different inverter 1) the IGBT inverter used in the baseline, 2) the SiC inverter developed by I&M within EM-TECH.

	AFM solution with IGBT inverter	AFM solution with SiC inverter
Use phase carbon footprint (kgCO2eq/drivetrain) @150,000 km lifetime	1.58E3	1.01E3
Use phase cost (EUR/drivetrain) @150,000 km lifetime	577.7	370.9

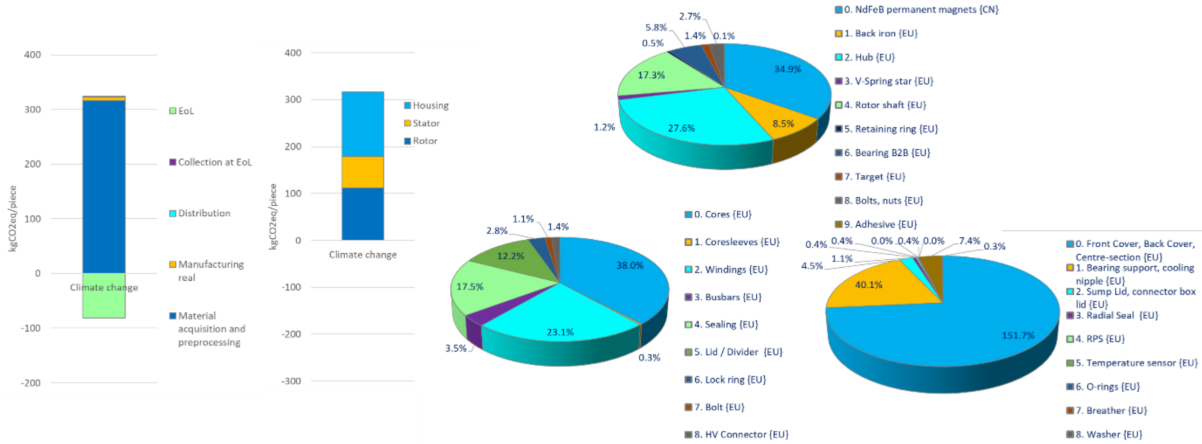


Figure 31 Detailed carbon footprint emissions of the AFM only (use phase excluded). EoL is included and PMs are assumed to be recovered.

3.4.2 Effects of recycling

Figure 32 shows the LCA results for one AFM, showing the contribution of different life cycle stages to various environmental impact categories. The vertical bars are normalized to 100%, with positive and negative values indicating environmental burdens and benefits, respectively. Each colour represents a distinct life cycle phase: material acquisition and pre-processing, manufacturing, distribution, collection at EoL, and EoL treatment (light blue).

Overall, the dark blue sections dominate most categories, showing that material acquisition and pre-processing are the main contributors to environmental impacts. This indicates that the extraction and preparation of raw materials are the most resource- and energy-intensive stages in the product's life cycle (use phase excluded). In contrast, the EoL phase almost always shows negative contributions, meaning that recycling or recovery processes provide environmental benefits that offset some of the upstream impacts. **It is important to notice that recycling allows for a reduction in climate change that is 25% in life cycle perspective.**

