Rare Earth Free e-Drives Featuring Low Cost Manufacturing

ReFreeDrive

Collaborative Project

Grant Agreement Number 770143

Start date of the project: 1st October 2017, Duration: 36 months

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 770143

Deliverable no.: D 8.2

Title of the deliverable: LCA Technologies Analyses

Contractual Date of Delivery: **30 September 2020**

Actual Date of Delivery: **30 March 2021**

Lead contractor for this deliverable: **CIDAUT**

Author(s): **Manuel González (CIDAUT)**

Participants(s): **Tomas Jezdinsky (ECI), Fernando Nuño (ECI), Ladji Tikana (ECI), Jorge Velasco (CIDAUT), Alicia Rodriguez (CIDAUT)**

Work package contributing to the deliverable: **WP3, WP4, WP5 and WP6**

Nature: **Public**

Version: **02**

REVISION TABLE		
Document version	**Date**	***Modified sections - Details***
V0	20 05 2020	Preliminary Draft Version
V1	11-03-2021	Circulation of first draft within REFREEDRIVE consortium
V2	29-03-2021	Introduction of minor changes after first review

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Abbreviations

Al	Aluminium
ASR	Auto shredder residues
CRM	Critical Raw Materials
EDU	Electric Drive Unit
EE	Electric and Electronic
ELV	End-of-Life Vehicles
EoL	End of Life
EPA	Environmental Protection Agency
EV	Electric Vehicles
EWG	Ethylene-Water-Glycol
FU	Functional Unit
G&S	Goal and Scope
HEV	Hybrid Electric Vehicles
HWFET	Highway Fuel Economy Test cycle
ILCD	International Life Cycle Data system
IM	Induction motors
JLR	Jaguar Land Rover
LC	Life Cycle
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LSC	Laminar Squeeze Casting method
NdFeB PM	Permanent Magnets of Neodymium-Iron-Boron
NVH	Noise, Vibration, and Harshness
PCBs	Printed Circuit Boards
PE	Power Electronic
PED	Primary Energy Demand
PET	Polyethylene terephthalate
PM	Particulate matter

PMa	Motor assisted by Permanent Magnets
REE	Rare Earth Element
RFD	ReFreeDrive
SiC	Silicon Carbide
SynRel	Synchronous Reluctance motors
UDDS	Urban Dynamometer Drive Schedule
WBG	Wide Band Gap
WEEE	Waste Electrical and Electronic Equipment
WP/WPs	Work Package(s)

Executive Summary

This report aims to show the findings extracted for a Life Cycle Assessment (LCA) performed on the motors developed within the REFREEDRIVE project. This study has been carried out by CIDAUT, in Task 8.2 within REFREEDRIVE Work Package 8 (WP8).

To performance this LCA task within the REFREDRIVE project, as part of the final evaluation of the developed motors (environmental impact), it has been necessary to handle information previously generated in activities mainly related with WP3 (Induction Machine Design), WP4 (Synchronous Reluctance Machine Design) WP5 (e-Drive Design) and WP6 (Prototypes manufacturing).

The fulfillment degree of the objectives in D8.2 is complete, without any deviations on time or content with respect to what was stated in the Grant Agreement..

LCA is the methodology used for evaluating the environmental loads of manufactruring processes for the electrical motors developed within REFREEDRVE, according to ISO 14040:2006 and ISO14044:2006 standards, from a ”Cradle-to-Gate” approach.

With this LCA, an estimation of the potential environmental impacts related to the manufacturing process for each REFREEDRIVE electric motors (75 kW and 200 kW) has been performed, taking into account the different technologies employed during the project (Induction machines and also Permanent Magnet assisted (PMa) and Pure Synchronous Reluctance (SynRel) machines).

That LCA has provided an accurate comparison of environmental impacts among the different developments within the REFREEDRIVE project, but also in comparison with a representative motor type for electric vehicles (NdFeB permanent magnet - NdFeB PM - SynRel machine), currently employed in automotive industry.

In general, and as a result of the findings obtained from the Life Cycle Assessment, it can be confirmed that the motors developed in the REFREEDRIVE (RFD) project present a lower environmental impact than the motors used as reference in the study (NdFeB PM SynRel). This is mainly due to an optimized design, which results in a proper use of materials (less material needed, less environmental impact), but above all, to the elimination of the use of NdFeB permanent magnets.

The use of NdFeB PM significantly marks the environmental impact of the manufacturing process for the reference motors, despite its small contribution to the overall motor weight (just 3%). Therefore, the lack of this material (NdFeB magnets) in the manufacture of RFD motors makes its environmental impact significantly lower than impact of reference motors.

The present report provides the Life Cycle Inventory (LCI), involving data collection and modelling of the manufactruring processes for the different RFD motor technologies and power, but also, the manufacturing processes of the benchmarking motors. For each identified manufacturing process, data for incoming/outgoing flows are presented in tables along the report.

Finally, Life Cycle Impact Assessment (LCIA) results from the different electric motors within the performed LCA are introduced, for each environmental impact category related with the selected method (ILCD - International Life Cycle Data system) for the environmental impact evaluation.

1 Life Cycle Assessment Overview

1.1 Introduction

Life Cycle Assessment (LCA) is a structured, comprehensive and internationally standardised method to quantify all relevant emissions and resources consumed and the related environmental and health impacts and resource depletion issues that are associated with any goods or services (“products”) [1].

Life Cycle Assessment (LCA) is a methodology for evaluating the environmental loads of processes and products (in terms of materials and energy) during their whole Life Cycle (LC) stages: processing of raw materials, manufacturing processes, use, maintenance, recycling and final disposal (End of Life, EoL), according to ISO 14040:2006 and ISO14044:2006 standards [3].

LCA methodology includes four stages (Figure 1):

- **Goals and Scope definition (G&S)**, in which the **Functional Unit (FU)** and **system boundaries** are defined.
- **Life Cycle Inventory (LCI)**. The **data collection** is the core of this analysis because it should consider all elements included in system boundaries and flows in terms of both materials and energy inputs/outputs.
- **Life Cycle Impact Assessment (LCIA)** which consists in classifying and characterizing data collected in the LCI; the final result of this stage is the **quantitative evaluation** and **assessment** of the environmental and economic outcomes.
- **Life Cycle Interpretation**. In this phase a readily understandable, complete and consistent presentation of LCA **results** is provided, taking into account a sensitivity analysis.

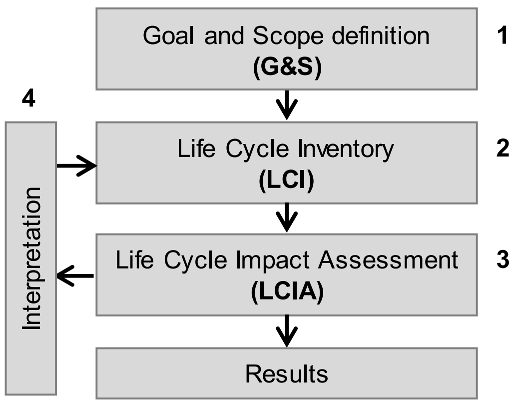


Figure 1: The four stages of LCA

To carry out an LCA study is almost always an **iterative process** (Figure 2). Once the **goal** of the work is defined, the initial **scope** settings are derived that define the requirements on the subsequent work. However, as during the **life cycle inventory phase** of data collection and during the subsequent **impact assessment** and **interpretation** more information becomes available, the initial scope settings will typically need to be refined and sometimes also revised.

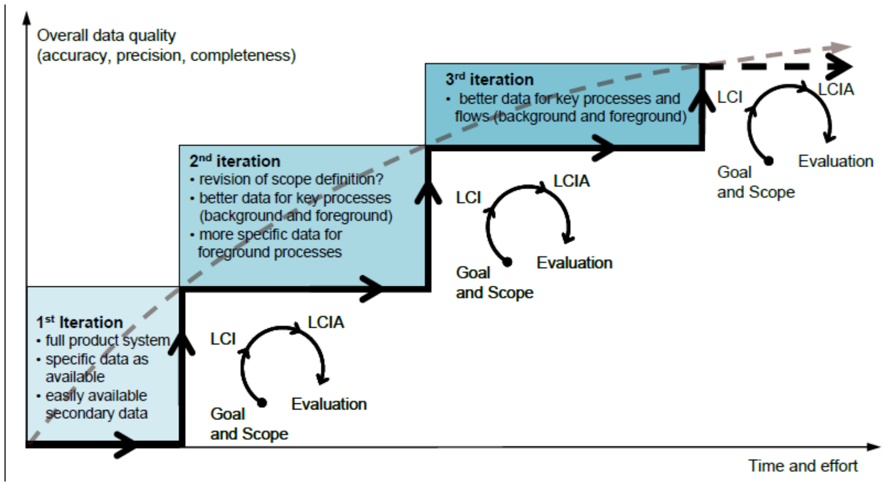


Figure 2: LCAs performed as iterative loops

LCAs are performed in iterative loops (Figure 3) of goal and scope definition, inventory data collection and modelling (LCI), impact assessment (LCIA), and with completeness, sensitivity and consistency checks (Evaluation) as a steering instrument. This is done - with a possible, limited revision of the goal and scope - until the required accuracy of the system's model and processes and the required completeness and precision of the inventory results has been attained.

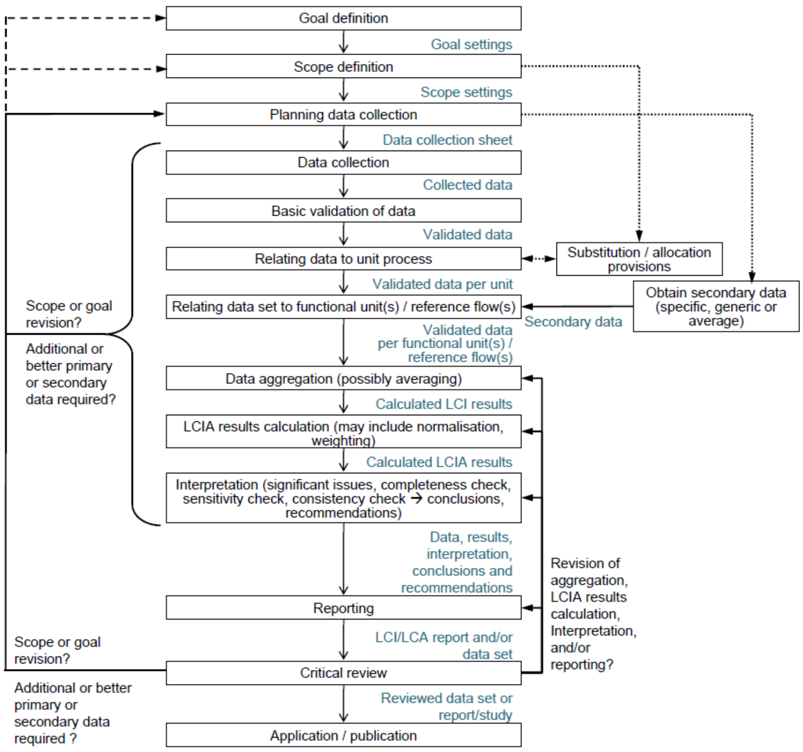


Figure 3: Details of the iterative approach to LCA, with focus on inventory data collection and modelling (from ISO 14044:2006, modified).

In order to achieve the required precision with the minimum necessary effort, it is recommended to collect data and select external data sources in an iterative manner.

1.2 Goal and Scope

This section within the RFD LCA report covers the first stage within the Life Cycle Assessment methodology, in which the aim of the study, and in relation to that, the breadth and depth of the study are established.

In the goal and scope definition phase of an ISO-standardized LCA, the purpose of the assessment is established and decisions are made about the details of the product system being studied. It is a very important phase of LCA methodology because this is where the exact approach to be followed is determined

Items to be defined in the goal and scope definition phase include the functional unit, system boundaries, data characteristics reflecting process-specificity or generality (i.e. foreground or background) data, exclusion of life cycle stages or inputs, and the selection of impact indicators and characterization factors, as follows.

1.2.1 Goal of the study

With this Life Cycle Assessment, the **objectives** to achieve are the following ones:

- Estimate the **potential environmental impacts** related to the manufacturing process for each **REFREEDRIVE electric motors** (75 kW and 200 kW), taking into account the different technologies employed during the project (Induction machines and also permanent magnet assisted (PMa) and Pure SynRel machines)
- Provide an accurate **comparison** of environmental impacts among the different developments within the project, but also in comparison with a **representative** type of motor for electric vehicles, **currently employed** in automotive (NdFeB permanent magnet SynRel machine)

The **target audience** of this report are **members** of the REFREEDRIVE **consortium**. Additionally, as public report, Intended audience for this study are also **stakeholders** in the **automotive** and **electric motor industries**.

The **generated data** and **LCA models** could be used as baseline to carry out further environmental studies for the electric motors developed during the REFREEDRIVE project, in future work.

1.2.2 Scope of the Study

During the scope definition phase, the object of the LCA study is identified and defined in detail, and this is done in line with the goal definition (see previous section). Therefore, the REFREEDRIVE LCA scope of the study defines the systems boundary in terms of technological, geographical, and temporal coverage of the study, the attributes of the product system, and the level of detail and complexity addressed by the study, which are essential for a correct interpretation of the results.

Following sections (products description, life cycle stages considered within the LCA, functional unit, system boundaries, geographic, time and technology coverage, impact categories & LCIA methods, software and database to use, etc.) describe the general scope of the project to achieve the stated goal.

1.2.2.1 Products description

As introduced in the goal definition, this LCA is focused in the assessment of the environmental impact for manufacturing process of electric motors. An **electric motor** (traction machine) is one of the key elements in all electric vehicles, together with batteries and power electronic unit, as it converts electrical energy into mechanical energy. There is a considerable variability in electric motor design for electric vehicles, but all of them have a series of common characteristics. The moving part of the machine attached to a shaft is therefore called rotor in any type of electrical machine. Another stationary part is called stator, and the two parts are separated by a small air gap. Mechanically the stator and rotor are joined via bearings mounted on the shaft.

In an electric vehicle, the **power electronic** has the task to adapt the electrical energy from the battery to the requirements of the electric machine. It is a key component of all Electric Vehicles (EVs) and Hybrid Electric Vehicles (HEVs) and has a high impact on the overall energy efficiency of the drive train. Within the REFREEDRIVE project, power electronics were developed in accordance with the developments of electric motors.

From an environmental point of view, the REFREEDRIVE project has more interest in a detailed study of the implications of the design decisions made in the electric motors, than those made on power electronics, which is practically common for all versions of motor in RFD, in line with current technical trends.

For this reason, special emphasis is placed in this section on describing the main design differences in the electric motors developed in the RFD project, compared to the machines used in the automotive sector as the most representative at the current time (NdFeB PM SynRel machines, used as reference). The next section of the document begins by describing the machines that are the object of the RFD project, to finish with the description of the machines taken as baseline in the comparative study.

REFREEDRIVE electric machines

The REFREEDRIVE project is focused on contributing to avoid the use of rare earth magnets through the development of a next generation of electric drivetrains, ensuring the industrial feasibility for mass production while focusing on the low cost and environmental footprint of the manufacturing technologies. Through their configurations, these machines not only are rare-earth magnet free, but also share common features that were exploited during the design step, as well as in the manufacturing process.

The design of the REFREEDRIVE motors took as a premise the reduction of use of materials, mainly by off-setting permanent magnet use as well as minimization of manufacturing costs. One of the key avenues for further cost reduction is the reduction of size through different techniques (outer rotor, higher rotational speed, compact hairpin winding, etc.).

This project has studied and developed simultaneously two solutions (see Figure 4) for the power traction system of electrical vehicles:

- **Induction Motors (IM)** with **fabricated** and copper **die-cast rotor**, and
- **Synchronous Reluctance Motors (SynRel)** in two configurations: **Pure** and **assisted** by rare earth free permanent magnets (ferrite magnets).

Two meaningful **power ranges** for electric vehicles (**75kW** and **200kW**) have been designed and prototyped. IM motors have the same physical structure for 75 kW and 200 kW versions. The variation for the power is due to changes into the power electronic set up. However, 75 kW and 200 kW SynRel machines have different sizes. Therefore, eight electric drivetrains (with six different types of electric motors) have been investigated in total within the REFREEDRIVE project. Consequently, the LCA study has to cover also all that machines configurations.

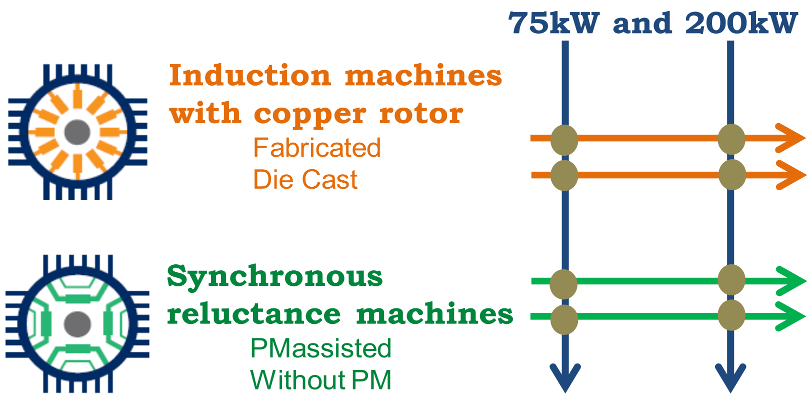


Figure 4: REFREEDRIVE machines to study under a LCA approach

Synchronous reluctance (SynRel) motors

Two different SynRel motor configuration have been developed within the REFREEDRIVE project

REFREEDRIVE Pure synchronous reluctance motors (Figure 5) do not require magnets of any kind in order to operate, and are able to give high power densities at low cost. To withstand very high rotational speeds and to decrease the ripple at low speeds, a new design strategy has been developed to take into account the mechanical stress related to the centrifugal forces in the optimization steps.

Figure 5: Wound stator and rotor core for a 75 kW Pure SynRel motor (Deliverable 6.3)

On the other hand, these SynRel motors can be assisted by rare earth free PM, as low cost **ferrites**, in order to increase the torque and keep the ripple low. In the REFREEDRIVE permanent magnet assisted motor (Figure 6), the main issue is the demagnetization of ferrite magnets. The final design within REFREEDRIVE project is based on a 10 pole rotor with distributed round wire winding. The best performance was obtained using a rotor without radial ribs.

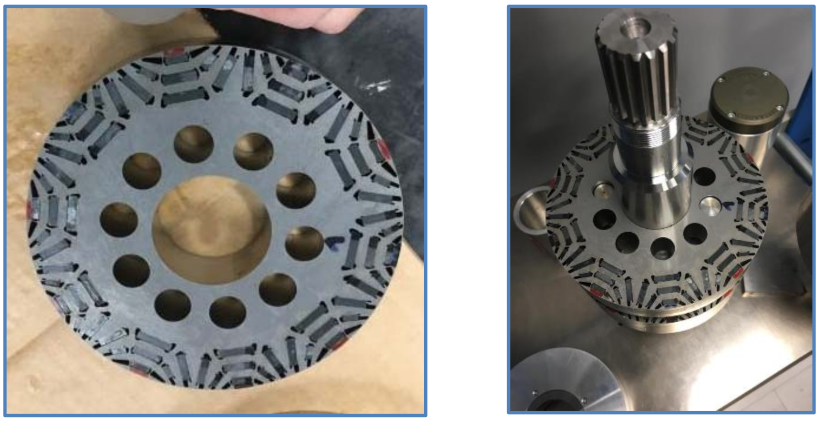


Figure 6: Permanent Magnet and Shaft insertion for a 75 kW Assisted SynRel motor (Deliverable 6.4)

The **cooling jacket** for both SynRel motor configurations (PM assisted and Pure) has been designed by MAVEL and manufactured by sub-contractor HK KG Model Co LTD (China). The liquid system cooling is all in series: inverter and stator jacket. The cooling fluid is a mixture Ethylene-Water-Glycol (EWG).

The cooling housing is the same for medium power 75 kW and high power 200 kW SynRel motors. This fact penalizes 75 kW motors in weight and environmental impact, since they use a device sized for a 200 kW motor. Nevertheless, from the point of view of its design, this strategy has significantly simplified the cooling casing design throughout the REFREEDRIVE project, which allowed focusing the design efforts on the active motor parts.

The length of housing is 325 mm. Figure 7 shows a detail of the stator jacket and shields that have been assembled with the drive housing.

Figure 7: Cooling Jacket manufactured in Aluminium, for SynRel machines

Induction Machines

For the Induction Motors (IM), the developed motors achieve more power per unit of volume compared with commercially available motors. Inner rotor topology is used in combination with high rotational speed, and the torque density and the specific power are increased.

The proposed design for the IM uses exceptional performance of the proprietary **hairpin stator windings** (Figure 8). In contrast to conventional round-wire windings, the hairpin stator winding uses precision-formed rectangular wires. Multiple layers of interlocking "hairpins" produce a superior slot fill (up to 73 percent vs. 40 percent for typical round-wire windings).

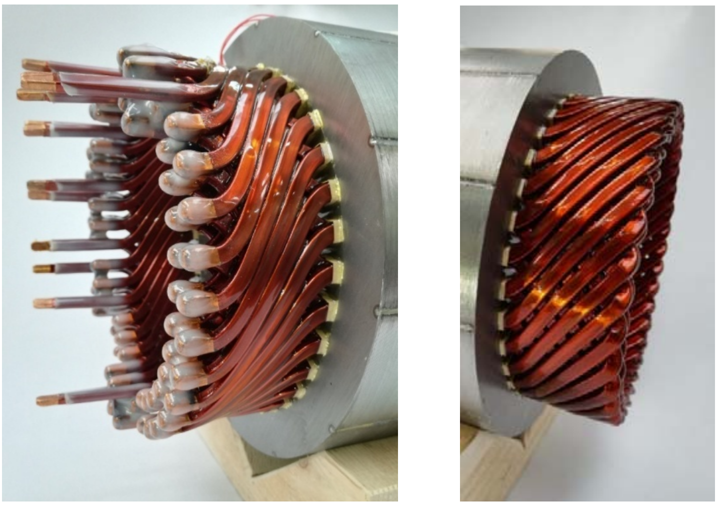


Figure 8: IM Stator winding with varnishing by roll dipping and epoxy resin applied on the stripped portions of the wire.

Two manufacturing avenues are considered for the **IM copper rotor**: die casted (Figure 9) and fabricated (Figure 10). The main technical issue regarding die cast rotors was solved by using the advanced technique of Laminar Squeeze Casting (LSC) with a vertical casting machine. LSC allows parallel filling of all slots, this way the entrapped air is pressed out by the liquid metal itself, achieving zero porosity.

Figure 9: Illustration of die-cast rotor IM

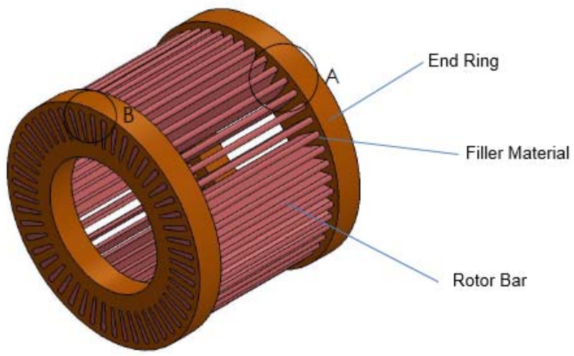


Figure 10. Illustrative for fabricated rotor cage assembly

For this motor topology, the optimum cooling system uses water ethylene-glycol mixture as heat extraction fluid.

The housing is the same for medium power 75 kW and high power 200 kW induction motors (Figure 11). Like in the SynRel case, this fact penalizes 75 kW motors in weight and environmental impact, since they use a device sized for a 200 kW motor, but it also allow simplifying its design stage.

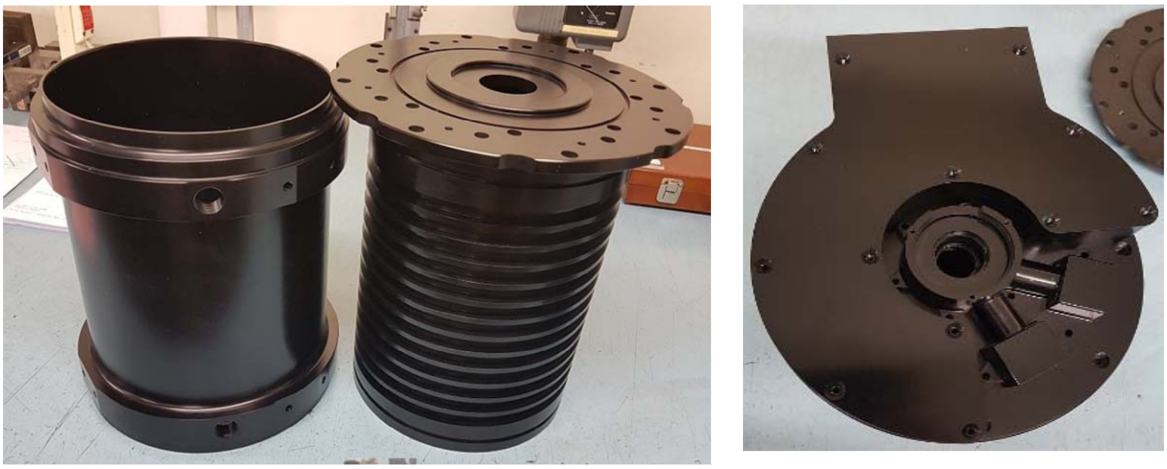


Figure 11: Cooling Jacket manufactured in Aluminium, for Induction machines

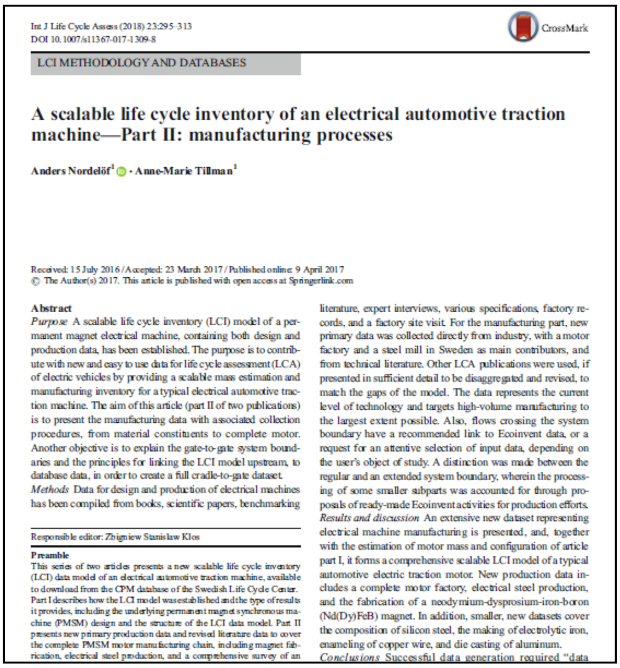
State of the Art (NdFeB PM SynRel)

As **baseline** for the **LCA comparison** of the REFREEDRIVE machines, published Life Cycle Inventory (LCI) for PM SynRel machines (which is the most common type of motor for electric vehicles) has been chosen and used, which was accomplished by the Department of Energy and Environment, Division of Environmental Systems Analysis in the Chalmers University of Technology (Sweden) (Figure 12).

In these available publications [11] [12], a scalable LCI model of a permanent magnet electrical machine (PM synchronous reluctance machine), containing both design and production data, has been established. The purpose of its authors was to contribute with an easy-to-use data for LCA of electric vehicles by providing a scalable mass estimation and manufacturing inventory for a typical electrical automotive traction machine, provided through two publications:

- Part I of this study describes how the LCI model was established and the type of results it provides, including the underlying permanent magnet synchronous machine (PM SynRel) design and the structure of the LCI data model.
- Part II presents primary production data and revised literature data to cover the complete PM SynRel motor manufacturing chain, including magnet fabrication, electrical steel production, and a comprehensive survey of an electrical motor factory. It also discusses the data collection methods and explains the selection of system boundaries and how to link the **gate to gate** inventory to the chosen database.

Regarding the comments from the authors, for the design part, one small and one large reference machine were constructed in a software tool, which linked the machines' maximum ability to deliver torque to the mass of its electromagnetically active parts. Additional data for remaining parts was then gathered separately to make the design complete. In their study, two datasets were combined into one model, which calculates the mass of all motor subparts from an input of maximum power and torque. Due to the scaling process of the motors, as the motor increases in power, the number of magnets to be implemented increases, as well as the size of the stator, rotor and housing of the cooling system. The range of the model is 20–200 kW and 48–477 Nm, which matches with the REFREEDRIVE machines ranges and therefore, is appropriate to be used, in the comparative study, as reference.


Int J Life Cycle Assess (2018) 23:295–313
DOI 10.1007/s11367-017-1309-8

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LCI METHODOLOGY AND DATABASES

A scalable life cycle inventory of an electrical automotive traction machine—Part II: manufacturing processes

Anders Nordelöf[1] · Anne-Marie Tillman[1]

Received: 15 July 2016 / Accepted: 23 March 2017 / Published online: 9 April 2017
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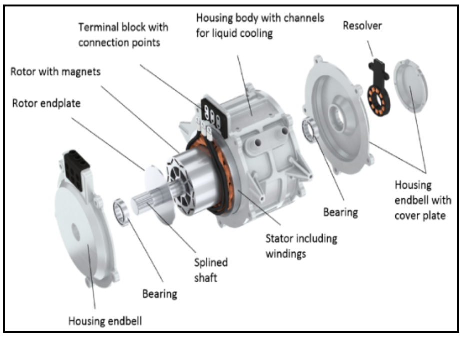
Abstract
Purpose A scalable life cycle inventory (LCI) model of a permanent magnet electrical machine, containing both design and production data, has been established. The purpose is to contribute with new and easy to use data for life cycle assessment (LCA) of electric vehicles by providing a scalable mass estimation and manufacturing inventory for a typical electrical automotive traction machine. The aim of this article (part II of two publications) is to present the manufacturing data with associated collection procedures, from material constituents to complete motor. Another objective is to explain the gate-to-gate system boundaries and the principles for linking the LCI model upstream, to database data, in order to create a full cradle-to-gate dataset.
Methods Data for design and production of electrical machines has been compiled from books, scientific papers, benchmarking literature, expert interviews, various specifications, factory records, and a factory site visit. For the manufacturing part, new primary data was collected directly from industry, with a motor factory and a steel mill in Sweden as main contributors, and from technical literature. Other LCA publications were used, if presented in sufficient detail to be disaggregated and revised, to match the gaps of the model. The data represents the current level of technology and targets high-volume manufacturing to the largest extent possible. Also, flows crossing the system boundary have a recommended link to Ecoinvent data, or a request for an attentive selection of input data, depending on the user's object of study. A distinction was made between the regular and an extended system boundary, wherein the processing of some smaller subparts was accounted for through proposals of ready-made Ecoinvent activities for production efforts.
Results and discussion An extensive new dataset representing electrical machine manufacturing is presented, and, together with the estimation of motor mass and configuration of article part I, it forms a comprehensive scalable LCI model of a typical automotive electric traction motor. New production data includes a complete motor factory, electrical steel production, and the fabrication of a neodymium-dysprosium-iron-boron (Nd(Dy)FeB) magnet. In addition, smaller, new datasets cover the composition of silicon steel, the making of electrolytic iron, enameling of copper wire, and die casting of aluminum.
Conclusions Successful data generation required "data

Responsible editor: Zbigniew Stanislaw Klos

Preamble
This series of two articles presents a new scalable life cycle inventory (LCI) data model of an electrical automotive traction machine, available to download from the CPM database of the Swedish Life Cycle Center. Part I describes how the LCI model was established and the type of results it provides, including the underlying permanent magnet synchronous machine (PMSM) design and the structure of the LCI data model. Part II presents new primary production data and revised literature data to cover the complete PMSM motor manufacturing chain, including magnet fabrication, electrical steel production, and a comprehensive survey of an



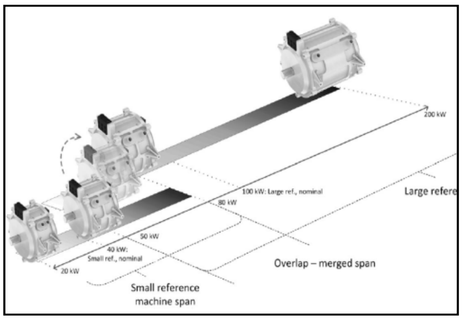


Figure 12: Details of technical paper employed as reference for the comparative LCA against REFREEDRIVE machines [11] [12]

Attending to the comments from the authors, the LCI model was successfully implemented to calculate the mass content of 20 different materials in the motor. The model results form a rough and reasonable median in comparison to the pattern created by all data points. Also, the reference motors were assessed for performance, showing that the electromagnetic efficiency reaches 96–97%.

The validity of the model was evaluated through comparison with seven permanent magnet electrical traction machines from established brands. LCI model generated representative mass estimations when compared with recently published data for electrical traction machines. Hence, for permanent magnet-type machines, the LCI model may be used as generic component estimation for LCA of electric vehicles, when specific data is lacking.

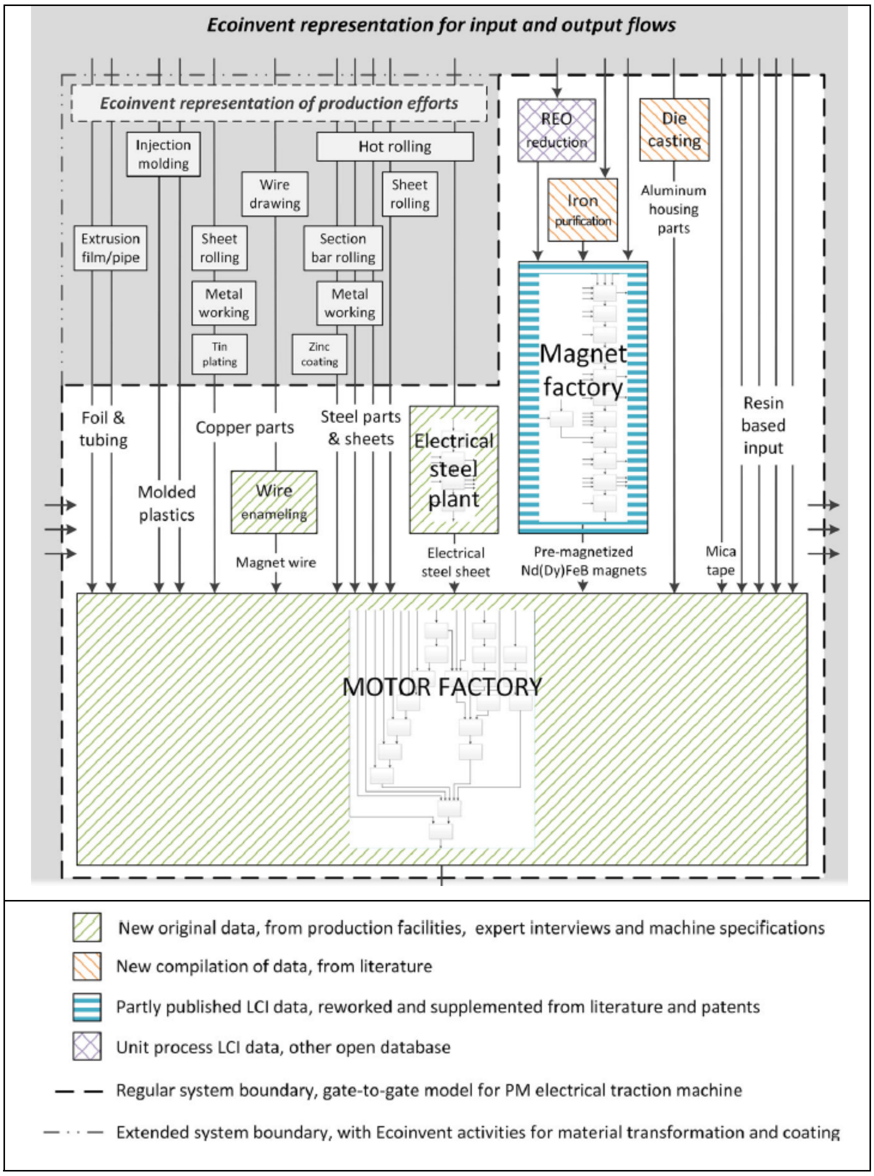


Figure 13: Overview of the technical system boundaries within the research to be employed as reference, for the collected production data, including different main information sources [11] [12]

System boundaries (Figure 13) and Motor factory process flowchart (Figure 14), described within the research of reference for the REFREEDRIVE LCA, have also been a source of inspiration to carry out the work accomplished in this report, such as it will introduced in further sections.

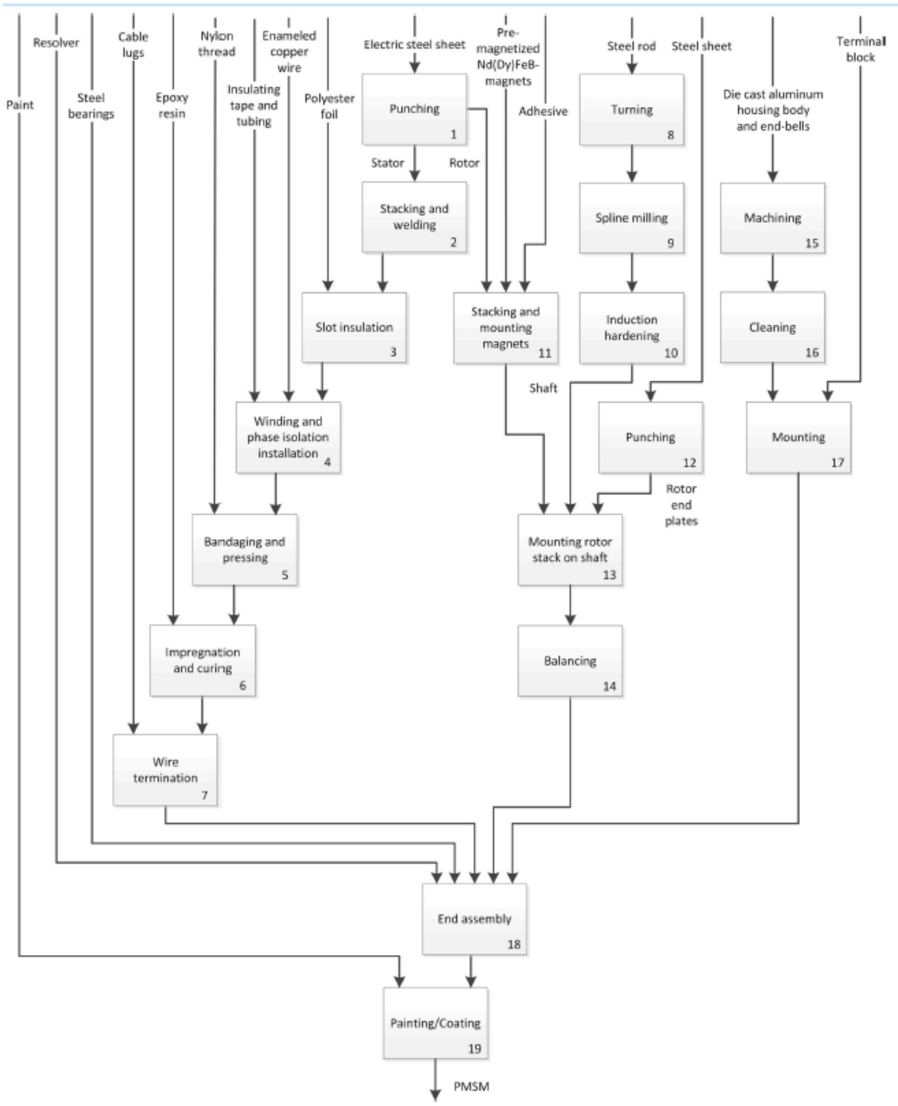


Figure 14: Motor factory process flowchart for a PMSM, divided into 19 processes [13][14]

1.2.2.2 LCA Stages

As previously introduced in the goal and scope description, the LCA performed within the project analyses the **production** stage for eight different configurations of the **REFREEDRIVE traction machines** (Induction and SynRel machines), by a **"cradle-to-gate" approach**. In order to achieve a comparison of the REFREEDRIVE developments against current electric motor technologies, other additional models have been performed (SynRel machines employing NdFeB permanent magnets, as **reference** representing current state-of-art in automotive), establishing an evaluation of its environmental impact regarding the manufacturing process of **75 kW** and **200 kW machines**.

Beyond the "cradle-to-gate" approach, although it is not the objective of the study, a brief analysis is also accomplished concerning the issues related with the **"use"** and **"end-of-life" phases** of the REFREEDRIVE machines (Figure 15), demonstrating the advantages of the REFREEDRIVE developments also in these phases of the life cycle, although they cannot be compared with a reference. If the scope of this study was a "cradle to grave" approach, it would cover the production, but also the use (utilisation) and end-of-life stage of the product. However, taking into account that the aim of the REFREEDRIVE LCA is to compare the developed machines against current traction machines in automotive, availability of feasible data for these last machines, concerning use and end-of-life phases, is quite reduced, which do not allow performing a "cradle-to-grave" LCA.

Taking into account that within the REFREEDRIVE project, **power electronic (PE) units** have been also developed together with several technologies of electric motors, a brief analysis concerning its environmental impact implications, has been also carried out, analyzing its manufacturing, use and end-of-life phases, on its life cycle, as it is described in the next sections.

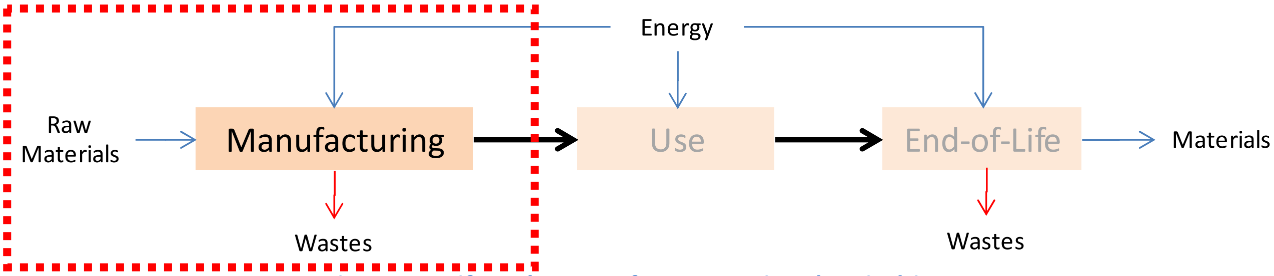


Figure 15: Life cycle stages for automotive electric drives.

Production

As previously mentioned, considering the "Cradle-to-Gate" approach taken to carry out the LCA study, the production stage is the step of the life cycle where it is focused the study to determine the environmental impact of traction systems developed in the project, and more specifically, for the motors.

Traction machine

The main active machine parts, the rotor and the stator cores, generally consist of electrical steel (stacked electrical steel laminations) in order to concentrate the magnetic flux, and thus to minimize flux leakage to the surrounding air, which would not contribute to the torque production.

A current conducting wire is placed in the stator slots to convert electrical energy into magnetic energy. A regular wire consists of a base metal, typically copper which is isolated by one or multiple layers of insulation materials. Usually, the copper conductors in the stator are wound in several turns through the core slots to form coils. The winding coils must be firmly mounted and insulated to be protected from short circuiting, to each other and to the stator core.

The task of the rotor is to produce a torque which can be transmitted to the wheels. By providing a magnetic field which interacts with the magnetic field of the stator windings, it converts magnetic power to mechanical power. In the case of a Permanent Magnets (PM) SynRel machines, the rotor field is generated by permanent magnets (as in the case of the reference machine for the comparison with the REFREEDRIVE machines).

A shaft (often made of carbon steel) is put inside the rotor. The role of the shaft is to transmit the torque produced by the motor to the external load, via the mechanical drivetrain.

In order to protect and contain the stator and rotor packages, housing is needed. For automotive powertrains, aluminium is a common material.

The electrical steel laminations, used in the stator and rotor cores of electrical machines, are typically obtained by cutting through punching or laser, from steel sheets. Punching induces shearing forces at the cut edges causing plastic deformation while laser causes thermal stresses at the edges. Laser cutting is a non-contact method of cutting and it is mainly used during the manufacturing of prototypes or small-scale production motors.

During the manufacturing of the REFREEDRIVE machines prototypes, laser cutting was employed in order to reduce its costs and its supply time (Figure 16). However, the developers of the electric motors within the REFREEDRIVE project have commented that for an industrial process, punching process has to be the method to obtain the steel stacks, for both stator and rotor. Therefore, models used in the LCA task within the RFD project incorporate a punching stage in the manufacturing process, instead of a laser cutting process.

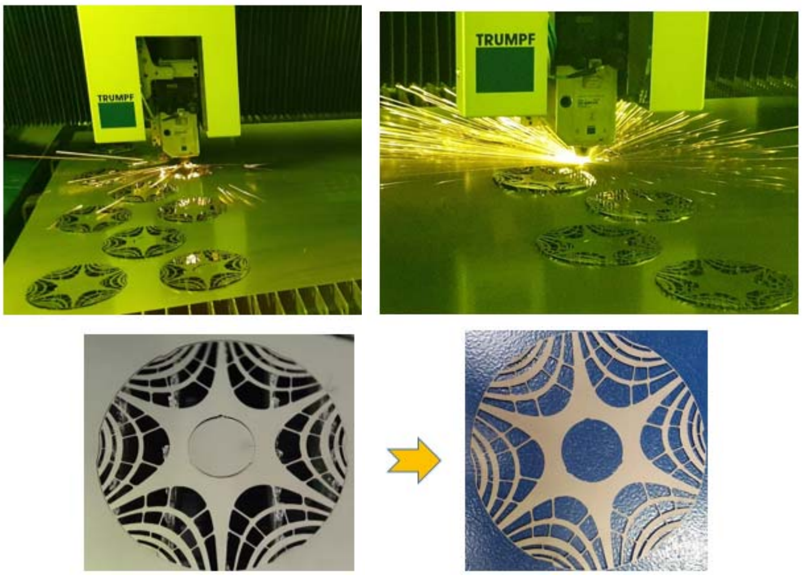


Figure 16: Laser cut for the rotor cores of Pure SynRel motor prototypes (Courtesy by LCD) [8]

The next manufacturing step after cutting the core laminations is the stacking process. There are several methods for stacking the core laminations. Main techniques for holding the stack together are welding, cleating and gluing (Figure 17).

- **Welding:** During the welding process, the lamination stack of the core is assembled through welding seams in the direction of the active length of the machine.
- **Cleating:** Cleating is a method used for holding the lamination stack together. In this technique, metal strips are placed into slots in the periphery of the stator core. These strips are called cleats. Once the laminations are pressed together, the two ends of the cleats are bent over so that they create a holding tab.
- **Gluing (Bonding):** An alternative method of holding the lamination stack pressed together is gluing. Gluing is mostly used in applications where light weighted stator cores are required and there is no extra material available for welding or cleating. An adhesive

varnish is applied to the core laminations. Afterwards, the stack is assembled through a heating process. The gluing has very low or negligible effect on the magnetic properties of the material, since the varnish has non magnetic substances. Therefore, any possible degradation due to gluing is because of the thermal treatment.

Welded stacks

Cleated stacks

Glued/Bonded stacks

Figure 17: Main techniques for holding the steel stack together, in electric motors

Along the Life Cycle Assessment within REFREEDRIVE project, both welding process and bonding process have been used, for different motors configurations. Therefore, reference SynRel motors and RFD induction motors have got welded their steel stacks (for stators and rotors). On the other hand, RFD SynRel motors use a bonding technique for the stacking process (varnish “Backlack” technique), which is briefly described in the section devoted to the SynRel motor technologies.

Together with the steel employed in the stator and rotor stacks, which is usually the main contributor to the overall weight of the motors, the cooling system casing is usually other main contributor, despite to be manufactured employing a light alloy (aluminium).

A third material hugely used in the motor manufacturing is the copper, but attending to the handled technical literature, ever in less amount that steel (stator and rotor) or aluminium (cooling casing). In the motors developed within the RFD project, cooper is used for the manufacturing of the stator winding in all the technologies (SynRel and Induction), and additionally, for the rotor in the induction machines.

The electric motors with permanent magnets embedded on the rotor, use a little amount of magnets manufactured employing different materials, depending of the performance to achieve. Currently, rare earths are usually employed in the manufacturing of these permanent magnets, obtaining as example, different formulations of NdFeB magnets, which are vastly employed in automotive traction. The NdFeB magnets only mean a low contribution to the overall weight of the motor (around 3%). However its contribution to the environmental impact is relevant in comparison with the other materials, as will be confirmed in followings sections, when reference motors are analysed from an environmental point of view.

Such as was previously commented, REFREEDRIVE project is focused on contributing to avoid the use of rare earth magnets through the development of a next generation of electric drivetrains.

Along the REFREEDRIVE project, two solutions for the power traction system of electrical vehicles were simultaneously developed: Induction Motors (IM) with fabricated and copper die-cast rotor and Synchronous Reluctance Motors (SynRel) (pure and assisted by Rare Earth Free Permanent Magnet).

The success of the project is based on the knowledge of the project consortium, integrated by designers (of electric motors and power electronics), manufacturers and/or suppliers of different parts of the electric machines, or at least, with direct control on its manufacturing process. From the Life Cycle Assessment viewpoint, this facilitates the process of gathering the necessary information to model the manufacturing phase of motors within LCA activities.

Power electronics

Most current EVs and HEVs integrate in one module, the so-called power electronics module, the inverter for the electric machine, the DC voltage converter for the on-board electric system and the control electronics. This module usually has an overall weight of approximately 12-15 kg. Dismantling investigations [4] [13] of typical power electronics in electric vehicles provided the following components and individual contributions to the overall weight:

- Casing and cooling system (mainly aluminium) (50%–60%)
- Capacitors (15%–20%)
- Power module (10%–20%)
- Laminated bus bars (2%–10%)
- Several printed circuit boards with small electronic components (1%–5%)
- Mounting material, wiring, others (5%–10%)

Therefore, the aluminium casing represents a majority of the mass for most power electronic configurations on automotive, where the heat-sink design (air or liquid cooling), is an important factor for the mass variation. Other important components from the weight distribution viewpoint are the capacitors and the laminated bus bars, such as is shown in the Figure 18.

As was commented in REFREEDRIVE D 5.2 and D5.3, nowadays, most of automotive drivetrain research and development activities are oriented to Wide Band Gap (WBG) devices based on Silicon Carbide (SiC) technology, despite of the higher cost and more complex fabrication process. Market analysis is forecasting an important market penetration of SiC in automotive application. Its features have made the silicon carbide more attractive to enhance power density and efficiency in automotive applications, considering the potential system optimization due to smaller devices, including smaller passive components and simpler cooling system. Due to the advantages linked with the use of this technology, REFREEDRIVE power electronic units were developed using this type of inverters, characterized by higher efficiency and better electrical characteristics, achieving the same electrical resistance with smaller mass compared to other technologies.

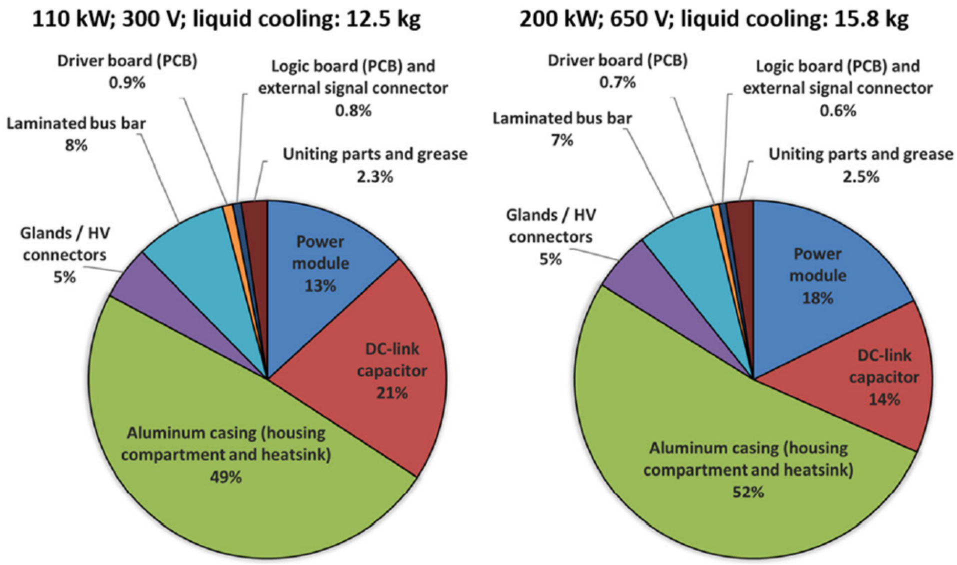


Figure 18: Examples of LCI model total mass and component composition results for different combinations of nominal power, voltage, and cooling method for automotive power electronic [13]

Along the REFREEDRIVE project, power electronic units for medium and high power range electric drive (75 kW & 200 kW) were designed and assembled, from commercial electronic components. The variety and huge amount of different electronic components (Figure 19 and Figure 20), with very dissimilar nature, provided by a wide number of providers/manufactures, make unapproachable the task of carry out a Life Cycle Assessment of the REFREEDRIVE power electronic units. The information necessary to perform a reliable LCA (for instance, a complete and exhaustive bill-of-materials, as well as a detailed description of how its manufacture and assembly has been carried out) is not accessible by REFREEDRIVE partners, which makes not possible to carry out this task, unlike the case of traction machines, which has been carried out successfully.

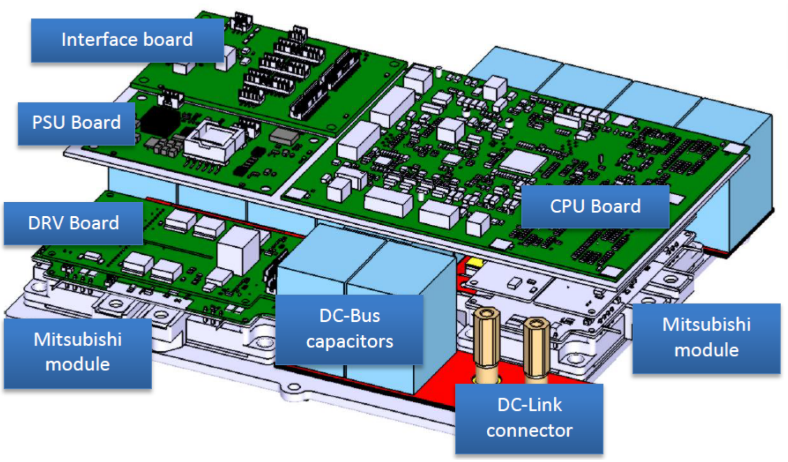


Figure 19: Preliminary sketch for mechanical integration of all electrical boards of the REFREEDRIVE 200kW inverter, taken from D5.2 [6]

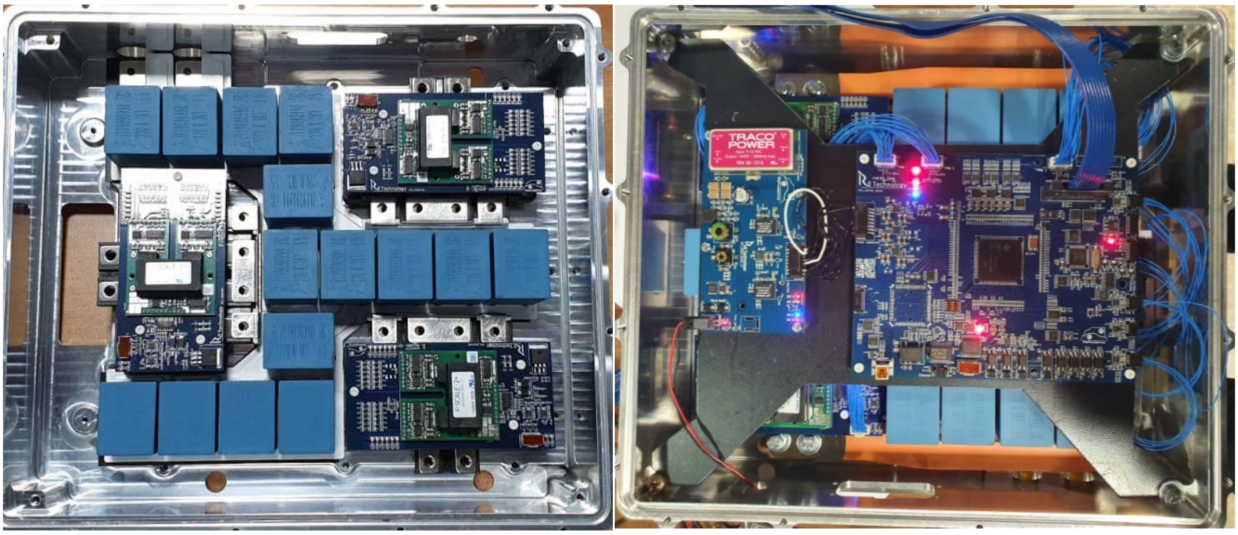


Figure 20: Different layers of 75kW REFREEDRIVE power electronic prototype, on housing, taken from D6.9

In the next Table 1, the contributions of each main parts of the REFREEDRIVE PE units, to its overall mass, are summarized. The figures shown that the most important contribution is due to the aluminium case, in both REFREDRIVE configurations, as shown in the Figure 18.

Table 1: -Estiimated weight breakdown for the two designs of the REFREEDRIVE power electronic units

Electronics components	Weight breakdown (kg / %)	
	Medium Power Range (75 kW)	High Power Range (200 kW)
Casing and cooling (aluminium)	**6,43 kg (60,33 %)**	
Capacitors	**1,10 kg (10,37 %)**	
Power module	**1,38 kg (12,92 %)**	
Laminated bus bars	**1,08 kg (10,13 %)**	
Printed circuit boards	**0,17 kg (1,57 %)**	
Mounting material, wiring, others	**0,50 kg (4,69 %)**	
Full Weight (kg)	**10,66 kg**	

A comparison concerning the weight of the power electronics developed in the RFD project, against the one shown in Figure 18, which is used as a representative case of current technologies, is done. This comparison shows a reduction in weight (at the same motor power) for the proposed design in the RFD Project.

The weight of the power electronics (PE) taken as reference, is proportional to the motor power. However, in the case of RFD power electronics, these are structurally speaking, the same, regardless of the power they have to handle (i. e., same power electronics for 75 kW and 200 kW motors).

As can be concluded from the data (Figure 18 and Table 1), for the case of the 200 kW, the mass of the power electronics defined in RFD is around 65% of the weight of PE taken as a reference (10,66 kg versus 15,8 kg).

In both cases (RFD and reference), the aluminum casing is estimated to be the heaviest component. The RFD aluminium casing is slightly lighter, weighting 6,5 kg against more than 8 kg in the case of the 200 kW PE as reference. For the reference of 75 kW PE, aluminium casing weight is slightly more than 6 kg, and therefore, quite similar to the RFD aluminium casing.

Thus, where there is really a difference, is in the weight of the rest of the electronic components, requiring only 4 kg in RFD's power electronics, in comparison to 7,5 kg for the 200 kW (reference) or 6,4 kg for the 75 kW. This is mainly due to the integration of Wide Band Gap (WBG) devices based on Silicon Carbide (SiC) technology in the REFREEDRIVE developments.

Use

Energy consumption is the most relevant environmental impact category that can be considered within a LCA during use stage of an electric drivetrain. The amount of energy consumed by an electric powertrain is highly dependent on the efficiencies of the electric drive, which is why improving efficiency is regarded as crucial for decreasing the environmental damage produced by any electric drive. Therefore, the use stage of electric drives has to be modelled considering all the power required by a vehicle during its operation, considering the influence of the powertrain efficiency on this demanded power.

Concerning the analysis of the use phase within the LCA in the REFREEDRIVE project, underline that electric drives showing a higher overall efficiency, means lower environmental impact, due to a lower energy demand. In the REFREEDRIVE project, efficiency of the developed electric drives was characterized, being available in technical reports within the project (mainly, in Deliverable D 5.4). However, this information is not available for the electric machines taken as reference during the production stage within LCA study (see previous sections). That issue does not allow making a comparison study about the use phase of the REFREEDRIVE machines against the reference one (state of the art), reason why it has not been carried out.

In order to properly evaluate the energy consumptions related to the use phase of each REFREEDRIVE electric drive configuration (evaluating its overall efficiency), simulations of several driving cycles were used. An appropriate EPA (Environmental Protection Agency) drive cycle, broken down into Urban Dynamometer Drive Schedule cycle (UDDS) and Highway Fuel Economy Test cycle (HWFET), was used to calculate the total EDU (Electric Drive Unit) energy consumption over that cycle taking into account the parameters and the architecture of a Jaguar Land Rover vehicle. Use phase, which is related to the vehicle energy consumptions, must also consider the total vehicle in its entirety as it is affected by the vehicle weight and other parameters, e.g., tire rolling resistance, aerodynamic drag coefficient, etc. However, the construction and end-of-life phases refer only to the powertrain components.

Driving cycles were implemented in a simulation tool, in order to evaluate the energy demand during the use stage, as it was shown in Deliverable 5.4. REFREEDRIVE D 5.4 was focused on the integration of the 200kW high power electric drive units designed in a Jaguar Land Rover (JLR) vehicle. The results are based on simulations that rely on datasets which have been provided by Motor Design Limited, IFP Energies Nouvelles and University of l'Aquila and complemented by specific datasets related to mechanical and gearbox losses provided by JLR. Vehicle performance calculations were generated with a JLR-internal vehicle model.

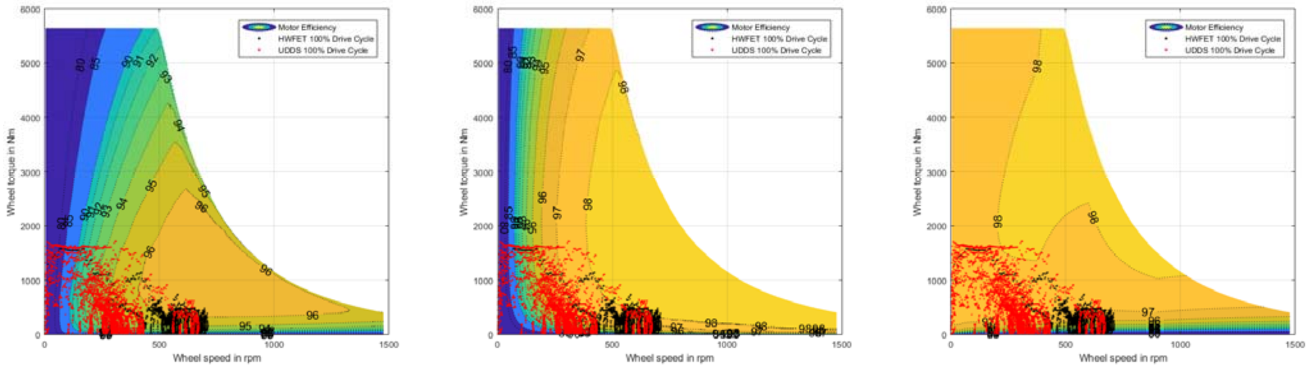


Figure 21: Example of efficiency map of each subcomponent (within the SynRel EDU): motor (left), inverter (center) and gearbox (right)

The efficiency maps of each subcomponent (motor, inverter and gearbox) for REFREEDRIVE machines were calculated according to the loss datasets (see Figure 21 taken from D 5.4 [7]). The separate loss maps were combined together into a single EDU loss map. According to the D 5.4, REFREEDRIVE EDU variants were run over the driving cycles previously described, given the results that are summarised in Table 2 (Consult cited report for extended conclusions).

Table 2: Powertrain efficiencies for different motor variants

Efficiency	Driving Cycles		
	HWFET	UDDS	EPA
PMa SynRel	88.7 %	89.0 %	88.9 %
Pure SynRel	86.5 %	85.3 %	85.8 %
IM	86.1 %	86.3 %	86.2 %

Life expectancy of an electric vehicle mainly depends on three components – motor life expectancy, battery life expectancy, and life expectancy of some other components. The life expectancy of an electric car motor depends on different types of factors. However, in general, an electric car motor can last for more than 15 to 20 years, provided it performs within the limits of specified values and at normal operating conditions.

Therefore, given that both the RFD IM as well as the 2 types of RFD SynRel are proven motor technologies, it can be expected that OEMs would grant the same warranty using the developed motors within RFD projects, than when the current technologies are used.

With exception perhaps of the bearings, in case of failure for the RFD motors, single components of either rotor (e.g. the Ferrites) or the stator (e.g. copper windings/ hairpins) will not be replaced or re-worked, , but rather the complete motor would be fully replaced, as currently happen with the conventional electric motors used in automotive.

Recycling

Typically, a recycling process consists of removing reusable components, shredding and separating remaining materials for material recovery (Figure 22). Profitability of this process depends on the quantity and type of components and materials recovered. The expected growth rate of Electric Vehicles (EVs) could become also a potential risk for the environment if current recycling processes are not updated and adapted to new needs. Experts are paying great attention to this topic, given both the critical and valuable materials embedded in EVs and their main components (especially traction batteries, but out of scope in REFREEDRIVE project), by offering interesting potential profits, and identifying the most promising End-of-Life (EoL) strategies for recycling both in technological and environmental terms. Therefore there is a need to improve the material value recovery and minimise the environmental impact in the EoL management of EV components.

According to the recommendations, EoL management solution for EVs has to be developed in the context of the waste management hierarchy, aiming to reduce waste at source in a first step (during raw material extraction and manufacturing process, as example), improve the feasibility of reuse in a second stage, and finally, conduct recovery and recycling in a more efficient way (to achieve the maximum economic benefits from products and generate the minimum amount of waste). That approach was taken into account by the REFREEDRIVE project along the design stages in order to achieve the least possible environmental impact.

Figure 22: EoL management during vehicle recycling process

Disassembly/Recycling of Electric Motors

Within the pre-treatment of conventional End-of-Life Vehicles (ELVs), already today, internal combustion engines are usually extracted. Apart from components for reuse, this is due to the applied materials and their high concentration. If these materials enter shredding, they are diluted, polluted or lost, resulting in lower earnings for the recyclers. It is stated that this should also be valid currently for electric motors from ELVs. Additionally, both the reference motors and the REFREEDRIVE ones would be recycled in the same way, since the main components in all the configurations are similar (with slight variations concerning the materials amount, but no in its nature), with the unique exception of the use of permanent magnets with rare earths, by the reference motors.

Because motors from electric vehicles contain high concentrations of valuable compounds (such as copper wiring and magnets, if any) that suffer from poor recycling efficiencies during processing of ASR (Auto shredder residues), dismantling process play a major role in the treatment of electric ELVs. Therefore, the valuable parts of the REFREEDRIVE machines should be separated by means of a preliminary disassembly process. The disassembly down to the rotor/stator level of

REFREEDRIVE motors is economically feasible and the major components (copper and steel) can be fed into conventional recycling routes as a simple and economically feasible process.

On the other hand, in the case of Rare Earth Element (REE) permanent magnets employment (reference machines for this LCA study), if magnet-containing rotors follow the steel recycling route, the REEs can be lost in the slag. Therefore, for these other machines, dismantling of the magnets is necessary for REE recycling, which makes the recycling of motors more complex.

After dismantling and, if necessary, demagnetization, the permanent magnets can theoretically be processed in a recycling plant. However, it is worth commenting here that until relatively recently, the recycling of NdFeB magnets did not exist outside China, where mainly production wastes are recycled. As China is the main producer of NdFeB magnets (market share >80%), sufficient quantities are available. Recycling of post-consumer scrap hardly takes place anywhere and is estimated to be a very low percentage. The main reasons for this were an inefficient collection, technical difficulties to extract the magnets from many applications, and a lack of economic incentives.

However, due to the REE supply situation outside China, different recycling concepts are currently under investigation around the world, especially in Europe, including the reuse of magnets, the reuse of the magnetic alloy, and raw material recovery. Nevertheless, recycling techniques for REEs have a number of environmental consequences including high energy use, consumption of large amounts of chemicals and the generation of waste chemicals and water. Therefore, the best option is not to use REE in the traction machines designed for automotive.

Disassembly/Recycling of Power Electronics

It is noted that one of the key differences in the design of EVs regarding conventional ones, is the significantly larger number of electrical and electronic components that involve the management of almost all functionalities of the vehicles. Therefore, this trend would lead to an increase in the production of electrical and electronic equipment and the generation of electrical and electronic waste (WEEE) that need to be recycled and recovered at vehicle end-of-life, such as Printed Circuit Boards (PCBs).

Despite the potential of valuable material recovery, there is currently no regulation for treating end-of-life (EoL) car electronics in Europe. Complexity and time variability of car electronics pose a challenge when defining the specific Electric and Electronic (EE) devices to include in a possible regulation. ELV Directive of the European Union is also under review, including an evaluation of the feasibility of setting material-specific recycling targets that may encourage dismantling of EE devices as a result.

Worldwide, end-of-life vehicle (ELV) treatment remains centred on shredding without much pre-shredder dismantling of electronics [15]. WEEES are simply left within ELVs which are sent for shredding and material recovery. However, this inappropriate recycling method results in a serious environmental impact arising from the discarding of hazardous materials, and poor economic performance due to the loss of the valuable materials that are in small quantities.

For some critical raw materials the rations that indicates what percentage of the mass of target materials contained in the component is feasible to be extracted and recovered, are included in Table 3 (fraction of critical material that is potentially recyclable). In this table, the difference between the two scenarios represents the net benefit related to the application of disassembly process, estimated in terms of the additional mass of materials (precious metals, copper) recycled per component:

- The first scenario (post-fragmentation separation) is the traditional recycling chain, where EV components go through de-pollution, fragmentation and material separation processes.
- The second scenario (pre-fragmentation disassembly) involves dismantling and disassembly of valuable or contaminating sub-assemblies for a separately processing procedure from the main vehicle core. These dismantled and disassembled components or sub-assemblies may follow after the same recycling chain (i.e. fragmentation and separation processes), but at a different time and possibly within different recycling facilities, which allow recovering a higher amount of material.

Table 3: Recovery of precious metals by different recovery routes [16]

	Recycling/recovery rate [%]			
Recycling routes	Cu	Ag	Au	Pd
Post-fragmentation separation	60%	11.50%	25.60%	25.60%
Pre-fragmentation disassembly	95%*	92%	97%	99%

Cu: Copper; Ag: silver; Au: gold; Pd: Palladium.
(*) IEC/TR 62635: recovery of copper from shredded parts

Therefore, current automotive power electronics can be treated similar to normal electronic scrap. That means that disassembly of preliminary individual components is followed by subsequent classifying and sorting to produce marketable metal concentrates for further metallurgical processing [17]. Power electronic units within the REFREEDRIVE project (both medium and high power) were developed taking into account the capacity of employ pre-fragmentation disassembly processes, at ELV stage, achieving a high recovery rate for the critical material used, in the terms shown on Table 3.

1.2.2.3 Functional unit of the study

An LCA is always anchored in a precise, quantitative description of the function(s) provided by the analysed system. This is generally done by using the **functional unit** that names and quantifies the qualitative and quantitative aspects of the analysed system.

For the LCA introduced in this report, the chosen functional unit has been the production of one electrical machine intended for vehicle propulsion, with a specific power requirement as main characteristic, and secondly, with a torque requirement related to required power.

To cover fully the power range in the REFREEDRIVE project, according to the goal defined for the LCA, two different functional units were selected (Table 4):

Table 4: Description of FU (functional unit) for the Life Cycle Assessment

	Rated Peak Power	(Peak Torque)
Functional Unit #1 (for **medium power** applications)	75 kW	(175 Nm)
Functional Unit #2 (for **high power** applications)	200 kW	(400 Nm)

1.2.2.4 System boundaries of the Study

As was commented in previous sections, the scope of the REFREEDRIVE LCA also identifies the analysed system in detail, and addresses the overall approach used to establish the **system boundaries**. The system boundary determines which life cycle stages and process steps are included in the LCA and which have been left out. The system boundaries define which parts of the life cycle and which processes belong to the analysed system, i.e. are required for providing its function as defined by its functional unit.

Once commented all the circumstances in the previous sections, as it is shown in the Figure 23, the LCA performance within the REFREEDRIVE project is focused on the **manufacturing** and **assembly processes** of the **electric motors**, from a “**cradle-to-gate” approach**, for all the studied machines (PM SynRel as reference, and the four technology of the REFREEDRIVE project (Induction and SynRel machines), in its different configuration), approach that covers the life cycle from resource extraction (cradle) to the factory gate. This system boundary was chosen considering that the use phase and end-of-life scenario for all the configurations of the REFREEDRIVE machines can be assumed as quite similar, do not showing relevant differences among them: efficiency, which define the consumption of energy during its use phase, is quite similar for all the REFREEDRIVE electric drives, and the reuse/recycling strategies for the REFREEDRIVE solutions are the same in each configuration on base of the used materials.

Manufacturing steps in the REFREEDRIVE LCA cover the production of the active parts of the electric motors (rotor, stator and shaft), but also the cooling jacket. Rotor and stator are mainly joined stacks of electrical steels. Stator also include cooper, either as winding or hairpins, depending of the type of motor. Rotor on induction machines has got copper, casted or in bars. SynRel motors do not use copper. One of the REFREEDRIVE SynRel motor uses ferrite magnets.

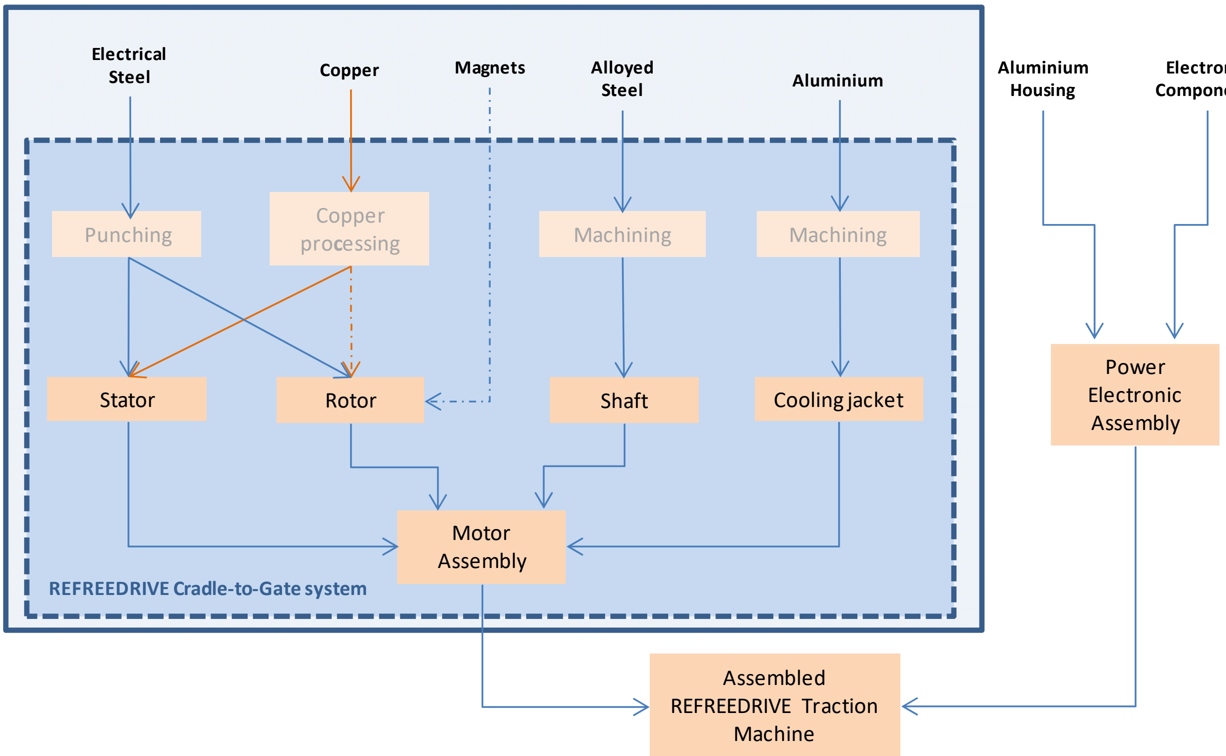


Figure 23: System Boundaries for the REFREEDRIVE Life Cycle Assessment

Power electronic of the REFREEDRIVE machines was also developed within the project. However, due to the difficulties to carry out a proper LCA study, both REFREEDRIVE PE and comparison baseline, the LCA carried out within the project was focused only on the production of the electric motors. As previously commented, the information necessary to perform a reliable LCA on the power electronics (for instance, a complete and exhaustive bill-of-materials, as well as a detailed description of how its manufacture and assembly has been carried out) is not accessible by REFREEDRIVE partners, which makes not possible to carry out this task.

Some complementary activities to the manufacturing process are not considered in this study on the basis that their influence on the environmental impact is negligible. Such activities would include capital equipment, business travel, administration, cleaning services etc. Similarly, capital goods and infrastructure have not been included in the present study.

Regarding the proposed system boundary (Figure 23), this allows differentiating between the processes of the foreground system and those of the background system, in order to identify which processes can be managed by direct control or decisive influence. The system under study on a LCA is the exact sum of the background and the foreground systems.

- The **foreground processes** are those that are under direct control of the producer of the good (in this specific case, the electric motors) or where he has decisive influence by their decision-making. In previous Figure 23, foreground processes are included into the area limited by the dashed dark blue line. These foreground processes within the REFREDRIVE

LCA are the manufacturing processes for the stator, rotor, shaft and cooling jacket, from the needed materials (electrical steel sheets, copper in different supply formats, magnets (if any), and aluminium), according with the designs and production technologies selected during the development activities within the REFREEDRIVE project.

- In contrast, the **background system** comprises those processes that are operated as part of the system but that are not under direct control or decisive influence of the producer of the good. In the previous Figure 23, background processes are included into the area limited by the continuous dark blue area, but out of the area bordered by the dashed dark blue line. The processes in the background system are, as example, those that provide commercial products purchased via a market. Therefore, here are included the manufacturing processes of the needed materials to manufacture the electric motors, which are not under the direct control of the REFREDRIVE partners, but nevertheless, they have a lot of relevance on the environmental impact of the product under analysis.

1.2.2.5 Geographic and time coverage

Concerning the geographic and time coverage, this LCA study includes processes representing current global conditions, for the design and manufacturing of automotive electric drives. This has been guaranteed by the project consortium, which includes companies and institutions whose business is currently focused on this technological market.

For the primary data[1], the production covers the year 2020 and it is representative of the European electric motor production for automotive traction in that time frame, such as is warranted by the industrial and research partners within the REFREEDRIVE project. The information related to the production stages have been gathered during the prototyping manufacturing stage, by the REFREEDRIVE partners.

Concerning secondary data[2], they have been extracted from an updated GaBi Professional database, by CIDAUT (updating during year 2020).

1.2.2.6 Technology coverage

The REFREEDRIVE consortium includes the necessary stakeholders needed to develop, demonstrate and bring both IM & SynRel technologies to the market, covering the main technological issues tackled in the project and applying the most advanced technologies.

Materials selection and characterization has been properly performed to gather innovative high performing options for the laminations of both motor technologies (Non-oriented electrical steel, silicon-iron type, has been considered), but also, for the copper alloys for the Induction machines rotors (in both configuration of Fabricated and Die Cast copper rotors).

[1] **Primary data** sources are the producers of goods and operators of processes and services, as well as their associations

[2] **Secondary data** sources which either give access to primary data (possibly after re-modelling / changing the data) and to generic data are e.g. national databases, consultants, and research groups

Different teams of experts on motors design have worked on each REFREEDRIVE machine technology. Motors designs have been based on the use of the most extended tools in this industrial sector (electromagnetic, thermal, mechanical and NVH (Noise, Vibration, and Harshness) simulations), which has allowed to successfully achieve the objectives of the project: avoid the use of rare earth magnets through the development of a next generation of electric drivetrains, ensuring the industrial feasibility for mass production while focusing on the low cost and environmental footprint of the manufacturing technologies.

Finally, expert manufacturers have been consulted and subcontracted in order to ensuring mass production processes with the most modern technologies. These advanced technologies for manufacturing the different machines parts have been considered within the Life Cycle Inventory.

1.2.2.7 Impact categories & LCIA methods in the study

The selection of **impact categories** (related with a specific LCIA method) must be consistent with the goal of the study and the intended applications of the results, and it must be comprehensive in the sense that it covers all the main environmental issues related to the system. The environmental impact categories have to be determined prior to the initial inventory analysis, as far as feasible. This is to ensure that their selection is not done interest-driven in view of the initial results.

The **LCIA method** to use in the environmental impact evaluation has to be identified as part of the scope definition. LCIA methods aim to connect, as far as possible, each life cycle inventory (LCI), where input and output are identified and quantified, to its potential environmental damages, on the basis of impact pathways. To achieve the connection between LCI results and environmental damages, types of LCI results with similar impact pathways have been grouped into impact categories (Figure 24). The relative contribution of each input and output within the product system is assigned to impact categories.

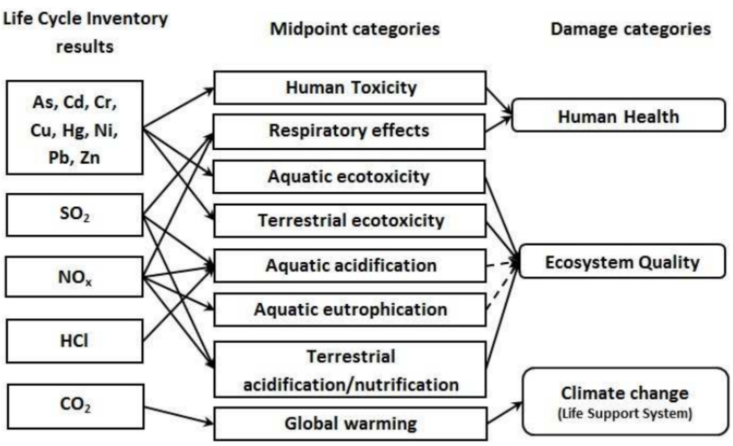


Figure 24: Scheme demonstrating environmental impacts of a product, based on a generic LCIA method, linking life cycle inventory results with impact categories (midpoint categories and damage categories)

The results obtained in the classification phase are multiplied by the **characterization factors** of each substance within each impact category, which are defined by the selected LCIA method.

Therefore, the importance of single flows relative to a specific basic flow is characterised by a factor. Through the "Characterisation" stage, inventory results for the individual elementary flows are multiplied by the impact factors defined within the applied LCIA methods. Resulting characterized indicator results are summed up within each impact category (Figure 25). The resulting collection of aggregated indicator results is the characterized impact profile of the product, i.e. its LCIA results.

In LCA practice, these steps are made directly by the LCA Software. Databases within LCA software typically provide elementary flows that have been classified and characterised and thereby "linked" with the LCIA methods.

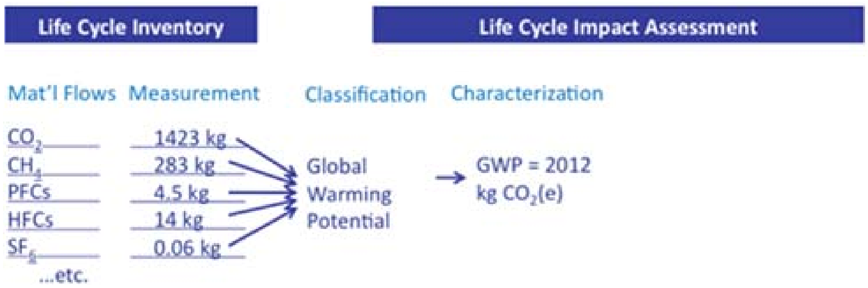


Figure 25: Example of "Classification" and "Characterisation" stages, for evaluation of environmental impact related to a impact category, employing a specific LCIA method.

LCIA methods

The ISO 14040 and 14044 standards provide an important framework for LCA. This framework, however, leaves the individual expert, practitioners and data developers, with a range of important choices that can be individually interpreted, leading difference in consistency, reliability and comparability of the results of an assessment.

Various impact assessment methodologies are applicable for use in the European context including e.g. CML, ReCiPe, and selected methods recommended by the ILCD. The environmental results within REFREEDRIVE project are carried out by the **ILCD/PEF method**, which is included in GaBi software tool. ILCD (**International Life Cycle Data system**) provides a common basis for consistent, robust and quality-assured life cycle data and studies. **Product Environmental Footprint (PEF)** is based on ILCD recommendations, as a multi-criteria measure of the environmental performance of a good or service throughout its life cycle. The method was published (2013 [18]) as an Annex to the Commission Recommendation on the use of common methods to measure and communicate the life cycle environmental performance of products and organisations.

The ILCD (**International Life Cycle Data system**) has been developed since 2005, to provide guidance and standards for greater consistency and quality assurance. The development of the ILCD was coordinated by the European Commission and has been carried out in a broad international consultation process with experts, stakeholders, and the general public. DG Environment has worked together with the European Commission's Joint Research Centre (JRC IES) and other European Commission services towards the development of a harmonised methodology for the calculation of the environmental footprint of products and organisations

Impact categories

Related to the selected method (**ILCD/PEF method)**, the following environmental impact categories were considered in the scope of this study. A brief description of these impact categories can be found in the section 3 – "Results - Life Cycle Impact Assessment (LCIA)" of this report.

- Climate Change
- Resource depletion
- Ozone Layer Depletion
- Human Toxicity
- Particulate matter/Respiratory inorganics
- Ionising radiation, human health
- Photochemical Ozone Formation
- Acidification
- Ecotoxicity freshwater
- Eutrophication
- Land Use

Furthermore, although not an impact category, the **Primary Energy Demand (PED)** is assessed as an additional LCI parameter, indicating the overall energy consumption, adding to the energy consumed during the manufacturing stage, also the energy transformation and distribution losses.

1.2.2.8 Software and Database

The LCA models were created by CIDAUT, based on the data provided by the REFREEDRIVE partners, using the GaBi Software system for life cycle engineering, developed by thinkstep, a Sphera company (https://sphera.com/). GaBi is the world's leading expert decision support Life Cycle Assessment software for product and service sustainability

The GaBi Professional database provides the life cycle inventory data for raw and process materials obtained from the background system. The GaBi databases are basic data sources for multiple stakeholder groups: Industry, academia and education, policy and regulation, research and development and consultancy. As any of these stakeholders aiming for solid result, also REFREEDRIVE project needs solid, accurate and reliable data. Without quality data, there is a high risk of inaccurate or misleading results.

1.3 Life Cycle Inventory (LCI) Overview

1.3.1 Introduction

During the life cycle inventory phase, the data collection and modelling of the system (e.g. product) have to be done in line with the goal definition and meeting the requirements derived in the scope phase. The inventory phase is building on the decisions made during goal and scope definition. The LCI results are the input to the subsequent LCIA phase. Typically, the LCI phase requires the highest efforts and resources of an LCA: for data collection, acquisition, and modelling. These steps are done in an iterative procedure.

For all processes that have been identified, the inventory data have to be collected. A collection of inventory data is typically required only for the foreground system (those that are under direct control of the producer of the good or where he has decisive influence by his decision-making). All data in the background system (those processes that are operated as part of the system but that are not under direct control or decisive influence of the producer of the good) use to be sourced from available background databases.

The inventory phase involves the collection of the required data for **flows to** and **from** processes (Elementary flows[3], Product flows[4] and Waste flows[5]) and other information identified in the scope definition as relevant for the analysed system. Process inventory data is collected or modelled on input side and output side (Figure 26):

- **Input side flows** include elementary flows such as material and energy resources, land use, product flows such as energy carriers, chemicals and materials, consumables, parts and components, semi-finished products, complex products, and services of all kind.
- **Output side flows** include – next to the one or more product(s) - generated waste, emissions to air, water and soil, and other environmental aspects that may be of relevance for the impact assessment (e.g. noise, nature littering, etc.) and for the given case.

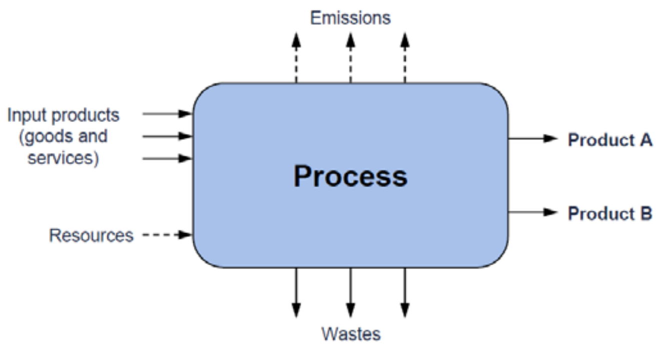


Figure 26: Process with several input products and resources consumed and various wastes and emissions generated as well as providing the two co-products 1 and 2.

[3] Elementary flows, such as resources and emissions but also other interventions with the ecosphere such as land use
[4] Product flows (i.e. goods and services both as "product" of a process and as input/consumables) that link the analysed process with other processes
[5] Waste flows (both wastewater and solid/liquid wastes) that need to be linked with waste management processes to ensure a complete modelling of the related efforts and environmental impacts.

1.3.2 Life Cycle Inventory (LCI) - Introduction

The foundation for the calculation of the LCA for the production of the REFREEDRIVE traction machines is information provided by the partners. During the data gathering process, the needed information has been requested by CIDAUT to the partners, attending to their expertise and development activities regarding the different configurations of the machines and technologies employed.

In order to make easier the way of gathering the information, in a first step, CIDAUT developed together with the REFREEDRIVE partners, different flowcharts (Figure 27) for the different motor components (rotor, stator, cooling housing, etc), for each motor technology, improving the mode of identification of all the incoming and outgoing flows for the production process. A specific workshop was carried, where CIDAUT showed the methodology, and the partners (from WP3 and WP4) completed the production processes together their associated incoming and outgoing flows (raw material, energy, wastes, emissions and products), in order to tune up the processes mapping.

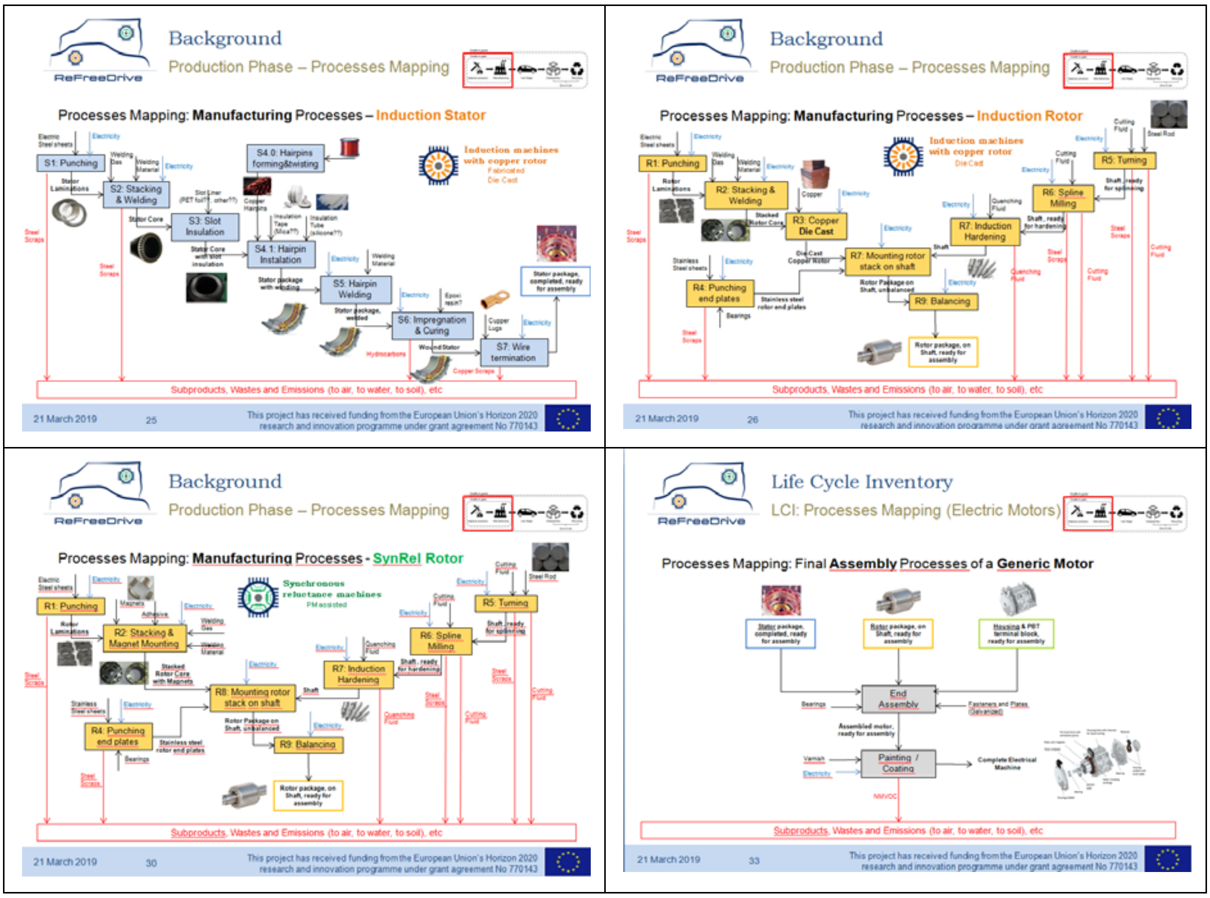


Figure 27: Processes mapping flowcharts employed in a face-to-face workshop, used to identify the production processes and the related incoming and outgoing flows.

In further months, CIDAUT shared specific flowcharts (Figure 28) with the involved partners in the development to each component within each machine technologies, in order to quantify the previously identified flows (estimation of amounts). Several iteration steps were needed during the determination of the values for the flows, in order to achieve the most complete information to build the LCA model of the production stages of each part in the REFREEDRIVE machines. This iterative process was finally finished, with the information gathered during the prototyping manufacturing process.

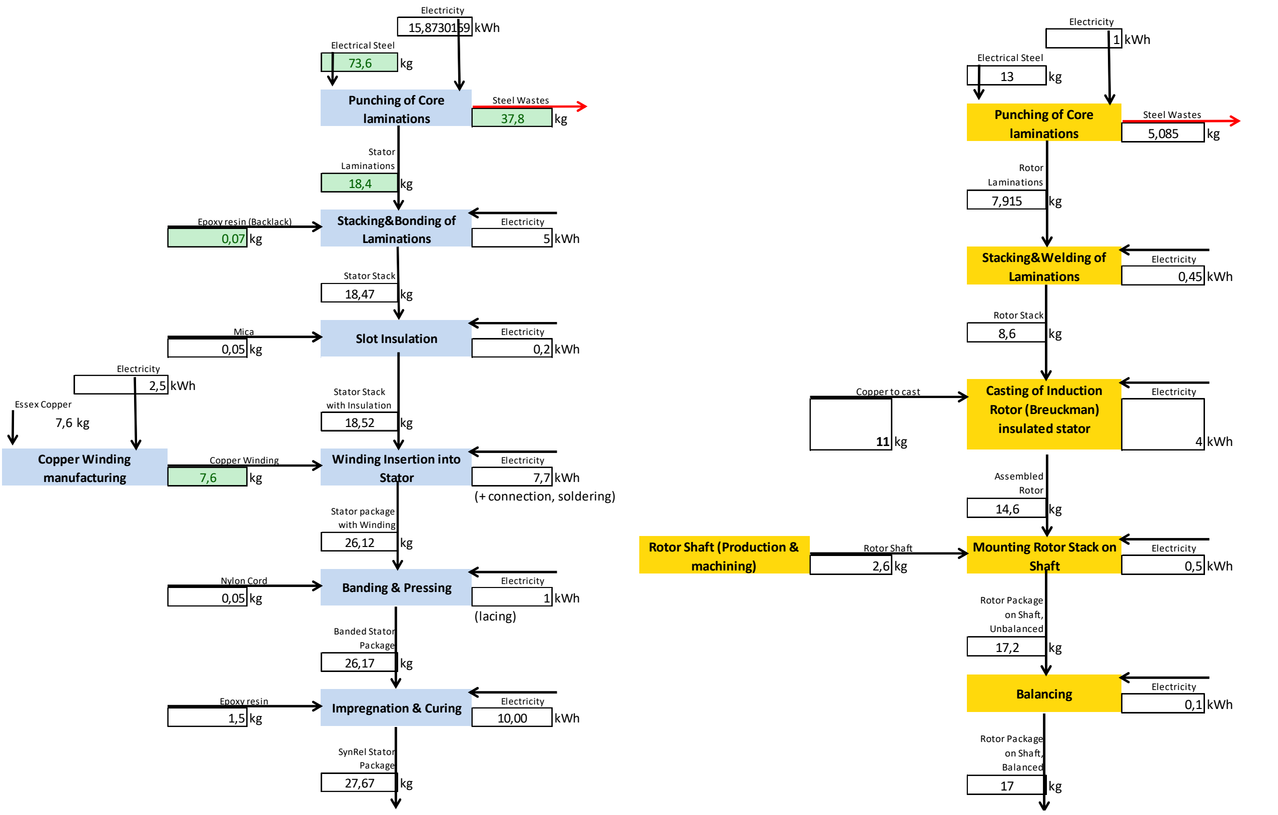


Figure 28: Flowcharts employed by the partners to quantify incoming and outgoing flows related to the production of the different components of the ReFreeDrive machines.

The gathered information from the partners allowed concluding the LCA models defined for each machine components (stator, rotor and cooling housing) in the GaBI software. This task was performed by CIDAUT, completing the needed information for the production stages, such as is shown in the Figure 29.

In the next section "2.- Description of Life Cycle Models - Inventory (LCI)" of this report, an extensive description of the inventory for each component related to each traction machine technology developed within REFREEDRIVE project is shown. Go to the cited section within this report to reach the inventory employed into the life cycle assessment.

As it will be confirmed in section "3 - Results - Life Cycle Impact Assessment (LCIA)", the environmental impact of each motor configuration is related to their size, through the materials consumption needed for its manufacturing process. Next Table 5 summarizes the dimensional characteristic of the electric motors analysed within the Life Cycle Assessment, and Table 6 and

Table 7 show a summary of the consumption of materials needed for the components manufacturing, as function of motor configurations (technologies and power ranges).

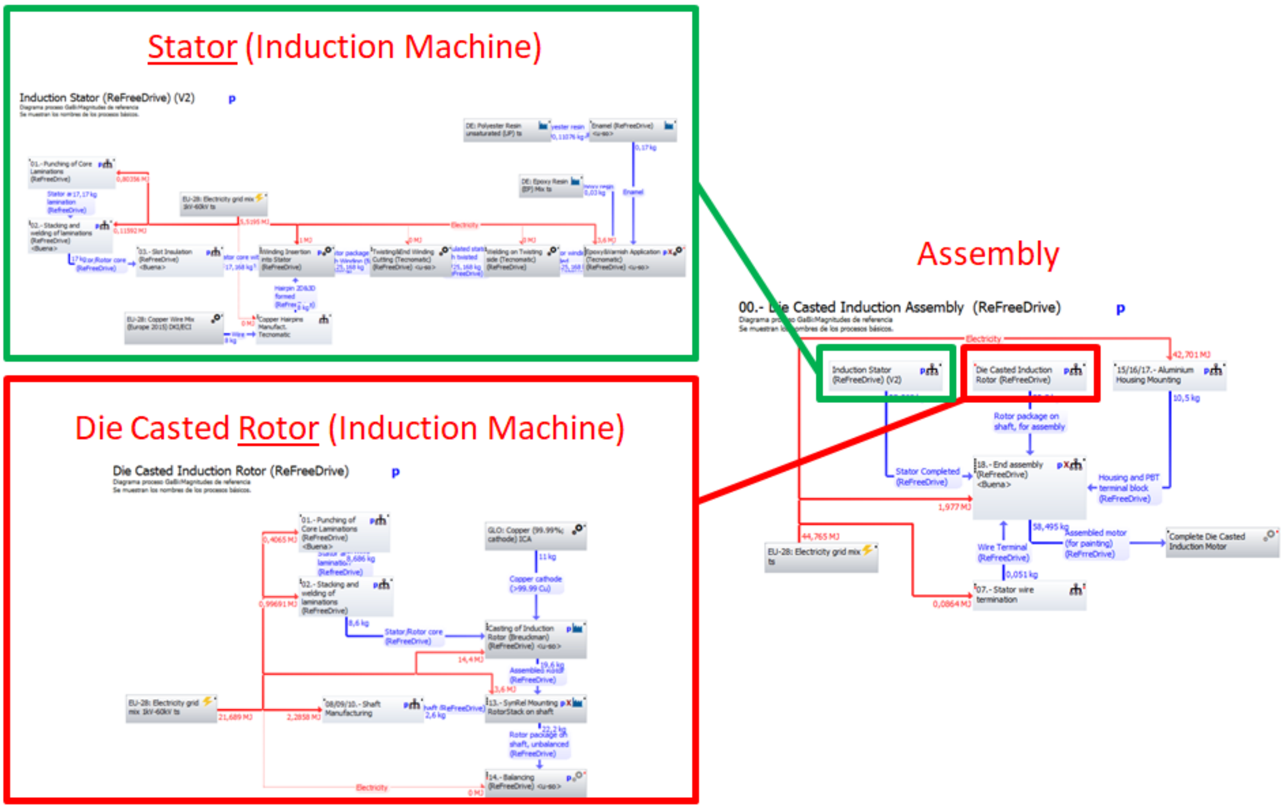


Figure 29: Example of the modelling within the LCA software, for the production stages of the REFREEDRIVE machines manufacturing process, from mapping processes flowcharts.