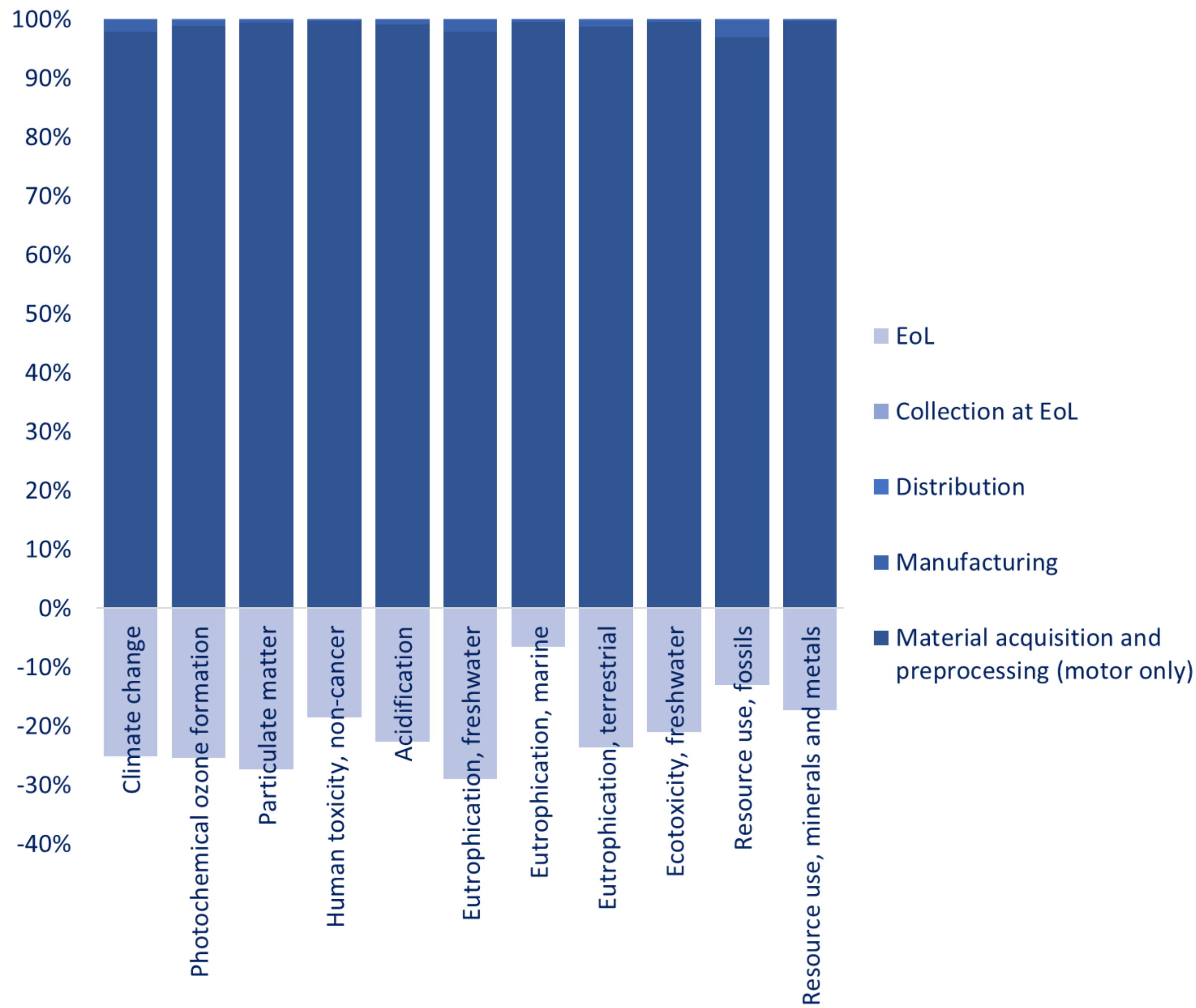


Figure 32 Results of the LCA of the AFM proto, including benefits of recycling in light blue.

Significant increases have been found in ozone depletion and ionizing radiation due to the recycling process (i.e., due to the percentage of fresh virgin material added).

3.4.3 Proto AFM LCC

Figure 33 shows the detailed cost breakdown of the AFM drivetrain life cycle without revenues while Figure 34 shows the detailed cost breakdown of the AFM drivetrain life cycle with revenues from sold secondary materials. The assumed indirect costs for the AFM are shown in Table 7.

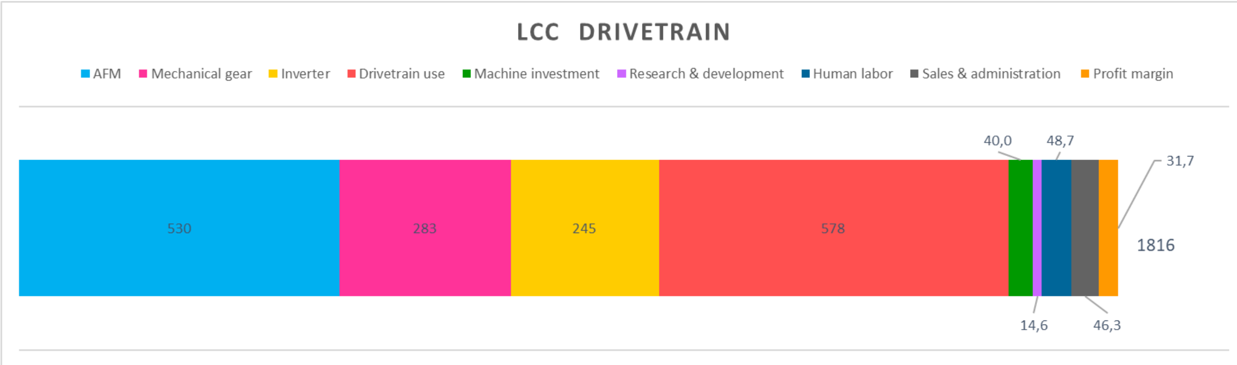


Figure 33 LCC of EM-TECH AFM solution, considering the Volkswagen ID3 Pro Performance as the reference vehicle. The delta approach is used to estimate the drivetrain-related use costs. EoL is included and PMs are assumed to be recovered without revenues. Indirect costs are included. Revenues are not included.