Table 5: Motor Characteristics defining its size

Technology		Power	Estimated weight (kg)	Active length (mm)	Outer Stator Diameter (mm)
Baseline (NdFeB PM SynRel) [11] [12]		75 kW	35,0	120	190
		200 kW	76,7	253	200
RFD SynRel	PM assisted	75 kW	38,0	75	220
		200 kW	65,7	200	220
	Pure	75 kW	33,6	95	220
		200 kW	54,2	202	220
RFD Induction	Die Cast	75 kW / 200 kW	52,3	161	190
	Fabricated	75 kW / 200 kW	52,3	161	190

Due to limits regarding time, logistics and budget, in the project it was decided to manufacture 75kW prototypes not following the ideal principles of industrial scaling adaption for the electric motors, but using some common parts and structure of the optimized 200 kW prototypes, e.g.:

- both 75kW SynRel prototypes, although with shorter stack lengths, are using the same shaft and cooling housing as the respective 200 kW Pure SynRel and Ferrite assisted SynRel machines.
- In case of the two 75kW induction motors, the "oversizing" is even more relevant as the 75kW variants are basically built exactly the same way as the 200kW same e-machine using identical stator, rotor size and cooling housing, only running at lower voltage and lower speed to simulate the 75kW performance

Therefore, 75kW prototypes are somehow a sub-optimal compromise to be used only as demonstrator. Design simulations of the initial phase of the REFREEDRIVE projects prove their capabilities.

Taking into account all of the above, and in view of the masses values for all the analyzed motors (prototypes), whose figures are summarized in Table 5, it is confirmed that the 75 kW RFD SynRel motors are approximately equivalent to the reference ones (NdFeB PM SynRel). In the case of comparing the 200 kW motors, the RFD SynRel motors are lighter and smaller than the reference ones.

Regarding the induction motors, when their masses are compared, it must be taken into account that in the project it was decided that the structure of the 75 kW motors should be constructively speaking, the same as that of the 200 kW motors. Thus, there is an oversizing of the induction motors of 75 kW, and this affects their comparison at the weight level with respect to the motors taken as a reference. However, the 200 kW IM motors are significantly lighter and smaller.

These differences in weight between the different versions of the motors are given by the use, in different forms and amounts, of the diversity of materials that are necessary to manufacture the motors, as shown in the following Table 6 for 200 kW motors and Table 7 for the motors of 75 kW.

Table 6: Consumption of materials (kg) needed for the components manufacturing of 200 kW electric motors

200 kW	Stator			Rotor					Cooling Housing	Assembly
	Steel (kg)	Copper (kg)	Resin (kg)	Steel (kg)	Magnet (kg)	Copper (kg)	Aluminium (kg)	Resin (kg)	Aluminium (kg)	Steel (kg)
NdFeB PM SynRel (Reference)	**19,82** (Stacks)	**7,01** (Wire)	**0,6064** (insulation)	**14,083** (Stacks) **0,58** (Endplates) **4,26** (Shaft)	**2,12** (NdFeB)				**22,4** (Housing) **5,0** (End bells)	**0,244** (Bearing) **0,25** (Screws)
PM assisted SynRel (RFD)	**18,4** (Stacks)	**7,403** (Wire)	**0,07** (Backlack) **2,915** (Insulation)	**17,4** (Stacks) **4,3** (Shaft)	**2,7** (Ferrite)		**0,730** (Endplates)	**0,06** (Backlack) **0,12** (Magnets adhesion)	**7,9** (Housing) **2,47** (End bells)	**0,28** (Bearing) **0,25** (Screws)

Pure SynRel (RFD)	**21,7** (Stacks)	**5,163** (Wire)	**0,07** (Backlack) **0,5** (Insulation)	**12,0** (Stacks) **3,0** (Shaft)				**0,06** (Backlack)	**7,9** (Housing) **2,47** (End bells)	**0,28** (Bearing) **0,25** (Screws)
Die Cast Induct. Machine (RFD)	**16,8** (Stacks)	**7,7** (Hair pins)		**7,9** (Stacks) **3,12** (Shaft)		**6,0** (Die Cast)			**11,19** (Housing) **3,5** (End bells)	**0,28** (Bearing) **0,25** (Screws)
Fabricated Induct. Machine (RFD)	**16,8** (Stacks)	**7,7** (Hair pins)		**7,9** (Stacks) **3,12** (Shaft)		**5,0** (Bars) **1,0** (End Plates)			**11,19** (Housing) **3,5** (End bells)	**0,28** (Bearing) **0,25** (Screws)

Table 7: Consumption of materials (kg) needed for the components manufacturing of 75 kW electric motors

75 kW	Stator			Rotor					Cooling Housing	Assembly
	Steel (kg)	Copper (kg)	Resin (kg)	Steel (kg)	Magnet (kg)	Copper (kg)	Aluminium (kg)	Resin (kg)	Aluminium (kg)	Steel (kg)
NdFeB PM SynRel (Reference)	**9,335** (Stacks)	**4,25** (Wire)	**0,3085** (insulation)	**6,584** (Stacks) **0,51** (Endplates) **1,26** (Shaft)	**0,99** (NdFeB)				**6,65** (Housing) **4,5** (End bells)	**0,139** (Bearing) **0,237** (Screws)
PM assisted SynRel (RFD)	**6,9** (Stacks)	**4,383** (Wire)	**0,03** (Backlack) **2,915** (Insulation)	**6,5** (Stacks) **4,1** (Shaft)	**1,0** (Ferrite)		**0,730** (Endplates)	**0,02** (Backlack) **0,045** (Magnets adhesion)	**7,9** (Housing) **2,47** (End bells)	**0,28** (Bearing) **0,25** (Screws)
Pure SynRel (RFD)	**9,6** (Stacks)	**3,507** (Wire)	**0,03** (Backlack) **0,5** (Insulation)	**5,5** (Stacks) **3,0** (Shaft)				**0,02** (Backlack)	**7,9** (Housing) **2,47** (End bells)	**0,28** (Bearing) **0,25** (Screws)
Die Cast Induct. Machine (RFD)	**16,8** (Stacks)	**7,7** (Hair pins)		**7,9** (Stacks) **3,12** (Shaft)		**6,0** (Die Cast)			**11,19** (Housing) **3,5** (End bells)	**0,28** (Bearing) **0,25** (Screws)
Fabricated Induct. Machine (RFD)	**16,8** (Stacks)	**7,7** (Hair pins)		**7,9** (Stacks) **3,12** (Shaft)		**5,0** (Bars) **1,0** (End Plates)			**11,19** (Housing) **3,5** (End bells)	**0,28** (Bearing) **0,25** (Screws)

2 Description of Life Cycle Models - Inventory (LCI)

As it has been previously commented, the 'Inventory' phase involves data collection and modelling of the system, as well as description and verification of data. This encompasses all data related to environmental (e.g. emissions) and technical (e.g. consumed raw materials) quantities for all relevant individual processes within the system boundaries that compose the analysed system. The data must be related to the functional unit defined in the scope.

In this section, for each REFREEDRIVE machine, data for incoming/outgoing flows are presented in tables for each manufacturing process. Incoming flows (mainly raw material, consumables and energy consumption) are located in the left columns of the cited tables. In the right side, are listed the outgoing flows, as products manufactured or wastes. Where it is applicable, a distinction has been made in these tables for the identified processes, regarding the values of the incoming and outgoing flows, depending on whether a 75 kW or 200 kW motor is being manufactured.

Therefore, results of the inventory is an LCI which provides information about all inputs and outputs in the form of elementary flows to and from the environment, for all the individual processes involved in the study.

In the first place, the inventory associated with the manufacturing process of the two machines taken as a reference will be shown (NdFeB SynRel), to then show the inventory of the machines developed within the REFREEDRIVE project, for the different technologies, for the two powers (75 kW and 200 kW)

2.1 Reference Machines (Permanent Magnet SynRel machine)

As **baseline automotive electric motor** representative of the **current state-of-the-art**, for the environmental impact comparison against the machines developed in REFREEDRIVE project, a **NdFeB PM SynRel machine** such as is described in the technical papers [11] [12] has been selected and was employed as reference for the LCI stage.

Together with the technical paper, authors provide a link to download a spreadsheet based on an Excel file, which is a scalable LCI model. This tool allows calculating LCI of a representative NdFeB PM SynRel machine, attending to two relatively easily accessible electrical machine parameters. The tool requests the user to enter a value for maximum **power** and optionally the **torque**.

After, the model provides a **gate-to-gate life cycle inventory** for the **production** of an internal permanent magnet synchronous electrical machine, together with the **mass configuration** of the machine and **recommendations** for how to link the **inventory** to the **database** (for the background data) to create a complete cradle-to-gate LCI. This LCI model provides mass and manufacturing data for one PM SynRel as delivered at the factory gate. Therefore, the approach is a gate-to-gate LCI. No use or end-of-life treatment has been included.

The **functional unit** in this work is one electrical machine intended for vehicle propulsion with specific power and torque requirements, which matches with the REFREEDRIVE LCA, and consequently they are **fully comparable**.

As output, this available tool for determining the LCI for a representative EV electric motor provides a set of datasheets with usable information for our comparative study. A schematic overview of the system and the different boundaries are shown on different sheets within the provided Excel file. First sheet provides the **mass configuration** of the electric motor. Next sheets on file, respectively present:

- the unit processes which constitute the **permanent magnet production** chain,
- the unit processes for the making of **electrical steel** and **die casting of aluminium**, together with a list of activities for general material transformation and coating of steel and **copper** parts,
- the unit processes for **enamelling pure copper wire** into magnet wire and the assembly of the **resolver**, together with a list of activities for material transformation of **plastics** and **silicone rubber**,
- and finally, a sheet that presents **nineteen individual process steps** constituting the **complete motor factory**

The **processes flow chart**, which shows this nineteen individual process steps, is shown in Figure 30. On this figure, the **value** of each **mass flows** have been marked for two configurations of PM SynRel machines, whose technical parameters that determine their performance, match with the REFREEDRIVE motors (machines of **75 kW** –red colour - and **200 kW** – blue colour -)

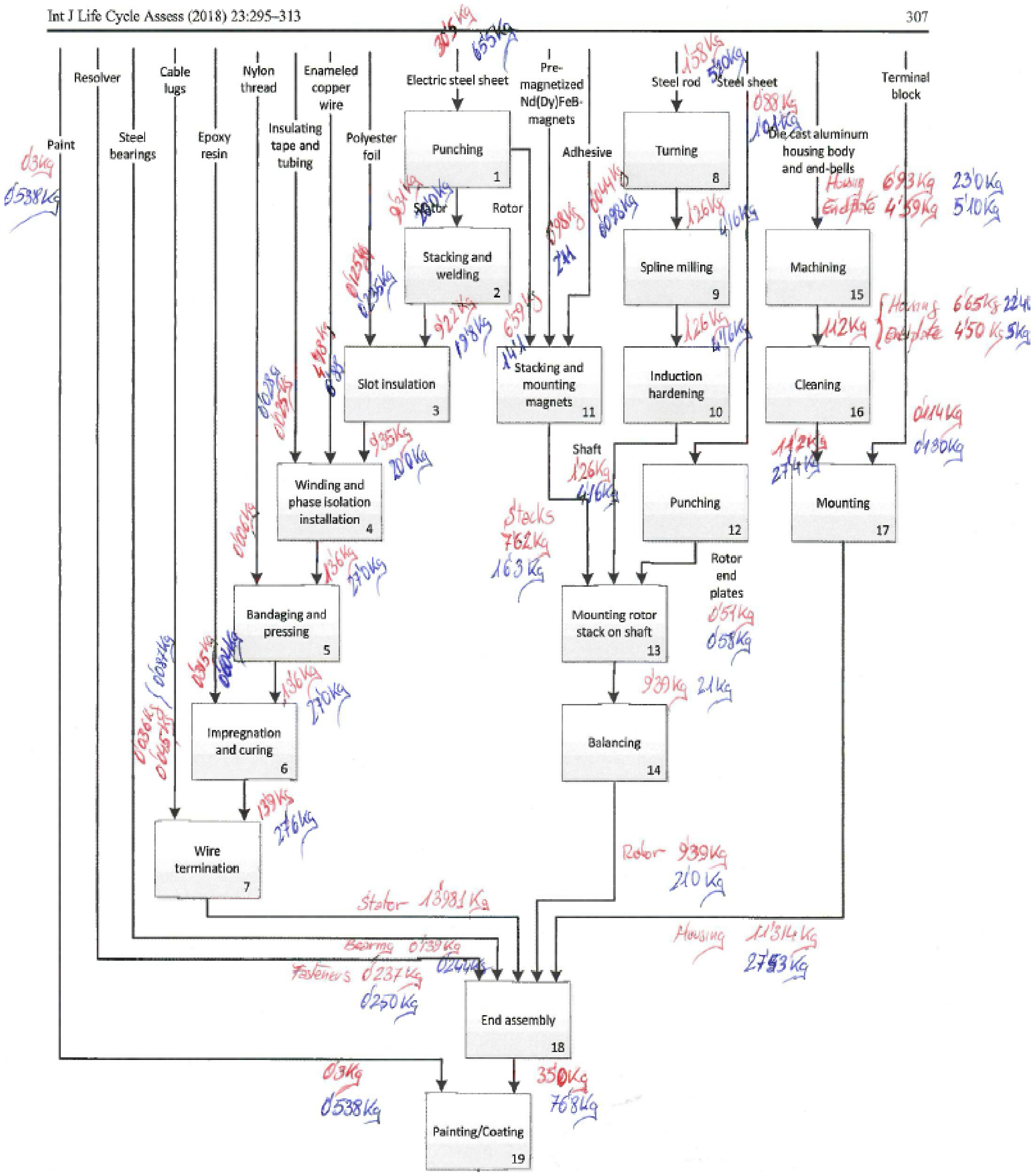


Figure 30: Flow chart showing the unit process steps constituting the complete motor factory, attending to the reference paper.

That flowchart, with the identified processes and values for the flows, concerning the LCI model provided by the author of the paper, was **employed as reference** for the comparative LCA study, and **reproduced** into the **LCA software** to determine the **associated environmental impact** for the two motors configuration (75 kW and 200 kW).

Following charts in Figure 31 show the materials distribution for the two motor configurations (75 kW and 200 kW) employed as reference for the comparison with the machines developed within the REFREEDRIVE project. The main contribution on overall motor weight (around 50%) is related to the use of electrical steel for the rotor and stator stacks and alloyed steel for the shaft manufacturing. Secondly, it appears the aluminium used in the production of the cooling jacket (30%-35%). The next material attending to their contribution on overall motor weight is the employment of copper (9% -12%) to produce the stator windings. The NdFeB magnets only mean a 3% of the motors weight. However its contribution to the environmental impact is relevant in comparison with the other materials, such as will be introduced in next sections. Others materials (resin, bearing, screws, nylon cords, etc), barely add 2% of all.

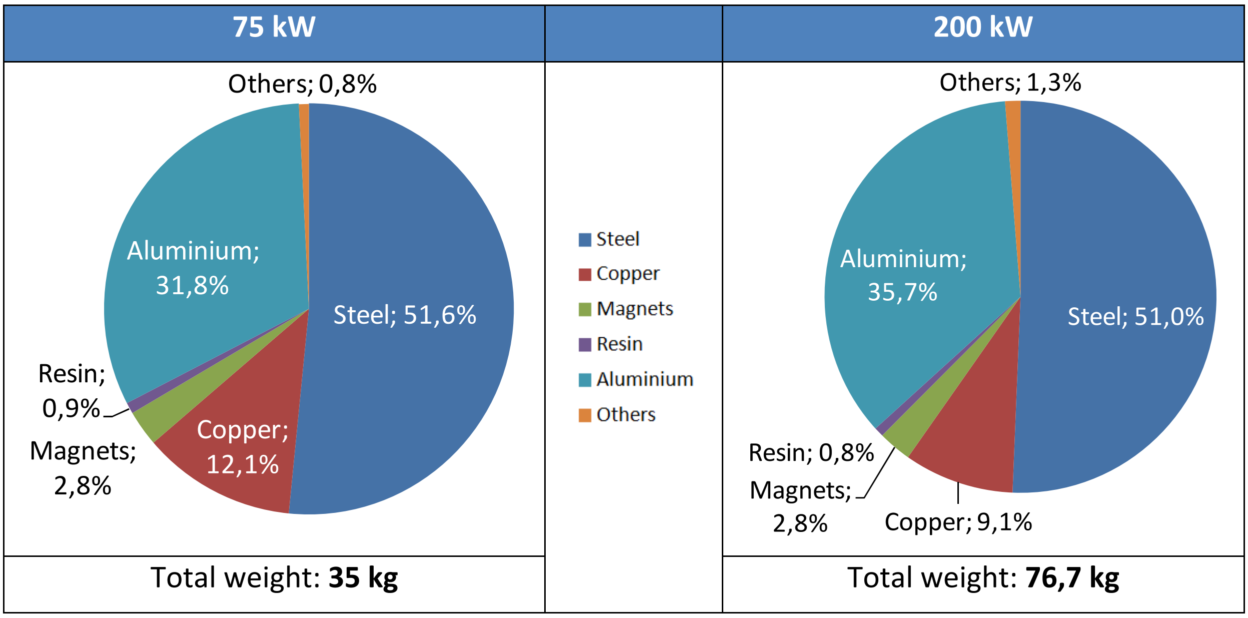


Figure 31: Mass configuration of the electrical machines (Permanent Magnet SynRel machines, as reference machines) based on components inventory from publications [13] y [14].

In the next points within this section, the **results** of the **LCI** for these motors are introduced, showing individually the inventory for the manufacturing processes of each active part, which were identified from the published flowchart (Figure 30).

2.1.1 Electrical Steel Punching

The two main active parts of the electrical machine are the **stator** and the **rotor**. The bulk of these parts, referred to as the core, are made of **electrical steel**, with specific electromagnetic, thermal, and mechanical properties.

Electric machine manufacturing begins with the **punching** of stator and rotor **laminations** from the same electrical steel sheet.

Such as the LCI authors commented, **energy use** for punching was based on expert estimations for suitable settings of stamping equipment. The same value for this **energy use per kilogram of punched electrical steel** was used for all the machines studied in this REFREEDRIVE LCA (for the reference machines but also for the REFREEDRIVE machines).

Table 8 summarizes the flows inventory of this punching process to manufacture the reference motors.

Table 8: Inventory of punching process for stator and rotor stacks (PM SynRel machine as reference)

Input	75 kW	200 kW	Output	75 kW	200 kW
Electrical Steel	30,554 kg	65,07 kg	Steel Laminations	15,918 kg	33,901 kg
			Stator Laminations	9,3348 kg	19,818 kg
			Rotor Laminations	6,5837 kg	14,083 kg
Electricity	0,745 MJ	1,5866 MJ	Steel Scraps	14,638 kg	31,168 kg
			Punching PERFORMANCE	0.521	0.521

Once the steel laminations for the stator and rotor have been obtained, they are used in the manufacture of each of these active parts of the motor, as follows.

2.1.2 Stator Manufacturing

As shown in Figure 29, manufacturing process of the motor stator is a sequence of several individual processes, as described below (stacking and slot insulation, installation of winding and insulation, and finally, stator impregnation and curing).

2.1.2.1 Stacking and Slot Insulation

Electrical steel laminations are **stacked** to form the cores. Stator laminations are stacked, pressed, and joined together on a fixture, often through **welding**.

Copper coils that build the stator winding must be **electrically isolated** to be protected from short circuiting with each other and the stator core. At the boundary to the core and between layers, polyethylene terephthalate (**PET) foils** are placed (called slot liners and separators), previously to the copper winding placing. Table 9 summarizes the flows inventory of this stacking and insulation process to manufacture the reference motors.

Table 9: Inventory of staking process for stator and slot insulation (PM SynRel machine as reference)

Input	75 kW	200 kW	Output	75 kW	200 kW
Stator lamination	9,3348 kg	19,818 kg	Stator core with Slot insulation	9,3535 kg	20,042 kg
Polyethylene terephthalate granulate (PET) foils	0,11114 kg	0,42035 kg			
Electricity	0,08588 MJ	0,32484 MJ			

2.1.2.2 Installation of Winding and Insulation

The **current conducting wire** placed in the stator slots consists of a copper base with layers of insulation materials. **Enamelled cooper wire** was selected for the motor design. The insulation consists of a hard glossy coating made from resins.

Copper coils must be firmly mounted and have good thermal conduction for heat dissipation. For the windings, copper wire is wound into coils, which are mounted onto a fixture matching the number of slots in the stator. The coils are then pulled through the stator into the slots, inside the slot liners.

Insulation tape is applied to the end-turns of the installed layer. Phase conductors are prepared by threading tubes (**silicone rubber**) over the copper wire conductors extending from the coils.

Table 10 summarizes the flows inventory of this winding installation process to manufacture the reference motors.

Table 10: Inventory of installation of Winding in stator (PM SynRel machine as reference)

Input	75 kW	200 kW	Output	75 kW	200 kW
Stator core with Slot insulation	9,3535 kg	20,042 kg	Stator package with winding	13,598 kg	27,0 kg
Enamelled copper wire	4,2519 kg	7,0106 kg			
Silicone cable insulation /tubing	0,02651 kg	0,02656 kg			
Electrical insulation tape	0,0360 kg	0,0361 kg			
Electricity (Copper enamelling)	7,6535 MJ	12,619 MJ			

2.1.2.3 Bandaging, Stator Impregnation & Curing

The **end-windings** are often also **laced** with **cords** of nylon or cotton to further secure the installation In order to secure the windings, end-turns are laced with a thread and then machine pressed. It was assumed that there were no losses of phase conductor insulation and nylon thread.

Stator is **impregnated** to fill all remaining voids of the stator slots and within the bundles of the end windings, for example, with an **epoxy compound** or a silicone elastomer. The **impregnation** of the stator windings is one of the most **energy-demanding** processes in the motor factory due to the need for oven heating.

Trickling is an extensively used method, well suited for the studied motor design. Resin is poured or sprayed onto the winding in a fine jet, often when the stator is rotating and slightly inclined, and then drawn into the cavities of the slots and end-windings by capillary action [13][14]. The amount of resin can be accurately managed without dripping losses and the processing time is relatively short, although the investment cost is high because advanced automation equipment is required.

The flows inventory for impregnation and curing processes, to manufacture the reference motors, are summarized on Table 11.

Table 11: Inventory of stator impregnation with resin and curing process (PM SynRel machine as reference)

Input	75 kW	200 kW	Output	75 kW	200 kW
Stator package with Winding	13,598 kg	27,0 kg	Stator package, impregnated	13,906 kg	27,606 kg
Epoxy resin impregnation	0,30846 kg	0,60643 kg			
Bandage (nylon lacing cord)	0,006 kg	0,006 kg			
Electricity	**1,0717 MJ** Bandaging: 0,0864 MJ Impreg&Curing: 0,98532 MJ	**1,842 MJ** Bandaging: 0,0864 MJ Impreg&Curing: 1,7554 MJ			

At the end of this process, stator is available to be assembled together with the rotor and the cooling jacket (Figure 30)

2.1.3 Rotor Manufacturing

As the stator, the rotor also has to undergo various manufacturing processes, from the electrical steel stacks, until achieving the finished rotor, including the mounting of the NdFeB magnets and the shaft.

2.1.3.1 Mounting magnets in Rotor

In this manufacturing process, **rotor core laminations** are **stacked** onto a fixture and **magnet segments** are **placed** and **fixed** within the rotor slot cavities. This process takes place in parallel with the preparation of the rotor shaft and the fabrication of the rotor endplates.

Rare earth metals, such as neodymium, can be used to create very strong permanent magnets. Neodymium-iron-boron **(NdFeB) magnets** have a high-energy product and high remanence, as well as good mechanical properties for processing complex shapes.

The flows inventory for magnets mounting process, to manufacture the reference motors, is summarized on Table 12.

Table 12: Inventory of ,magnets mounting process (PM SynRel machine as reference)

Input	75 kW	200 kW	Output	75 kW	200 kW
Rotor lamination	6,5837 kg	14,083 kg	Stacked rotor core with magnet	7,62 kg	16,3 kg
Sintered Magnet NdFeB	0,9906 kg	2,119 kg			
Magnet fixation resin	0,0457 kg	0,0978 kg			
Electricity (mounting of magnets)	5,3978 MJ	9,6163 MJ			

2.1.3.2 Assembly (&Pressing) of rotor package

Once the rotor parts are manufactured (stacked **rotor core** with **magnet**, rotor **end plates** and **shaft**), these are then integrated by threading the rotor core onto the shaft and pressing in the endplates to hold everything in place (inventory on Table 13).

Table 13: Inventory of stator assembly process (PM SynRel machine as reference)

Input	75 kW	200 kW	Output	75 kW	200 kW
Stacked rotor core with magnet	7,62 kg	16,3 kg	Rotor package on shaft, unbalanced	9,39 kg	21,04 kg
Shaft (Steel)	1,26 kg	4,16 kg			
Stainless Steel rotor endplates	0,51 kg	0,58 kg			
Electricity	**0,9751 MJ** Punching Endplates 0,0165 MJ Shaft manufact: 0,8074 MJ Shaft Mounting: 0,1512 MJ	**2,836 MJ** Punching Endplates 0,0188 MJ Shaft manufact: 2,666 MJ Shaft Mounting: 0,1512 MJ			

Endplates are **punched** from a steel sheet in a stamping machine, similar to the core laminations, but with lower energy use per kilogram of steel. A thick sheet requires a large punching force, but since each plate is punched in one hit, the punch rate is much lower. Parts are then integrated by threading the rotor core onto the shaft and pressing in the endplates to hold everything in place.

On the other hand, **shaft machining** procedures vary with the design, e.g., if hollow or solid and the type of mechanical joint. Primary processing step comprises turning and forming the incoming steel rod into the desired shaft. Other steps involve drilling and milling. For simplicity, the mass of low-alloy medium carbon steel was then estimated from a uniform and solid shaft. Carbon steel is the most common material used.

2.1.4 Cooling Housing Manufacturing

The **housing** contains the motor, acting as a frame holding it together. Two other main functions are **protection** and **cooling**. The housing consists of a casing encircling the stator as well as the end-windings and connection cables, referred to as the **housing body**, and **two caps** at the sides of the casing, referred to as **endbells**. Each endbell holds a **bearing** at the ends of the rotor core.

The shape and mass of the housing may vary, largely depending on the stator form, the requirements for cooling and protection (e.g., the casting wall thickness), and the conditions for mounting the machine in the vehicle.

For automotive applications, **cast aluminium** is a typical material selection. Die cast aluminium housing parts are machined at the motor factory before they are ready for final assembly.

Excessive material is removed from the workpiece, and holes or other types of fixation points are prepared.

Additionally, the motor is equipped with a **terminal block** to fasten **cables** or **bus bars** coming from the inverter. The structure and size of this **plastic** block with **galvanized steel connection** plates was estimated. Before the complete housing goes to final assembly, the terminal block is mounted onto the housing body.

Table 14 summarizes the flows inventory of aluminium casing manufacturing process for the reference motors.

Table 14: Inventory of cooling jacket manufacturing process (PM SynRel machine as reference)

Input	75 kW	200 kW	Output	75 kW	200 kW
Housing Body (Aluminium)	6,65 kg	22,4 kg	Aluminium Housing and terminal block	11,264 kg	27,53 kg
Endbell (Aluminium)	4,5 kg	5,0 kg			
Terminal block (Plastic part)	0,114 kg	0,13 kg			
Electricity	49,617 MJ	113,28 MJ			

2.1.5 Assembly Stage

In the end assembly, the complete machine is put together in several steps. Most assembly operations are done by hand with support from automated handheld tools, apart from fitting the stator package into the housing body and the bearings onto the shaft.

All parts are merged into one unit by means of **placing** the **bearings**, now joined with the **rotor package**, into the bores of the **endbells**. The endbells are then secured to the housing and stator package using the dedicated **fasteners**.

Single-row all-steel ball bearings, matching the scaling of the shaft, were selected. The role of a bearing is to couple the housing and stator to the shaft and thereby carry the rotor package in its correct position inside the stator.

The flows inventory for the last stage to manufacture the reference motors is summarized on Table 15.

Table 15: Inventory of assembly stage (PM SynRel machine as reference)

Input	75 kW	200 kW	Output	75 kW	200 kW
Stator package, impregnated	13,906 kg	27,606 kg	Assembled motor	34,987 kg	76,721 kg
Rotor package on shaft, for assembly	9,39 kg	21,04 kg			
Aluminium Housing and terminal block	11,264 kg	27,53 kg			
Wire Terminal	0,051 kg	0,051 kg			

Bearing	0,139 kg	0,244 kg			
Steel Screws	0,237 kg	0,250 kg			
Electricity	**2,063 MJ** Wire Termination: 0,0864 MJ Assembly: 1,977 MJ	**3,095 MJ** Wire Termination: 0,0864 MJ Assembly: 3,0082 MJ			

2.2 REFREEDRIVE Machines

Following, a description of the inventory of the **motors developed in the REFREEDRIVE project** is introduced in the same way as has been done in the case of the reference motors (based on the published inventory by [13] and [14]).

In the next sections they are individually introduced the Life Cycle inventory for the motors developed within the REFREEDRIVE project making use of the four cited technologies (PMa SynRel, Pure SynRel, Cast rotor IM and Fabricated rotor IM)

2.2.1 Permanent Magnet Assisted (PMa) SynRel motor

In this part of the report, the results of the inventory of the REFREEDRIVE **PMa SynRel machines** are introduced**,** showing the list of materials and energy consumption for the manufacturing of each active part.

As a background before going into describing the inventory of this motor technology, charts in Figure 32 show the material breakdown for the two motor configurations (75 kW and 200 kW):

- The main contribution on motor mass is related to the use of electrical steel for the rotor and stator stacks and alloyed steel for the shaft manufacturing. The motor of 200 kW employs a higher proportion of steel than the 75 kW motor (62% of overall mass against 47%).
- Secondly, it appears the aluminium used in the production of the cooling jacket. Taking into account that both motors employ the same aluminium cooling jacket, in the smaller motor it means a higher relevancy on the weight breakdown (29%) than in the case of the bigger motor (17%).
- The next material, attending to their contribution to the overall weight, is the copper employed for the stator windings manufacturing (around at 11,5% in both motor configurations).
- The use of resin for the electrical insulation in this motor technology is also significant from a weight viewpoint (4,5% - 8,0%).
- The ferrite magnets means almost a 3%-4% of the motors weight, but its contributions to the environmental impact is quite insignificant, unlike what happens if NdFeB magnets were used.

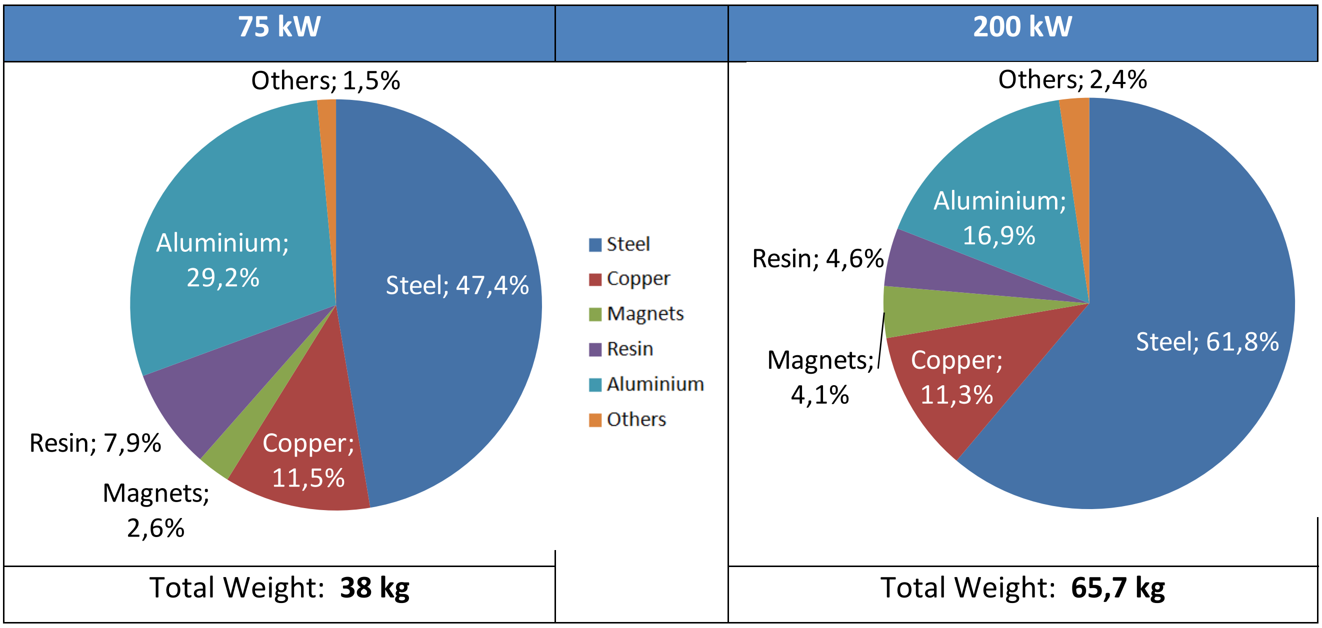


Figure 32: Mass configuration of the electrical machines (REFREEDRIVE SynRel machines, Permanent Magnet Assisted configuration) based on components inventory.

Once the contribution to the weight of each material used in the two versions of the analyzed motors has been presented, the flows inventory of each motor is presented, individually for all of each manufacturing stages (manufacturing of stator, rotor and cooling casing, and finally, end assembly stage)

2.2.1.1 Stator Manufacturing

The manufacturing process of the stator in this motor technology has many points in common with the reference technology explained in the previous section (NdFeB PM SynRel), except in the way in which the laminations of electrical steel are joined together, to obtain the stator stack. The flow inventories for the stages in the manufacturing process of the stator are described below.

Stator Punching, Stacking & Bonding

In the case of all the SynRel machines within the REFREEDRIVE project, the technique for holding the stack together is a bonding process, named varnish “Backlack”, which is an epoxy resin based lamination coating. It acts as insulation layer and bonding layer in parallel. This bonding varnish is applied directly on the magnetic steel before the punching stage. For later stack production, the bonding varnish cross-link under pressure and temperature, acting as a fixing element among the different steel laminations (Figure 33).

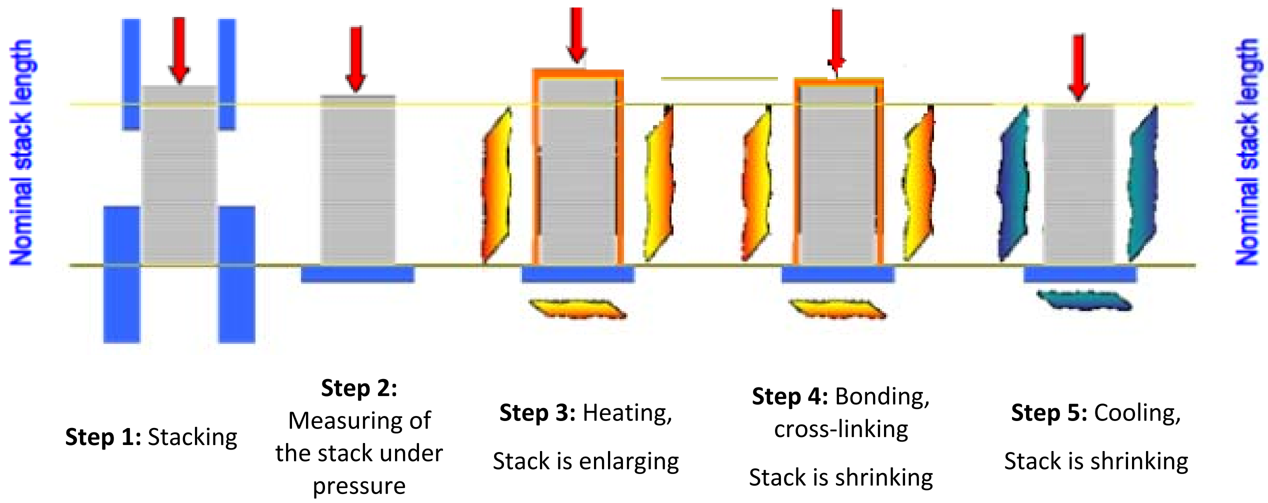


Figure 33: "Backlack" bonding process

The flow inventory for the punching, stacking and bonding processes for the stator is the shown in the Table 16.

Table 16: Inventory of punching and stacking process for stator (PM assisted SynRel machine)

Input	75 kW	200 kW	Output	75 kW	200 kW
Electrical Steel	13,244 kg	35,317 kg	Stacked stator core	6,93 kg	18,47 kg
Epoxy resin	0,0299 kg	0,0697 kg	Steel Scraps	6,344 kg	16,917 kg
Electricity	**0,941 -MJ** Punching 0,323 MJ Stacking/Bonding 0,618 MJ	**2,51 MJ** Punching 0,861 MJ Stacking/Bonding 1,65 MJ	Punching PERFORMANCE	0.521	0.521

Stator Slot Insulation

For this technology, stator has also to be insulated by means of PET foils (Figure 34) with the following materials consumption (Table 17)

Figure 34: Slot liner insertion into the stator slots for a PMa SynRel motor (Deliverable 6.4)

Table 17: Inventory of Slot Insulation for stator (PM assisted SynRel machine)

Input	75 kW	200 kW	Output	75 kW	200 kW
Stacked stator core	6,93 kg	18,47 kg	Stator core with Slot insulation	7,054 kg	18,681 kg
Polyethylene terephthalate (PET) foil	0,124 kg	0,211 kg			

Installation of Winding & Insulation

The inventory for the installation of winding and insulation process for the stator (Figure 35 and Figure 36), is summarised in the Table 18

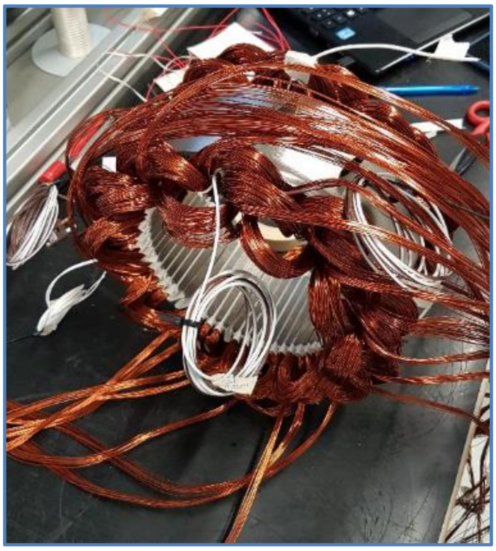


Figure 35: Stator winding with round copper wires

Figure 36: Wires separation, taping and coil forming

Table 18: Inventory of installation of Winding & Insulation for stator (PM assisted SynRel machine)

Input	75 kW	200 kW	Output	75 kW	200 kW
Stator core with Slot insulation	7,054 kg	18,681 kg	Stator package with Winding	14,564 kg	29,322 kg
Copper Winding	4,5757 kg	7,728 kg	Copper Scraps	0.07573 kg	0.1279 kg
Copper wire	4,383	7,403 kg			
Enamel	0,302 kg	0,510 kg			
Electricity (Copper enamelling)	8,236 MJ	13,91 MJ			
Electrical insulation tape (Mica)	0,01875 kg	0.05 kg			
Silicone cable insulation /tubing	0,0265 kg	0,0265 kg			
Nylon Bandage (lacing cord)	0,05 kg	0,05 kg			
Epoxy Resin Impregnation	2,915 kg	2,915 kg			
Electricity	**0,9383 MJ** Bandage 0,00864 MJ Impreg+Curing 0,929 MJ	**1,590 MJ** Bandage 0,00864 MJ Impreg+Curing 1,582 MJ			

2.2.1.2 Rotor Manufacturing

As the stator, the rotor also has to undergo various manufacturing processes, from the electrical steel stacks, until achieving the finished rotor, including the mounting of the ferrite magnets and the shaft.

Rotor Punching, Stacking & Bonding

The manufacturing of the rotor in this motor technology is equivalent to the previously commented during the stator manufacturing process, where Backlack technique is applied. Their inventory is summarised on Table 19.

Table 19: Inventory of Punching, Stacking & Bonding processes for rotor (PM assisted SynRel machine)

Input	75 kW	200 kW	Output	75 kW	200 kW
Electrical Steel	12,476 kg	33,397 kg	Stacked stator core	6,52 kg	17,46 kg
Epoxy resin	0,02 kg	0,06 kg	Steel Scraps	5,976 kg	15,997 kg
Electricity	**0,9252 MJ** Punching 0,3042 MJ	**2,470 MJ** Punching 0,8143 MJ			

	Stacking/Bonding 0,621 MJ	Stacking/Bonding 1,656 MJ	Punching PERFORMANCE	0,521	0,521

Magnets Insertion

This motor technology within REFREEDRIVE uses REE free magnets, based on ferrite (Figure 37), which have to be inserted on the rotor stack (Figure 38). Inventory data are shown in Table 20.

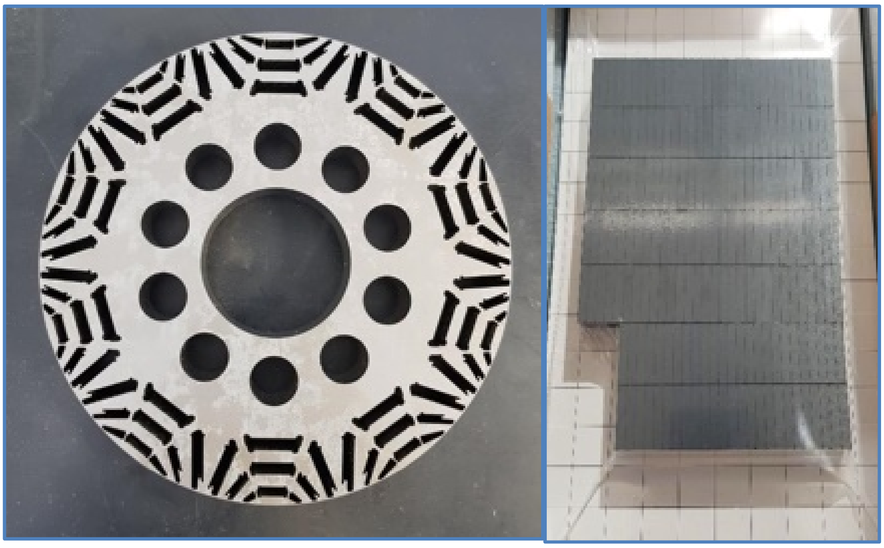


Figure 37: Rotor core, Permanent Magnets (PMs)

Figure 38: PM insertion

Table 20: Inventory of Magnets Insertion process for rotor (PM assisted SynRel machine)

Input	75 kW	200 kW	Output	75 kW	200 kW
Stacked Rotor Core	6,52 kg	17,46 kg	Stacked Rotor with Magnets	7,565 kg	20,28 kg
Ferrite Magnets	1,0 kg	2,7 kg			
Resin (adhesive)	0,045 kg	0,12 kg			
Electricity (mounting of magnets)	3,402 MJ	9,072 MJ			

Shaft Mounting into Rotor

In this case, together the steel shaft, during this process, two aluminium endplates also have to be mounted (Figure 39), which is collected in the Table 21 for the flows inventory.

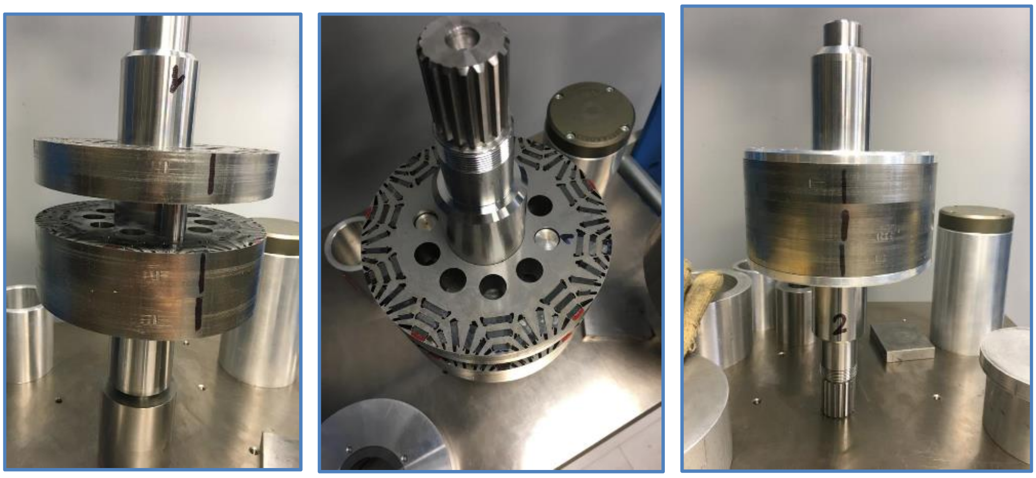


Figure 39: Insertion of rotor stacks with PMs on shaft

Table 21: Inventory of Shaft Mounting process for rotor (PM assisted SynRel machine)

Input	75 kW	200 kW	Output	75 kW	200 kW
Stacked Rotor with Magnets	7,565 kg	20,28 kg	Rotor Package on Shaft	12,395 kg	25,31 kg
Steel Shaft	4,1 kg	4,3 kg			
Aluminium End Plates	0,730 kg	0,730 kg			
Electricity	**5,484 MJ** Shaft Manufact. 2,6273 MJ Shaft Mounting 0.1512 MJ Al End Plates Manufact 2,7053 MJ	**5,612 MJ** Shaft Manufact. 2,7554 MJ Shaft Mounting 0.1512 MJ Al End Plates Manufact 2,7053 MJ			

2.2.1.3 Cooling Housing Manufacturing

The following Table 22 summarises the flows inventory related to the manufacturing process of the cooling housing.

Table 22: Inventory of Cooling Housing Manufacturing process (PM assisted SynRel machine)

Input	75 kW	200 kW	Output	75 kW	200 kW
Aluminium Housing	10,37 kg	10,37 kg	Housing and terminal block	10,5 kg	10,5 kg
Al Housing Body	7,9	7,9			
Al Endbell	2,47	2,47			
Plastic Part	0,13 kg	0,13 kg			
Electricity	**47,661 MJ**	**47,661 MJ**			

	Al cast part production: 38,178 MJ Al cast part machining: 5,488 MJ Al part cleaning: 3,132 MJ Plastic part production: 0,8635 MJ	Al cast part production: 38,178 MJ Al cast part machining: 5,488 MJ Al part cleaning: 3,132 MJ Plastic part production: 0,8635 MJ			

2.2.1.4 Assembly Stage

As final stage, in this section it is collected the data (Table 23) for the end assembly process for the PMa SynRel machines within the REFREEDRIVE project (Figure 40 and Figure 41)

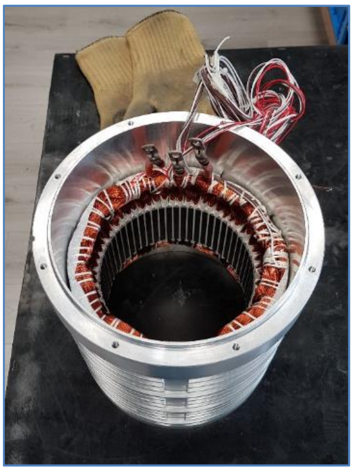


Figure 40: Stator insertion in the cooling jacket

Figure 41: Stator potting final result

Table 23: Inventory of assembly process (PM assisted SynRel machine)

Input	75 kW	200 kW	Output	75 kW	200 kW
Stator package, impregnated	14,564 kg	29,322 kg	Assembled motor	38,04 kg	65,713 kg
Rotor package on shaft	12,395 kg	25,31 kg			
Wire Terminal	0,051 kg	0,051 kg			
Al Housing and terminal block	10,5 kg	10,5 kg			
Bearing	0,28 kg	0,28 kg			
Steel Screws	0,25 kg	0,25 kg			
Electricity	3,362 MJ	3,362 MJ			

2.2.2 Pure SynRel motor

In this section, inventory for Pure SynRel motors is introduced, showing the register of materials and energy consumption related to the manufacturing of each active part.