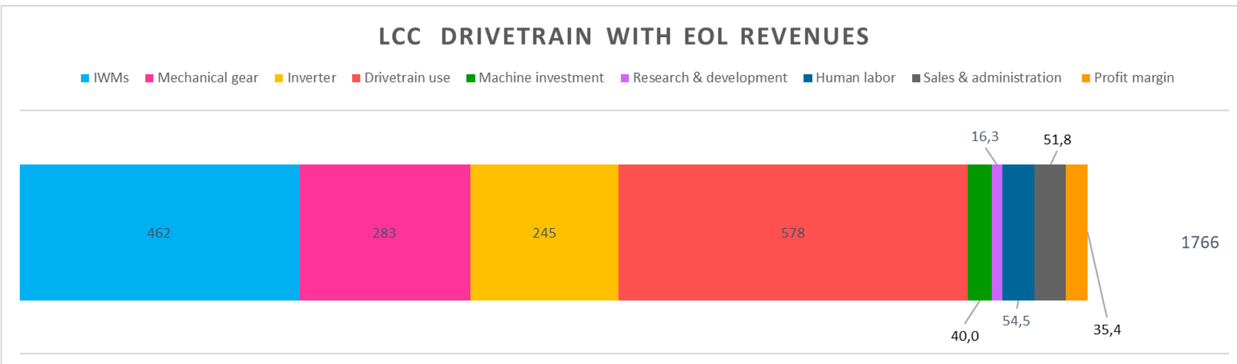


Figure 34 LCC of EM-TECH AFM solution, considering the Volkswagen ID3 Pro Performance as the reference vehicle. The delta approach is used to estimate the drivetrain-related use costs. EoL is included and PMs are assumed to be recovered with revenues. Indirect costs are included. Revenues are included.

Table 7 Indirect costs of the AFM prototype.

	Indirect costs		
Machine investment	28 million € over 7 years, with a production volume of 100000 pieces/year	40	EUR/motor
Research & development	3% of the motor cost	14.6	EUR/motor
Human labor	10% of the motor cost	48.7	EUR/motor
Sales & administration	9,5% of the motor cost	46.3	EUR/motor
Total indirect costs (motor manufacturer perspective)		**149.6**	**EUR/motor**
Profit margin	6,5% of the motor cost	31.7	EUR/motor
Total indirect costs (OEM perspective)		**181.3**	**EUR/motor**

Figure 35 shows the detailed cost breakdown of one AFM prototype (use phase excluded), where the raw material acquisition and pre-processing phase (first bar chart on the left) accounts for 476 €/motor. As in the baseline, the raw material acquisition and pre-processing phase is the major cost driver. More specifically, the rotor is the major cost driver, in compliance with the BoM cost reported by TRX in deliverable D3.3. The three pie charts on the right show the cost breakdown of the rotor (top), stator (middle), and housing (bottom). On the rotor side, the main cost drivers are the magnets, followed by the hub and the rotor shaft. Hub and rotor shaft costs are mainly driven by the cost of steel turning. On the stator side, the main cost driver are the copper windings, while on the housing side, the cost is almost equally driven by front and back cover, centre section and bolts and bushings.