As introduction, before a detailed inventory, process by process, next chart in Figure 42 shows the materials breakdown for the two motor configurations (75kW and 200 kW) with regard to this machine technology, developed within the REFREEDRIVE project:

- As occurs in the PMa version for the RFD SynRel motors, the main contribution on motor mass is related here to the use of steel (electrical steel for rotor and stator stacks - Figure 43 - and alloyed steel for the shaft). The motor of 200 kW employs a higher proportion of steel than the 75 kW motor (69% of overall mass against 55%, respectively).
- The aluminium cooling casing is the second component regarding to its contributions to the overall weight. Both motors (75 kW and 200 kW) employ the same cooling jacket. This means a higher contribution in the smaller motor (31%) than in the case of the bigger motor (19%).
- The following component with relevance on the overall weight is the copper employed for the stator windings, with a contribution around of 10% for both motors configuration (75 kW and 200 kW).
- The resin use for the stator insulation has barely relevance on the overall weight (around 1,5%)
- These motors do not need magnets

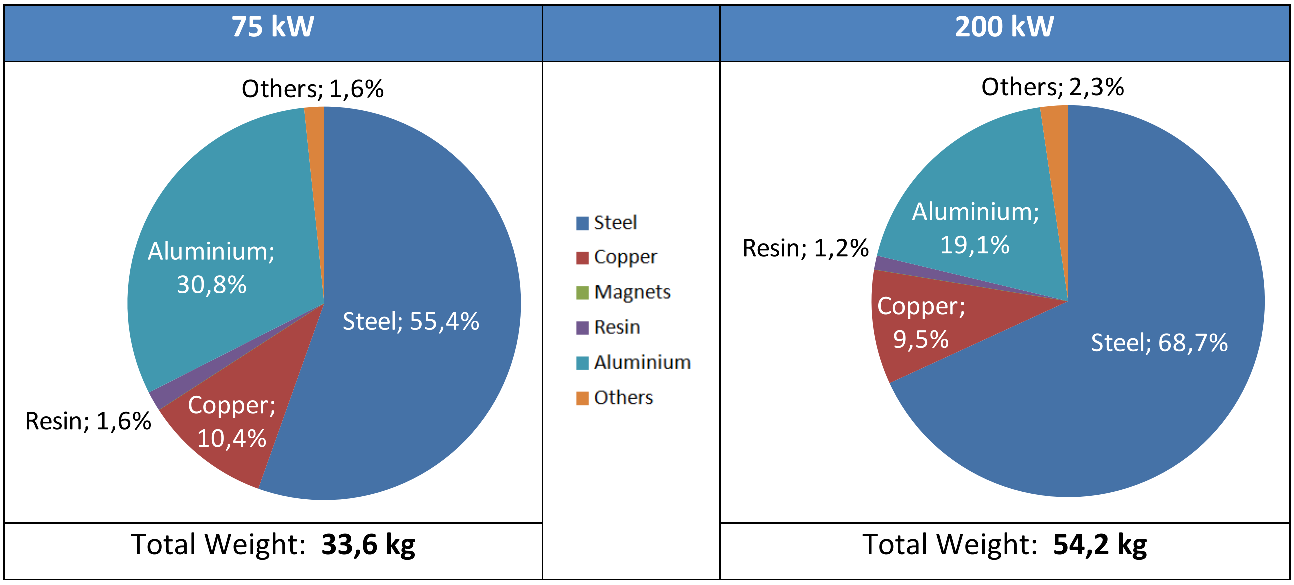


Figure 42: Mass configuration of the electrical machines (REFREEDRIVE SynRel machines, Pure configuration) based on component inventory.

After the introduction regarding the contribution analysis to the overall weight by each material used in the two versions of the studied motors, the flows inventory is presented following, for each manufacturing stages (manufacturing processes of stator, rotor and cooling casing, and finally, end assembly stage).

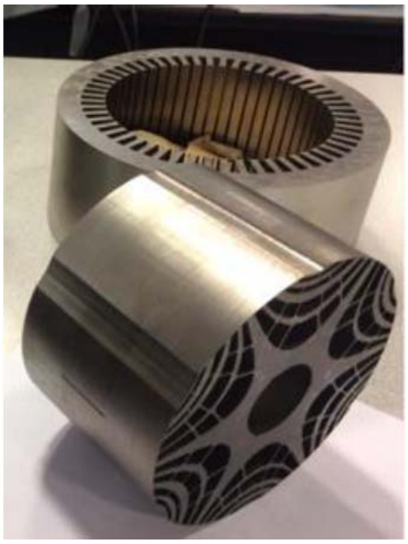


Figure 43: 75 kW Pure SynRel motor: stator and rotor cores

2.2.2.1 Stator Manufacturing

Manufacturing process for this version of the RFD SynRel motor is equivalent to the previously commented for the RFD motor employing ferrite magnets (PMa SynRel), including the use of the "Backlack" technique to join the steel laminations. The flows inventories for the needed stages in the manufacturing process of the stator are the following ones.

Stator Punching, Stacking & Bonding

The flow inventory for the punching, stacking and bonding processes for the stator of the Pure SynRel motor is the shown in the Table 24.

Table 24: Inventory of punching and stacking process for stator (Pure SynRel machine)

Input	75 kW	200 kW	Output	75 kW	200 kW
Electrical Steel	18,426 kg	41,651 kg	Stacked Stator	9,63 kg	21,77 kg
Epoxy Resin	0,03 kg	0,07 kg	Steel Scraps	8,826 kg	19,951 kg
Electricity	**1,306 MJ** Punching 0,44928 Stacking 0,8568 MJ	**2,474 MJ** Punching 1,0156 Stacking 1,458 MJ	Punching PERFORMANCE	0,521	0,521

Stator Slot Insulation

Concerning the insulation step of the stator by means of the use of PET foils, the following materials consumption is considered (Table 25)

Table 25: Inventory of Slot Insulation for stator (Pure SynRel machine)

Input	75 kW	200 kW	Output	75 kW	200 kW
Stacked stator core	9,63 kg	21,77 kg	Stator core with Slot insulation	9,754 kg	21,981 kg
Polyethylene terephthalate granulate (PET) Foil	0,124 kg	0,211 kg			

Installation of Winding & Insulation

The inventory for the winding installation and insulation process for the stator (Figure 44), is summarised in the Table 26.

Figure 44: Manufacturing processes of the 75 kW stator winding

Table 26: Inventory of installation of Winding & Insulation for stator (Pure SynRel machine)

Input	75 kW	200 kW	Output	75 kW	200 kW
Stator core with Slot insulation	9,754 kg	21,981 kg	Stator package with Winding	14,03 kg	28,057 kg
Copper Winding	3,66 kg	5,389 kg	Copper Scraps	0,0606 kg	0,089 kg
Copper wire	3,507 kg	5,163 kg			
Enamel	0,2416 kg	0,3557 kg			
Electricity	6,589 MJ	9,700 MJ			
Electrical insulation tape (Mica)	0,1 kg	0,2 kg			
Silicone sealing compound	0,0265 kg	0,0265 kg			
Nylon Bandage	0,05 kg	0,05 kg			
Epoxy Resin Impregnation	0,5 kg	0,5 kg			

Electricity	**0,9383 MJ** Bandage 0,008648 MJ Impreg+Curing 0,9296 MJ	**1,590 MJ** Bandage 0,008648 MJ Impreg+Curing 1,5819 MJ			

2.2.2.2 Rotor Manufacturing

In the next points, the inventories of the rotor manufacturing process are introduced, which are similar to the commented for the RFD PMa SynRel.

Rotor Punching, Stacking & Bonding

For the stacking process of the rotor core (Figure 45), the steel laminations are bonded by means of the "Backlack" technique, as was previously described. Their inventory is summarised on Table 27.

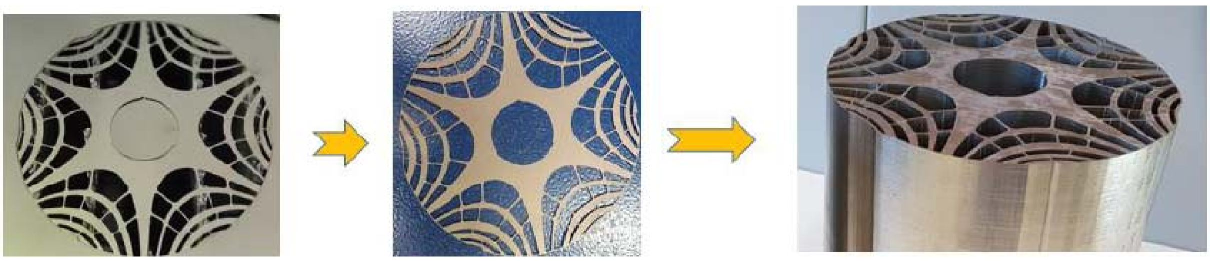


Figure 45: Stacking of rotor cores for Pure SynRel motors (Courtesy by LCD, Deliverable 6.3)

Table 27: Inventory of Punching, Stacking & Bonding processes for rotor (Pure SynRel machine)

Input	75 kW	200 kW	Output	75 kW	200 kW
Electrical Steel	10,557 kg	23,033 kg	Stacked Rotor	5,52 kg	12,06 kg
Epoxy Resin	0,02 kg	0,06 kg	Steel Scraps	5,057 kg	11,033 kg
Electricity	**1,243 MJ** Punching 0,2574 MJ Stacking 0,9853 MJ	**2,239 MJ** Punching 0,5616 MJ Stacking 1,677 MJ	Punching PERFORMANCE	0,521	0,521

Shaft Mounting into Rotor

To finish the rotor, in the case of the RFD Pure SynRel, no use of magnet is needed. Additionally, the steel shaft is mounted without the necessity of include endplates as in the PMa SynRel (Figure 46). This mounting stage has a simplified inventory, which is collected in the Table 28.

Figure 46: Insertion of rotor stacks on shaft

Table 28: Inventory of Shaft Mounting process for rotor (Pure SynRel machine)

Input	75 kW	200 kW	Output	75 kW	200 kW
Bonded and Bonded Rotor Core	5,52 kg	12,06 kg	Rotor package on shaft	8,52 kg	15,06 kg
Steel Shaft	3,0 kg	3,0 kg			
Electricity	0,1512 MJ	0,1512 MJ			

2.2.2.3 Cooling Housing Manufacturing

The cooling jacket employed for this Pure SynRel motor is exactly the same to the aluminium housing employed for the RFD PMa SynRel configurations. Therefore, the inventory of manufacturing process for the cooling jacket is as shown above in Table 22.

2.2.2.4 Assembly Stage

As final stage, the inventory of the end assembly process (Figure 47 and Figure 48) for the Pure SynRel machines within the REFREEDRIVE project is collected in the following Table 29.

Table 29: Inventory of assembly process (Pure SynRel machine)

Input	75 kW	200 kW	Output	75 kW	200 kW
Stator package, impregnated	14,03 kg	28,057 kg	Assembled motor	33,63 kg	54,20 kg
Rotor package on shaft	8,52 kg	15,06 kg			
Wire Terminal	0,051 kg	0,051 kg			
Al Housing and terminal block	10,5 kg	10,5 kg			

Bearing	0,28 kg	0,28 kg			
Steel Screws	0,25 kg	0,25 kg			
Electricity	3,3617 MJ	3,3617 MJ			

Figure 47: Wound stator insertion in the internal cooling case

Figure 48: Final motor assembly (75 kW Pure SynRel motor)

2.2.3 Induction Machines

In the following sections, the inventories of the copper rotor induction machines, developed within the REFREEDRIVE project, are presented. As it has been previously commented, two different options have been considered to manufacture the copper rotor: die cast or fabricated.

Additionally, comment here that the designed induction motors can be scaled and used for various power levels, simply by changing the control unit (power electronic). This means that the same motor can be used as an electro-mechanical converter for power levels between 75kW and 200kW [5]. That implies that there are not differences for the manufacturing process, between the version of medium power motor (75 kW) and the high power motor version (200 kW). That subject is already considered within the graphs and tables used in the explanations given in the next sections.

On the other hand, the only difference between one technology and another, for the induction motors in the RFD project, is the way in what copper is incorporated into the manufacturing process. The amount of copper introduced in the designs of each of the motors, is the same, which is shown in the fact that both motors have identical percentage distribution for the employed materials with respect to the final weight of the motor, as shown in the graphs in Figure 49.

Copper gains prominence in the RFD induction motors with respect to the RFD SynRel motors previously analyzed, going from 10% of its contribution to the overall weight of the motors (due to the copper in the winding of the stator for the SynRel motors), up to a value of 24% (including the copper in the stator plus the one used in the rotor).

Anyway, steel continues to be the component that makes the greatest contribution to the overall weight of induction motors, representing almost half of the weight.

On the other hand, the aluminium casing of the cooling system represents a quarter of the weight of the induction motors.

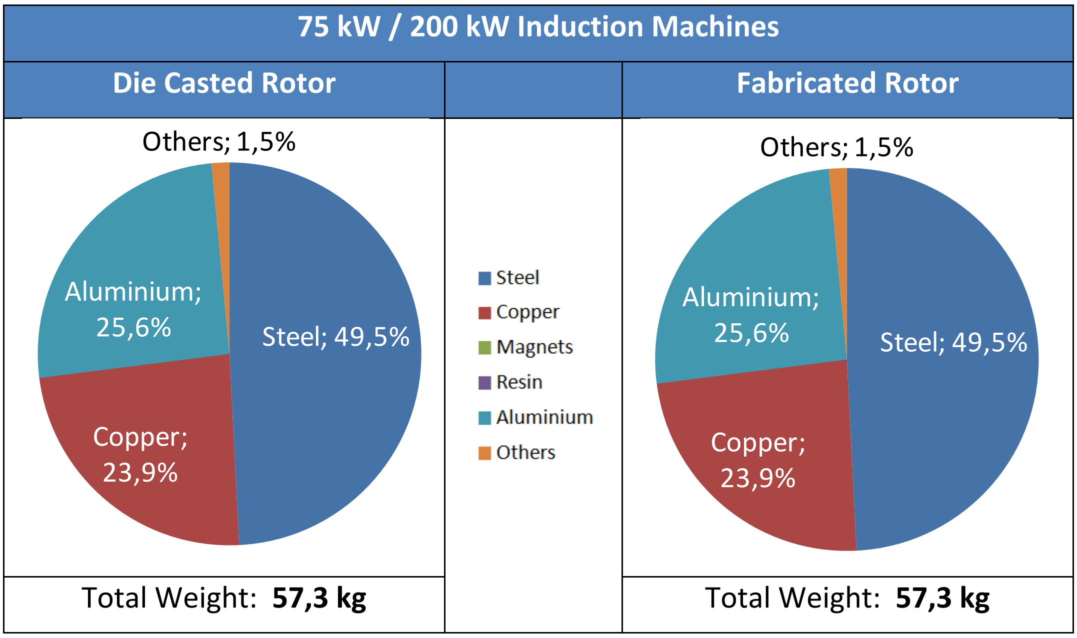


Figure 49: Mass configuration of the electrical machines (REFREEDRIVE Induction Machines with Die Cast Rotor and Fabricated Rotor) based on component inventory.

The flows inventory of each of the processes associated with the manufacture of the different components of each motor is detailed below making a single differentiation between them, when copper is incorporated in the rotor, due to that the rest of the manufacturing processes are common to both configurations (die cast rotor and fabricated rotor).

2.2.3.1 Stator Manufacturing (Die Cast Rotor and Fabricated Rotor IM)

The manufacturing process of the stator in this motor technology (Figure 50) is not different to the previously described for the other type of motor already shown in this document. The flow inventories for the stages in the manufacturing process of the stator are described below.

Stator Punching, Stacking & Welding

In the case of all the induction machines within the REFREEDRIVE project, the technique for holding the stack together is a welding process (Figure 50). The flow inventory for the punching, stacking and welding processes for the stator is the shown in the Table 30.

Figure 50: Stator stacks for the IMs (each stator is built with 36 slots).

Table 30: Inventory of punching and stacking process for stator (RFD Induction Machines)

Input	75 kW	200 kW	Output	75 kW	200 kW
Electrical Steel	32,568 kg		Stacked stator core	16,8 kg	
Electricity	**0,91 MJ** Punching 0,7941 MJ Stacking (Welding) 0,1159 MJ		Steel Scraps	15,6 kg	
			Punching PERFORMANCE	0.521	

Stator Slot Insulator

For this technology, stator is also insulated by means of PET foils (Figure 34) with the following materials consumption (Table 31).

Table 31: Inventory of Slot Insulation for stator (RFD Induction Machines)

Input	75 kW	200 kW	Output	75 kW	200 kW
Stacked stator core	16,8 kg		Stator core with Slot insulation	16,95 kg	
Polyethylene terephthalate (PET) foil	0,15 kg				

Installation of Winding & Insulation

As progress of electrification of vehicles, the motor technology comes to a new era for low-cost and high-volume production. Rectangular conductor winding (hairpins) is considered as one of the most promising solutions suitable for high performance and low-cost motors. It is supposed to have high filling factor, high thermal performance, high power density, and easy procedures for automatic production. This kind of winding has been implemented in the manufacturing of the stator for the RFD induction motors (Figure 51 and Figure 52).

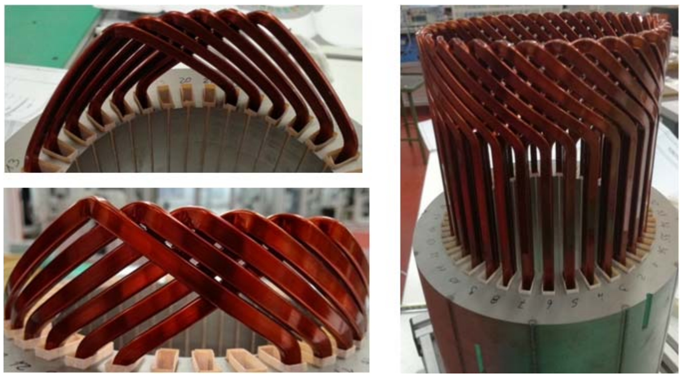


Figure 51: Hairpin winding insertion

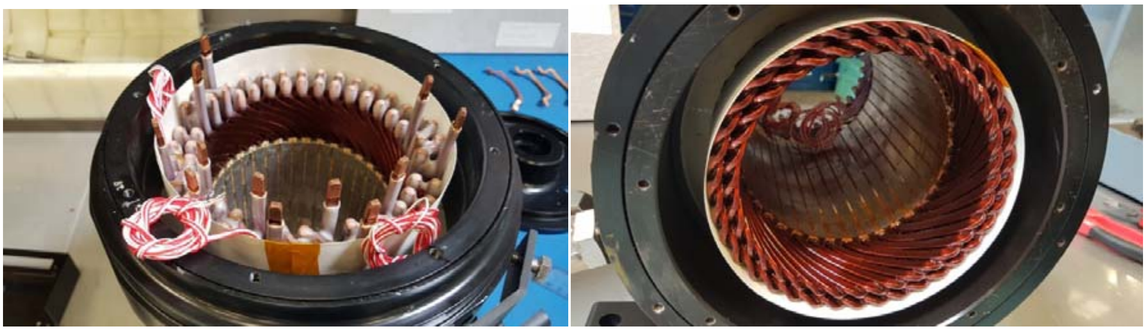


Figure 52: Finished hairpin winding on stator

Overall hairpins forming and assembly process (Figure 53) is material and electricity consuming, which also has to be considered into the LCA model

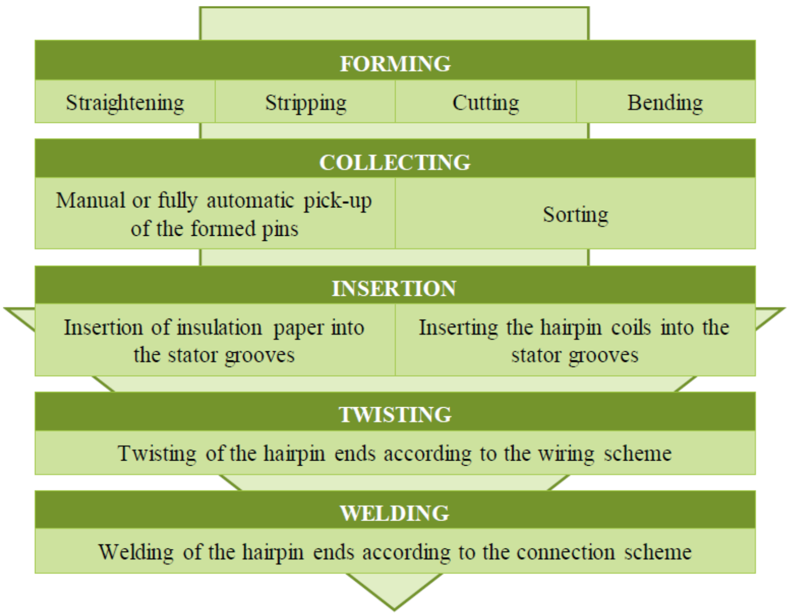


Figure 53: Process steps for manufacturing a hairpin stator [19]

In general, the process for equipping stators with hairpin coils is divided into the following steps (Figure 54):

- **Hairpin forming:** the hairpin is bent from insulated enamelled copper flat-wire. Once the winding head has been formed, the next step is to bring the hairpin to the desired length, strip it at the end analogous to the other end and then cut it off.
- **Hairpin assembly:** For assembly, the individual hairpins are first ordered in the respective arrangement of the layer structure. During the arrangement stage, due to better accessibility, the innermost layer is usually built up first and the outermost layer last. A distinction can also be made as to whether the wires are arranged directly in the stator grooves and connected directly or the arrangement is carried out with the aid of a joining and assembly tool. After the arrangement, the half-shaped formed coils must be inserted in the axial direction into the usually half-closed or closed stator slots.

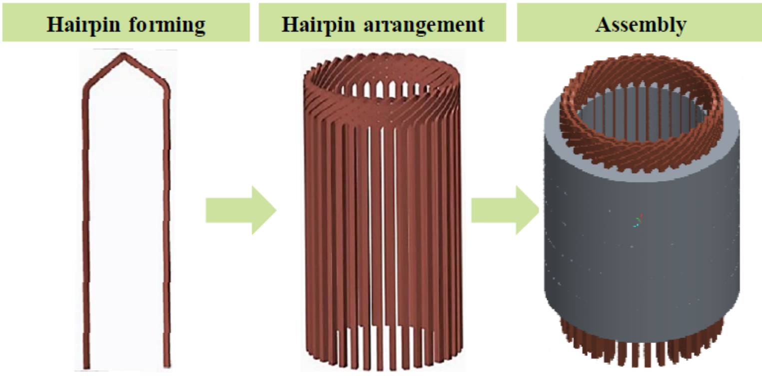


Figure 54: Hairpin arrangement and assembly

The flow inventory of the hairpin windings **forming** process from insulated enamelled copper flat-wire is summarized on the next Table 32, with data courtesy of Tecnomatic.

Table 32: Inventory of copper hairpins forming process (RFD Induction Machines)

Input	75 kW	200 kW	Output	75 kW	200 kW
Copper Coil	7,79 kg		Copper Hair Pin formed	7,7 kg	
Electricity	**9,0 MJ** Pin bar forming 7,2 MJ Hairpin 2D&3D forming 1,8 MJ		Cooper Scraps	0,09 kg	

Additionally, once the individual hairpins are available, the flow inventory of the hairpin windings **installation** process on the stator for RFD induction machines is summarized on the Table 33 (data also provided by Tecnomatic).

Table 33: Inventory of installation of hair Pin Winding for stator (Induction Machines)

Input	75 kW	200 kW	Output	75 kW	200 kW
Stator core with Slot insulation	16,95 kg		Stator package with	24,85 kg	

Copper Hair Pin formed	7,7 kg	Winding	
Electricity	**7,524 MJ** Insertion 1,8 MJ Twisting and Cutting 2,52 MJ Welding 1,044 MJ Varnishing and Curing 2,16 MJ		

2.2.3.2 Rotor Manufacturing (Die Cast Rotor and Fabricated Rotor IM)

In the next sections, the inventories of the rotor manufacturing process for the induction motors are shown, taking into account that the implementation of the copper for each motor technology (die-cast rotor or fabricated rotor) follows different industrial process. Manufacturing process for the rotor steel stacks is the same in both induction motors technologies.

Rotor Punching, Stacking & Welding

For the stacking process of the rotor core (Figure 55), the steel laminations are welded, in a similar way to how the stator stacks were also obtained. Their inventory is summarised on Table 34.

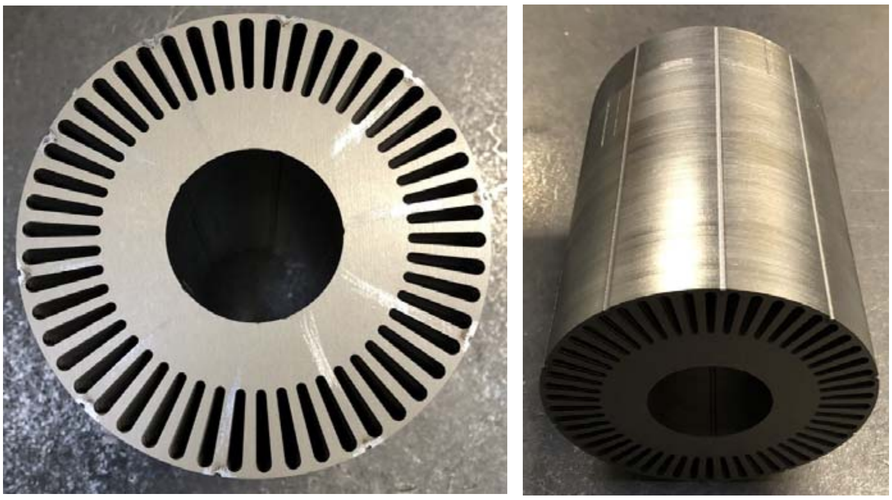


Figure 55: Rotor stack for copper rotor in induction machines (Fabricated or Die Cast Rotor)

Table 34: Inventory of Punching, & Stacking processes for rotor (RFD Induction Machines)

Input	75 kW	200 kW	Output	75 kW	200 kW
Electrical Steel	15,135 kg		Stacked Rotor core	7,9 kg	
Electricity	**0,489 MJ** Punching 0,3734 MJ Stacking (Welding) 0,1159 MJ		Steel Scraps	7,336 kg	
			Punching PERFORMANCE	0.521	

Once the rotor core is manufactured, copper has to be incorporated by means of the two technologies employed within the REFREEDRIVE project (die cast rotor or fabricated rotor), as follows.

Copper Casting of Induction Rotor (Die Cast Rotor IM)

Breuckmann produces rotors using a process that is similar to die casting (Figure 56 and Figure 57), by means of a casting process named Laminar Squeeze Casting. Due to this working method, the amount of conductive material as well as the fill factor of rotors is maximized. The result is that the slots inside of the rotor are completely filled.

Table 35 summarizes the flows inventory related with the Breuckmann´s process to obtain the die cast rotor to use in the RFD induction machine.

Figure 56: Stack on casting mandrel.

Figure 57: End-ring at melt ingate side, after machining.

Table 35: Inventory of Copper casting process for rotor (Induction Machine with Die Cast Rotor)

Input	75 kW	200 kW	Output	75 kW	200 kW
Stacked Rotor core	7,9 kg		Assembled Rotor	13,9 kg	
Copper	6 kg				
Electricity	7,8545 MJ				

Copper Bar/End rings Mounting on Rotor (Fabricated Rotor IM)

The rotor bars and end-rings shown in Figure 58, were manufactured in the production facilities at Aurubis, such as described into REFREEDRIVE deliverable D6.6 [9]. Table 36 summarises the flow inventory for the fabricated rotor

Figure 58: Induction motor fabricated copper cage (assembled for demonstration purposes).

Table 36: Inventory of Copper mounting process for rotor (Induction Machine with Fabricated Rotor)

Input	75 kW	200 kW	Output	75 kW	200 kW
Stacked Rotor core	7,9 kg		Assembled Rotor	13,9 kg	
Copper Bars	5,0 kg				
Copper Ends Rings	1,0 kg				
Electricity	1 MJ				

Data concerning the manufacturing processes for the cooper bars and end rings were provided to CIDAUT by Aurubis, in order to allow modelling their production stages on the LCA software. Following Table 37 and Table 38 collect the flow inventories related to the manufacturing processes of both copper parts employed on the fabricated rotor within the RFD induction machines.

According to the data provided [9], the raw materials, scrap and blister copper, are melted at 1150°C in a shaft furnace. The molten copper is cast in the mould and subsequently cooled. Then, an electrolysis process is applied to obtain a cathode of 99.9995% pure copper. After that, Copper cathodes are melted in a furnace and hydrostatically cast upwards from the molten metal, into a rod. Then, copper rods are extruded to obtain the needed copper bars shape. The inventory of this process is summarised on Table 37.

Table 37: Inventory of Copper bars manufacturing process (Induction Machine with Fabricated Rotor)

Input	75 kW	200 kW	Output	75 kW	200 kW
Blister copper	5 kg		Copper Bars	5 kg	
In-home Copper scraps	2,38 kg		Copper scraps	2,38 kg	
Electricity	**40,731 MJ**				

In the case of the copper end rings, manufacturing process is slight different. The end rings are wire eroded from a drawn rectangular bar. The process involves an initial cut; this allows for the relaxation of the contained stresses and then a final wire pass is done to achieve the required geometrical form. Table 38 summarises the flow inventory of this manufacturing process.

Table 38: Inventory of Copper ends rings manufacturing process (Induction Machine with Fabricated Rotor)

Input	75 kW	200 kW	Output	75 kW	200 kW
Blister copper	1,00 kg		Copper Ends Rings	1,00 kg	
In-home Copper scraps	0,935 kg		Copper scraps	0,935 kg	
Electricity	**11,364 MJ**				

Mounting Rotor on Shaft

To finish the rotor, the steel shaft is mounted on it. This mounting stage has a simplified inventory, which is collected in the Table 39.

Table 39: Inventory of Shaft mounting process for rotor (Induction Machines)

Input	75 kW	200 kW	Output	75 kW	200 kW
Assembled Rotor	13,9 kg		Rotor Package on Shaft	17,02 kg	
Steel Shaft	3,12 kg				
Electricity	0,1512 MJ				

Cooling Housing Manufacturing

The following Table 40 summarises the flows inventory related to the manufacturing process of the cooling housing.

Table 40: Inventory of Cooling Housing Manufacturing process (RFD Induction Machines)

Input	75 kW	200 kW	Output	75 kW	200 kW
Aluminium Housing	14,69 kg		Housing and terminal block	14,82 kg	
Plastic Part	0,13 kg				
Electricity	**59,965 MJ** Al cast part production: 53,38 MJ Al cast part machining: 2,59 MJ Al part cleaning: 3,132 MJ Plastic part production: 0,8635 MJ				

Assembly Stage

As final stage, in this section it is collected the inventory data (Table 41) for the end assembly process for the induction machines within the REFREEDRIVE project (Figure 59)

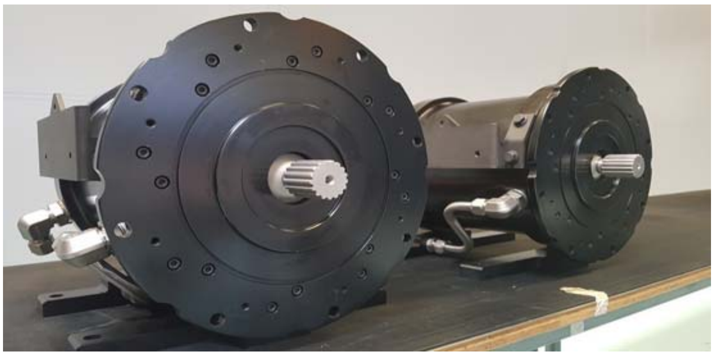


Figure 59: Induction Machine complete assembly

Table 41: Inventory of assembly process (Induction Machines)

Input	75 kW	200 kW	Output	75 kW	200 kW
Stator package, impregnated	24,85 kg		Assembled motor	57,271 kg	
Rotor package on shaft	17,02 kg				
Wire Terminal	0,051 kg				
Al Housing and terminal block	14,82 kg				
Bearing	0,28 kg				
Steel Screws	0,25 kg				
Electricity	3,3617 MJ				

3 Results - Life Cycle Impact Assessment (LCIA)

The ISO 14044 standard defines Life Cycle Impact Assessment (LCIA) as the phase of life cycle assessment aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts of a product system. The purpose of the impact assessment phase is thus to interpret the life cycle emissions and resource consumption inventory [2].

Therefore, Life Cycle Impact Assessment (LCIA) is the phase in an LCA where the **inputs** and **outputs** of elementary flows that have been collected and reported in the inventory are **translated** into **impact indicator results**. The results of LCIA should be seen as environmentally relevant impact potential indicators, rather than predictions of actual environmental effects.

In the next sections, LCIA results from the different electric motors within the performed LCA are introduced, for each environmental impact category. First of all, a brief description of the meaning of each environmental impact category is introduced, before showing a summary for the LCA results of the electric motors, which allow comparing its environmental impact, individually, for each impact category. First, a comparison of the results of all electric machine versions is made (overall comparison), and then each type of technology is analyzed separately (individual comparison for reference machine, RFD SynRel and RFD IM).

The study will be accompanied by tables of values (from Table 42 to Table 63), as well as graphs (from Figure 60 to Figure 88) where the contributions of each part of the motor to the environmental impact that is being analyzed in each case are displayed.

As extended complement, in the "Annex Extended Results", it is exposed the breakdown of the environmental impact of each electric motor part, of each and every one of the machines (reference and REFREEDRIVE ones), showing which components are the most relevant from the environmental impact viewpoint, in each of the impact categories analyzed.

3.1 Primary Energy Demand

Energy demand is the term used to describe the consumption of energy by human activity. Primary energy consumption measures total energy demand, while final energy consumption refers to what end users consume. The difference between both concepts relates mainly to what the energy sector needs itself and to transformation and distribution losses.

Therefore, primary energy consists of unconverted or original fuels, including as primary energy sources, petroleum, natural gas, coal, biomass, flowing water, wind, and solar radiation. An additional classification for the primary energy demand can be performed according to the renewable/non renewable origin of the energy source.

The measurement unit for the Primary Energy Demand impact category is mega joules (MJ).

Table 42: Environmental impact comparison among analysed machines – Primary Energy Demand

Primary energy demand from ren. and non ren. resources (gross cal. value) [MJ]			75 kW	200 kW
Reference (PM SynRel)			5125,5 MJ	11676,0 MJ
REFREEDRIVE Machines	Syn Rel	PM assisted	3929,8 MJ	5503,5 MJ
		Pure	3451,6 MJ	4648,5 MJ
	Induction Machine	Die Cast	5001,31 MJ	
		Fabricated	5369,9 MJ	

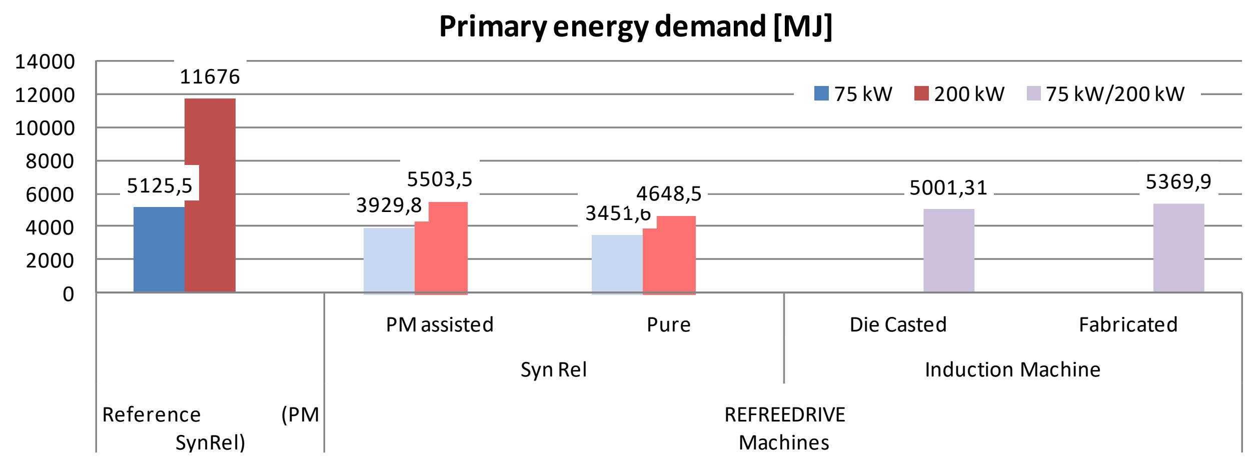


Figure 60: Environmental impact comparison among analysed machines – Primary Energy Demand

3.1.1 Overall Comparison

It can be stated that REFREEDRIVE solutions consume less amount of primary energy, related to the manufacturing phase, than their reference counterparts.

Below there is a brief analysis based on the power of the electric motors.

3.1.1.1 200 kW configuration

The **200 kW RFD motors** (all technologies Induction and Synrel- Table 43), consume up to 55% less energy than their 200 kW NdFeB PM counterpart.

The difference in energy consumption between the 200 kW motors within the REFREEDRIVE project, and the motor taken as a reference, is mainly due to the non-need to use NdFeB permanent magnets (valuated in 3530 MJ), but also, due to the use of an optimized cooling casing. The manufacture of the RFD motor cooling jacket represents at least half of the energy demand of the reference (valued at 4,900 MJ)

The steel consumption in SynRel motors (2100 MJ -2200 MJ) is very similar in all the technological variations (reference, PMs and Pure). Induction motors use less electrical steel, and therefore have lower energy consumption (1540 MJ).

However, if the required copper (mainly within the rotor, but also in the stator) is taken into account, the overall energy consumption related to the steel and the copper, is similar for all the different types of motors (2150 MJ – 2330 MJ), with the exception of the Die Cast rotor machines, whose value is only 1715 MJ.

Table 43: Environmental impact comparison among 200 kW machines – Primary Energy Demand

200 kW Primary energy demand (MJ)	SynRel			Induction	
	NdFeB PM (Reference)	PM assisted (RFD)	Pure (RFD)	Die Cast (RFD)	Fabricated (RFD)
TOTAL	**11676**	**5503,5**	**4648,5**	**5001,31**	**5369,9**
Steel Stacks (Stator & Rotor)	2093,4	2210,6	2081,09	1540,5	1540,5
Copper Winding	84,04	92,64	64,602	97,476	97,476
Copper on Rotor	----	----	----	75,077	455,82
Magnets on Rotor	3530	23,96	----	----	----
Steel Rotor Shaft	436,52	451,21	314,81	327,4	327,39
Insulation Resin	26,23	346	74,55	----	----
Al End Plates on rotor	----	125,92	----	----	----
Cooling Housing	4899	1859,6	1859,6	2630,1	2630,1
Others	606,8	393,57	253,85	330,77	318,61

3.1.1.2 75 kW configuration

The **75 kW RFD SynRel motors** consume around 28% less primary energy than the reference motor, mainly due to the absence of permanent NdFeB magnets (its contribution is valued at 1650 MJ, as seen in the Table 44).

Despite the optimization of the cooling system, the use in the 75kW RFD motors of an aluminium casing dimensioned for a 200 kW motor avoids further reducing the overall energy demand. The aluminium casings in these motors (both in the reference and in the RFDs), have a similar contribution to the total energy consumption (around 1900 MJ)

Table 44: Environmental impact comparison among 75 kW SynRel machines – Primary Energy Demand

75 kW Primary energy demand (MJ)	SynRel machines		
	NdFeB PM Reference	PM assisted (RFD)	Pure (RFD)
TOTAL	**5125,5**	**3929,8**	**3451,6**
Steel Stacks (Stator & Rotor)	982,95	827,48	932,41
Copper Winding	50,97	54,85	43,881
Magnets on Rotor	1650,2	8,87	---

Steel Rotor Shaft	132,21	430,22	314,81
Insulation Resin	15,91	334,21	66,08
Al endplates on rotors	---	125,95	---
Cooling Housing	1983,3	1859,6	1859,6
Others	309,96	288,65	234,82

The **75 kW RFD IM motors** consume approximately the same energy as the 75kW PM NdFeB motors (about 5200 MJ, in Table 45), since the former are sized to provide up to 200 kW, modifying its power electronics, what conditions its direct comparison.

This over sizing of the 75 kW motors (which implies the use of more steel and copper), partially compensates the effect on the primary energy demand of the NdFeB magnets used by the reference motor.

Furthermore, the aluminium casing in RFD motors has a greater contribution to the total primary energy consumption (2630 MJ) than in the reference motor (around 2000 MJ), because it is also dimensioned for 200 kW motors, as the active parts of the motor.

Table 45: Environmental impact comparison for 75 kW Induction machines – Primary Energy Demand

75 kW Primary energy demand (MJ)	SynRel	Induction	
	NdFeB PM (Reference)	Die Cast (RFD)	Fabricated (RFD)
TOTAL	**5125,5**	**5001,31**	**5369,9**
Steel Stacks (Stator & Rotor)	982,95	1540,5	1540,5
Copper Winding (Stator)	50,97	97,476	97,476
Copper on Rotor	----	75,077	455,82
Magnets on Rotor	1650,2	----	----
Steel Rotor Shaft	132,21	327,4	327,39
Insulation Resin	15,91	----	----
Al End Plates on rotor	----	----	----
Cooling Housing	1983,3	2630,1	2630,1
Others	309,96	330,77	318,614

3.1.2 Individual Comparison, by motor technology

3.1.2.1 Reference (NdFeB PM SynRel)

The levels of primary energy consumption in the reference motors are given by each of its parts in different contributions.

Therefore, aluminium housings demand about 40% of the total energy required (see Figure 61: Contribution to Primary Energy Demand, of main parts of reference motor (NdFeB PM SynRel machines). Obtaining NdFeB permanent magnets, implies around 30% of the overall energy demand, while the energy consumption related to obtaining electrical steel laminations, means 20% of energy consumption. This allocation is very similar regardless of the motor power, such as shown on Figure 61.

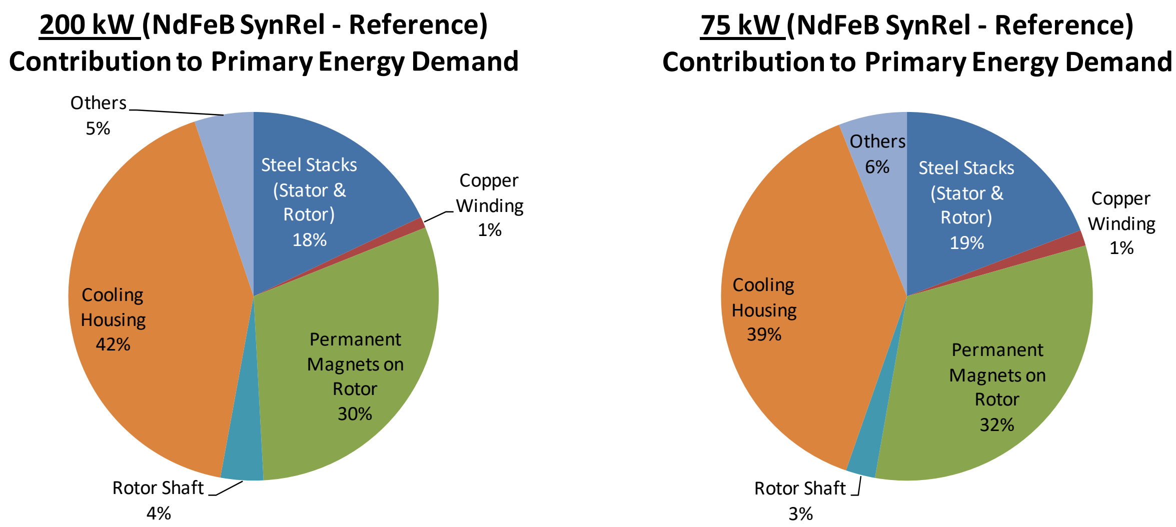


Figure 61: Contribution to Primary Energy Demand, of main parts of reference motor (NdFeB PM SynRel machines).

3.1.2.2 REFREEDRIVE SynRel

In the case of the REFREEDRIVE motors with ferrite magnets (**PMa SynRel**), for the 200 kW motors, the highest energy consumption is given by the use of electrical steels in the stator and rotor (40% of the overall primary energy demand), followed by the aluminium casing (34%) (see left diagram in Figure 62). In the 200 kW motor, steel shaft accounts for 8% of the energy demand.

By scaling up to the 75 kW version, keeping the same casing and shaft as the case of the 200 kW version, the aluminium casing represents in this other case, more than 45% of the energy consumption (see right diagram in Figure 62). The contribution of the electrical steel used in the stator and rotor decreases in this case (when scaled for a lower power), up to 21%.

In either of the two power configurations, the ferrite magnets used have little relevance from the energy demand viewpoint (about 1%), unlike the use of NdFeB magnets in the reference motors

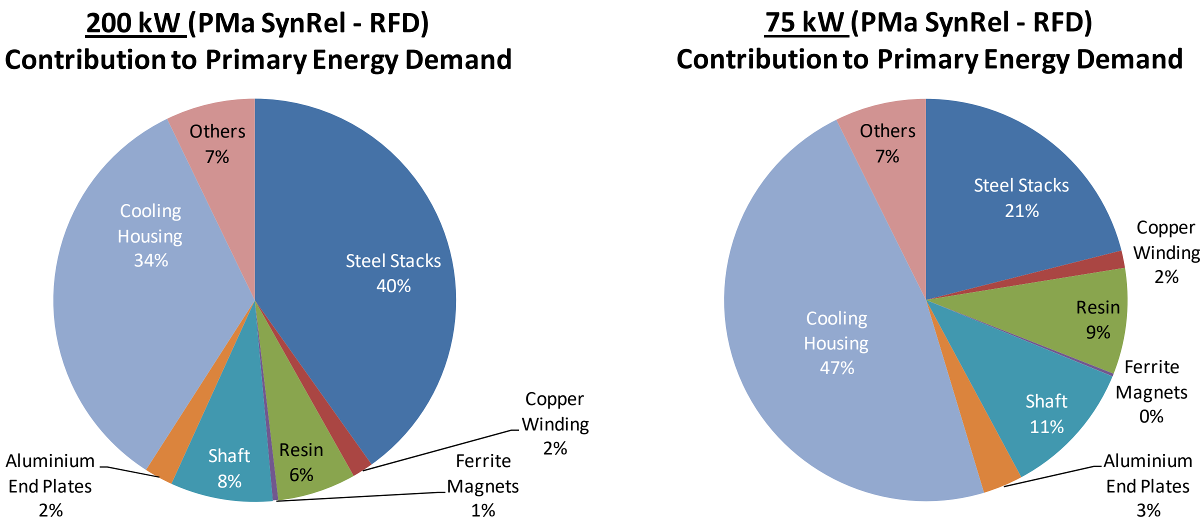


Figure 62: Contribution to Primary Energy Demand, of main parts of REFREEDRIVE PMa SynRel machines.

For the **Pure SynRel** versions (Figure 63), the conclusions of the analysis carried out are similar to the case of its version with ferrite magnets (PMa SynRel). In the 200 kW motor, the use of electric steels (45%) and the aluminium casing (40%) are also particularly relevant. Moving to the smaller motor (75 kW), while retaining the 200 kW casing and shaft, the relevance of the aluminium casing rises to almost 54%, while the electric steel drops to 27%.

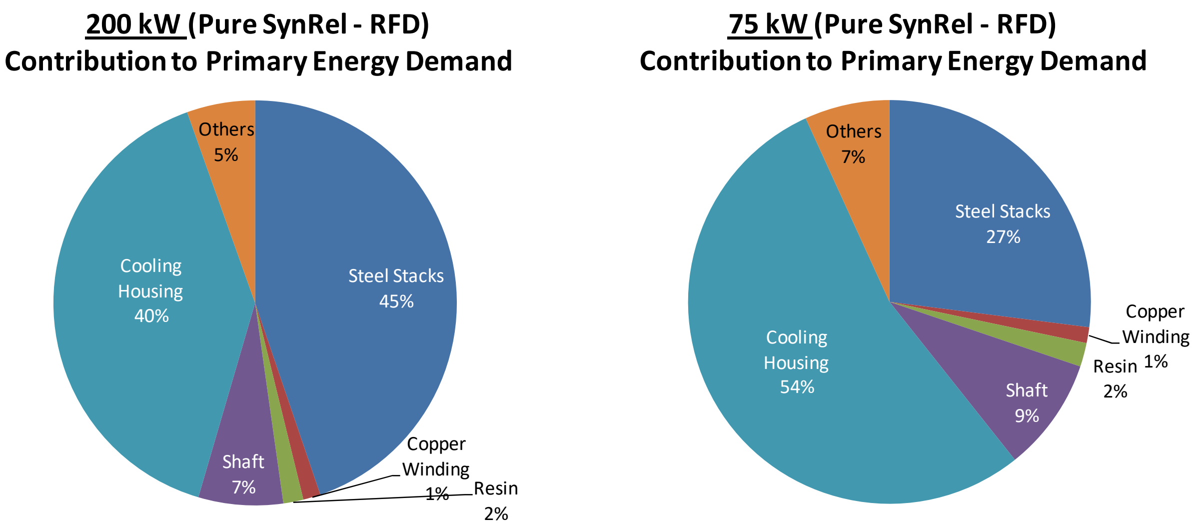


Figure 63: Contribution to Primary Energy Demand, of main parts of REFREEDRIVE Pure SynRel machines.

In the different configurations of RFD SynRel motors (both in terms of power and technology), the rotor shaft represents between 7% and 11% of the energy demand (a higher proportion in PM than in Pure ones, and a lower ratio in the 200 kW to the 75 kW by maintaining the shaft size)

On the other hand, in all SynRel motors (reference, RFD PM assisted or RFD Pure), the impact of the stator copper is not very relevant, oscillating between 1% and 2%, depending on the power and the motor technology (Figure 63)

3.1.2.3 REFREEDRIVE Induction

In the two versions of the Induction motors within the project (Die-cast and Fabricated Rotors), the aluminium casing represents approximately half of the energy demand for the manufacture of the motors (Figure 64).

The use of electrical steel in the stator and rotor accounts for almost 30% of energy consumption, while the steel shaft, slightly more than 6%.

Regarding the incorporation of copper in the rotor (in addition to that used in the stator), it implies that the total impact of copper increases from slightly less than 2% (in the case of SynRel motors; Figure 62 and Figure 63), to 3,5% for the "Casted IM" version and up to 10,3% in the "Fabricated IM" version (Figure 64). These slight differences between induction motors are due to the different characteristics associated with the source of the copper in each case.

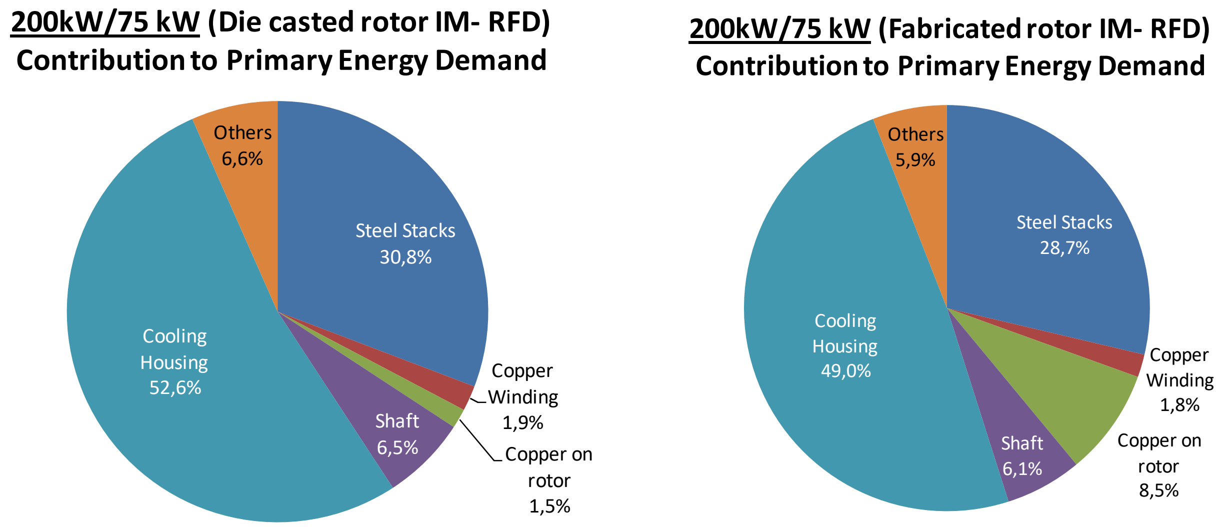


Figure 64: Contribution to Primary Energy Demand, of main parts of REFREEDRIVE Induction machines.

3.2 *Climate change*

Climate change involves a number of environmental mechanisms that affect both the Human Health and Natural Environment. Man-made climate change is caused by the emission of greenhouse gases.

Greenhouse gases are gas molecules that have the property of absorbing infrared radiation (net heat energy) emitted from Earth's surface and reradiating it back to Earth's surface, thus contributing to the phenomenon known as the greenhouse effect. The greenhouse effect is the way in which heat is trapped close to the surface of the Earth by greenhouse gases.

Rising concentrations of greenhouse gases produce an increase in the average surface temperature of the Earth over time. Rising temperatures may produce changes in precipitation patterns, storm severity, and sea level

Its unit of measurement is Kilogram of Carbon Dioxide equivalent (kg CO_2 eq).

Table 46: Environmental impact comparison among analysed machines – Climate change

<table>
<tr><th colspan="3">Climate change (incl. biogenic carbon)
[kg CO_2-Equiv.]</th><th>75 kW</th><th>200 kW</th></tr>
<tr><td colspan="3">Reference (PM SynRel)</td><td>306,67 kg</td><td>692,51 kg</td></tr>
<tr><td rowspan="4">REFREEDRIVE Machines</td><td rowspan="2">Syn Rel</td><td>PM assisted</td><td>231,73 kg</td><td>368,45 kg</td></tr>
<tr><td>Pure</td><td>214,05 kg</td><td>322,52 kg</td></tr>
<tr><td rowspan="2">Induction Machine</td><td>Die Cast</td><td colspan="2">319,55 kg</td></tr>
<tr><td>Fabricated</td><td colspan="2">339,64 kg</td></tr>
</table>

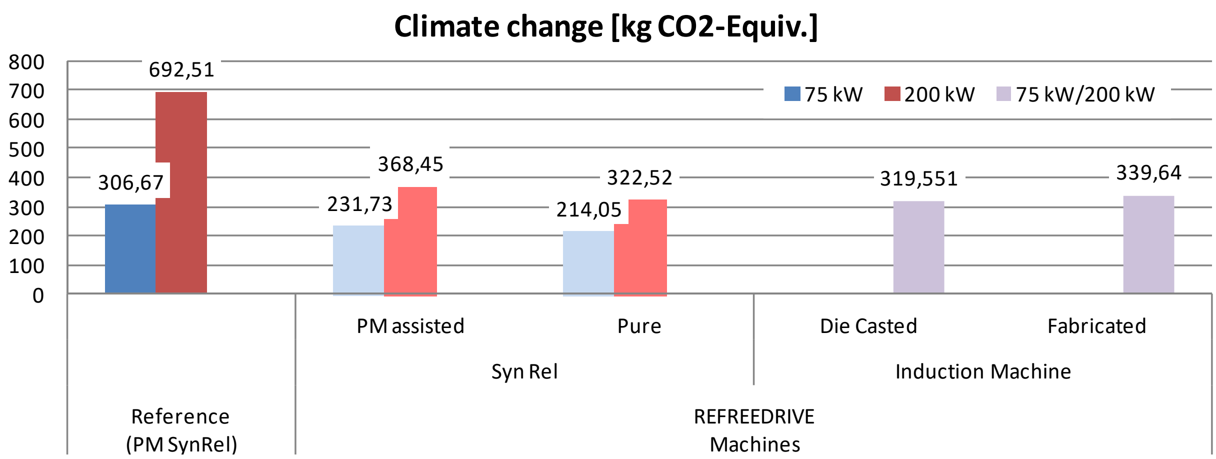


Figure 65: Environmental impact comparison among analysed machines – Climate change

A very important part of the greenhouse gas emissions linked to any process or product, is directly related to its demand of primary energy (impact category analyzed in the previous section). Thus, for the impact category called "Climate Change", which is analysed in this section, the conclusions drawn from the LCA study are very similar to what was previously commented in the previous section (Primary energy demand).

3.2.1 Overall Comparison

As in the previous case (Primary energy demand), it can be stated that REFREEDRIVE solutions emit a lower amount of greenhouse gases during their manufacturing phase than their reference counterpart (NdFeB PM SynRel motors).

3.2.1.1 200 kW configuration

The **RFD 200 kW motors** (Induction and SynRel) emit approximately half the greenhouse gases of their NdFeB PM counterpart (approximately 340 kg CO_2 eq versus 690 kg CO_2 eq as shown within Table 47), due to the non-need to use permanent NdFeB magnets (contributing with 190 kg), as well as optimization of the cooling system, so the size of the aluminium casing in RFD motors is smaller than that of the motor taken as a reference (95 kg – 135 kg versus 250 kg).

Table 47: Environmental impact comparison among 200 kW machines - Climate Change

200 kW Climate Change (kg CO_2 eq)	SynRel			Induction	
	NdFeB PM (Reference)	PM assisted (RFD)	Pure (RFD)	Die Cast (RFD)	Fabricated (RFD)
TOTAL	**692,51**	**368,45**	**322,52**	**319,55**	**339,64**
Steel Stacks (Stator & Rotor)	193,24	204,061	192,09	142,2	141,2
Copper Winding	5,345	5,892	4,11	6,199	6,199
Copper on Rotor	----	----	----	4,775	25,209
Magnets on Rotor	191,15	1,606	----	----	----
Steel Rotor Shaft	23,761	6,516	17,135	17,821	17,821
Insulation Resin	0,8796	14,31	2,97	----	----
Al End Plates on rotor	----	24,561	----	----	----
Cooling Housing	253,55	95,9	95,9	135,76	135,76
Others	24,584	15,60	10,315	12,90	13,45

3.2.1.2 75 kW configuration

The **75 kW RFD SynRel motors** emits around 27% less greenhouse gases during its manufacturing process, a value that is the contribution related to the elimination of permanent NdFeB magnets (90 kg CO_2 eq, Table 48).

The contribution of the aluminium casing production is similar for the three motors (approximately 100 kg), although it must be taken into account that in the case of RFD motors, this casing is oversized, to be used also in the 200 kW motors.

Table 48: Environmental impact comparison among 75 kW SynRel machines – Climate Change

75 kW Climate Change (kg CO_2 eq)	SynRel machines		
	NdFeB PM Reference	PM assisted (RFD)	Pure (RFD)
TOTAL	**306,67**	**231,73**	**214,05**
Steel Stacks (Stator & Rotor)	90,736	76,382	86,071
Copper Winding	3,242	3,489	2,79
Magnets on Rotor	89,36	0,595	----
Steel Rotor Shaft	7,2	6,516	17,135
Insulation Resin	0,533	13,914	2,75
Al endplates on rotors	---	23,418	---
Cooling Housing	102,34	95,9	95,9
Others	13,259	11,516	9,404

The **75 kW IM motors** in the RFD project emit approximately the same amount of greenhouse gases as those of NdFeB PM ones (also 75kW), since the former are sized to provide 200 kW (which implies greater use of steel in stator and rotor, and aluminium in the cooling housing). This fact penalizes the 75 kW IM motors from an environmental point of view, and does not compensate the elimination of the NdFeB magnets use (almost 90 kg CO_2 eq).

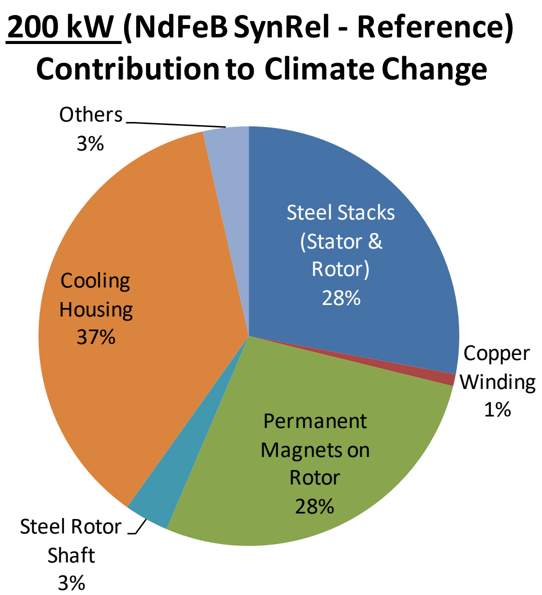
Table 49: Environmental impact comparison for 75 kW Induction machines – Climate Change

75 kW Climate Change (kg CO_2 eq)	SynRel	Induction	
	NdFeB PM (Reference)	Die Cast (RFD)	Fabricated (RFD)
TOTAL	**306,67**	**319,55**	**339,64**
Steel Stacks (Stator & Rotor)	90,736	142,2	141,2
Copper Winding (Stator)	3,242	6,199	6,199
Copper on Rotor	----	4,775	25,209
Magnets on Rotor	89,36	----	----
Steel Rotor Shaft	7,2	17,821	17,821
Insulation Resin	0,533	----	----
Al End Plates on rotor	----	----	----
Cooling Housing	102,34	135,76	135,76
Others	13,259	12,90	13,451

3.2.2 Individual Comparison, by motor technology

3.2.2.1 Reference (NdFeB PM SynRel)

The value of greenhouse gas emissions in the motors taken as a reference in the LCA study (NdFeB PM SynRel), are given in approximately equal parts (around 30%), by the use of electrical steels, the aluminium of the cooling casing, and the permanent magnets. The contributions of each component are very similar regardless of motor power (Figure 66)



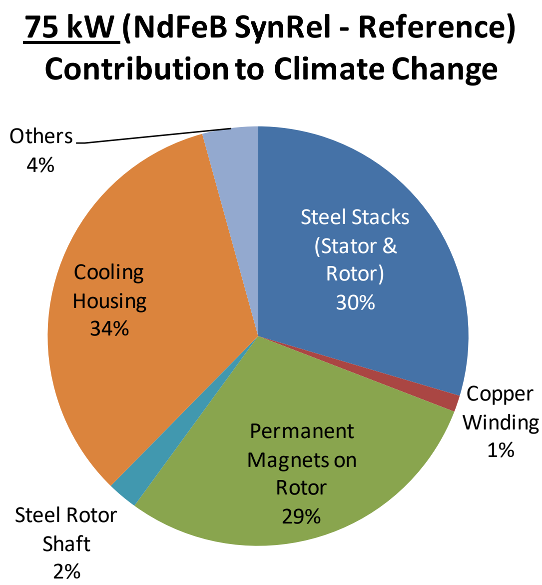


Figure 66: Contribution to Climate Change, of main parts of reference motor (NdFeB PM SynRel machines).

3.2.2.2 REFREEDRIVE SynRel

In the **200 kW RFD PMa SynRel** motor configuration, the component with the highest contribution to greenhouse effect emissions (see left graph on Figure 67), is the electrical steel used in the construction of the stator and rotor (55%), followed at a significant distance by the aluminium casing of the cooling system (26%).

In the **75 kW RFD PMa SynRel** version, keeping the casing and the axis of the 200 kW model, but scaling down the rest of the components, it is the aluminium casing that supplies the greatest contribution to the emission of greenhouse gases present (41%), decreasing the contribution of electrical steel up to 33% (right graph on Figure 67).

The contribution of the ferrite magnets in both versions of the motor is negligible.

It is worth highlighting the contribution of the two aluminium endplates used in the rotor, despite their light weight, representing between 7% and 10% of the total contribution, depending on the motor power.

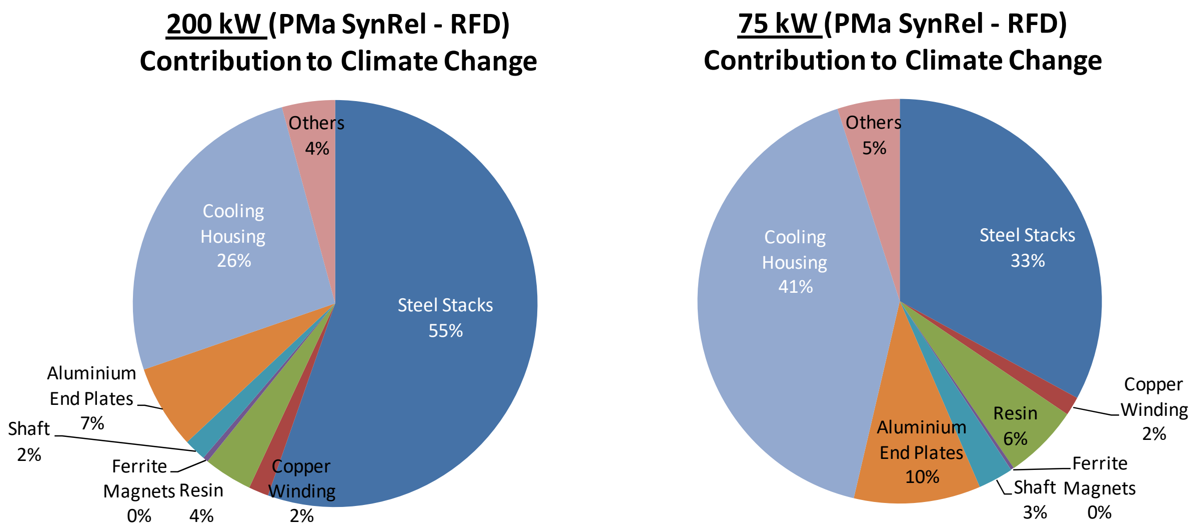


Figure 67: Contribution to Climate Change, of main parts of REFREEDRIVE PMa SynRel machines.

For the **Pure SynRel** motors within the project, the conclusions regarding the electrical steels and the aluminium casing are very similar to the case of motors with ferrite magnets (PMa SynRel), also significantly changing their contributions depending on the power of the motors (Figure 68).

According to the environmental study for the Pure SynRel motors, the global percentages vary with respect to the values previously shown for the PMa SynRel, mainly due to the fact that in the case of the Pure SynRel motors, aluminium endplates are not used in its rotor, together with that the size of the shaft is slightly higher than the PMa SynRel motor. Greenhouse gases emission is also influenced by the use of a lower amount of resin for the insulation.

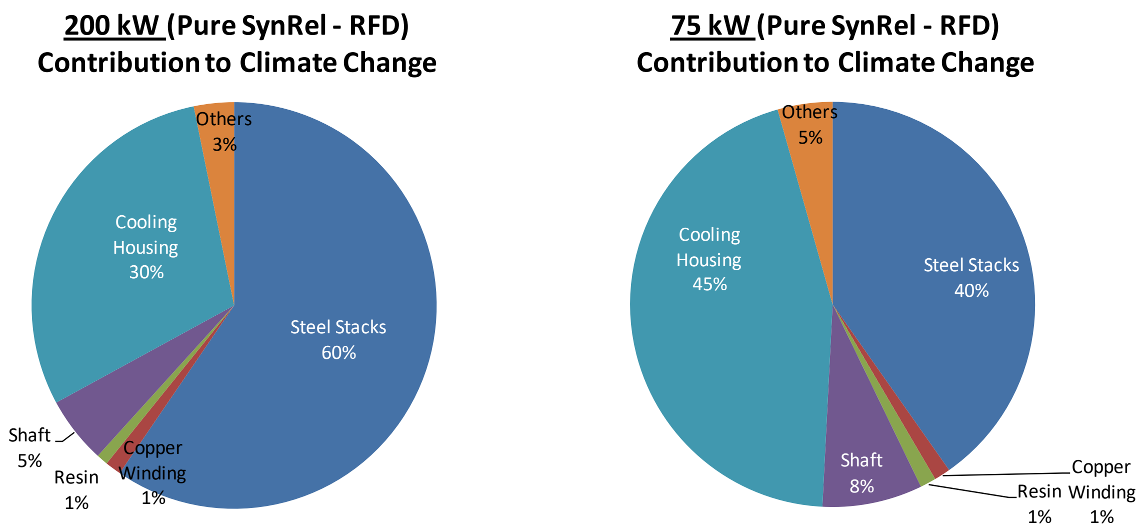


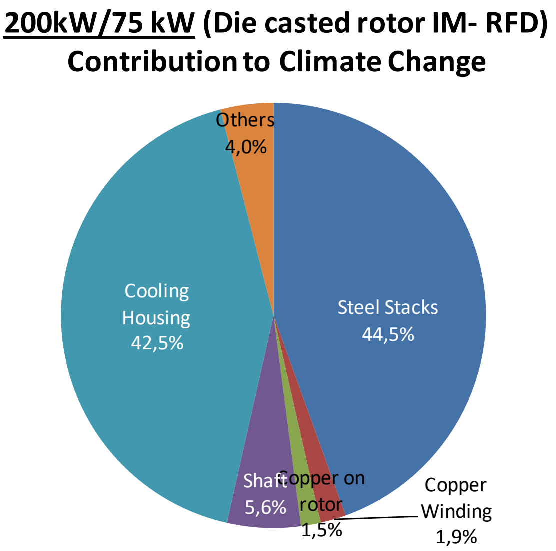
Figure 68: Contribution to Climate Change, of main parts of REFREEDRIVE Pure SynRel machines.

3.2.2.3 REFREEDRIVE Induction

In both configurations of RFD induction motors, both the use of electrical steels and the use of aluminium in the cooling casing, imply a similar contribution, among them, to greenhouse gas emissions (around 40% each one of them, as it is shown on Figure 69).

Steel shaft provides a little more of a 5% of the impact in this environmental category.

The contribution of the copper used in both the stator and the rotor is the next element with the greatest impact on climate change, reaching between 3,5% and 9%, depending on the rotor manufacturing technology (Die-cast or fabricated rotors, respectively).



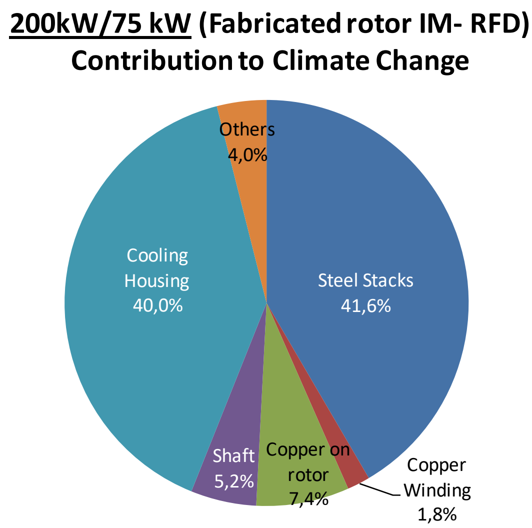


Figure 69: Contribution to Climate Change, of main parts of REFREEDRIVE Induction machines.

3.3 Resource depletion

This impact category is referred to the consumption of resources, addressing use of natural resources, either renewable or non-renewable, either biotic or abiotic[6]. Its measurement unit is kilogram of antimony (Sb) equivalent.

The Earth contains a finite amount of non-renewable resources, such as metals and fuels. Depletion of resources (abiotic resource depletion) is the decrease of availability of the total reserve of potential functions of resources, due to the use beyond their rate of replacement. This impact category considers the effect on both renewable and non-renewable resources. Depletion of minerals and fossil fuels falls within the category of non-renewable resources, while extraction of water, wind (abiotic) and wood (biotic) falls within renewable resources.

[6] Abiotic resources are inorganic or non-living materials at the moment of extraction (e.g. water, metals, also dead organic matter such as peat, coal).
Biotic resources are living at least until the moment of extraction from the natural environment (e.g. wood, fish)

Extraction and entire process of metal productions are well known for their high energy intensiveness and also high associated environmental impacts. These circumstances (high energy demand and high environmental impact) are maximized in the case of rare earth extraction. The list of environmental concerns that can be connected with rare earth elements is not a brief one. Throughout the cycle of mining processes that rare earth elements go through, there is potential for negative effects on the environment (see section 4.1.2.1 Rare Earths for magnets).

Table 50: Environmental impact comparison among analysed machines – Resource depletion

Resource depletion, mineral, fossils and renewables, [kg Sb eq.]			75 kW	200 kW
Reference (PM SynRel)			0,38174 kg	0,81521 kg
REFREEDRIVE Machines	Syn Rel	PM assisted	0,003565 kg	0,004655 kg
		Pure	0,003218 kg	0,0038826 kg
	Induction Machine	Die Cast	0,006766 kg	
		Fabricated	0,09343 kg	

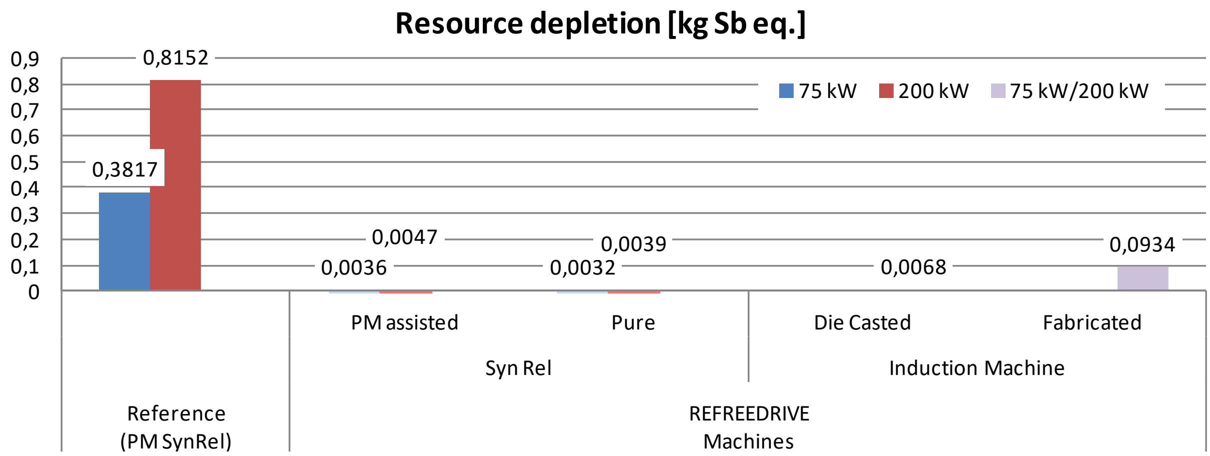


Figure 70: Environmental impact comparison among analysed machines – Resource depletion

3.3.1 Overall Comparison

The results in this impact category are mainly determined by the use of permanent magnets in the reference motors. No other material needed in the construction of any of the motors studied in the REFREEDRIVE project, supposes as much environmental impact related to this category, as the use of rare earths to obtain the permanent magnets to be inserted in the rotor. Thus, the motors developed in the REFREDRIVE project imply the reduction of a very important part of the value obtained for this impact category.

In the case of **SynRel motors**, regardless of their power, its impact is negligible compared to that caused by motors with NdFeB magnets, reducing their value by more than 99,5% (see Table 51 for 200 kW machines and Table 52 for 75kW motors)

In the case of **200 kW RFD induction motors**, where significant amounts of copper are used in the rotor, their impact on Resource depletion have different relevance, due to the difference in the source of the copper as raw material. In the case of the Die Cast rotor, the copper is mainly obtained from scraps, with lower impact on this environmental impact category. For the copper needed for the fabricated rotor, in its manufacturing process, the proportion of scraps is significantly lower. Despite this, in the case of the fabricated rotor, it is reached a level of 11,5% of the impact presented in this category, compared with motors that use NdFeB magnets (reduction of 88,5%, as shown in Table 51). The impact of the die cast rotor machine is negligible as in the case of the SynRel motors.

In the **75 kW RFD induction motors** with **fabricated rotor** (Table 52), which use the same amounts of material as the 200 kW, still their environmental impact is reduced by 75% despite its oversizing, in comparison with the 75kW motors using NdFeB magnets. The impact of the die cast rotor machine is insignificant regards the reference motor.

Table 51: Environmental impact comparison among 200 kW machines – Resource depletion

200 kW Resource depletion (kg Sb eq.]	SynRel			Induction	
	NdFeB PM (Reference)	PM assisted (RFD)	Pure (RFD)	Die Cast (RFD)	Fabricated (RFD)
TOTAL	**0,81521**	**0,00466**	**0,00388**	**0,006766**	**0,09343**
Steel Stacks (Stator & Rotor)	0,00039	0,00041	0,00039	0,00029	0,00029
Copper Winding	0,00183	0,00201	0,00140	0,00211	0,00211
Copper on Rotor	----	----	----	0,001627	0,08831
Magnets on Rotor	0,80734	---	----	----	----
Steel Rotor Shaft	0,00003	0,00011	0,00002	0,00002	0,00002
Insulation Resin	---	0,00001	0,00000	----	----
Al End Plates on rotor	----	0,00003	----	----	----
Cooling Housing	0,00409	0,00154	0,00154	0,00219	0,00219
Others	0,00153	0,00055	0,00053	0,00054	0,00051

Table 52: Environmental impact comparison among 75 kW machines – Resource depletion

75 kW Resource depletion (kg Sb eq.]	SynRel			Induction	
	NdFeB PM (Reference)	PM assisted (RFD)	Pure (RFD)	Die Cast (RFD)	Fabricated (RFD)
TOTAL	**0,38174**	**0,00357**	**0,00322**	**0,006766**	**0,09343**

Steel Stacks (Stator & Rotor)	0,00018	0,00015	0,00017	0,00029	0,00029
Copper Winding	0,00111	0,00119	0,00095	0,00211	0,00211
Copper on Rotor	----	----	----	0,001627	0,08831
Magnets on Rotor	0,37742	---	---	----	----
Steel Rotor Shaft	0,00001	0,00011	0,00002	0,00002	0,00002
Insulation Resin	---	---	0,00000	----	----
Al End Plates on rotor	----	0,00003	---	----	----
Cooling Housing	0,00165	0,00154	0,00154	0,00219	0,00219
Others	0,00137	0,00054	0,00053	0,00054	0,00051

3.3.2 Individual Comparison, by motor technology

3.3.2.1 Reference (NdFeB PM SynRel)

As previously mentioned, it should be noted again that in the reference motors (PM SynRel), the permanent NdFeB magnets represent around 99.0% of the impact in this impact category, such as shown in the Figure 71.

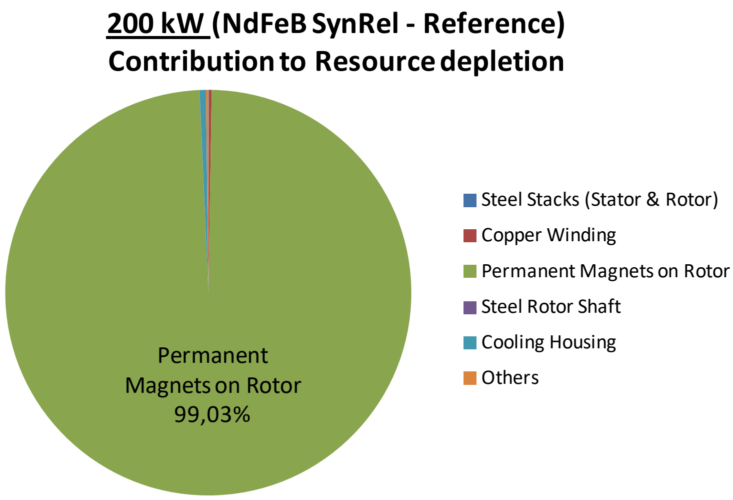


Figure 71: Contribution to Resource depletion, of main parts of reference motor (NdFeB PM SynRel machines).

3.3.2.2 REFREEDRIVE SynRel

In these motors (RFD SynRel, where the use of NdFeB magnets is not necessary), regardless of technology and power, the aluminium casing is the most relevant part of the motors (33% -48%) in Resource Depletion category, together with the use of copper for the manufacturing of the stator windings, in similar contribution (30% - 43%) to the aluminium casing. At a great distance from these two components, it is the use of electrical steels (4,5% - 10%).

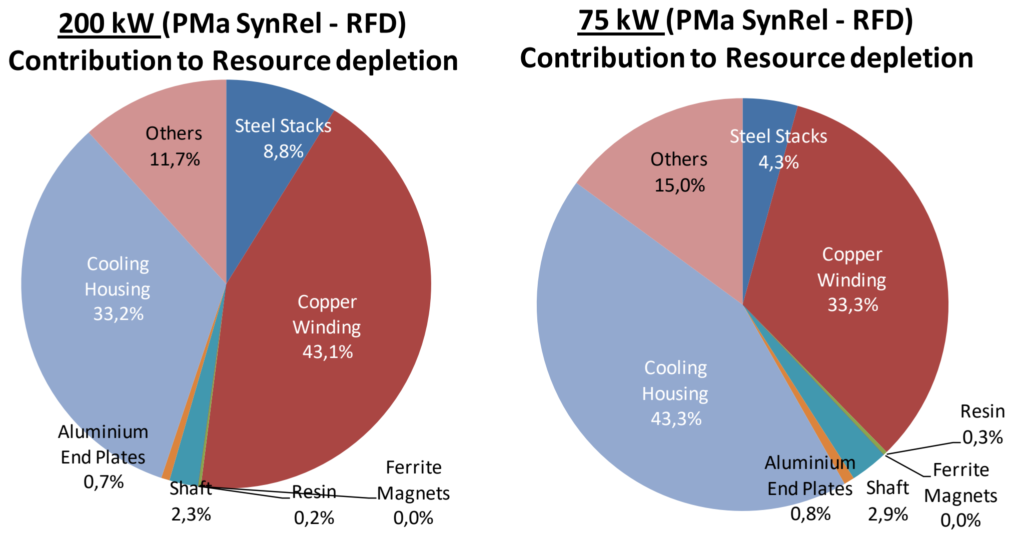


Figure 72: Contribution to Resource depletion, of main parts of REFREEDRIVE PMa SynRel machines.

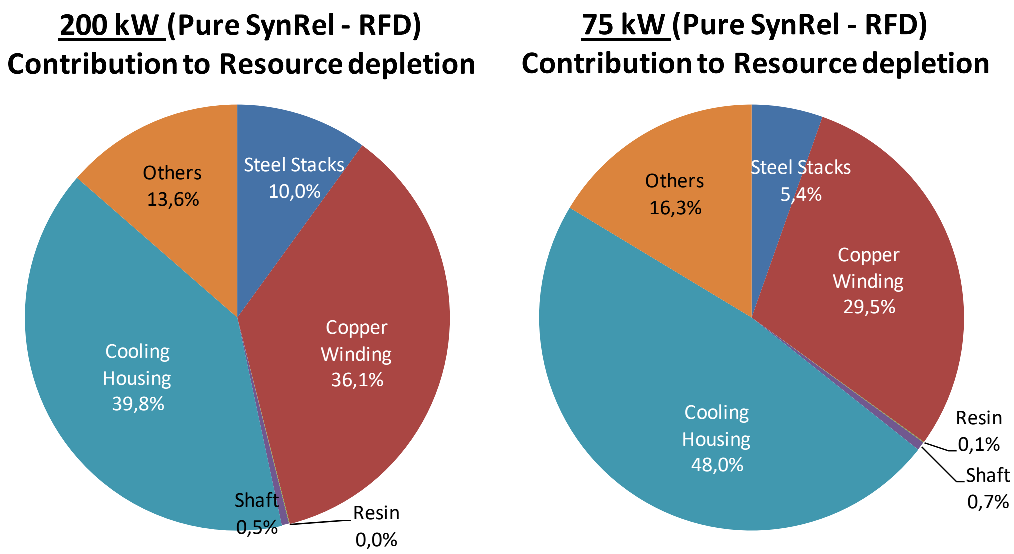


Figure 73: Contribution to Resource depletion, of main parts of REFREEDRIVE Pure SynRel machines.

Electric motor components that, in other impact categories and in other technologies, barely presented a relevant contribution to environmental impact, in this case (SynRel motor technology, and for this specific impact category “Resource depletion”), they have a non-negligible relevance, since they represent between 12% and 16% of the overall impact, aggregated under the heading "Others" (see Figure 72 and Figure 73).

The explanation to this issue is that regarding this environmental impact category, these motors (RFD SynRel) have very little impact. Some motor parts are the same for all motor configurations analyzed within the REFREEDRIVE LCA, with an identical contribution to the overall environmental impact. For this environmental impact, if these parts in other motors go unnoticed in terms of their contribution to the overall impact, in the case of the SynRel motors, these components stand out for their percentage contribution (see “Others” item in Figure 72 and Figure 73). These components, common to all the motors configurations, are mainly the copper terminals for the connections, and the fixing elements of the aluminium housing, where galvanized steel screws are used:

- Before the final assembly can take place, the stator connection wires must be equipped with the designated copper lugs (Figure 74). According to [10], this is done by hot crimping, i.e. the copper in the wire and in the connector is joined into piece using a form of welding. Wires are stripped and placed compactly inside a lug.

Figure 74: Sketch of copper lugs, and motor prototyping

- At last, the rotor and stator packages can be merged into one unit by placing the bearings into the bores of the end-bells [10] and then secure the end-bell and body parts of the housing into one unit using fasteners (such as galvanized screws like shown in Figure 75).

Figure 75: Detail of fixing fasteners used on motor prototypes

3.3.2.3 REFREEDRIVE Induction

The results for induction motors in this impact category are highly determined by the source of the copper used in the manufacture of the rotor. The two technologies used to manufacture the induction motor rotor in the REFREEDRIVE project use different raw materials, and their difference in impact is due to this fact.

If the copper used is obtained by a process where an important amount of scraps has been used, its impact in this category is low. This happens in the case of rotors obtained through the **die casting** process, whose impact in this category is almost negligible compared to the reference motor, because the copper of the rotor as raw material, mainly proceeding of scraps, has little impact in this category.

On the other hand, for **fabricated rotor RFD IM**, the related impact in this category is due to the copper that has been used in the manufacture of the rotor. Almost 95% of the impact is due solely to the copper in the rotor, but in any case, its impact is quite lower than in the case of the use of NdFeB magnets. The copper in the stator windings represents an additional 2,3%. The aluminium casing barely represents 2,3% of the total impact. The rest of the components are not quite relevant in this category.

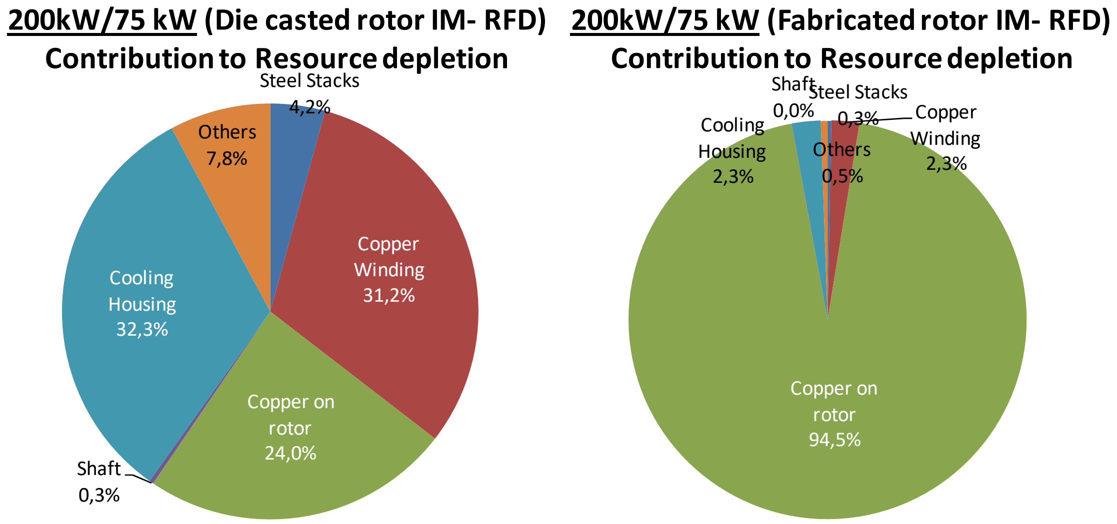


Figure 76: Contribution to Resource depletion, of main parts of REFREEDRIVE Induction machines.

3.4 *Ozone depletion*

Stratospheric ozone, which is 90% of the total ozone in the atmosphere, is vital for life. Damage to the ozone layer reduces its ability to prevent ultraviolet (UV) light entering the earth's atmosphere, increasing the amount of carcinogenic UVB light reaching the earth's surface.

Ozone is continuously formed and destroyed by sunlight and chemical reactions in the stratosphere. Ozone depletion occurs if the rate of ozone destruction is increased due to fugitive losses of anthropogenic substances which persist in the atmosphere.

Ozone Depletion Potential is expressed as kilograms of R11 equivalents (trichlorofluoromethane).

Table 53: Environmental impact comparison among analysed machines – Ozone depletion

Ozone Depletion [kg R11-Equiv.]			75 kW	200 kW
Reference (PM SynRel)			2,483 10-7 kg	4,082 10-7 kg
REFREEDRIVE Machines	Syn Rel	PM assisted	2,718 10-7 kg	4,538 10-7 kg
		Pure	2,145 10-7 kg	3,143 10-7 kg
	Induction Machine	Die Cast	8,334210-7 kg	
		Fabricated	4,7175 10-7 kg	

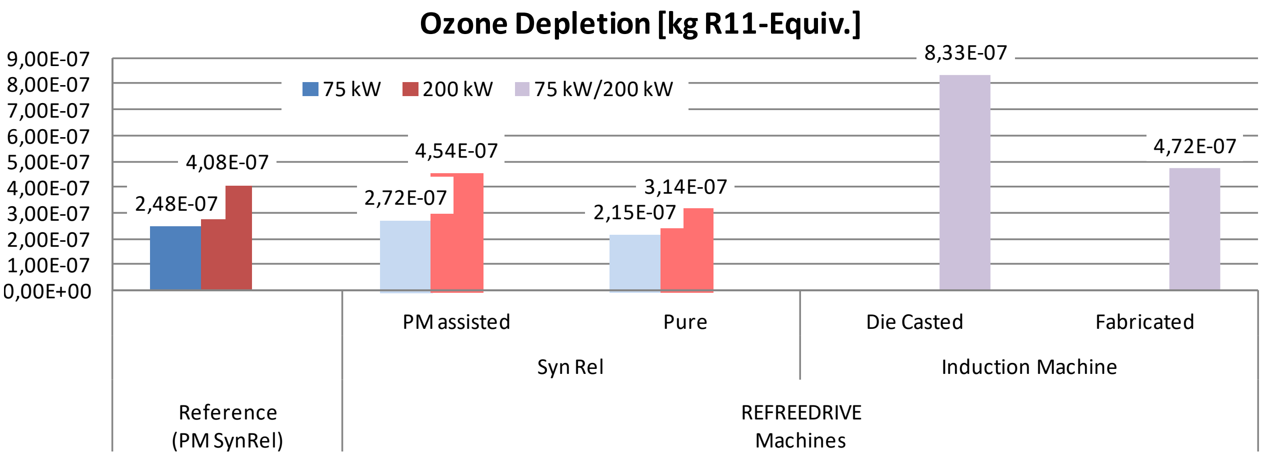


Figure 77: Environmental impact comparison among analysed machines – Ozone depletion

In accordance with the analysis carried out, the impact evaluated in this environmental category is mainly influenced (as shown in Table 54 and Table 55), by the amount of copper used in the construction of the stator winding, in the different versions of the analysed motors (both using wound winding or using hair pin winding). In the case of the die cast rotor induction machine, the cooper used also has a relevant contribution, but not the copper used in the rotor of the fabricated version. That is due to the source of the copper used in each case within the LCA study (see point devoted to copper on section 4.1.2 Raw materials).

In all cases where the copper is relevant concerning this impact category, a copper wire representative of the existing commercial mix in Europe has been used to model the raw material ("EU-25, Copper wire; technology mix; market mix, at plant; cross section 1 mm"), using the GaBi database. This copper wiring is the standard in motor driven systems such as is commented in the GaBi database, based on recent industry data supplied by the European copper industry, and thus reflecting the reality in copper semis fabrication.

Table 54: Environmental impact comparison among 200 kW machines – Ozone depletion

200 kW Ozone Depletion [kg R11-Equiv.]	SynRel			Induction	
	NdFeB PM (Reference)	PM assisted (RFD)	Pure (RFD)	Die Cast (RFD)	Fabricated (RFD)
TOTAL	**4,08E-07**	**4,54E-07**	**3,14E-07**	**8,334-07**	**4,72E-07**
Copper Winding	4,05E-07	4,46E-07	3,11E-07	4,70E-07	4,70E-07
Copper on Rotor	---	---	---	3,62E-07	---
Others	3,40E-09	7,54E-09	3,10E-09	2,18E-09	2,18E-09

Table 55: Environmental impact comparison among 75 kW machines – Ozone depletion

200 kW Ozone Depletion [kg R11-Equiv.]	SynRel			Induction	
	NdFeB PM (Reference)	PM assisted (RFD)	Pure (RFD)	Die Cast (RFD)	Fabricated (RFD)
TOTAL	**2,48E-07**	**2,72E-07**	**2,15E-07**	**8,334-07**	**4,72E-07**
Copper Winding	2,46E-07	2,64E-07	2,11E-07	4,70E-07	4,70E-07
Copper on Rotor	---	---	---	3,62E-07	---
Others	2,77E-09	7,57E-09	3,10E-09	2,18E-09	2,18E-09

3.5 *Others Environmental Impact Categories*

The results of the four impact categories introduced in the previous sections (“primary energy demand”, “climate change”, “resource depletion” and “ozone depletion”), are representative of the results obtained in the rest of the categories analyzed within this LCA study. In order not to make too hard the results presentation of the rest of the analyzed impact categories, this section shows these results just in a summary form.

As a summary of its analysis, to say that what was commented in the results for the Primary Energy Demand or the emission of Greenhouse Gases (Climate Change), can be completely extrapolated to the analysis of the impact categories that remain to be exposed (See graphs in Figure 78, Figure 79, Figure 80, Figure 81, Figure 82 and Figure 83), whose results are shown below, in a similar way to the previous categories already shown, but without a detailed evaluation.

3.5.1 Particulate matter/Respiratory inorganics

Environmental impact category that considers the adverse health effects on human health caused by emissions of Particulate Matter (PM: Atmospheric particles or dust) and its precursors (NOx, SOx, NH_3, etc.), considering that Particulate Matter is a complex mixture of extremely small particles, expressed as kilograms of PM2.5 equivalents.

Damage on human health due to Particulate matter (PM) is worldwide recognised as an important issue. Atmospheric particles or dust have been considered a major component of air pollution. The impact of airborne particles on human health is today seen as the probably most important environmental issue in Europe. A multitude of health problems, especially of the respiratory tract, are linked to particle pollution. Epidemiological studies in recent years gave a strong evidence for increased morbidity and mortality due to cardiovascular disease and lung cancer, even at relatively low PM burdens.

Table 56: Environmental impact comparison among analysed machines – Particulate matter

Particulate matter/Respiratory inorganics [kg PM2.5 eq]			75 kW	200 kW
Reference (PM SynRel)			0,1232 kg	0,2726 kg
REFREEDRIVE Machines	SynRel	PM assisted	0,053552 kg	0,078897 kg
		Pure	0,05061 kg	0,07052 kg
	Induction Machine	Die Cast	0,077077 kg	
		Fabricated	0,085915 kg	

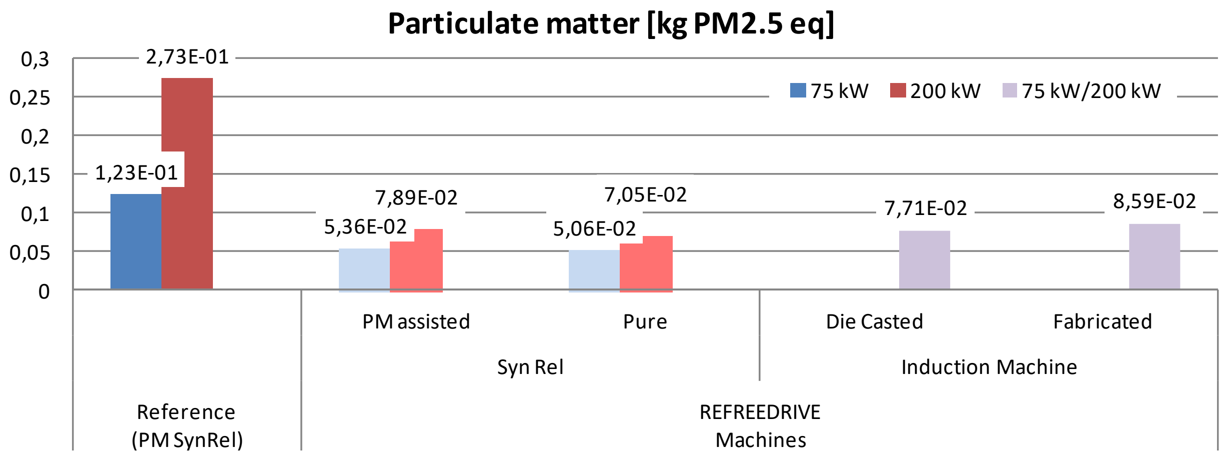


Figure 78: Environmental impact comparison among analysed machines – Particulate matter

3.5.2 Ionising radiation, human health

This is an environmental impact category that considers the adverse health effects on human health caused by radioactive releases. Ionising radiation is an impact category in LCA related to the damage to human health and ecosystems that is linked to the emissions of radionuclides throughout a product or installation life cycle. The category takes into account the radiation composed of particles with enough energy to liberate an electron from an atom or molecule, which effect on humans can be health decline, cancer, illnesses, etc.

This impact is expressed as kilo Becquerel (kBq) uranium 235 equivalents

Table 57: Environmental impact comparison among analysed machines – Ionising radiation

Ionising radiation, human health [kBq U235 eq]			75 kW	200 kW
Reference (PM SynRel)			22,685 kBq	53,707 kBq
REFREEDRIVE Machines	SynRel	PM assisted	22,089 kBq	25,597 kBq
		Pure	19,858 kBq	21,699 kBq
	Induction Machine	Die Cast	29,1382 kBq	
		Fabricated	31,068 kBq	

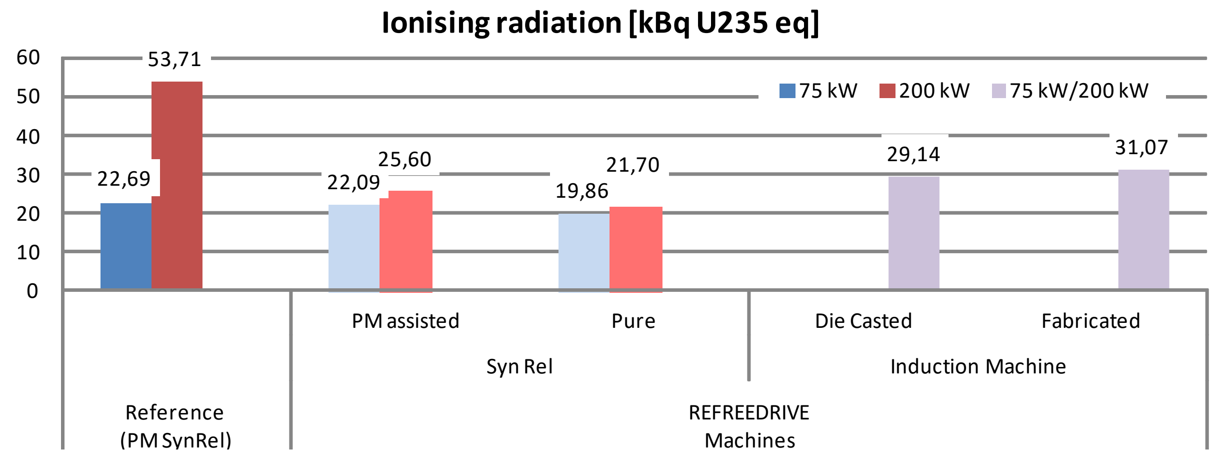


Figure 79: Environmental impact comparison among analysed machines – Ionising radiation

3.5.3 Photochemical Ozone Formation

Ozone is protective in the stratosphere, but on the ground-level it is toxic to humans in high concentration. This is the environmental impact category that accounts for the formation of ozone at the ground level of the troposphere. Photochemical ozone, also called "summer smog", is formed by the reaction of volatile organic compounds and nitrogen oxides in the presence of heat and sunlight.

High concentrations of ground-level tropospheric ozone damage vegetation, human respiratory tracts and manmade materials through reaction with organic materials.

- Impacts on humans arise when the ozone and other reactive oxygen compounds are inhaled and come into contact with the surface of the respiratory tract, where they damage tissue and cause respiratory diseases.
- Impacts on vegetation arise when the reactive compounds attack the surfaces of the plants or enter the stomata of the plant leaves, and cause oxidative damage on photosynthetic organelles.
- Impacts on man-made materials are caused by oxidation and damage to many types of organic materials which are exposed to ambient air.

Impact on this environmental category is expressed as kilograms of Non-methane volatile organic compounds (NMVOC) equivalent emissions.