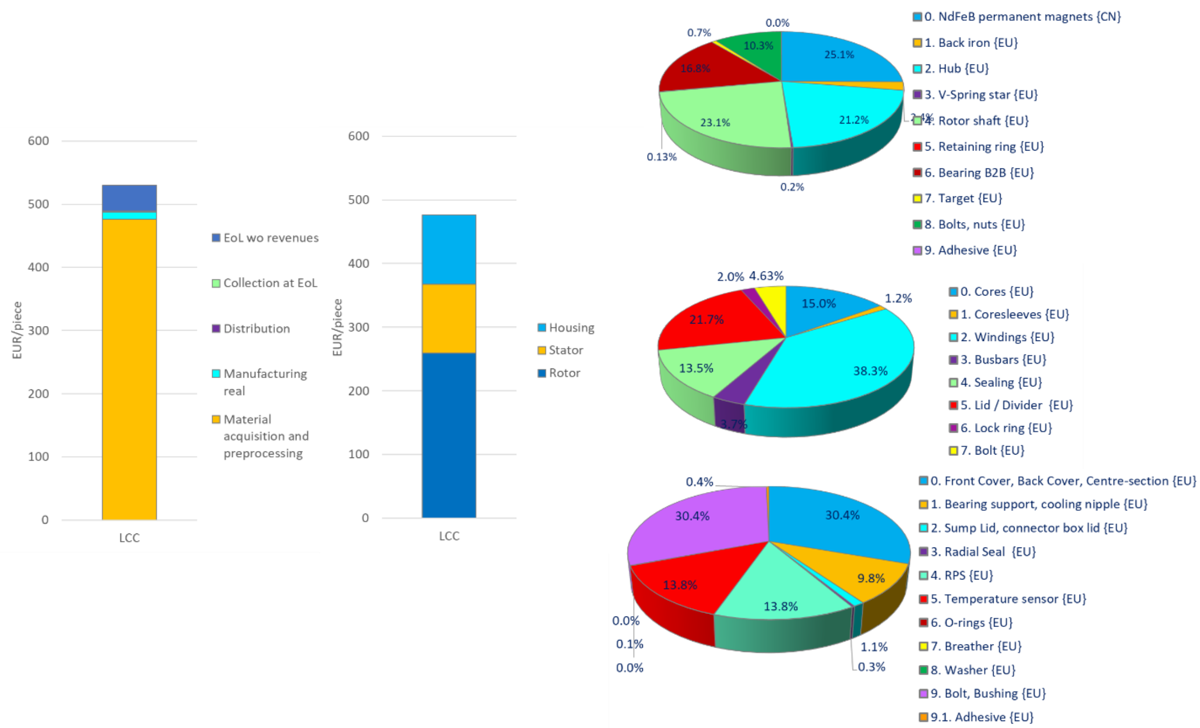


Figure 35 Detailed life cycle costs of the IWM only (use phase excluded), considering literature manufacturing data. EoL is included and PMs are assumed to be recovered. However, no revenues are considered for sold recovered materials.

3.4.4 Comparison with the baseline AFM

Figure 36 shows the comparison the carbon footprint (left) and LCC (right) related to the entire life cycles of the baseline and proto OBMs. This project has no objective in terms of carbon footprint reduction, but we wanted to be sure to not increase the carbon footprint in the effort of increasing the performance and reducing costs.

In both charts, the first bar is the baseline motor with SotA EoL disposals.

The second bar is the proto AFM with the dismantling procedure developed by URBANGOLD and recycling through hydrogen decrepitation, that demonstrated the recoverability of REEs as well as iron, aluminium and copper.

Moreover, an additional scenario (the third bar) has been included in the comparison to evaluate the effect of circularity, by assuming 60% reuse of PMs. Target for AFM is >60% reduction of the use of REEs with respect to the current SotA designs, and adoption of recycled PMs as a viable circularity solution based on a recycling circuit proposal.

The proto has no significant increase in the carbon footprint with respect to the baseline. On the contrary, due to the significantly lower motor mass of the AFM (24.1 kg) against the baseline (54.1 kg), the AFM proto has around one third the carbon footprint of the baseline. **Against the SotA**, EM-TECH advancements comprised of dismantling of motor parts and PMs and their recycling, allowed to obtain **66% carbon footprint reduction as well as 29% LCC reduction**. Assuming **circular recycling** with a 60% reuse of PM allowed to obtain **65% carbon footprint reduction and 45% LCC reduction**.