Table 58: Environmental impact comparison among analysed machines – Photochemical Ozone Formation

Photochemical Ozone Formation [kg NMVOC Equiv.]			75 kW	200 kW
Reference (PM SynRel)			0,6760 kg	1,514 kg
REFREEDRIVE Machines	SynRel	PM assisted	0,44349 kg	0,70117 kg
		Pure	0,4141 kg	0,6200 kg
	Induction Machine	Die Cast	0,6248 kg	
		Fabricated	0,67656 kg	

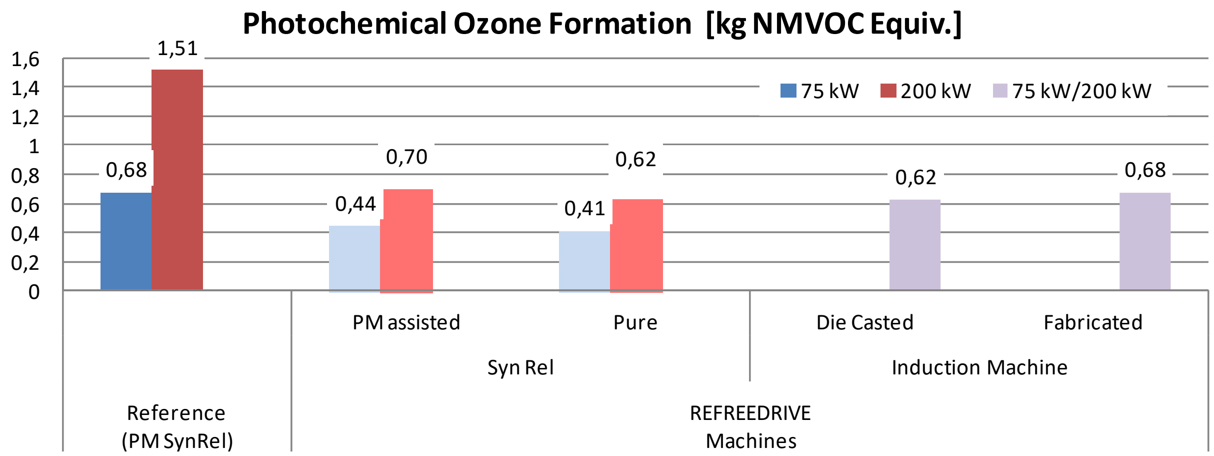


Figure 80: Environmental impact comparison among analysed machines – Photochemical Ozone Formation

3.5.4 Acidification

Environmental impact category that addresses impacts due to acidifying substances in the environment is called Acidification Potential. This impact category addresses the impacts from acidification generated by the emission of airborne acidifying chemicals. Acidification refers literally to processes that increase the acidity of water and soil systems by hydrogen ion concentration.

Acidification is caused by atmospheric deposition of acidifying substances generated largely from emissions of nitrogen oxides (NO_x), sulphur dioxide (SO_2) and ammonia (NH_3), the latter contributing to acidification after it is nitrified (in the soil). Emissions of NOx, NH_3 and SOx lead to releases of hydrogen ions (H^+) when the gases are mineralised. The protons contribute to the acidification of soils and water when they are released in areas where the buffering capacity is low, resulting in forest decline and lake acidification.

Acidic gases such as sulphur dioxide (SO_2) react with water in the atmosphere to form "acid rain", a process known as acid deposition. When this rain falls, often a considerable distance from the original source of the gas, it causes ecosystem impairment of varying degree, depending upon the nature of the landscape ecosystems.

Table 59: Environmental impact comparison among analysed machines – Acidification

<table>
<tr><th colspan="3">Acidification [Mole of H+ eq.]</th><th>75 kW</th><th>200 kW</th></tr>
<tr><td colspan="3">Reference (PM SynRel)</td><td>1,4953 mol</td><td>3,3532 mol</td></tr>
<tr><td rowspan="4">REFREEDRIVE Machines</td><td rowspan="2">SynRel</td><td>PM assisted</td><td>0,84221 mol</td><td>1,2013 mol</td></tr>
<tr><td>Pure</td><td>0,79365 mol</td><td>1,0789 mol</td></tr>
<tr><td rowspan="2">Induction Machine</td><td>Die Cast</td><td colspan="2">1,2000 mol</td></tr>
<tr><td>Fabricated</td><td colspan="2">1,3495 mol</td></tr>
</table>

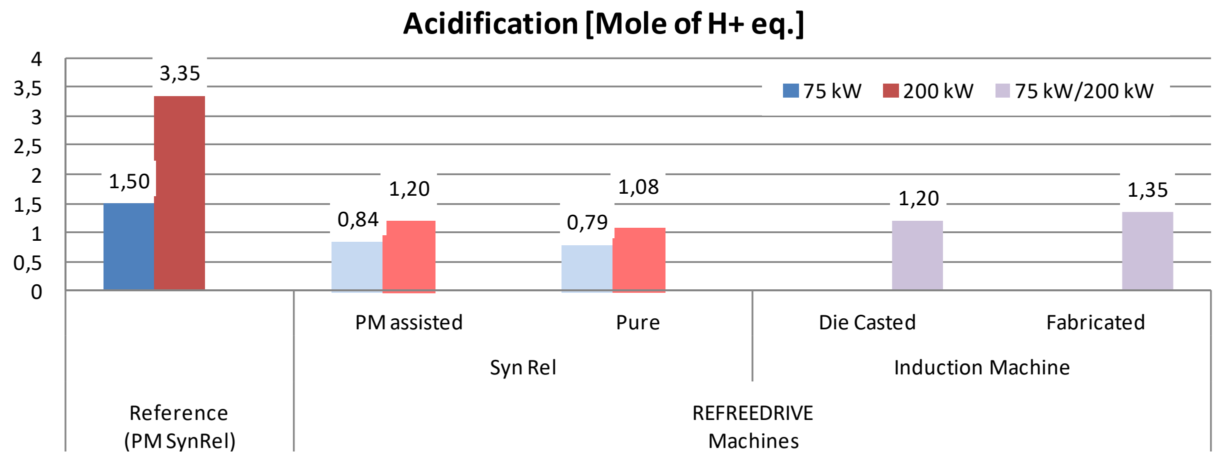


Figure 81: Environmental impact comparison among analysed machines – Acidification

3.5.5 Human Toxicity

This category concerns the effects of toxic substances on the human environment, evaluating the relative risk and associated consequences of chemicals that are released into the environment. The Human Toxicity Potential is a calculated index that reflects the potential harm of a unit of chemical released into the environment, and it is based on both the inherent toxicity of a compound and its potential dose. This environmental category is broken into cancer and non-cancer indicators, as follows:

- Human Toxicity – cancer: impact category that accounts for the adverse health effects on human beings caused by the intake of toxic substances through inhalation of air, food/water ingestion, penetration through the skin insofar as they are related to cancer.
- Human Toxicity - non cancer : impact category that accounts for the adverse health effects on human beings caused by the intake of toxic substances through inhalation of air, food/water ingestion, penetration through the skin insofar as they are related to non-cancer effects that are not caused by particulate matter/respiratory inorganics or ionising radiation.

Comparative Toxic Unit for human (CTUh) express the estimated increase in morbidity in the total human population per unit mass of a chemical emitted (cases per kilogramme).

Table 60: Environmental impact comparison among analysed machines – Human Toxicity

Human Toxicity, cancer and non cancer effects [CTUh]			Cancer		Non Cancer	
			75 kW	200 kW	75 kW	200 kW
Reference (PM SynRel)			1,112 10-6 CTUh	2,419 10-6 CTUh	2,6655 10-5 CTUh	5,6744 10-5 CTUh
REFREEDRIVE Machines	SynRel	PM assisted	0,6178 10-6 CTUh	0,8613 10-6 CTUh	1,9739 10-5 CTUh	2,5278 10-5 CTU
		Pure	0,4440 10-6 CTUh	0,5516 10-6 CTUh	1,4613 10-5 CTUh	1,8266 10-5 CTU

	Induction Machine	Die Cast	0,68253 10-6 CTUh	2,4995 10-5 CTUh
		Fabricated	0,83907 10-6 CTUh	4,8398 10-5 CTUh

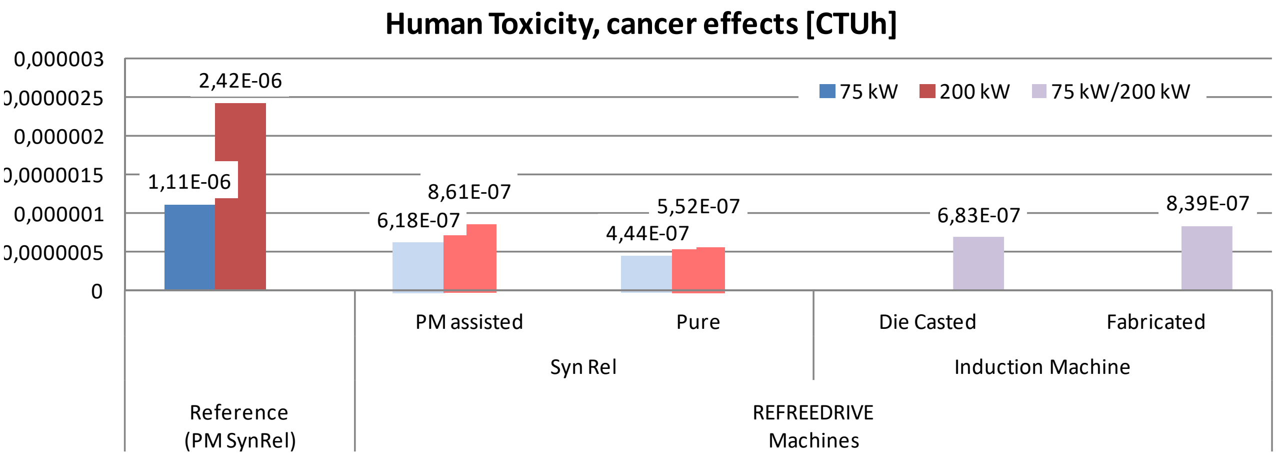


Figure 82: Environmental impact comparison among analysed machines – Human Toxicity (cancer)

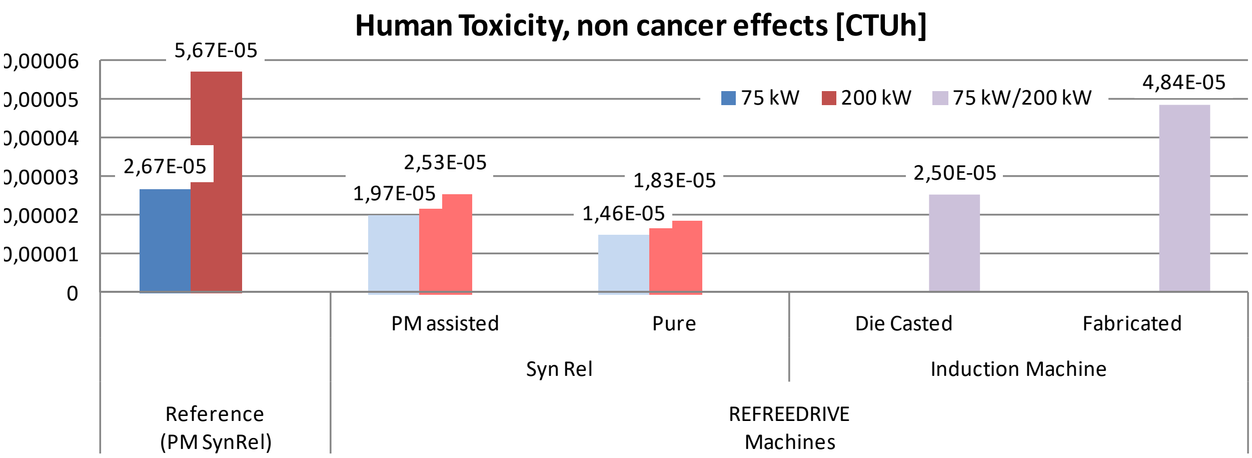


Figure 83: Environmental impact comparison among analysed machines – Human Toxicity (non cancer)

3.5.6 Ecotoxicity freshwater

Freshwater aquatic ecotoxicity indicator refers to the impact on fresh water ecosystems, as a result of emissions of toxic substances to air, water and soil.

Freshwater is a vital component in the global ecosystem. Freshwater is a unique environmental habitat and also essential for human life. Freshwater pollution not only poses a risk to the environment, but it can also impact human health as well. Therefore, it is important to maintain anthropogenic pollution below a threshold that would characterise a risk.

The comparative toxic unit for aquatic ecotoxicity impacts (CTUe) expresses the estimated potentially affected fraction of species integrated over time and the volume of the freshwater compartment, per unit of mass of the chemical emitted.

Table 61: Environmental impact comparison among analysed machines – Ecotoxicity freshwater

Ecotoxicity freshwater [CTUe]			75 kW	200 kW
Reference (PM SynRel)			66,9568	141,039
REFREEDRIVE Machines	SynRel	PM assisted	21,9787	31,5535
		Pure	16,811	22,6545
	Induction Machine	Die Cast	33,5444	
		Fabricated	102,3239	

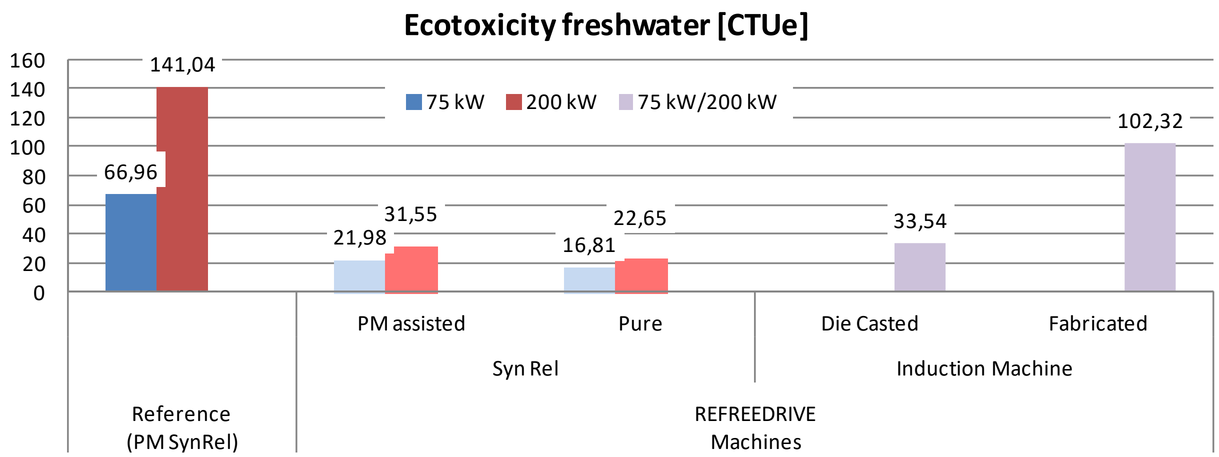


Figure 84: Environmental impact comparison among analysed machines – Ecotoxicity freshwater

3.5.7 Eutrophication

Eutrophication is the build-up of a concentration of chemical nutrients in an ecosystem which leads to abnormal productivity. This causes excessive plant growth like algae in rivers which causes severe reductions in water quality and animal populations. The degradation of organic material consumes oxygen resulting in oxygen deficiency and, in some cases, fish death. Emissions of ammonia, nitrates, nitrogen oxides and phosphorous all have an impact on eutrophication.

In natural **terrestrial** systems, the addition of nutrients may change the species composition of the vegetation by favouring those species which benefit from higher levels of nutrients to grow faster than more nutrient efficient plants. The primary impact on the plant community leads to secondary impacts on other species in the terrestrial ecosystem.

In **aquatic** systems (freshwater and marine aquatic systems), the addition of nutrients has a similar primary impact by fertilising the plants (algae or macrophytes) with a number of consequences for the ecosystem:

- Species composition of the plant community changes to more nutrient-demanding species;

- Algal blooms create shadowing, filtering the light penetrating into the water mass, changing life conditions from the macrophytes, which need the light for photosynthesis, and for predatory fish which need the light to see and catch their prey;
- Oxygen depletion near the bottom of the water body where dead algae deposit and degrade.

All these consequences lead to a change in the species composition and of the function of the exposed aquatic ecosystem.

Table 62: Environmental impact comparison among analysed machines – Eutrophication

Eutrophication			Freshwater [kg P eq.]		Marine [kg N eq.]		Terrestrial [Mole of N eq.]	
			75 kW	200 kW	75 kW	200 kW	75 kW	200 kW
Reference (PM SynRel)			0,000256	0,000577	0,21399	0,47944	2,324252	5,206364
RFD Machines	SynRel	PM assisted	0,000282	0,000362	0,137535	0,21204	1,47447	2,273634
		Pure	0,000183	0,000236	0,12774	0,18686	1,3726	2,0078
	Induction Machine	Die Cast	0,0002459		0,19242		2,0694	
		Fabricated	0,0002856		0,210463		2,256375	

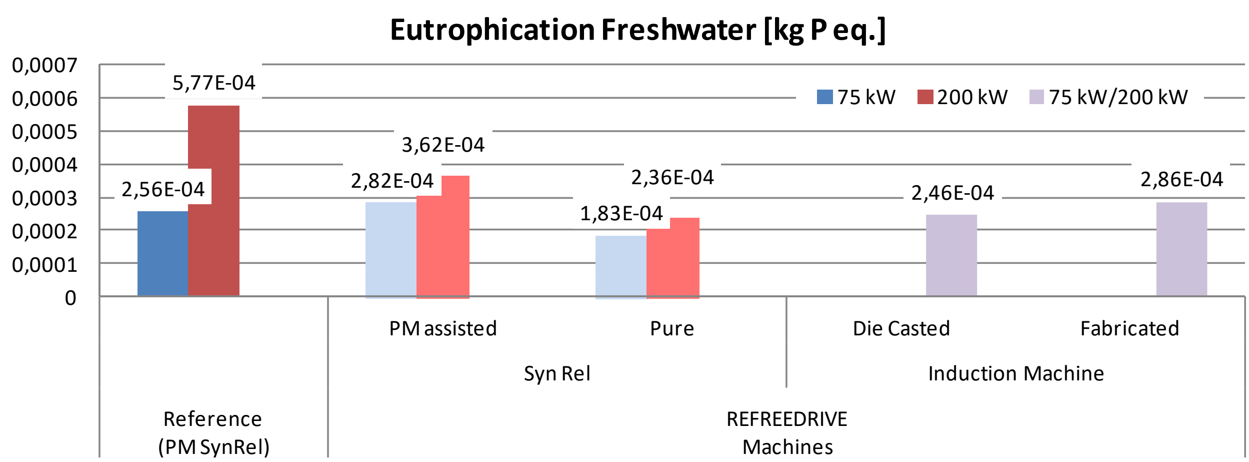


Figure 85: Environmental impact comparison among analysed machines – Eutrophication Freswater

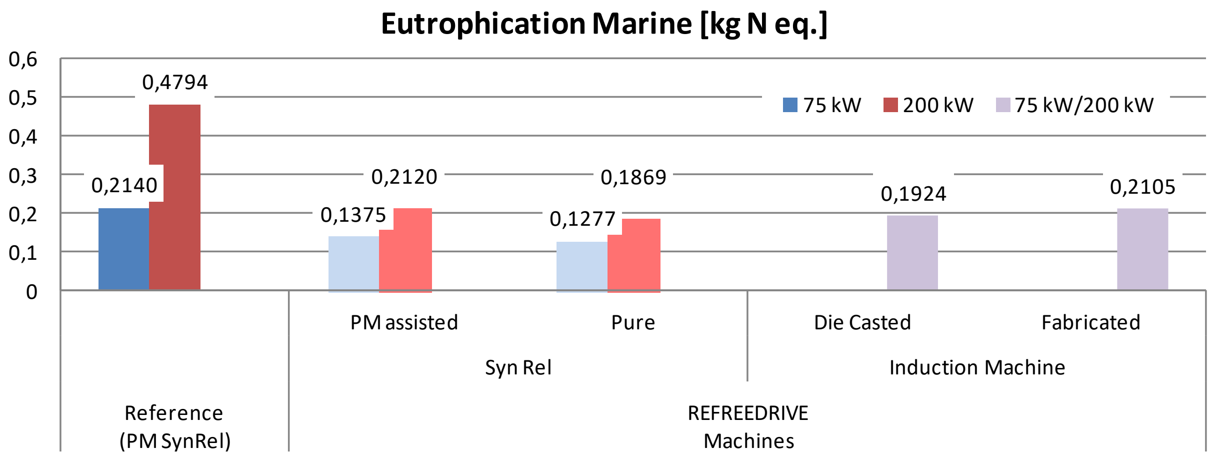


Figure 86: Environmental impact comparison among analysed machines – Eutrophication Marine

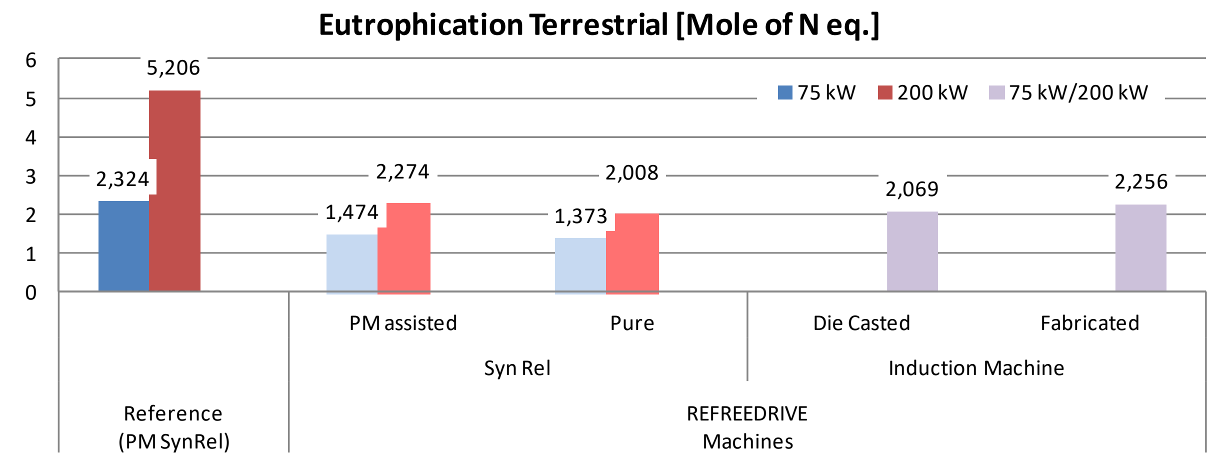


Figure 87: Environmental impact comparison among analysed machines – Eutrophication Terrestrial

3.5.8 Land Use

This impact category describes in the LCA methodology, the environmental impacts of occupying, reshaping and managing land for human purposes. Land use can either be the long-term use of land (e.g. for arable farming) or changing the type of land use (e.g. from natural to urban area).

Category 'land use' comprises those environmental consequences, which impact the environment due to the land use itself, for instance through the reduction of landscape elements, the planting of monocultures or artificial vegetation, or the sealing of surfaces.

Important environmental consequences of land use are the decreasing availability of habitats and the decreasing diversity of wildlife species. Land use leads to a degradation of the naturalness of the area utilised.

Table 63: Environmental impact comparison among analysed machines – Land Use

Land use midpoint [kg C deficit eq.]			75 kW	200 kW
Reference (PM SynRel)			1198,82	2690,517
REFREEDRIVE Machines	SynRel	PM assisted	11,109	13,4304
		Pure	7,466	8,163
	Induction Machine	Die Cast	9,30182	
		Fabricated	45,2569	

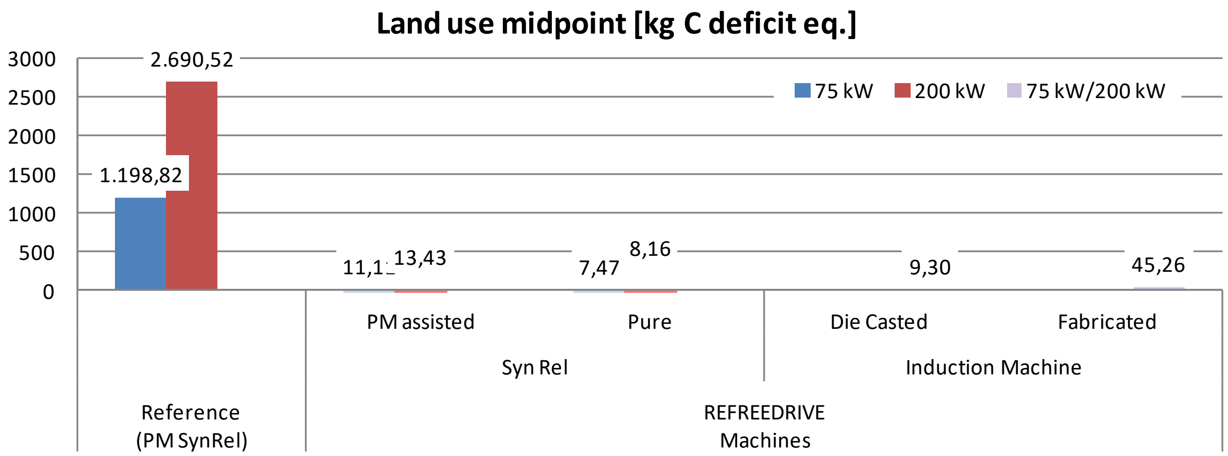


Figure 88: Environmental impact comparison among analysed machines – Land Use

4 Life Cycle Interpretation and Conclusions

4.1.1 Overview

In this last section (Life Cycle Interpretation and Conclusions), they are introduced both a summary of the most relevant LCA results (extendedly introduced into section 3.- Results - Life Cycle Impact Assessment (LCIA)) and the main findings related to the REFREEDRIVE developments under study.

As initial part of this section, comments concerning the assumptions on the needed raw materials have been introduced due to the results and conclusions are closely related with the hypothesis taken into account in the LCA models.

Then, Life Cycle Interpretation and Conclusions are properly exposed. Finally, results related with slight changes on assumptions are commented in order to analyse other scenarios concerning the RFD manufacturing process

4.1.2 Raw materials

In this section, the most significant characteristics of the materials used in the manufacture of the motors are described, and how these have been modelled within the LCA software, because the way in which their implementation is carried out has an impact on the results, and therefore, on the conclusions.

4.1.2.1 Rare Earths Elements

Automotive electric motors usually use permanent magnets, generally NdFeB type, due to the high performance that they provide (Table 64). For this reason, the electric motor selected as a reference for the environmental comparison of the motors developed within the RFD project, have been of this type of motor (NdFeB PM SynRel machine).

Table 64: Electric motor benchmarking (taken from REFREEDRIVE Grant Agreement)

Vehicle	Vehicle type	Motor Type	Specifics
Audi A3 e-tron	PHEV	Permanent Magnet	Rare-Earth
BMW i3	EV*	Interior Permanent Magnet	Rare-Earth
Chevrolet Volt	PHEV	Interior Permanent Magnet	Ferrite / Rare-Earth
Hyunday Sonata	PHEV	Surface Permanent Magnet	Rare-Earth
Mitsubishi Outlander PHEV	PHEV	Interior Permanent Magnet	Rare-Earth
Nissan Leaf	EV	Interior Permanent Magnet	Rare-Earth
Porsche Panamera	PHEV	Surface Permanent Magnet	Rare-Earth
Renault Zoe	EV	Synchronous Wound Field	Copper windings
Tesla S	EV	Induction Motor	Copper Cage
Toyota Prius	PHEV	Interior Permanent Magnet	Rare-Earth
VW e-Golf	EV	Permanent Magnet	Rare-Earth
VW GTE	PHEV	Permanent Magnet	Rare-Earth

*) – range extender option

The contribution of rare earth permanent magnets to the overall motor weight is usually small (no more than 5% as a general rule), but its global implications are very important (economic and supply implications, but also, for environmental reasons, as discussed below).

As a consequence of the objectives set for the project, the motors developed in RFD project are motors free of the use of rare earths, a very relevant aspect in the manufacture of electric motors for the automotive industry, due to the aforementioned implications.

Rare Earths for magnets

Rare earth extraction process is well known for their high energy intensiveness and also high associated environmental impacts. Throughout the cycle of mining processes that rare earth elements go through, there is potential for negative effects on the environment. Extracting rare earth elements begins with mining. This is followed by the refining process, and then even with its disposal[7].

The physical process of removing the ores from the ground (**mining**) is disruptive to the environment. Most rare earth elements are mined through open pit mining, which creates a disruption on the surface of the earth which disrupts thriving ecosystems. Furthermore, mines are the point source of release for contaminants which escapes the mines in different ways and they each have different detrimental effects on the environment.

On the other hand, ores that are extracted from the earth do not come out pure, instead they need to undergo a **refining** process. This refining process introduces another set of environmental concerns, mostly revolving around the release of metal by-products into the environment. It is easy for metals to enter the air, ground, or water, and once there it is nearly impossible to remove them. The metals in an environment can also prove devastating to organisms.

Concerning its **disposal**, the contamination of the water is the main concern and once contaminated is difficult to restore it to its original quality. The by-product of mining rare earth elements (tailings and waste rock stockpiles) are usually waste that is full of further threats to the environment. It is the tailings that are of particular concern as they are full of small, fine particles that can be absorbed into the water and ground surrounding a particular mine.

NdFeB magnets

SynRel electric machines, used as reference for the REFREDRIVE LCA analysis, use NdFeB permanent magnets, such as it is described by the technical paper used to model this kind of machines within the LCA software [10] [11] [12].

The detailed modelling of this type of magnet is completely out the scope of the REFREEDRIVE project. However, its correct modelling has a very significant relevance on the comparison of LCA results regards to the REFREEDRIVE machines.

Normally, there is no detailed breakdown of the environmental impact values of this type of magnets in the literature about this type of products, beyond the primary energy demand and the global warming potential, if any. That is not enough for the ambitious goal of the LCA to be achieved within REFREEDRIVE project, where more environmental impact categories have to be studied.

[7] https://web.mit.edu/12.000/www/m2016/finalwebsite/problems/environment.html

Therefore, other sources of information were searched. CIDAUT, as consortium member of the NEOHIRE project[8], and as partner involved in the LCA task of this EU funded project, has got the opportunity to achieve valuable information about life cycle inventory and environmental results regards the NdFeB magnets used in the cited project. This fact has allowed and facilitated an adequate modelling of the NdFeB PM on SynRel motors, taking into account a wide set of environmental impact categories, that otherwise could not have been studied.

4.1.2.2 Steel

Steel is a very important material in the manufacturing stage of electric motors. Active parts on electric motors (stators and rotors) use important amount of electrical steel in its stacks. Additionally, motors shafts also are made of steel. As function of the power and technology, amount of steel used in the manufacturing of the electric motor can achieve up to 69% (Figure 42), and being at least a 50%.

Within the RFD LCA sturdy, the employed data set to implement the use of the steel in the different models includes steel production, from cradle to steel factory gate. Data set is based on weighted average site-specific data (gate-to-gate) of **European steel producers**. Electricity grid mix is country-specific.

This dataset includes raw material extraction (e.g. coal, iron, ore, etc.) and processing, e.g. scrap, coke making, sinter, blast furnace, basic oxygen furnace, electric arc furnace, hot strip mill, rolling, annealing and tempering.

Inputs included in the Life Cycle Inventory relate to all raw material inputs, including steel scrap, energy, water, and transport. Outputs include steel and other co-products, emissions to air, water and land.

4.1.2.3 Aluminium

In weight, aluminium is, together with steel, one of the two main materials used in the manufacturing of the analysed motors. In the case of the motors studied in the RFD LCA, aluminium is not used in the active parts of the motors. It is used just to obtain the necessary casing for the motor cooling system. The contribution (on percentage) for the aluminium casing with respect to the overall weight of the motor, can reach in some of the analyzed motors up to 35%,

in the RFD LCA task, manufacturing process of the aluminium housing that provide the cooling jacket to the electric motors is modelled as an aluminium die-casted part, which is machined and cleaned to obtain the different aluminium components (housing and end-bells), to be assembled together at the end, to obtain the finished aluminium casing.

Initially, aluminium die-casted part is modelled as manufactured from primary aluminium ingots, representing **current European primary aluminium ingot mix**, like it is set by GaBi professional

[8] NEOHIRE main objective was to reduce the use of rare earth elements (REE), and Co and Ga (CRM), in the permanent magnets used in wind turbine generators (https://neohire.eu/). Start date: 01/02/2017 - End date: 31/01/2020.

database. This data set covers all relevant process steps/technologies over the supply chain of the represented cradle to gate inventory. The primary Al ingot is produced as a mixture of imported and locally produced ingot. Its inventory is mainly based on industry data and is completed, where necessary, by secondary data.

4.1.2.4 Copper

Copper is other of the relevant materials from a technical point of view, directly related with the electric motors performances. In the motor technologies studied within the RFD LCA, copper is used for the manufacturing of the stator windings. Additionally, in RFD Induction motors, copper is also used for the rotor manufacture. In SynRel motors under study, copper achieve in some references, a 12% of the overall motor weight, due to the stator windings. In the Induction motor, incorporating copper to the rotor manufacturing, this contribution increases up to 24 %.

Copper is one of the few raw materials which can be recycled repeatedly without any loss of performance. Based on the global copper stocks and recent flows model (see Figure 89), it is estimated that two thirds out of the 550 million tonnes of copper produced since 1900 are still in productive use.

Meeting future metals demand require a combination of primary raw materials, coming from mines, as well as recycled materials, while innovative policies and technology is continuing to contribute to improvements in recycling performance and resource efficiency.

Copper belongs to the base technical materials which are not seen as a critical raw material, due to a low risk associated with its availability, supply and market conditions. Technological innovations ensure new mine production continues to provide vital copper supplies. As mining techniques or technology improves and becomes affordable the copper reserve base increases. Currently global copper reserves are estimated at 830 million tonnes, and annual copper demand is 28 million tonnes. Furthermore, since 1950 there has always been, on average, 40 years of copper reserves available and over 200 years of resources, which include reserves, discovered and potentially profitable deposits and undiscovered deposits predicted based on preliminary geological surveys. These copper resources total 5,000 million tonnes.

In addition, recycling of copper plays an important role in copper availability. Today’s primary copper is tomorrow’s recycled material, or secondary copper. Currently more than 9 million tonnes of copper per year comes from the recycling of “old” scrap (copper contained in end-of-life products) and “new” scrap (scrap generated during production and manufacturing processes). This means that around 35% of annual copper use comes from recycled sources.

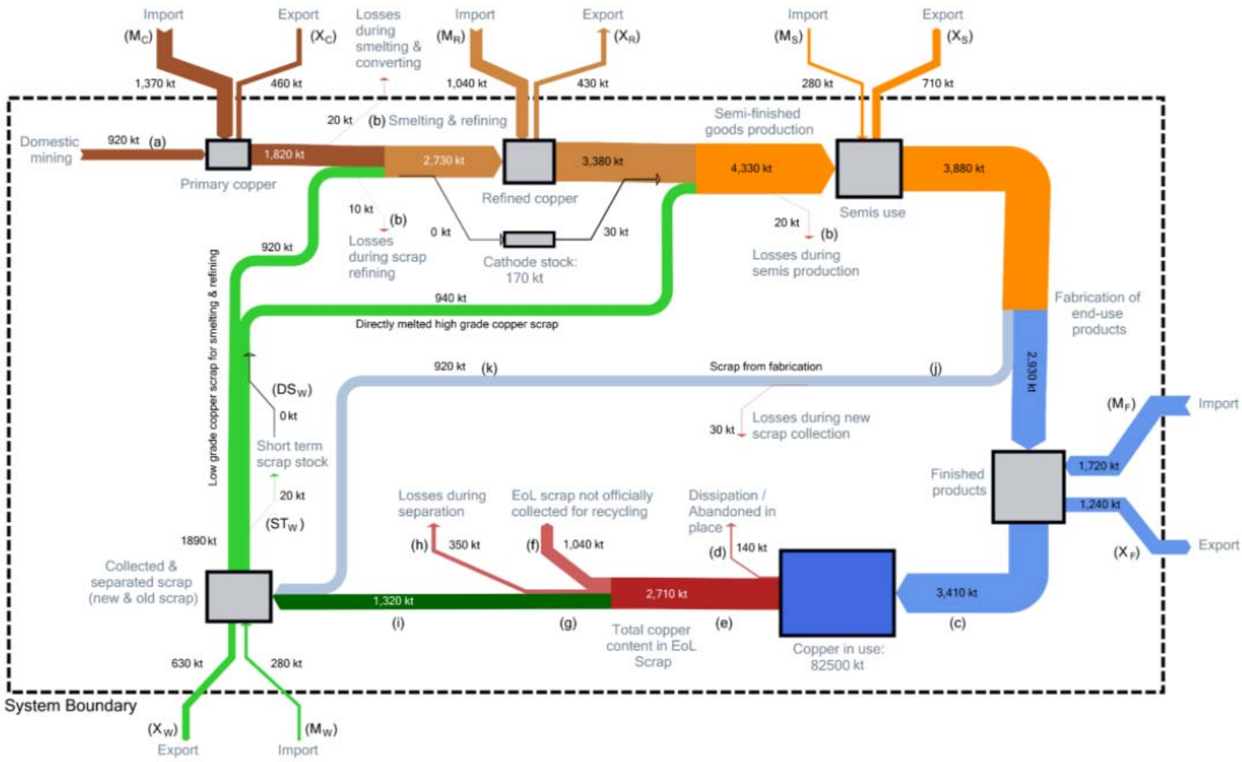


Figure 89: Summary of copper stocks and flows in the EU28 at 2018 (Version August 2020) [20]

The active parts of the motors analyzed in the LCA task use different manufacturing processes in which copper is incorporated as a fundamental material to achieve the desired performance.

Each type of motor analyzed in the RFD LCA uses a different technology, which requires for each of the active parts of the motors, a specific copper supply format (raw material), as reflected in the following Table 65, which compiles the information provided by the project partners, as applicants of cited copper formats to develop their products.

Regarding the modelling of these copper supplies as raw material, the GaBi database has different references for copper potentially usable in the LCA models of the REFREEDRIVE project. During the LCA task, an analysis and pre-selection of said references has been carried out from the GaBi database, in order to choose those that most appropriately represent the copper supply formats to be used in the modelling of the manufacture of the motors, according to the production processes described by the project partners. For this, the information provided by the partners has been taken into account, regarding the type of copper they use in their manufacturing processes (Table 65).

According to the information provided, both in the manufacture of the **stator windings** (for all machines), and in the manufacture of the **rotor by casting process**, the partners use **semi-fabricated copper**, as shown in the Table 66.

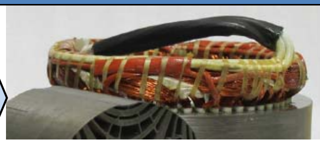
Table 65: Details of the copper supply as raw material for manufacturing active parts

Motor Technology	Active Part	Raw Material		Information provided by
		Copper product	Format	
SynRel Machines	Stator Windings	ESSEX Magnetemp CA-200 0,560 G2		MAVEL
Induction Machines	Stator (Hair Pins)	ESSEX Magnetemp CA-200 (Section = 3.15x5.60 mm)		TECNOMATIC
	Die Cast Rotor	Cu-ETP (Electrolytic Tough Pitch Copper) in shape of pellets, made out of a rod		BREUCKMANN
	Fabricated Rotor	Copper Cathode + In-home Scraps		AURUBIS

On the other hand, to manufacture the **fabricated version** of the **rotor**, the partner that manufactures the copper bars and endbells (Aurubis), in addition to using the scraps generated in its own facilities (in-home scraps), also needs **pure copper** (**cathode**) (Table 66), which is processed according to additional transformation processes (developed by Aurubis), to obtain the semi-fabricated ones that will be used later in the manufacture of the rotor.

For the model in the LCA software, the **semi-fabricated copper products** used by Mavel, Tecnomatic and Breuckmann, have been related to a specific reference process from the GaBi database, characterized by the flow diagram of the following Figure 90, which corresponds with a "Copper wire; technology mix; market mix, at plant; ECI/ELCD". This reference has been considered as representative for Cu semi-fabricated products within the REFREEDRIVE LCA, which takes into account a flow of Cu scraps for determining its environmental impact. The data set from GaBi is part of a LCA study on copper products based on recent industry data supplied by the European copper industry, and thus reflecting the reality in copper semis fabrication. European Copper Institute (ECI) was in charge of the official approval of this dataset.

Table 66: Relationship between copper from GaBi database and copper supply format employed in the RFD motors manufacturing processes.

GaBi Dataset	Supply Format	Motor Active Parts
Semi-fabricated copper EU-25: Copper wire; technology mix; market mix, at plant; cross section 1 mm ECI/ELCD		 Stator Windings
		 Stator Hair Pins
		 Die Cast Rotor
Copper cathode DE: Copper mix (99,999% from electrolysis) ts		 Fabricated Rotor

On the other hand, the selected process concerning the production of the **Cu cathode**, as Aurubis needs for the manufacturing of its products within the REFREEDRIVE project, is related to European routes (German data) for copper flows defined in the GaBi database as “Copper mix (99,999% from electrolysis)”. This dataset would cover in Figure 90, up to the generation of copper cathode, this being the previous step to the generation of semi-fabricated products. This dataset refers to the primary copper cathode consumption mix in Germany. Imports and local production make up the total mix. The dataset covers all relevant process steps/technologies over the supply chain of the represented cradle to gate inventory with a good overall data quality.

For the RFD fabricated rotor, considering the operating temperature of the Copper, bars manufactured from CuOFE (Oxygen-Free Electronic Copper) could be used up to a temperature of 150°C approximately, before the mechanical conditions are compromised (see REFREEDRIVE D3.1). For operating temperatures up to 200°C it is advisable to use a silver alloy. Attending to the information provided by Aurubis, commercially there are available copper-silver alloys contain between 0.03% and 0.12% Ag. In the case of the RFD induction motors, a minimum content of 0,04% Silver was determined. Also in the case of the fabricated rotor, the choice of alloys for the end ring was limited to CuOFE alloy. From an environmental point of view, the employment of CUOFE or alloyed Cu is not relevant in the RFD LCA due to the small amount of silver employed.

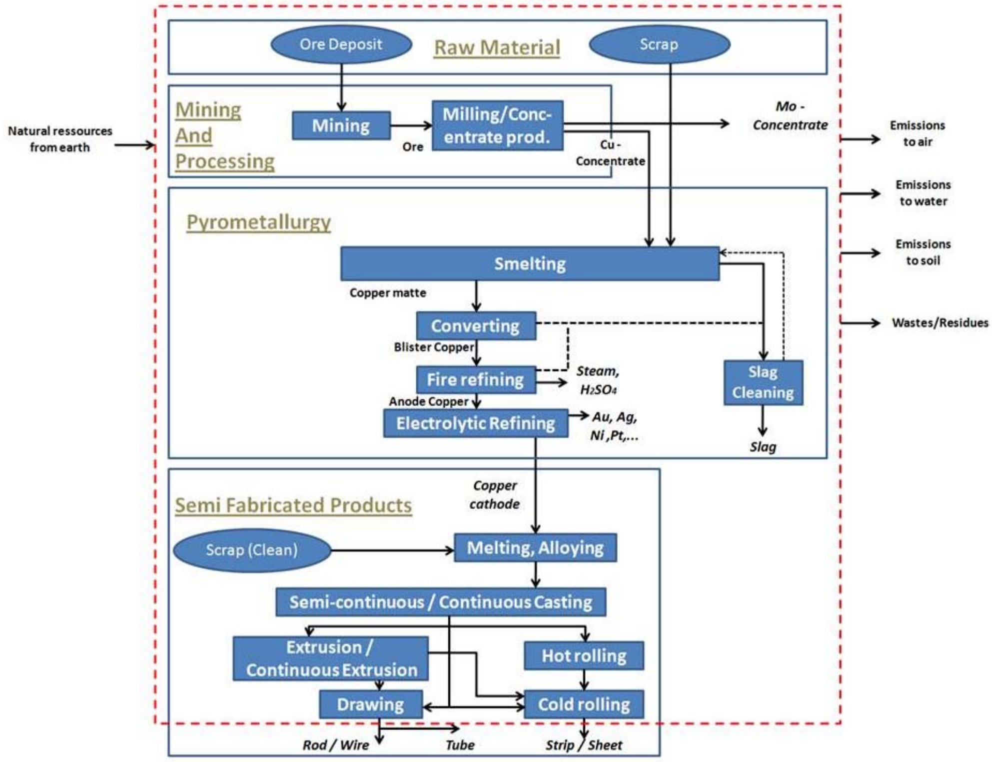


Figure 90: Diagram flow from description of the GaBi database for the semi-fabricated copper product

4.1.3 Life Cycle Interpretation of the study

The motors developed in the REFREEDRIVE project have been compared, from the point of view of the environmental impact associated with its manufacturing process, regarding to motors of equal powers, but using these latter, NdFeB permanent magnets.

In general, and as a result of the findings obtained from the Life Cycle Assessment, it can be confirmed that the motors developed in the RFD project present a lower environmental impact, in many different impact categories, than the motors used as reference in the study (NdFeB PM SynRel). This is mainly due to an optimized design, which results in a proper use of materials (less material needed, less environmental impact), but above all, to the elimination of the use of NdFeB permanent magnets.

As shown in previous sections, in many of the impact categories analyzed, the use of **NdFeB PM** by the reference motors significantly marks the environmental impact of the manufacturing of cited motors. Therefore, the elimination of the need to use that material (NdFeB magnets) in the manufacture of RFD motors, makes its environmental impact significantly less than that of reference motors. This is deeply highlighted when the categories “Resource depletion” and “Land use” are analyzed, but the elimination of the use of NdFeB magnets also has a huge impact on the results in other impact categories, such as “Primary energy demand” or “Climate change”.

The optimization of the **cooling casing** design developed within REFRREDRIVE project, requiring a lower consumption of material (**aluminium**) through its proper design, has an important relevance on the environmental impact of the new motors (in all SynRel motor versions, and in induction motors of 200 kW), in environmental categories such as “Primary energy demand” and “Climate change”, regarding to those motors taken as reference.

In new RFD motor designs, the ability to use less steel in the manufacture of the stator and rotor gives them an environmental advantage over the reference motors, as shown in categories such as primary energy demand (very manifest in the case of 200 kW induction motors)

As an exception to the concluded in the rest of the impact categories analyzed, the new motors developed in the REFREEDRIVE project present a similar impact (in the case of SynRel) or a significantly greater impact (induction motors), compared regarding the reference motors, in the impact category "Ozone layer depletion", due entirely to the use of copper to obtain the stator windings and/or the die-cast rotor.

In the case of Synrel motors, the amount of copper used among the different motor technologies (NdFeB PM, RFD PMa and Pure) is very similar, hence their environmental impact is also similar. However, in the case of induction motors (RFD IM), a greater amount of copper is used, and also, in Die-cast rotor motors, more use of the type of copper that has the greatest impact on this environmental category is made, which means a significant impact for these motors, in this category.

4.1.3.1 RFD SynRel Motors

After the analysis carried out, it can be concluded that any configuration of the SynRel motors developed in the project has a lower environmental impact than the motors taken as a reference, as seen in the following Figure 91 (200 kW motors) and Figure 92 (75 kW motors). In these graphs a comparison between RFD PMa and Pure Synrel motors, and the reference motors, is introduced, for the different impact categories analyzed and related with the ILCD method.

The 200 RFD kW motors (regardless of their technology) are clearly more environmentally friendly than the reference motors (NdFeB PM SynRel). In most impact categories (see Figure 91), proposed RFD motors show less than half the impact of benchmark motors. In categories as "Resource depletion" or "Land use", the difference is even more significant. There is only one category of those analyzed (“Ozone Depletion”), in which RFD motors, specifically in its PMa SynRel version, present a slightly higher impact value than the motor taken as a reference.

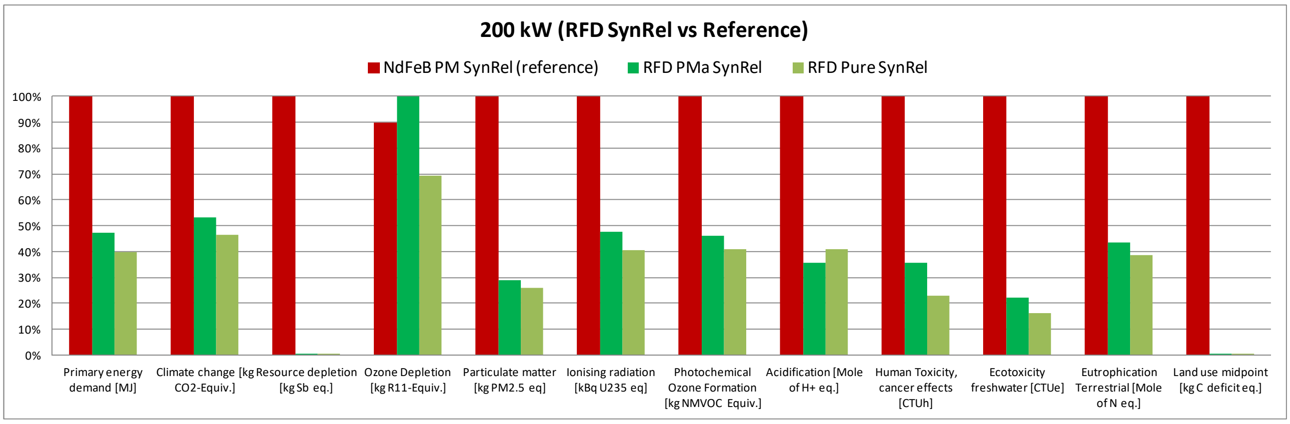


Figure 91: Comparison of SynRel motors developed within REFREEDRIVE project, against reference (NdFeB PM SynRel) – 200 kW

For the 75 kW RFD motors, the conclusions are the same as those indicated in the case of the 200 kW motors, although the differences with respect to the reference motor are somewhat smaller, but are still lower (Figure 92).

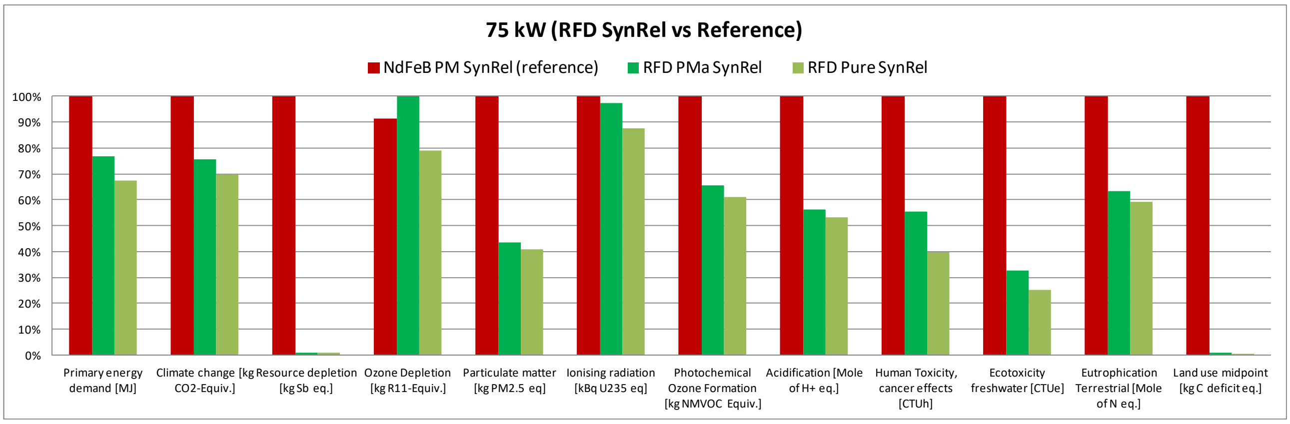


Figure 92: Comparison of SynRel motors developed within REFREEDRIVE project, against reference (NdFeB PM SynRel) – 75 kW

4.1.3.2 RFD Induction Motors

Like the RFD SynRel motors developed, the new 200 kW RFD Induction motors also present a lower environmental impact than their counterpart selected as a reference in the comparison (NdFeB PM SynRel), as shown in the following Figure 93.