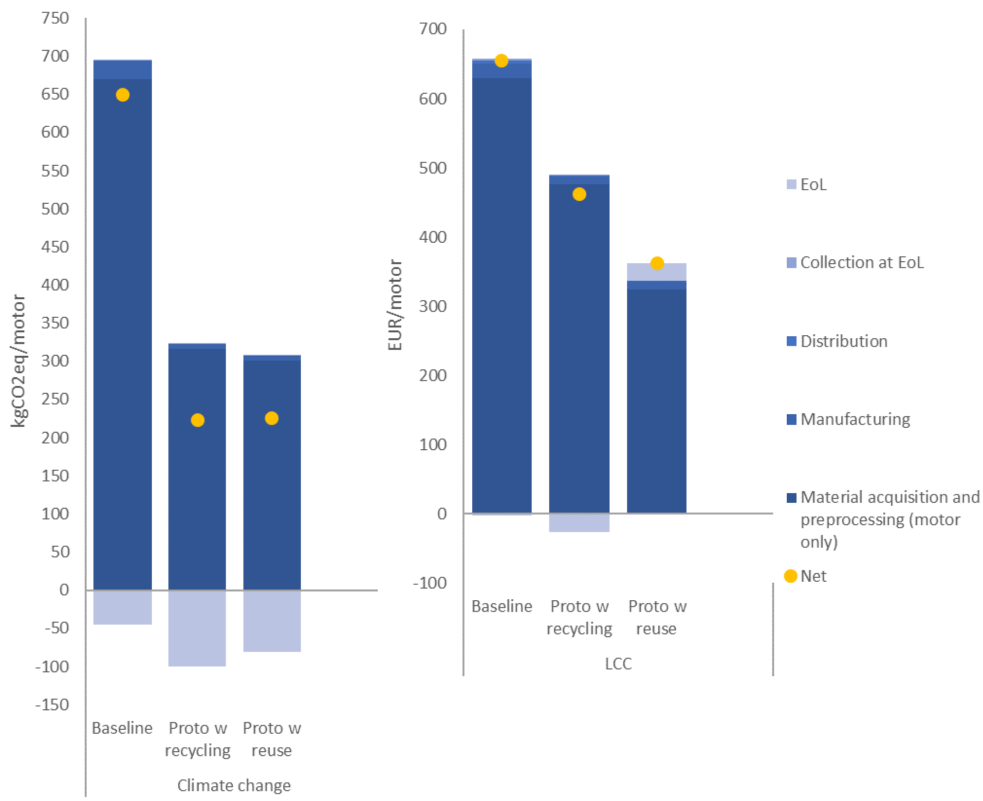


Figure 36 Comparison of carbon footprint and LCC of the baseline and proto AFM assuming recycling and reuse (revenues for sold secondary materials included).

3.5 Key Performance Indicators

Apart from the motor performance objectives, we had one very important project objective to achieve, which is the motor cost target. This objective was initially defined as EUR/kg unit, but shortly after the project started it was modified to a more appropriate EUR/kW unit. Weight of the powertrain is of course a very important characteristic of the system but looking at the cost per power value is more fitting from OEM's perspective, as this is a more common powertrain characteristic used for powertrain comparisons and overall costing of the vehicle system.

Table 8 summarizes all LCC for the IWM and Table 9 summarizes the costs for the AFM.

Table 8 IWM LCA and LCC overall results at motor level: use phase excluded. Other assembly needed components included.

	Carbon footprint (kgCO2eq/motor)	Life Cycle Cost (EUR/motor)
Baseline	**282**	**797**

Proto with **literature** manufacturing data	**227**	**741**
Material acquisition and pre-processing	435	736
IWM materials	339	539
Other assembly needed components	96	197
Manufacturing	8.27	16.7
Distribution	0.21	1.38
Collection at EoL	0.23	1.19
EoL	-122	-13.8
Proto with **real** manufacturing data	**247**	**745**
Material acquisition and pre-processing	438	742
IWM materials	342	544.3
Other assembly needed components	96	197.4
Manufacturing	25.3	14.4
Distribution	0.21	1.39
Collection at EoL	0.23	1.19
EoL	-217	-13.8
Total indirect costs (motor manufacturer perspective)		**162.6**
Total indirect costs (OEM perspective)		**198.0**

Table 9 AFM LCA and LCC overall results at motor level: use phase excluded.

	Carbon footprint (kgCO2eq/motor)	Life Cycle Cost (EUR/motor)
Baseline	**649.3**	**654**
Proto with **literature** manufacturing data	**223.1**	**462**
Material acquisition and pre-processing	316	476

Manufacturing	6.5	11.1
Distribution	0.147	0.967
Collection at EoL	0.159	0.827
EoL	-100.1	-26.8
Total indirect costs (motor manufacturer perspective)		**149.6**
Total indirect costs (OEM perspective)		**181.3**

Target for IWM is cost lower than 6€/kW. Hereafter, we reported the equations used for key performance indicator (KPI) calculations in two scenarios:

1. ***Motor manufacturer perspective***
2. ***OEM perspective***

The KPI is calculated as the sum of direct C_{dir} and indirect costs C_{ind}, divided by the motor power P (128 kW for the IWM and 202 kW for the AFM).

$$KPI = \frac{C_{dir} + C_{ind}}{P}$$

Direct costs are the costs of motor production and are calculated as the sum of material costs C_{mat}, manufacturing costs C_{manuf} and distribution costs C_{dist}. Manufacturing costs are based on real process data provided by ELA. The so-called "other assembly components" of the IWM are excluded,

$$C_{dir} = C_{mat} + C_{manuf} + C_{dist}$$

While indirect costs vary as follows:

1. ***Motor manufacturer perspective***: Indirect costs include machine investment, R&D, labour costs, and sales & administration costs.
2. ***OEM perspective***: Indirect costs machine investment, R&D, labour costs, sales & administration costs as well as manufacturer profit margin.

For the IWM, the KPI results as **5.65 €/kW** in the motor manufacturer perspective and **5.92 €/kW** in the OEM perspective. For the AFM, the KPI results as **3.16 €/kW** in the motor manufacturer perspective and **3.31 €/kW** in the OEM perspective. All these costs are value added tax (VAT) excluded.

Lastly, it is interesting to note that, if we consider the LCC costs, thus including the entire life cycle of the motor, the KPIs are even lower, thanks to the recycling revenues R_{EoL}.

$$KPI_{LCC} = \frac{C_{dir,LCC} + C_{ind}}{P}$$

$$C_{dir,LCC} = C_{mat} + C_{manuf} + C_{dist} + C_{Coll,EoL} + C_{EoL} - R_{EoL}$$

For the IWM, in the LCC perspective, KPI results as **5.55 €/kW** in the motor manufacturer perspective, and **5.82 €/kW** in the OEM perspective. For the AFM, the KPI results as **3.03 €/kW** in the motor manufacturer perspective and **3.19 €/kW** in the OEM perspective. All these costs are VAT excluded.

Assuming to reuse the recovered REE oxides **in a circular way**, the motor would significantly benefit from this project EoL procedure because:

- For the IWM → the LCC would result as **627 €/motor instead of 745€/motor** and the carbon footprint would result as **209 kgCO2eq/motor instead of 247 kgCO2eq/motor**.
- For the AFM → the LCC would result as **377 €/motor instead of 654€/motor** and the carbon footprint would result as **226 kgCO2eq/motor instead of 650 kgCO2eq/motor**.

Even higher benefits can be obtained reusing the recovered fractions of iron, aluminium and copper.

4 Conclusion

The climate change impact as well as LCC of a drivetrain strongly depends on the architecture, motor technology, vehicle type, electricity mix assumed and driving mission considered.

In the IWM case, the **use phase** drives the carbon footprint due to vehicle energy consumption and electricity production. However, **motor production and recycling** drive the environmental impact in 10 out of 16 indicators and in terms of LCC. Recycling significantly reduces impacts in the majority of indicators, demonstrating the importance of eco-design for dismantling, material separation, and circularity. Structural design choices, material combinations (e.g., copper and aluminium), and assembly methods directly influence dismantling feasibility and material separation. **IWM recycling allows for a carbon footprint reduction of 59%**, and even higher if recycled PMs as well as the recovered fractions of iron, aluminium, and copper are reused.

In the AFM case, the **use phase drives the environmental impacts in 13 out of 16 indicators**. **Recycling significantly reduces impacts in almost all indicators** (only two exceptions). AFM recycling allows for a carbon footprint reduction of 25%.

Against the SotA, EM-TECH advancements comprised of dismantling of motor parts and PMs and their recycling, would allow to obtain **23% carbon footprint reduction as well as 11% LCC reduction in the IWM**. **Also**, EM-TECH advancements would allow to obtain **66% carbon footprint reduction as well as 29% LCC reduction in the AFM**.

Based on the emission hotspots found, effective **eco-design strategies** would be:

1. Reduction in the use of NdFeB magnets
2. Reduction/substitution in the use of aluminium in the housing.
3. Search for sustainable alternative electrical steel
4. General reduction of the motor mass
5. Use of recycled materials such as NdFeB magnets as well as iron, copper and aluminium recovered fractions
6. Innovations towards highly efficient drives and reduction of operational energy consumption

Assuming **circular recycling** with a 60% reuse of PMs, EM-TECH advancements would allow to obtain **24% carbon footprint reduction and 28% LCC reduction in the IWM. Also, EM-TECH advancements would allow to obtain 65% carbon footprint reduction and 45% LCC reduction in the AFM.**

IWM cost is below €6/kW, even in LCC perspective. **AFM cost is well below 5 €/kW.**

This work encourages novel design strategies for future electric motors and drivetrains aimed at implementing **design for dismantling** concepts to improve recycling.

4.1 Deviations, Impact and Recovery Actions

A minor delay occurred due to the finalization of the quality review.

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