In most impact categories, the environmental impact is estimated to be below 50%, with a few exceptions. In the categories "Resource Depletion" and "Land Use" the differences are even more significant. As in the previous cases (RFD SynRel machines), only in the “Ozone Depletion” category, the new RFD Induction motors present a worse indicator value than the reference motor.

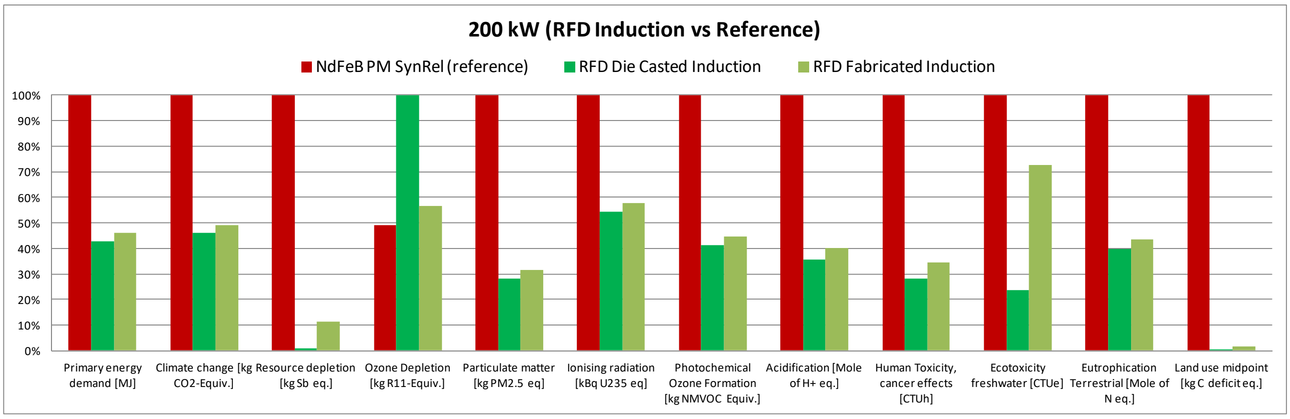


Figure 93: Comparison of Induction motors developed within REFREEDRIVE project, against reference (NdFeB PM SynRel) – 200 kW

When carrying out the analysis of the environmental impact of 75 kW RFD induction motors, it must be taken in mind that these motors are oversized, so that they are able of providing 200 kW, just by modifying their power electronics. This means that compared to the 75 kW motors of the reference technology, the new motors apparently do not offer too many environmental advantages compared to their counterpart. Even so, in many categories the impacts are very similar ("Primary Energy Demand", "Climate Change", "Photochemical Ozone Formation"), or even lower ("Resource Depletion", "Particulate Matter", "Acidification", "Human Toxicity - Cancer "," Eutrophication Terrestrial "and" Land use "), as shown in Figure 94.

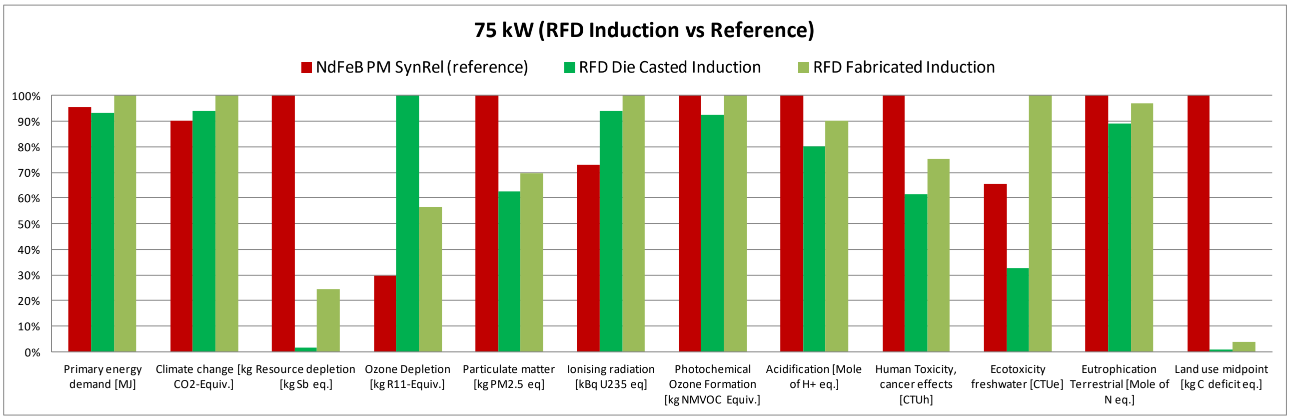


Figure 94: Comparison of Induction motors developed within REFREEDRIVE project, against reference (NdFeB PM SynRel) – 75 kW

4.1.4 Alternative Scenarios

4.1.4.1 Primary aluminium against Secondary aluminium (Cooling Jacket)

In the analysis of the manufacturing process for the aluminium casing, most of the environmental impact is due to the production of the primary aluminium ingots, which must be produced in a first and preliminary stage, before carrying out casting, machining and cleaning processes of the different aluminium housing parts (housing and end-bells).

For this reason, an hypothetical replacement of raw material to be used (primary Al ingots by secondary Al ingots), has a high significance in the final environmental impact of the aluminium casing, taking into account that the use of a secondary ingot implies a reduction of more than 95% of its environmental impact, due to the elimination of the most energy-demanding stages in the process of obtaining said primary ingots (extraction of raw material – bauxite - and electrolysis of alumina).

In previous sections within this document, it has been verified that for all the configurations analyzed in this LCA (for example, Figure 61, Figure 62, Figure 63, Figure 64, etc.), the aluminium casing (generated from primary ingot), represents an important fraction of the environmental impact of the motors, in comparison with the use of other materials, such as steel or copper.

Therefore, it has been considered interesting in this study to analyze how the modification of the environmental impact by the motors would be, if the use of primary aluminium ingots is replaced by secondary ingots. As an exercise, some modifications on environmental impact have been analyzed for 200 kW motors, in which the cooling housing has, as a general rule, a lower impact than in 75 kW motors, where in some of which an oversized frame is used. The following figures compare the energy demand associated in the manufacture process of 200 kW motors, using primary or secondary aluminium ingots.

In Figure 95, the reduction of the primary energy demand by type of motor (200 kW) is shown, due to the use of secondary aluminium ingots instead of primary Al ingots. A reduction in energy consumption between 30% and 45% is observed, depending on the type of motor that is analyzed. In any case, it was demonstrated that the modification of the source of aluminium as a raw material has a significant impact on the environmental impact.

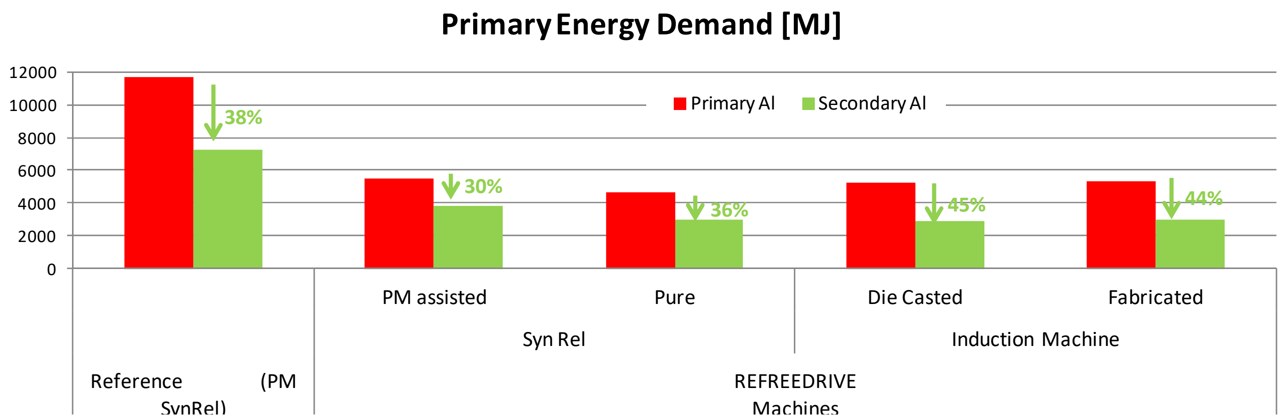
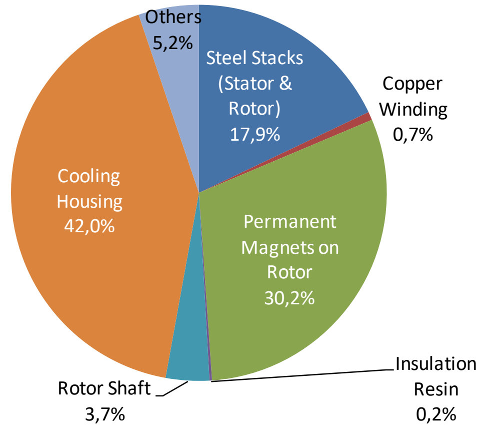
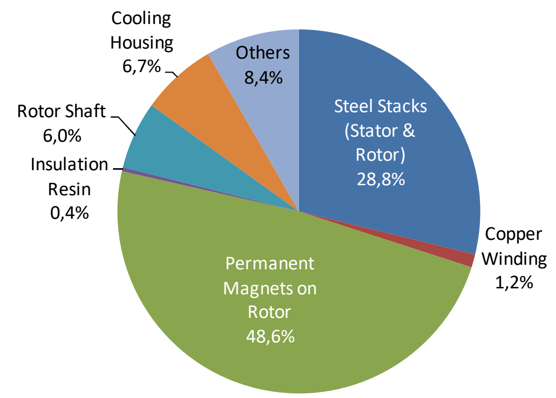
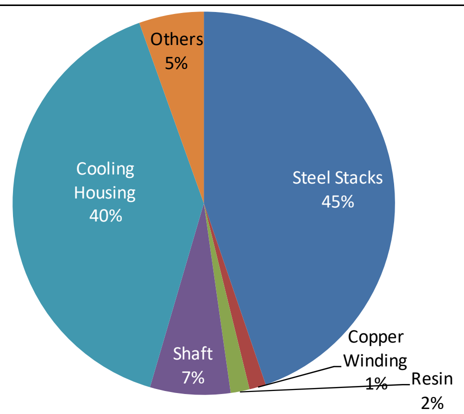
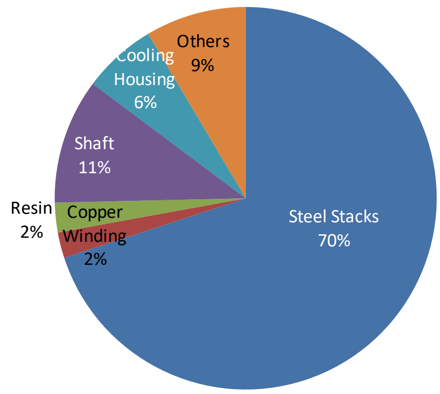
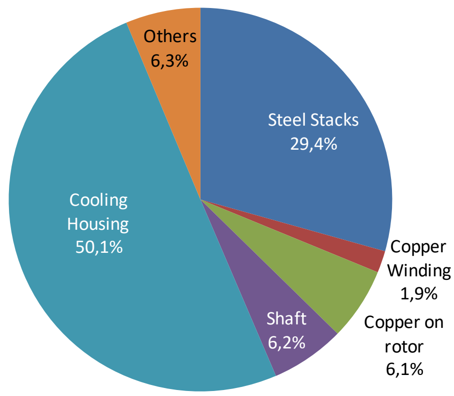
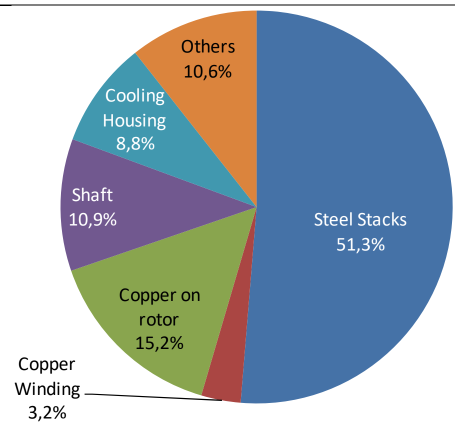


Figure 95: Effect on environmental impact for using secondary Al ingots instead of primary ones - Primary Energy Demand

Regarding the contribution to the environmental impact of each motor component (for example, on primary energy demand, as shown on Table 67), once the secondary aluminium ingots are used, it is clearly observed that the contribution of the aluminium casing is significantly reduced, so that the rest of the components gain relevance, speaking in percentage, although its absolute value is maintained. That occurs especially for the steel in all technologies, and for permanent magnets and copper on the rotor, in those motors where they are used.

Table 67: - Estimation for the contribution breakdown variation on environmental impact, for motors components – Primary Energy Demand

Estimation for the variation on Primary Energy demand [200 kW]		
	Primary aluminium ingot	**Secondary** aluminium ingot
NdFeB PM SynRel		
RFD Pure SynRel		
RFD Die-Cast Rotor Induction		

5 Annex Extended Results

5.1 Introduction

In this annex, the breakdown of the environmental impact of each electric motors, for each and every one of the technologies (reference and REFREEDRIVE ones), is exposed, showing which components are most relevant from the environmental impact viewpoint, in all the impact categories analyzed related with the selected environmental impact method (ILCD).

In each impact category, for each motor technology, a table shows the values of the overall environmental impact, and additionally, the absolute value and the contribution (relative value) to the overall impact, of the most relevant components within the type of studied motors (stator, rotor, aluminium casing, magnets if any, etc.).

In some occasions, in order to demonstrate and identify properly the contribution of the motors components and materials to the overall environmental impact, further diagrams are introduced, extracted directly from the LCA software (GaBI), showing these contributions. In this extra diagrams, in the first column (with two bars for the SynRel machines, one for the 75 kW motor and other for the 200 kW motor, but just one bar for induction motors due to there is just one motor configuration), the overall environmental impact is shown. The other set of columns show the individual contribution of the motor parts.

There is little difference in the breakdown of the environmental impact due to the components; for the PMa SynRel and Pure SynRel motors versions, so in most cases, this section only shows the graphic of the first one. Something similar occurs with the RFD Induction Motors. Where contribution breakdowns do not show significant differences, just one graph is introduced.

5.2 Results

The extended results are presented in a first division, for each impact category, and within each one of them, for each of the studied motors technologies, as follows.

5.2.1 Primary Energy Demand

5.2.1.1 Reference (PM SynRel)

Table 68: Reference (PM SynRel) environmental impact – Primary Energy Demand

Primary energy demand from ren. and non ren. resources (gross cal. value) [MJ]	75 kW		200 kW	
Reference (PM SynRel)	**5125,5 MJ**		**11676,0 MJ**	
Steel Stacks (Stator & Rotor)	982,95 MJ	19,18%	2093,4 MJ	17,93%
Copper Winding	70,88 MJ	1,38%	114,28 MJ	0,98%
Permanent Magnets on Rotor	1650,2 MJ	32,20%	3530,0 MJ	30,23%

Steel Rotor Shaft	132,21 MJ	2,58%	436,52 MJ	3,74%
Cooling Housing	1983,3 MJ	38,69%	4899,0 MJ	41,96%

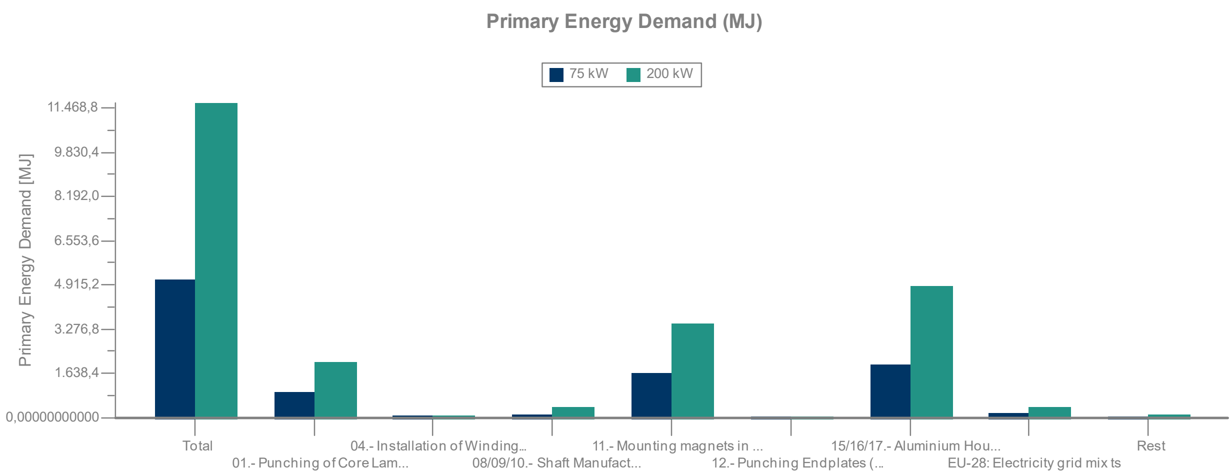


Figure 96: Primary Energy Demand - Reference (PM SynRel)

5.2.1.2 PM assisted SynRel (REFREEDRIVE)

Table 69: PM assisted SynRel (REFREEDRIVE) environmental impact – Primary Energy Demand

Primary energy demand from ren. and non ren. resources (gross cal. value) [MJ]	75 kW		200 kW	
PM assisted SynRel (REFREEDRIVE)	**3929,8 MJ**		**5503,5 MJ**	
Stator	872,93 MJ	22,21%	1667,9 MJ	30,31%
Steel Stacks	426,08 MJ	10,84%	1136,2 MJ	20,65%
Copper Winding	54,85 MJ	1,40%	92,64 MJ	1,68%
Resin	334,21 MJ	8,50%	346,0 MJ	6,29%
Rotor	1030,8 MJ	26,23%	1823,6 MJ	33,14%
Steel Stacks	401,4 MJ	10,21%	1074,4 MJ	19,52%
Ferrite Magnets	8,87 MJ	0,23%	23,96 MJ	0,44%
Shaft	430,22 MJ	10,95%	451,21 MJ	8,20%
Aluminium End Plates	125,92 MJ	3,20%	125,92 MJ	2,29%
Cooling Housing	1859,6 MJ	47,32%	1859,6 MJ	33,79%

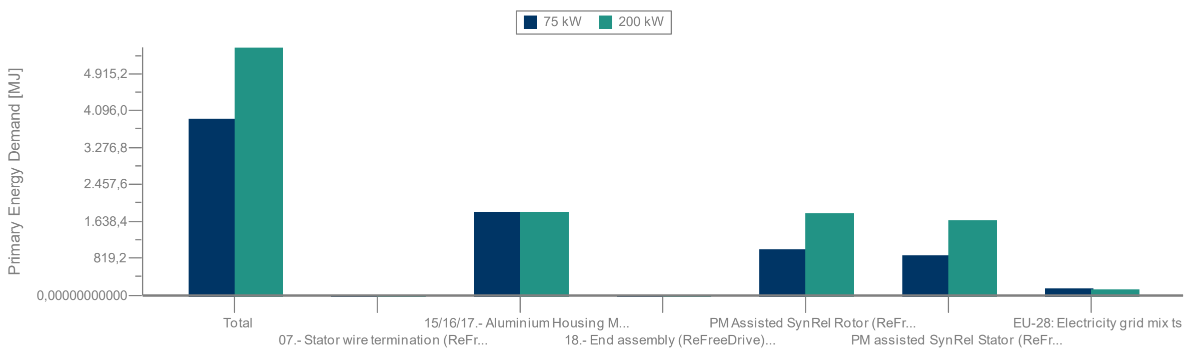


Figure 97: Primary Energy Demand - PM assisted SynRel (REFREEDRIVE)

5.2.1.3 Pure SynRel (REFREEDRIVE)

Table 70: Pure SynRel (REFREEDRIVE) environmental impact – Primary Energy Demand

Primary energy demand from ren. And non ren. Resources (gross cal. Value) [MJ]	75 kW		200 kW	
Pure SynRel (REFREEDRIVE)	**3451,6 MJ**		**4648,5 MJ**	
Stator	758,95 MJ	21,99%	1560,2 MJ	33,56%
Steel Stacks	592,79 MJ	17,17%	1340,1 MJ	28,83%
Copper Winding	43,881 MJ	1,27%	64,602 MJ	1,39%
Resin	66,08 MJ	1,91%	74,55 MJ	1,60%
Rotor	666,6 MJ	19,31%	1076,3 MJ	23,15%
Steel Stacks	339,62 MJ	9,84%	740,99 MJ	15,94%
Shaft	314,81 MJ	9,12%	314,81 MJ	6,77%
Cooling Housing	1859,6 MJ	53,88%	1859,6 MJ	40,00%

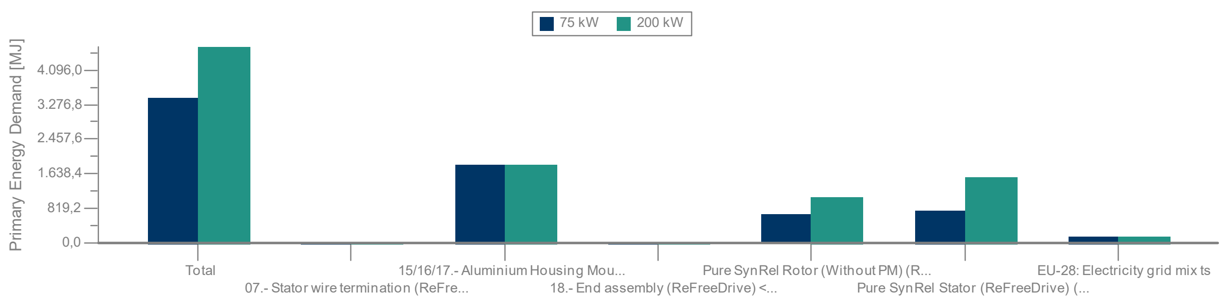


Figure 98: Primary Energy Demand - Pure SynRel (REFREEDRIVE)

5.2.1.4 Die Cast Rotor Induction Machine (REFREEDRIVE)

Table 71: Die Cast rotor Induction Machine (REFREEDRIVE) environmental impact – Primary Energy Demand

Primary energy demand from ren. and non ren. resources (gross cal. value) [MJ]	75 kW / 200 kW	
Die Cast Rotor Induction Machine (REFREEDRIVE)	**5001,31 MJ**	
Stator	1225,8 MJ	24,51%
Steel Stacks	1047,8 MJ	20,95%
Copper Winding	97,476 MJ	1,95%
Rotor	925,31 MJ	18,50%
Steel Stacks	492,7 MJ	9,85%
Copper	75,077 MJ	1,50%
Shaft	327,4 MJ	6,55%
Cooling Housing	2630,1 MJ	52,59%

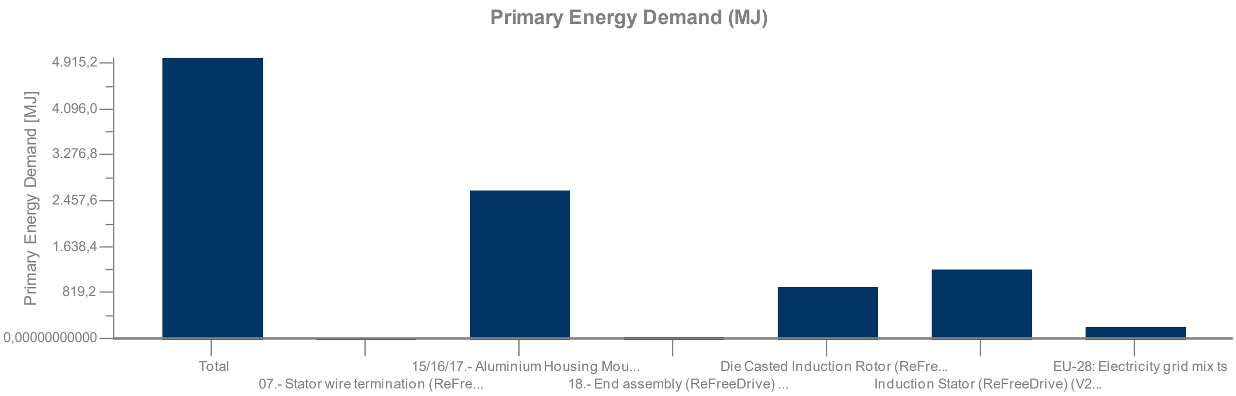


Figure 99: Primary Energy Demand - Die Cast rotor Induction Machine (REFREEDRIVE)

5.2.1.5 Fabricated Rotor Induction Machine (REFREEDRIVE)

Table 72: Fabricated rotor Induction Machine (REFREEDRIVE) environmental impact – Primary Energy Demand

Primary energy demand from ren. and non ren. resources (gross cal. value) [MJ]	75 kW / 200 kW	
Fabricated Rotor Induction Machine (REFREEDRIVE)	**5369,9 MJ**	
Stator	1225,8 MJ	22,83%
Steel Stacks	1047,8 MJ	19,51%
Copper Winding	97,476 MJ	1,82%

Rotor	1293,9,2 MJ	24,10%
Steel Stacks	492,7 MJ	9,18%
Copper	455,82 MJ	8,49%
Copper Bars	372,96 MJ	6,95%
Copper End Plates	82,86 MJ	1,54%
Shaft	327,39 MJ	6,10%
Cooling Housing	2630,1 MJ	48,98%

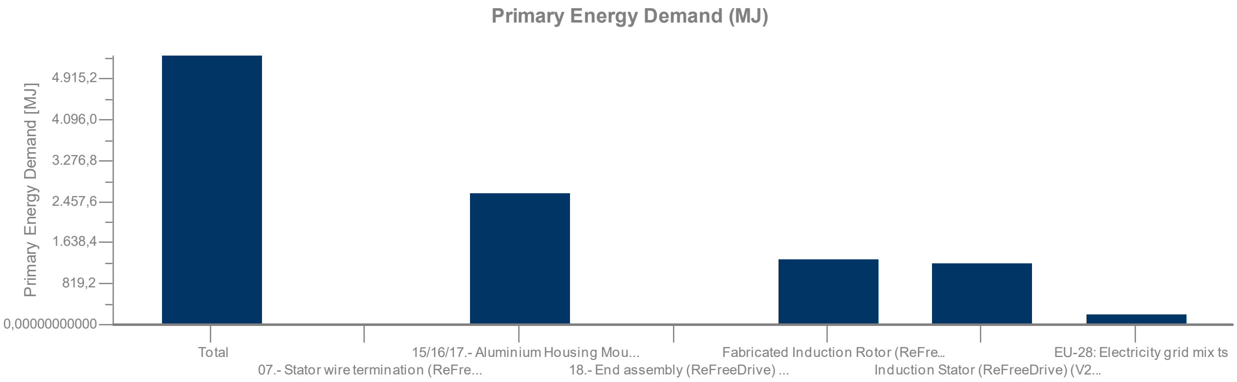


Figure 100: Primary Energy Demand - Fabricated Rotor Induction Machine (REFREEDRIVE)

5.2.2 Climate change

5.2.2.1 Reference (PM SynRel)

Table 73: Reference (PM SynRel) environmental impact – Climate change

Climate change (incl. biogenic carbon) (Impacts ILCD/PEF) [kg CO2-Equiv.]	75 kW		200 kW	
Reference (PM SynRel)	**306,67 kg**		**692,51 kg**	
Steel Stacks (Stator & Rotor)	90,736 kg	29,59%	193,24 kg	27,90%
Copper Winding	3,92 kg	1,28%	6,37 kg	0,92%
Permanent Magnets on Rotor	89,36 kg	29,14%	191,15 kg	27,60%
Steel Rotor Shaft	7,20 kg	2,35%	23,761 kg	3,43%
Cooling Housing	102,34 kg	33,37%	253,55 kg	36,61%

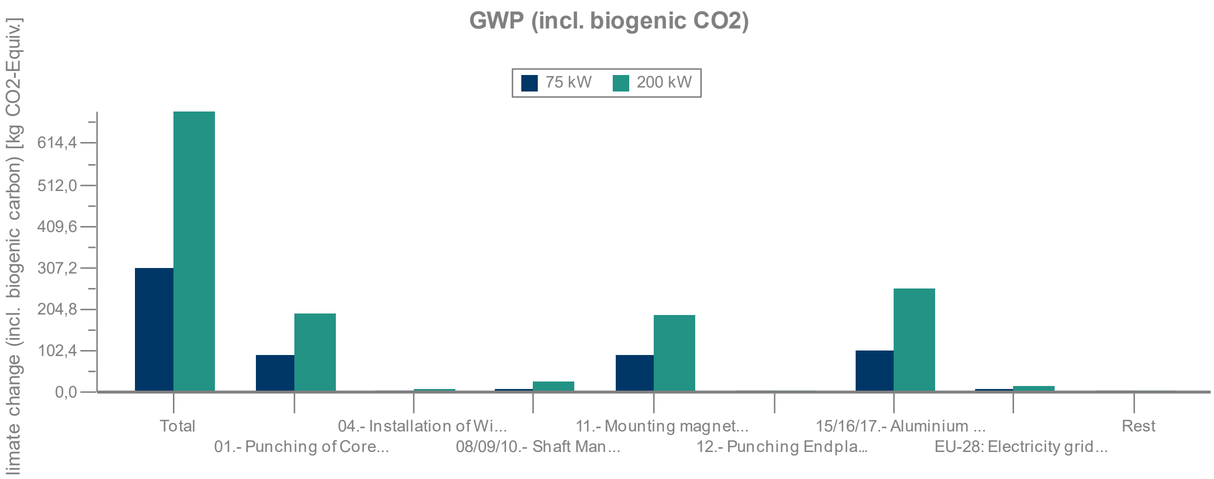


Figure 101: Climate change - Reference (PM SynRel)

5.2.2.2 PM assisted SynRel (REFREEDRIVE)

Table 74: PM assisted SynRel (REFREEDRIVE) environmental impact – Climate change

Climate change (incl. biogenic carbon) (Impacts ILCD/PEF) [kg CO2-Equiv.]	75 kW		200 kW	
PM assisted SynRel (REFREEDRIVE)	**231,73 kg**		**368,45 kg**	
Stator	58,971 kg	25,45%	128,63 kg	34,91%
Steel Stacks	39,331 kg	16,97%	104,88 kg	28,47%
Copper Winding	3,489kg	1,51%	5,892 kg	1,60%
Resin	13,914 kg	6,00%	14,31 kg	3,88%
Rotor	70,026 kg	30,22%	137,51 kg	37,32%
Steel Stacks	37,051 kg	15,99%	99,181 kg	26,92%
Ferrite Magnets	0,595 kg	0,26%	1,606 kg	0,44%
Aluminium End Plates	6,516 kg	2,81%	6,516 kg	1,77%
Shaft	23,418 kg	10,11%	24,561 kg	6,67%
Cooling Housing	95,90 kg	41,38%	95,90 kg	26,03%

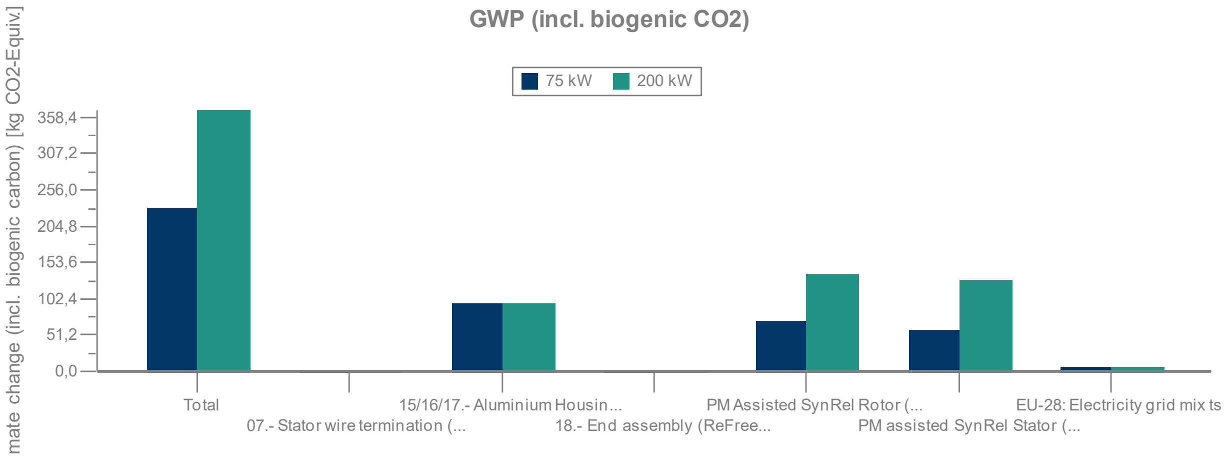


Figure 102: Climate change - PM assisted SynRel (REFREEDRIVE)

5.2.2.3 Pure SynRel (REFREEDRIVE)

Table 75: Pure SynRel (REFREEDRIVE) environmental impact – Climate change

Climate change (incl. biogenic carbon) (Impacts ILCD/PEF) [kg CO2-Equiv.]	75 kW / 200 kW		200 kW	
Pure SynRel (REFREEDRIVE)	**214,05 kg**		**322,52 kg**	
Stator	62,361 kg	29,13%	133,86 kg	41,50%
Steel Stacks	54,721 kg	25,56%	123,69 kg	38,35%
Copper Winding	2,79 kg	1,30%	4,11 kg	1,27%
Resin	2,75 kg	1,28%	2,97 kg	0,92%
Rotor	48,953 kg	22,87%	86,34 kg	26,77%
Steel Stacks	31,35 kg	14,65%	68,40 kg	21,21%
Shaft	17,135 kg	8,01%	17,135 kg	5,31%
Cooling Housing	95,90 kg	44,80%	95,90 kg	29,73%

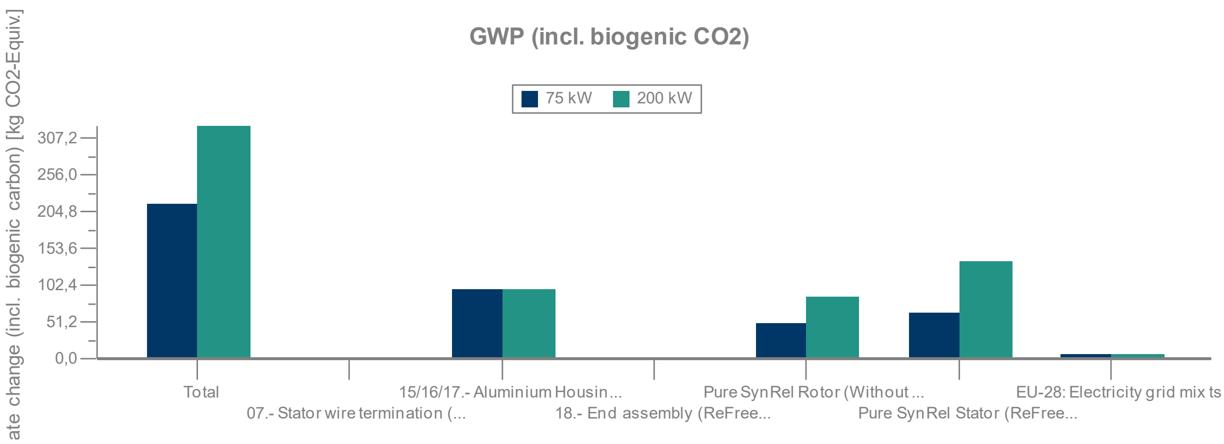


Figure 103: Climate change - Pure SynRel (REFREEDRIVE)

5.2.2.4 Die Cast Rotor Induction Machine (REFREEDRIVE)

Table 76: Die Cast rotor Induction Machine (REFREEDRIVE) environmental impact – Climate change

Climate change (incl. biogenic carbon) (Impacts ILCD/PEF) [kg CO2-Equiv.]	75 kW / 200 kW	
Die Cast Rotor Induction Machine (REFREEDRIVE)	**319,551 kg**	
Stator	105,86 kg	33,13%
Steel Stacks	96,719 kg	30,27%
Copper Winding	6,199 kg	1,94%
Rotor	69,2093 kg	21,66%
Steel Stacks	45,481 kg	14,23%
Copper	4,775 kg	1,49%
Shaft	17,821 kg	5,58%
Cooling Housing	135,76 kg	42,48%

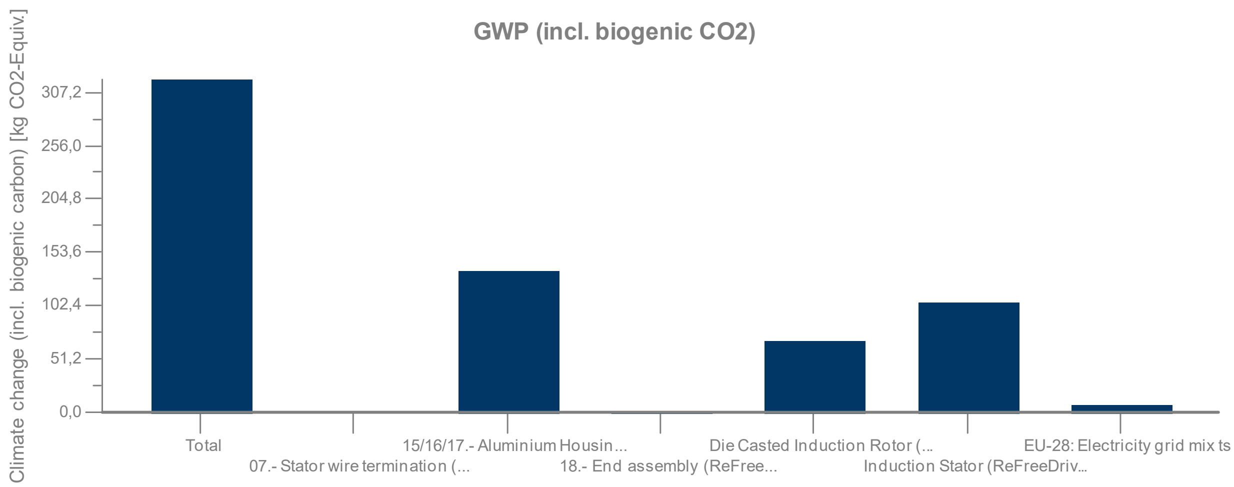


Figure 104: Climate change - Die Cast Rotor Induction Machine (REFREEDRIVE)

5.2.2.5 Fabricated Rotor Induction Machine (REFREEDRIVE)

Table 77: Fabricated rotor Induction Machine (REFREEDRIVE) environmental impact – Climate change

Climate change (incl. biogenic carbon) (Impacts ILCD/PEF) [kg CO2-Equiv.]	75 kW / 200 kW	
Fabricated Rotor Induction Machine (REFREEDRIVE)	339,64 kg	
Stator	105,86 kg	31,17%

Steel Stacks	96,719 kg	28,48%
Copper Winding	6,199 kg	1,83%
Rotor	89,194 kg	26,26%
Steel Stacks	44,481 kg	13,10%
Copper	25,21 kg	7,42%
Copper Bars	20,86 kg	6,14%
Copper End Plates	4,349 kg	1,28%
Shaft	17,821 kg	5,25%
Cooling Housing	135,76 kg	39,97%

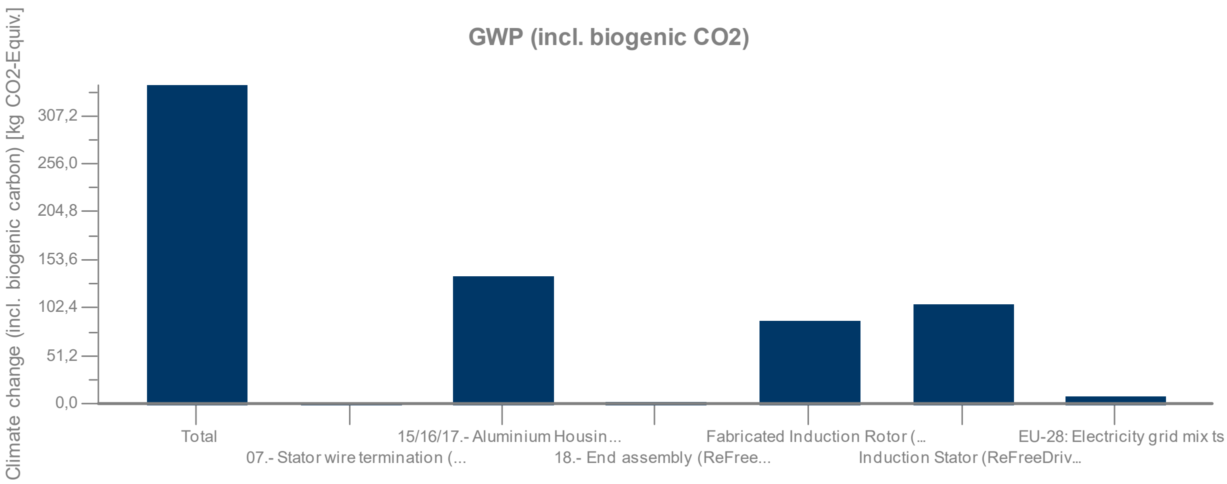


Figure 105: Climate change - Fabricated Rotor Induction Machine (REFREEDRIVE)

5.2.3 Resource depletion

5.2.3.1 Reference (PM SynRel)

Table 78: Reference (PM SynRel) environmental impact – Resource depletion

Resource depletion, mineral, fossils and renewables, midpoint (Impacts ILCD/PEF) [kg Sb eq.]	75 kW		200 kW	
Reference (PM SynRel)	**0,38174 kg**		**0,81521 kg**	
Steel Stacks (Stator & Rotor)	0,00018 kg	0,05%	0,00039 kg	0,05%
Copper Winding	0,00111 kg	0,29%	0,00183 kg	0,22%
Permanent Magnets on Rotor	0,37742 kg	98,87%	0,80734 kg	99,03%
Steel Rotor Shaft	0,000009 kg	0,002%	0,00003 kg	0,004%

Cooling Housing	0,00165 kg	0,43%	0,00409 kg	0,50%

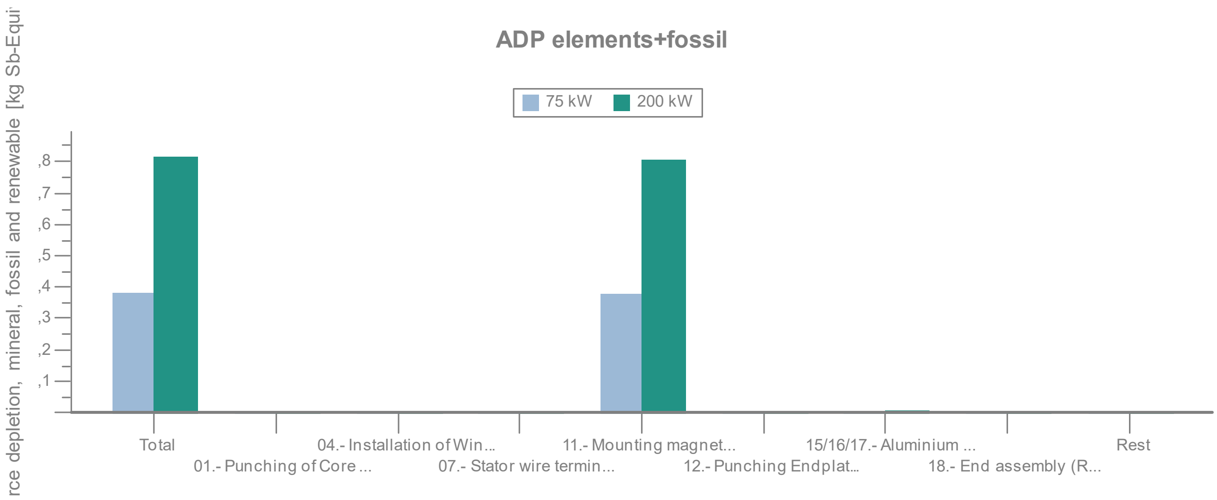


Figure 106: Resource depletion - Reference (PM SynRel)

5.2.3.2 PM assisted SynRel (REFREEDRIVE)

Table 79: PM assisted SynRel (REFREEDRIVE) environmental impact – Resource depletion

Resource depletion, mineral, fossils and renewables, midpoint (Impacts ILCD/PEF) [kg Sb eq.]	75 kW		200 kW	
PM assisted SynRel (REFREEDRIVE)	**0,003565 kg**		**0,004655 kg**	
Stator	1,2926 10-3 kg	36,26%	2,2474 10-3 kg	48,28%
Steel Stacks	0,0794 10-3 kg	2,23%	0,2117 10-3kg	4,55%
Copper Winding	1,1886 10-3 kg	33,34%	2,0075 10-3 kg	43,13%
Resin	1,12 10-5 kg	0,31%	1,12 10-5 kg	0,24%
Rotor	0,2166 10-3 kg	6,08%	0,3529 10-3 kg	7,58%
Steel Stacks	0,0748 10-3 kg	2,10%	0,2002 10-3 kg	4,30%
Ferrite Magnets	-----	-----	-----	-----
Aluminium End Plates	0,1051 10-3 kg	2,95%	0,1051 10-3 kg	2,26%
Shaft	0,0291 10-3 kg	0,82%	0,0305 10-3 kg	0,66%
Cooling Housing	1,5438 10-3 kg	43,30%	1,5438 10-3 kg	33,16%

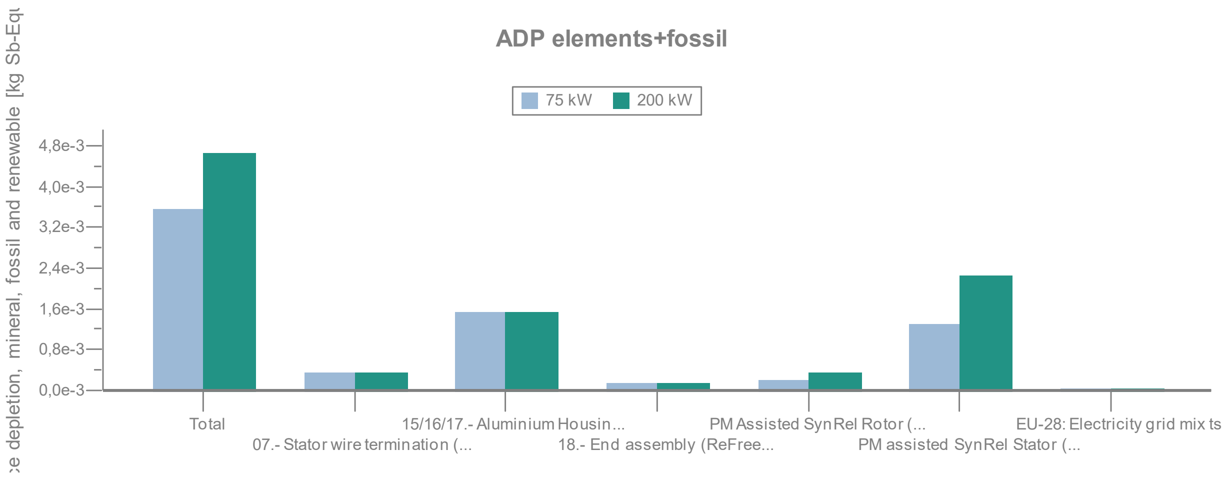


Figure 107: Resource depletion - PM assisted SynRel (REFREEDRIVE)

5.2.3.3 Pure SynRel (REFREEDRIVE)

Table 80: Pure SynRel (REFREEDRIVE) environmental impact – Resource depletion

Resource depletion, mineral, fossils and renewables, midpoint (Impacts ILCD/PEF) [kg Sb eq.]	75 kW		200 kW	
Pure SynRel (REFREEDRIVE)	**0,003218 kg**		**0,0038826 kg**	
Stator	0,001076 kg	33,44%	0,001666 kg	42,91%
Steel Stacks	0,0001105kg	3,43%	0,0002497 kg	6,43%
Copper Winding	0,0009509 kg	29,55%	0,00140 kg	36,06%
Resin	0,00000192 kg	0,06%	0,00000192 kg	0,05%
Rotor	0,00008587 kg	2,67%	0,0001612 kg	4,15%
Steel Stacks	0,00006329 kg	1,97%	0,0001381 kg	3,56%
Shaft	0,00002127 kg	0,66%	0,00002127 kg	0,55%
Cooling Housing	0,001544 kg	47,98%	0,001544 kg	39,77%

5.2.3.4 Die Cast Rotor Induction Machine (REFREEDRIVE)

Table 81: Die Cast rotor Induction Machine (REFREEDRIVE) environmental impact – Resource depletion

Resource depletion, mineral, fossils and renewables, midpoint (Impacts ILCD/PEF) [kg Sb eq.]	75 kW / 200 kW	
Die Cast Rotor Induction Machine (REFREEDRIVE)	**0,0067659 kg**	
Stator	0,0023153 kg	34,22%

Steel Stacks	0,0001953 kg	2,89%
Copper Winding	0,002112 kg	31,22%
Rotor	0,00174474 kg	25,79%
Steel Stacks	0,000092 kg	1,36%
Copper	0,001627 kg	24,05%
Shaft	0,000022 kg	0,33%
Cooling Housing	0,002187 kg	32,32%

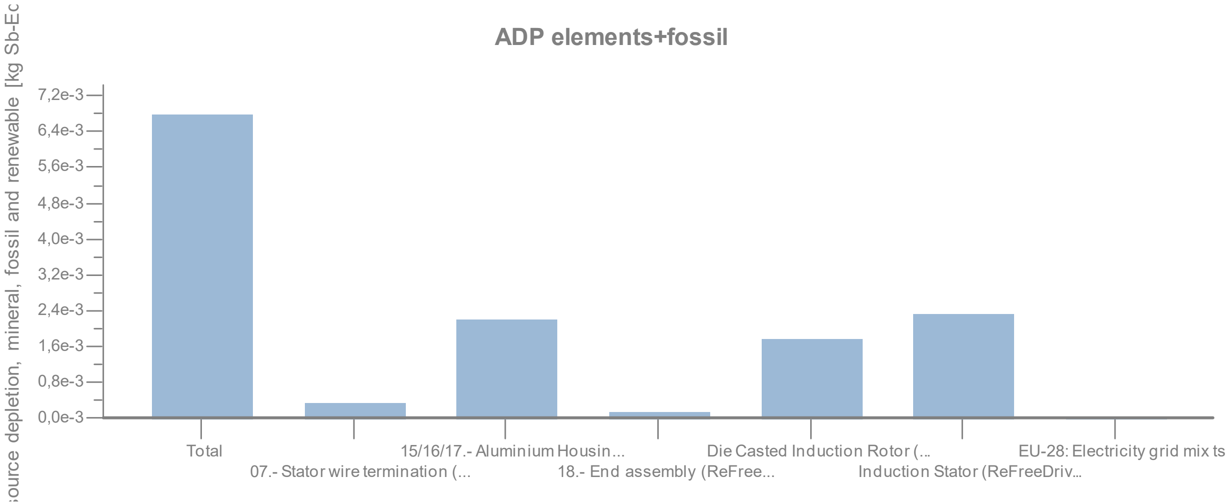


Figure 108: Resource depletion - Die Cast Rotor Induction Machine (REFREEDRIVE)

5.2.3.5 Fabricated Rotor Induction Machine (REFREEDRIVE)

Table 82: Fabricated rotor Induction Machine (REFREEDRIVE) environmental impact – Resource depletion

Resource depletion, mineral, fossils and renewables, midpoint (Impacts ILCD/PEF) [kg Sb eq.]	75 kW / 200 kW	
Fabricated Induction Machine (REFREEDRIVE)	0,09343 kg	
Stator	0,0023153 kg	2,48%
Steel Stacks	0,00019527 kg	0,21%
Copper Winding	0,0021124 kg	2,26%
Rotor	0,088431 kg	94,65%
Steel Stacks	9,18 E-05 kg	0,10 %
Copper	0,08831 kg	94,52%
Copper Bars	0,073594 kg	78,77%

Copper End Plates	0,01472 kg	15,76%
Shaft	2,2 E-05 kg	0,02 %
Cooling Housing	0,002187 kg	2,34%

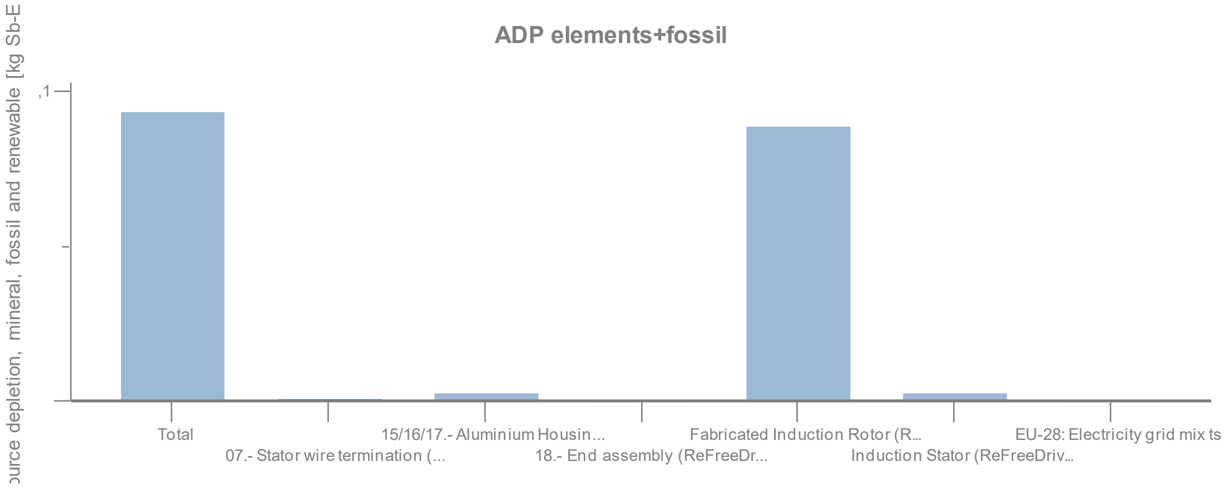


Figure 109: Resource depletion –Fabricated Rotor Induction Machine (REFREEDRIVE)

5.2.4 Ozone depletion

5.2.4.1 Reference (PM SynRel)

Table 83: Reference (PM SynRel) environmental impact – Ozone Depletion

Ozone Depletion (Impacts ILCD/PEF) [kg R11-Equiv.]	75 kW		200 kW	
Reference (PM SynRel)	**2,483 10-7 kg**		**4,082 10-7 kg**	
Steel Stacks (Stator & Rotor)	1,225 10-13 kg	0,00%	2,61 10-13 kg	0,00%
Copper Winding	2,4553 10-7 kg	98,88%	4,048 10-7 kg	99,17%
Permanent Magnets on Rotor	2,67 10-11 kg	0,01%	5,71 10-11 kg	0,01%
Steel Rotor Shaft	----	----	----	----
Cooling Housing	2,55 10-13 kg	0,00%	6,264 10-13 kg	0,00%

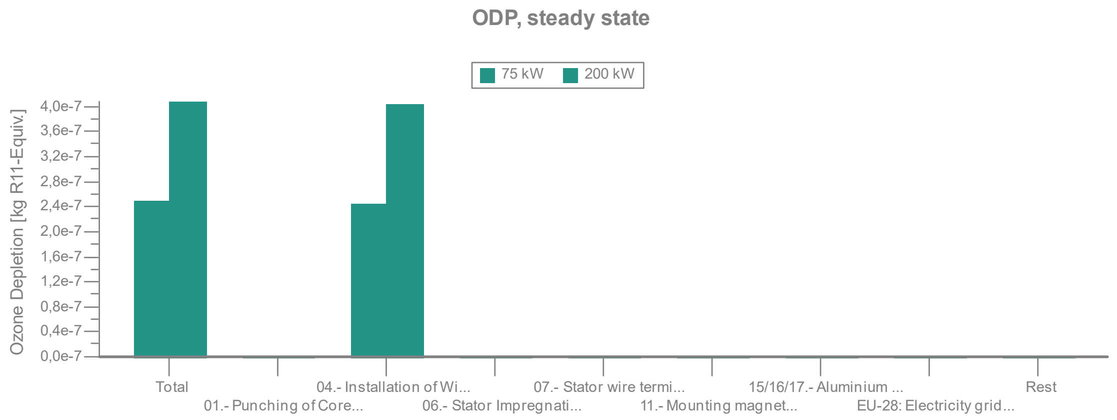


Figure 110: Ozone depletion - Reference (PM SynRel)

5.2.4.2 PM assisted SynRel (REFREEDRIVE)

Table 84: PM assisted SynRel (REFREEDRIVE) environmental impact – Ozone Depletion

Ozone Depletion (Impacts ILCD/PEF) [kg R11-Equiv.]	75 kW		200 kW	
PM assisted SynRel (REFREEDRIVE)	**2,718 10-7 kg**		**4,538 10-7 kg**	
Stator	2,6963 10-7 kg	99,20%	4,5166 10-7 kg	99,53%
Steel Stacks	-----	-----	-----	-----
Copper Winding	2,6423 10-7 kg	97,21%	4,4626 10-7 kg	98,34%
Resin	0,054 10-7 kg	1,99%	0,054 10-7 kg	1,19%
Rotor	-----	-----	-----	-----
Cooling Housing	-----	-----	-----	-----

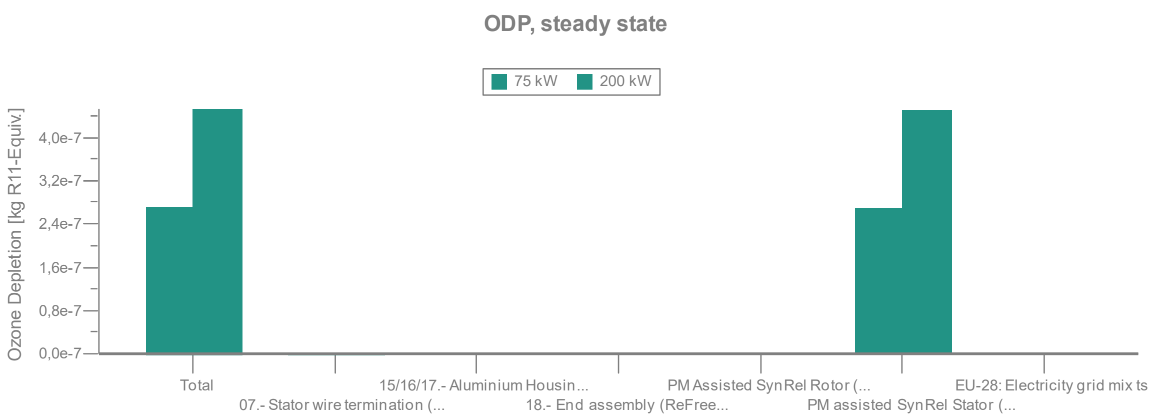


Figure 111: Ozone depletion - PM assisted SynRel (REFREEDRIVE)

5.2.4.3 Pure SynRel (REFREEDRIVE)

Table 85: Pure SynRel (REFREEDRIVE) environmental impact – Ozone Depletion

Ozone Depletion (Impacts ILCD/PEF) [kg R11-Equiv.]	75 kW		200 kW	
Pure SynRel (REFREEDRIVE)	**2,145 10-7 kg**		**3,143 10-7 kg**	
Stator	2,123 10-7 kg	98,97%	3,121 10-7 kg	99,30%
Steel Stacks	-----	-----	-----	-----
Copper Winding	2,114 10-7 kg	98,55%	3,112 10-7 kg	99,01%
Resin	0,00926 10-7 kg	0,43%	0,00926 10-7 kg	0,29%
Rotor	-----	-----	-----	-----
Cooling Housing	-----	-----	-----	-----

5.2.4.4 Die Cast Rotor Induction Machine (REFREEDRIVE)

Table 86: Die Cast rotor Induction Machine (REFREEDRIVE) environmental impact – Ozone Depletion

Ozone Depletion (Impacts ILCD/PEF) [kg R11-Equiv.]	75 kW / 200 kW	
Die Cast Rotor Induction Machine (REFREEDRIVE)	8,3342 10-7 kg	
Stator	4,6957 10-7 kg	56,34%
Steel Stacks	-----	-----
Copper Winding	4,6957 10-7 kg	56,34%
Rotor	3, 6167 10-7 kg	43,40%
Copper on Rotor	3, 6167 10-7 kg	43,40%
Cooling Housing	-----	

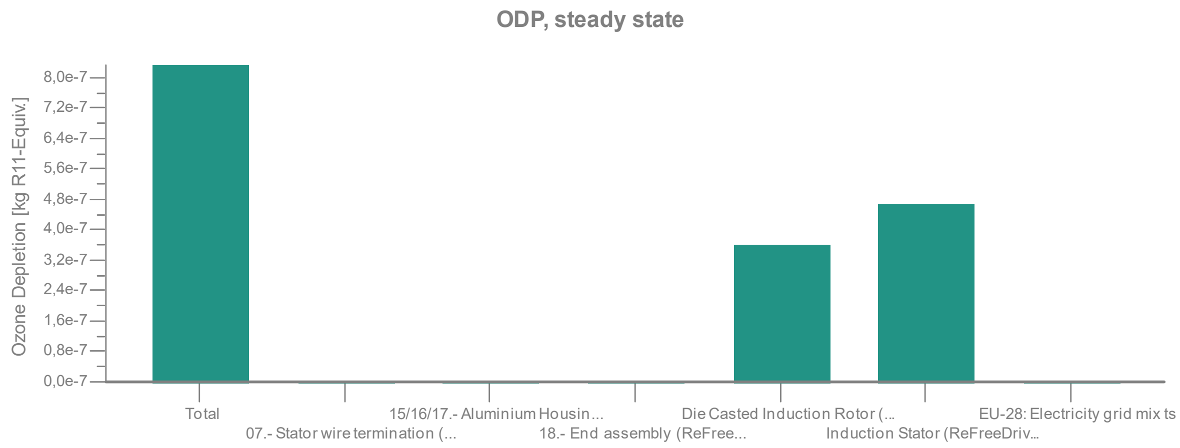


Figure 112: Ozone depletion - Die Cast Rotor Induction Machine (REFREEDRIVE)

5.2.4.5 Fabricated Rotor Induction Machine (REFREEDRIVE)

Table 87: Fabricated rotor Induction Machine (REFREEDRIVE) environmental impact – Ozone Depletion

Ozone Depletion (Impacts ILCD/PEF) [kg R11-Equiv.]	75 kW / 200 kW	
Fabricated Rotor Induction Machine (REFREEDRIVE)	4,7175 10-7 kg	
Stator	4,6957 10-7 kg	99,54%
Steel Stacks	-----	-----
Copper Winding	4,6957 10-7 kg	99,54%
Rotor	-----	
Cooling Housing	-----	

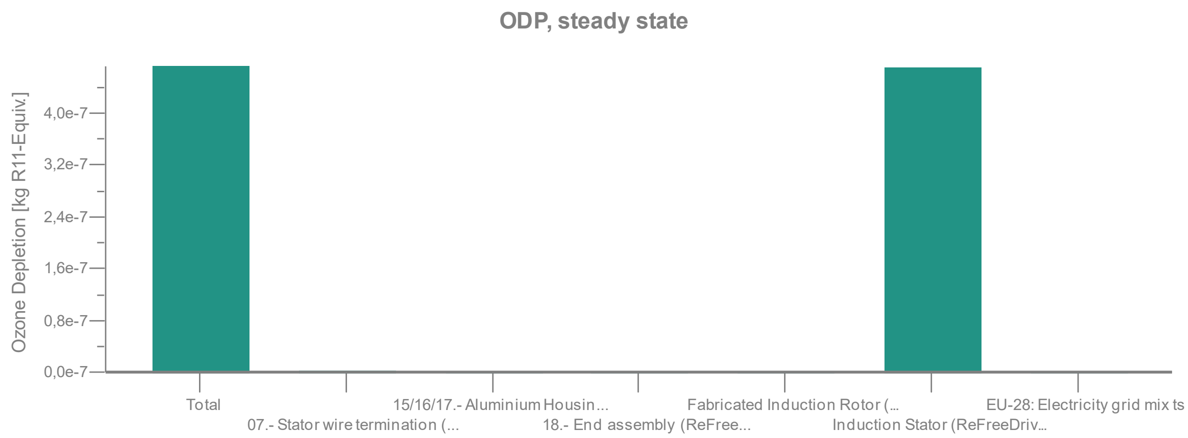


Figure 113: Ozone depletion - Fabricated Rotor Induction Machine (REFREEDRIVE)

5.2.5 Human Toxicity

5.2.5.1 Reference (PM SynRel)

Table 88: Reference (PM SynRel) environmental impact – Human Toxicity (cancer)

Human Toxicity, cancer effects (Impacts ILCD/PEF) [CTUh]	75 kW		200 kW	
Reference (PM SynRel)	**1,112 10-6 CTUh**		**2,419 10-6 CTUh**	
Steel Stacks (Stator & Rotor)	0,0694 10-6 CTUh	6,24%	0,1477 10-6 CTUh	6,11%
Copper Winding	0,0587 10-6 CTUh	5,28%	0,0926 10-6 CTUh	3,83%
Permanent Magnets on Rotor	0,654 10-6 CTUh	58,81%	1,3988 10-6 CTUh	57,83%
Steel Rotor Shaft	0,01735 10-6 CTUh	1,56%	0,0573 10-6 CTUh	2,37%
Cooling Housing	0,2517 10-6 CTUh	22,63%	0,620 10-6 CTUh	25,63%

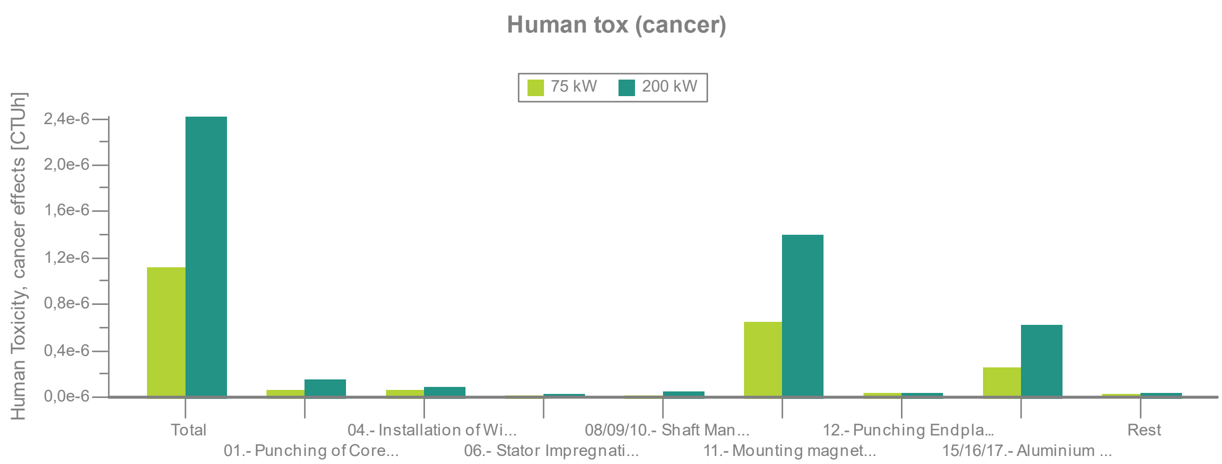


Figure 114: Human Toxicity (cancer) - Reference (PM SynRel)

5.2.5.2 PM assisted SynRel (REFREEDRIVE)

Table 89: PM assisted SynRel (REFREEDRIVE) environmental impact – Human Toxicity (cancer)

Human Toxicity, cancer effects (Impacts ILCD/PEF) [CTUh]	75 kW		200 kW	
PM assisted SynRel (REFREEDRIVE)	**0,6178 10-6 CTUh**		**0,8613 10-6 CTUh**	
Stator	0,1971 10-6 CTUh	31,90%	0,2902 10-6 CTUh	33,69%
Steel Stacks	0,0300 10-6 CTUh	4,86%	0,0802 10-6 CTUh	9,31%
Copper Winding	0.0514 10-6 CTUh	8,32%	0,08677 10-6 CTUh	10,07%

Resin	0,1014 10-6 CTUh	16,42%	0,1045 10-6 CTUh	12,14%
Rotor	0,1602 10-6 CTUh	25,93%	0,3109 10-6 CTUh	36,10%
Steel Stacks	0,02832 10-6 CTUh	4,58%	0,0758 10-6 CTUh	8,80%
Ferrite Magnets	0,055 10-6 CTUh	8,90%	0,1485 10-6 CTUh	17,24%
Aluminium End Plates	0,01587 10-6 CTUh	2,57%	0,01587 10-6 CTUh	1,84%
Shaft	0,0565 10-6 CTUh	9,15%	0,0562 10-6 CTUh	6,53%
Cooling Housing	0,2363 10-6 CTUh	38,25%	0,2363 10-6 CTUh	27,44%

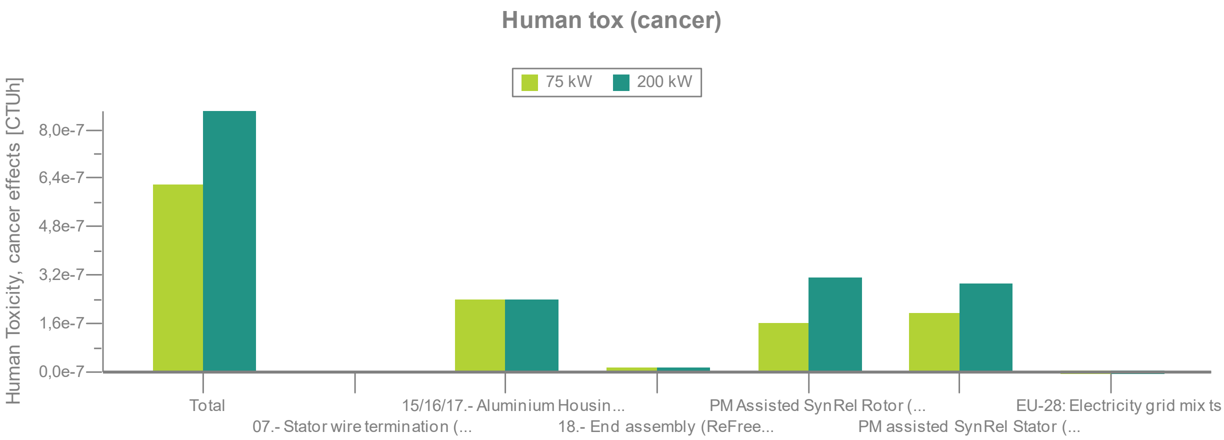


Figure 115: Human Toxicity (cancer) - PM assisted SynRel (REFREEDRIVE)

5.2.5.3 Pure SynRel (REFREEDRIVE)

Table 90: Pure SynRel (REFREEDRIVE) environmental impact – Human Toxicity (cancer)

Human Toxicity, cancer effects (Impacts ILCD/PEF) [CTUh]	75 kW		200 kW	
Pure SynRel (REFREEDRIVE)	**0,4440 10-6 CTUh**		**0,5516 10-6 CTUh**	
Stator	0,1170 10-6 CTUh	26,35%	0,195 10-6 CTUh	35,35%
Steel Stacks	0,0418 10-6 CTUh	9,41%	0,0945 10-6 CTUh	17,13%
Copper Winding	0.0411 10-6 CTUh	9,26%	0,0605 10-6 CTUh	10,97%
Resin	0,0202 10-6 CTUh	4,55%	0,0218 10-6 CTUh	3,97%
Rotor	0,0664 10-6 CTUh	14,95%	0,09643 10-6 CTUh	17,48%
Steel Stacks	0,02396 10-6 CTUh	5,40%	0,05228 10-6 CTUh	9,48%
Shaft	0,04131 10-6 CTUh	9,30%	0,04131 10-6 CTUh	7,49%

Cooling Housing	0,2363 10-6 CTUh	53,22%	0,2363 10-6 CTUh	42,84%

5.2.5.4 Die Cast Rotor Induction Machine (REFREEDRIVE)

Table 91: Die Cast rotor Induction Machine (REFREEDRIVE) environmental impact – Human Toxicity (cancer)

Human Toxicity, cancer effects (Impacts ILCD/PEF) [CTUh]	75 kW / 200 kW	
Die Cast Rotor Induction Machine (REFREEDRIVE)	**0,68253 10-6 CTUh**	
Stator	1,7393E-07 CTUh	25,48%
Steel Stacks	7,392E-08 CTUh	10,83%
Copper Winding	9,1306E-08 CTUh	13,38%
Rotor	1,491E-07 CTUh	21,85%
Steel Stacks	3,476E-08 CTUh	5,09%
Copper	7,0325E-08 CTUh	10,30%
Shaft	4,29E-08 CTUh	6,29%
Cooling Housing	3,3337E-07 CTUh	48,84%

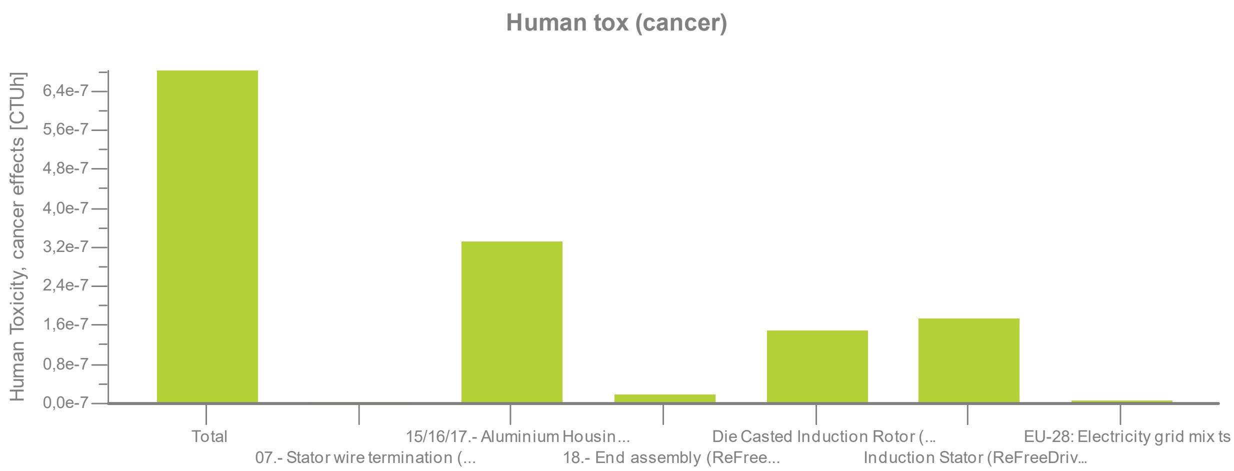


Figure 116: Human Toxicity (cancer) - Die Cast Rotor Induction Machine (REFREEDRIVE)

5.2.5.5 Fabricated Rotor Induction Machine (REFREEDRIVE)

Table 92: Fabricated rotor Induction Machine (REFREEDRIVE) environmental impact – Human Toxicity (cancer)

Human Toxicity, cancer effects (Impacts ILCD/PEF) [CTUh]	75 kW / 200 kW	
Fabricated Rotor Induction Machine (REFREEDRIVE)	**0,83907 10-6 CTUh**	
Stator	0,17393 10-6 CTUh	20,73%
Steel Stacks	0,073925 10-6 CTUh	8,81%
Copper Winding	0,091306 10-6 CTUh	10,88%
Rotor	0,30564 10-6 CTUh	36,43%
Steel Stacks	0,03476 10-6 CTUh	4,14%
Copper	0,22728 10-6 CTUh	27,09%
Copper Bars	0,18930 10-6 CTUh	22,56%
Copper End Plates	0,03798 10-6 CTUh	4,53%
Shaft	0,04296 10-6 CTUh	5,12%
Cooling Housing	0,33337 10-6 CTUh	39,73%

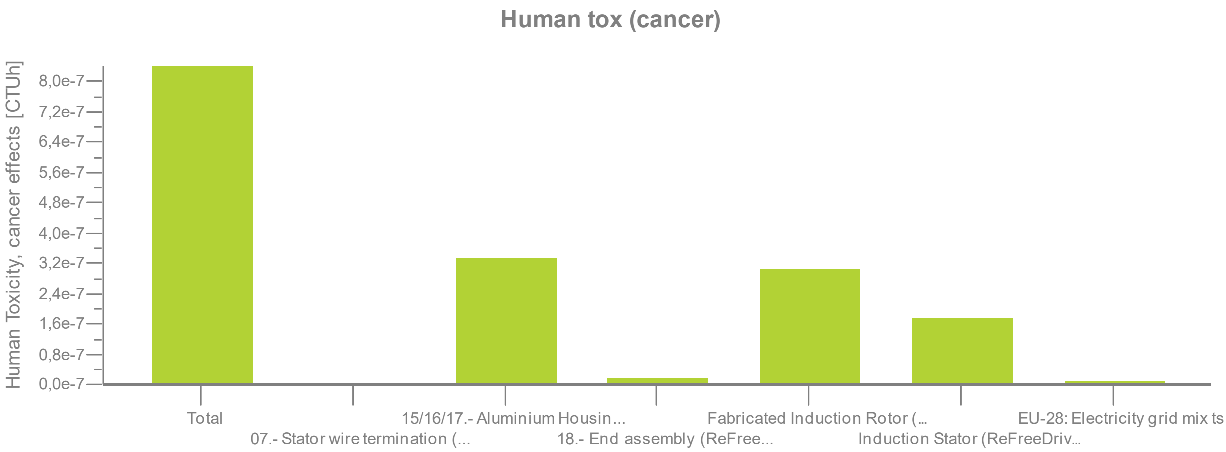


Figure 117: Human Toxicity (cancer) - Fabricated Rotor Induction Machine (REFREEDRIVE)

5.2.6 Particulate matter/Respiratory inorganics

5.2.6.1 Reference (PM SynRel)

Table 93: Reference (PM SynRel) environmental impact – Particulate matter

Particulate matter/Respiratory inorganics (Impacts ILCD/PEF) [kg PM2.5 eq]	75 kW		200 kW	
Reference (PM SynRel)	**0,1232 kg**		**0,2726 kg**	
Steel Stacks (Stator & Rotor)	0,01646 kg	13,36%	0,03505 kg	12,86%
Copper Winding	0,001536 kg	1,25%	0,002514 kg	0,92%
Permanent Magnets on Rotor	0,06953 kg	56,44%	0,14873 kg	54,56%
Steel Rotor Shaft	0,00114 kg	0,93%	0,00376 kg	1,38%
Cooling Housing	0,0315 kg	25,57%	0,07811 kg	28,65%

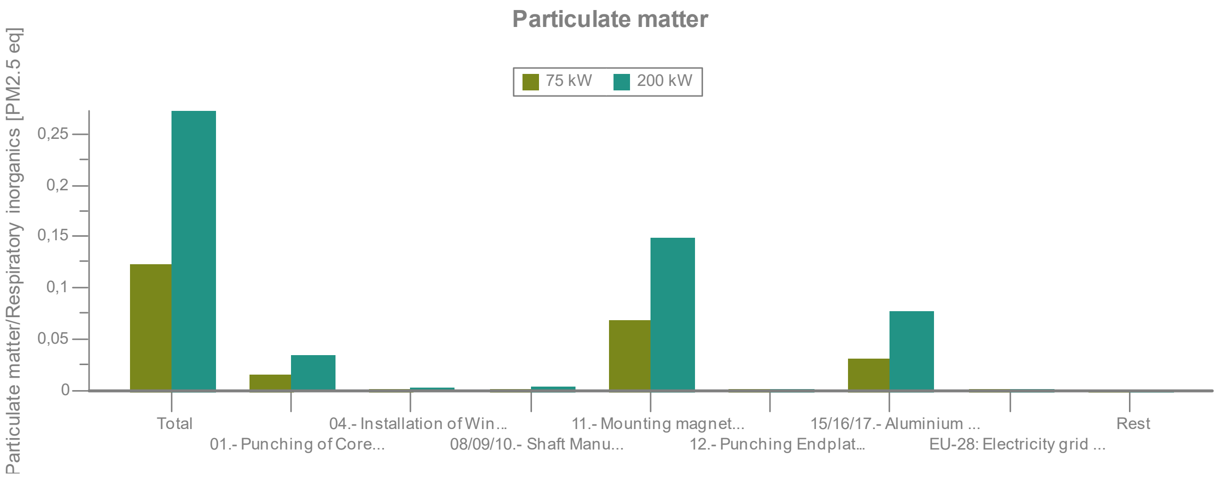


Figure 118: Particulate matter/Respiratory inorganics - Reference (PM SynRel)

5.2.6.2 PM assisted SynRel (REFREEDRIVE)

Table 94: PM assisted SynRel (REFREEDRIVE) environmental impact – Particulate matter

Particulate matter/Respiratory inorganics (Impacts ILCD/PEF) [kg PM2.5 eq]	75 kW		200 kW	
PM assisted SynRel (REFREEDRIVE)	**0,053552 kg**		**0,078897 kg**	
Stator	0,01001 kg	18,69%	0,023144 kg	29,33%
Steel Stacks	0,007134 kg	13,32%	0,01902 kg	24,11%
Copper Winding	0,001583 kg	2,96%	0,002673 kg	3,39%
Resin	0,001075 kg	2,01%	0,001105kg	1,40%
Rotor	0,012981 kg	24,24%	0,025248 kg	32,00%
Steel Stacks	0,006720 kg	12,55%	0,01799 kg	22,80%

Ferrite Magnets	0,000285 kg	0,53%	0,000768 kg	0,97%
Aluminium End Plates	0,000201 kg	0,38%	0,000201 kg	0,25%
Shaft	0,003708 kg	6,92%	0,003889 kg	4,93%
Cooling Housing	0,02952 kg	55,12%	0,02952 kg	37,42%

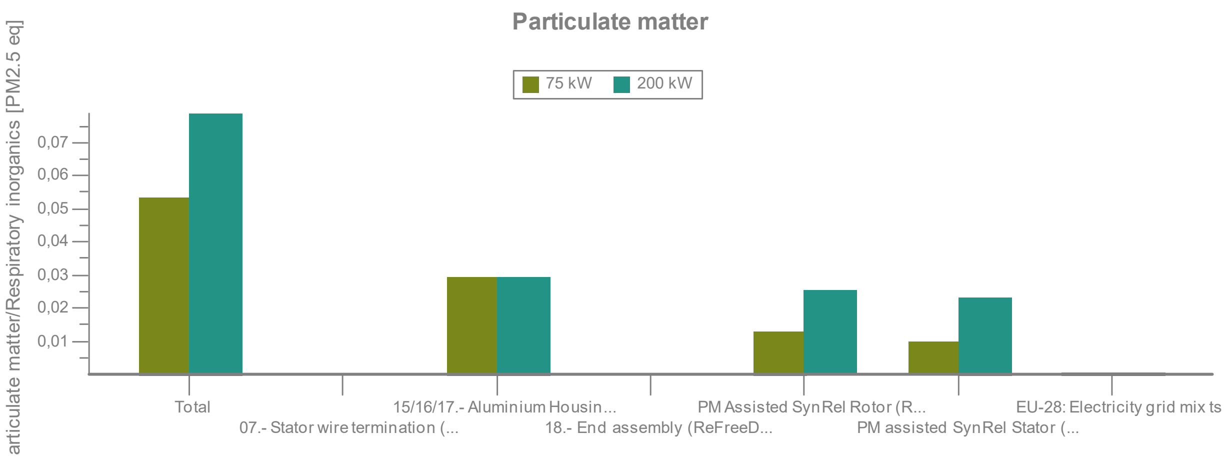


Figure 119: Particulate matter/Respiratory inorganics - PM assisted SynRel (REFREEDRIVE)

5.2.6.3 Pure SynRel (REFREEDRIVE)

Table 95: Pure SynRel (REFREEDRIVE) environmental impact – Particulate matter

Particulate matter/Respiratory inorganics (Impacts ILCD/PEF) [kg PM2.5 eq]	75 kW		200 kW	
Pure SynRel (REFREEDRIVE)	**0,05061 kg**		**0,07052 kg**	
Stator	0,011604 kg	22,93%	0,02482 kg	35,20%
Steel Stacks	0,009925 kg	19,61%	0,02243 kg	31,81%
Copper Winding	0,001266 kg	2,50%	0,001864 kg	2,64%
Resin	0,000210 kg	0,41%	0,000225 kg	0,32%
Rotor	0,008447 kg	16,69%	0,015197 kg	21,55%
Steel Stacks	0,005686 kg	11,23%	0,01246 kg	17,67%
Shaft	0,002713 kg	5,36%	0,002713 kg	3,85%
Cooling Housing	0,02952 kg	58,33%	0,02952 kg	41,86%

5.2.6.4 Die Cast Rotor Induction Machine (REFREEDRIVE)

Table 96: Die Cast rotor Induction Machine (REFREEDRIVE) environmental impact – Particulate matter

Particulate matter/Respiratory inorganics (Impacts ILCD/PEF) [kg PM2.5 eq]	75 kW / 200 kW	
Die Cast Rotor Induction Machine (REFREEDRIVE)	**0,077077 kg**	
Stator	0,020643 kg	26,78%
Steel Stacks	0,017543 kg	22,76%
Copper Winding	0,0028124 kg	3,65%
Rotor	0,013362 kg	17,34%
Steel Stacks	0,008249 kg	10,70%
Copper	0,002166 kg	2,81%
Shaft	0,002822 kg	3,66%
Cooling Housing	0,041808 kg	54,24%

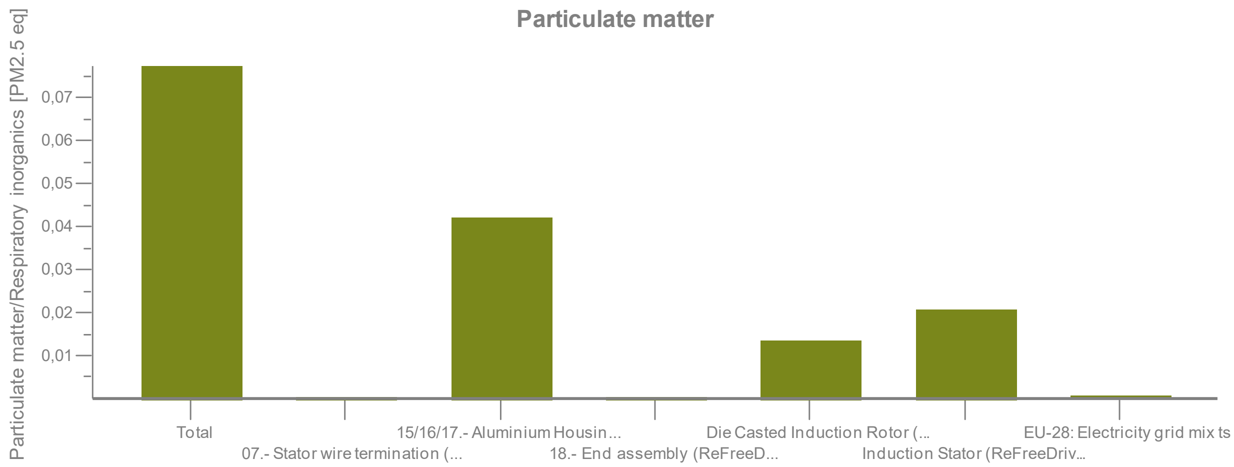


Figure 120: Particulate matter/Respiratory inorganics - Die Cast Rotor Induction Machine (REFREEDRIVE)

5.2.6.5 Fabricated Rotor Induction Machine (REFREEDRIVE)

Table 97: Fabricated rotor Induction Machine (REFREEDRIVE) environmental impact – Particulate matter

Particulate matter/Respiratory inorganics (Impacts ILCD/PEF) [kg PM2.5 eq]	75 kW / 200 kW	
Fabricated Rotor Induction Machine (REFREEDRIVE)	0,085915 kg	
Stator	0,020643 kg	24,03%
Steel Stacks	0,017543 kg	20,42%

Copper Winding	0,0028124 kg	3,27%
Rotor	0,02220 kg	25,84%
Steel Stacks	0,0082492 kg	9,60%
Copper	0,011054 kg	12,87%
Copper Bars	0,0092018 kg	10,71%
Copper End Plates	0,0018523 kg	2,16%
Shaft	0,0028216 kg	3,28%
Cooling Housing	0,041808 kg	48,66%

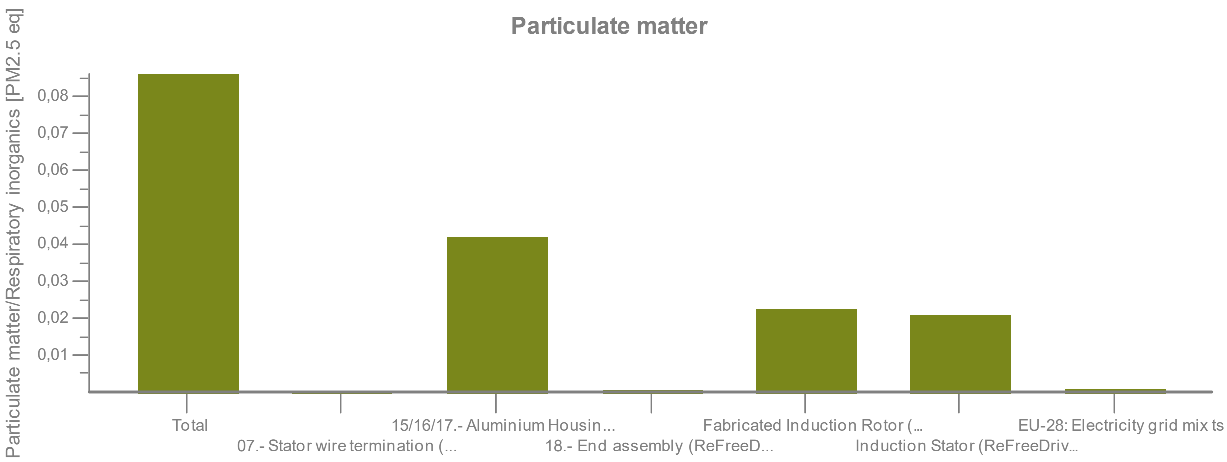


Figure 121: Particulate matter/Respiratory inorganics - Fabricated Rotor Induction Machine (REFREEDRIVE)

5.2.7 Ionising radiation, human health

5.2.7.1 Reference (PM SynRel)

Table 98: Reference (PM SynRel) environmental impact – Ionising radiation

Ionising radiation, human health (Impacts ILCD/PEF) [kBq U235 eq]	75 kW		200 kW	
Reference (PM SynRel)	**22,685 kBq**		**53,707 kBq**	
Steel Stacks (Stator & Rotor)	1,3695 kBq	6,04%	2,9165 kBq	5,43%
Copper Winding	0,3038 kBq	1,34%	0,4887 kBq	0,91%
Permanent Magnets on Rotor	1,5156 kBq	6,68%	3,242 kBq	6,04%

Steel Rotor Shaft	0,09746 kBq	0,43%	0,3218 kBq	0,60%
Cooling Housing	15,824 kBq	69,76%	39,247 kBq	73,08%

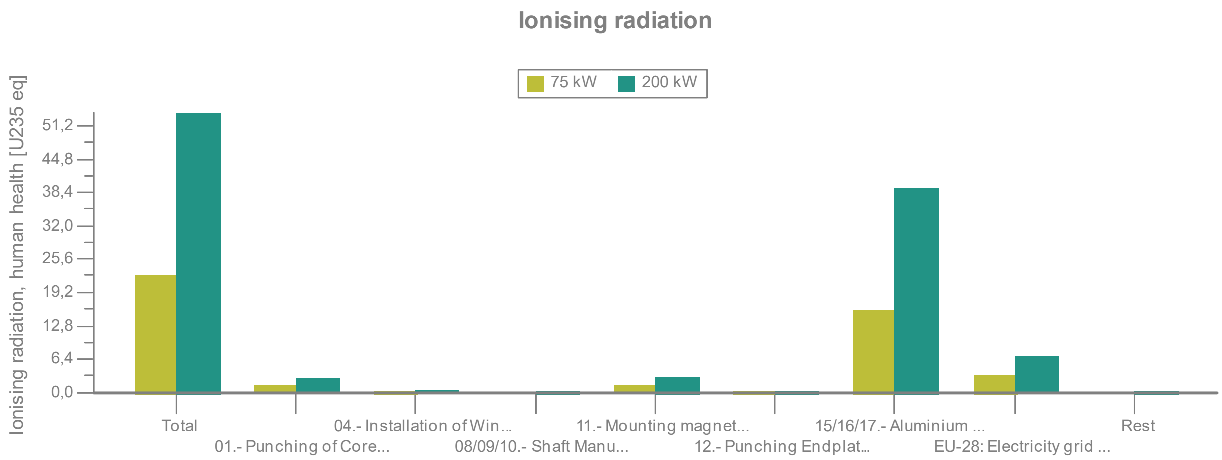


Figure 122: Ionising radiation, human health - Reference (PM SynRel)

5.2.7.2 PM assisted SynRel (REFREEDRIVE)

Table 99: PM assisted SynRel (REFREEDRIVE) environmental impact – Ionising radiation

Ionising radiation, human health (Impacts ILCD/PEF) [kBq U235 eq]	75 kW		200 kW	
PM assisted SynRel (REFREEDRIVE)	**22,089 kBq**		**25,597 kBq**	
Stator	1,923 kBq	8,71%	3,511 kBq	13,72%
Steel Stacks	0,5936 kBq	2,69%	1,583 kBq	6,18%
Copper Winding	0,2954 kBq	1,34%	0,4989 kBq	1,95%
Resin	0,4836 kBq	2,19%	0,4916 kBq	1,92%
Rotor	2,8155 kBq	12,75%	4,9121 kBq	19,19%
Steel Stacks	0,5592 kBq	2,53%	1,4969 kBq	5,85%
Ferrite Magnets	-----	-----	-----	-----
Aluminium End Plates	1,0091 kBq	4,57%	1,0091 kBq	3,94%
Shaft	0,3171 kBq	1,44%	0,3326 kBq	1,30%
Cooling Housing	14,823 kBq	67,11%	14,823 kBq	57,91%

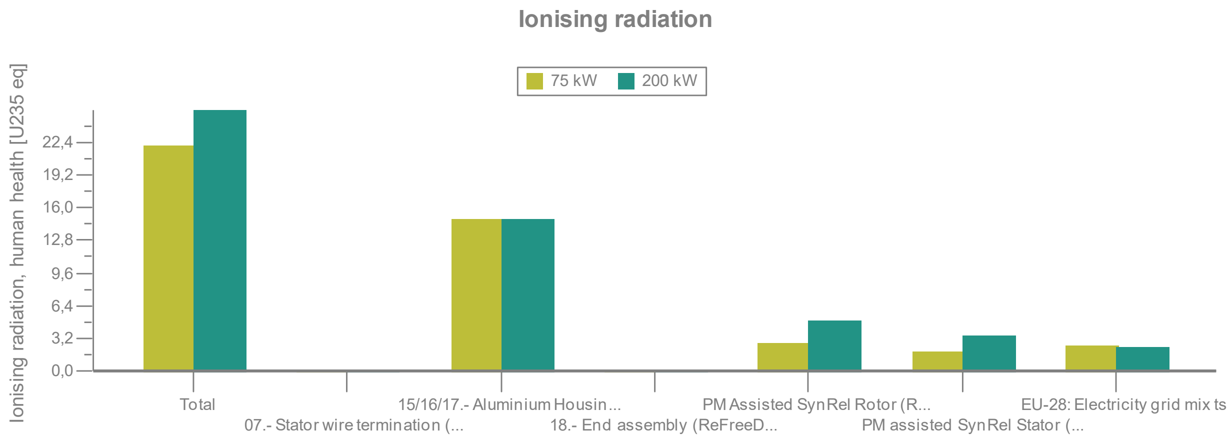


Figure 123: PM assisted SynRel (REFREEDRIVE)

5.2.7.3 Pure SynRel (REFREEDRIVE)

Table 100: Pure SynRel (REFREEDRIVE) environmental impact – Ionising radiation

Ionising radiation, human health (Impacts ILCD/PEF) [kBq U235 eq]	75 kW		200 kW	
Pure SynRel (REFREEDRIVE)	**19,858 kBq**		**21,699 kBq**	
Stator	1,6425 kBg	8,27%	3,048 kBg	14,05%
Steel Stacks	0,8259 kBg	4,16%	1,867 kBg	8,60%
Copper Winding	0,2363 kBg	1,19%	0,3479 kBg	1,60%
Resin	0,09 kBg	0,45%	0,0942 kBg	0,43%
Rotor	0,8649 kBq	4,36%	1,477 kBq	6,81%
Steel Stacks	0,4732 kBq	2,38%	1,03241 kBq	4,76%
Shaft	0,2320 kBq	1,17%	0,2320 kBq	1,07%
Cooling Housing	14,823 kBq	74,64%	14,823 kBq	68,31%

5.2.7.4 Die Cast Rotor Induction Machine (REFREEDRIVE)

Table 101: Die Cast rotor Induction Machine (REFREEDRIVE) environmental impact – Ionising radiation

Ionising radiation, human health (Impacts ILCD/PEF) [kBq U235 eq]	75 kW / 200 kW	
Die Cast Rotor Induction Machine (REFREEDRIVE)	**29,1382 kBq**	
Stator	2,9 kBq	9,95%

Steel Stacks	1,4598 kBq	5,01%
Copper Winding	0,52495 kBq	1,80%
Rotor	1,8249 kBq	6,26%
Steel Stacks	0,68643 kBq	2,36%
Copper	0,40432 kBq	1,39%
Shaft	0,24134 kBq	0,83%
Cooling Housing	20,995 kBq	72,05%

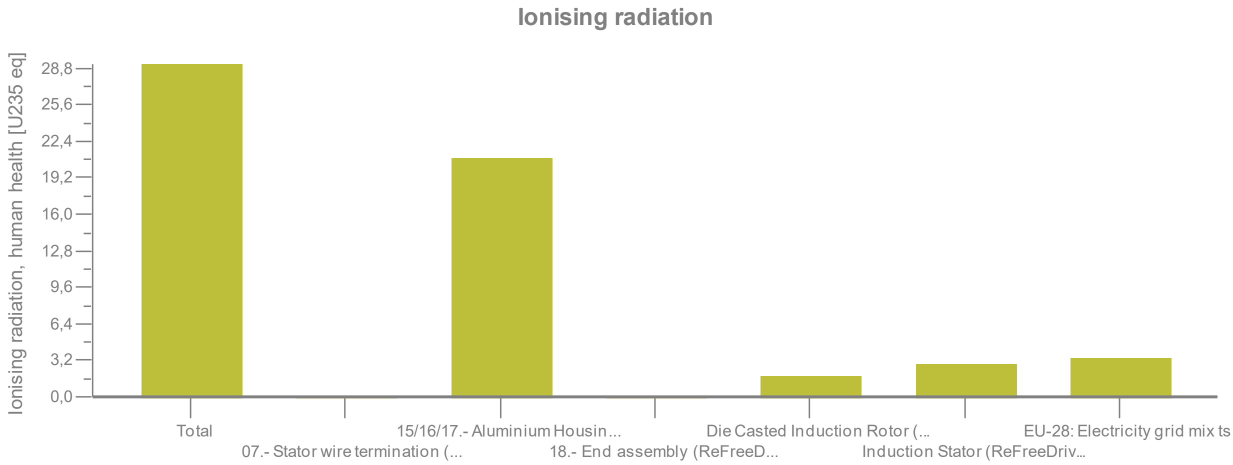


Figure 124: Ionising radiation, human health - Die Cast Rotor Induction Machine (REFREEDRIVE)

5.2.7.5 Fabricated Rotor Induction Machine (REFREEDRIVE)

Table 102: Fabricated rotor Induction Machine (REFREEDRIVE) environmental impact – Ionising radiation

Ionising radiation, human health (Impacts ILCD/PEF) [kBq U235 eq]	75 kW / 200 kW	
Fabricated Rotor Induction Machine (REFREEDRIVE)	31,068 kBq	
Stator	2,9000 kBq	9,33%
Steel Stacks	1,4598 kBq	4,70%

Copper Winding	0,52495 kBq	1,69%
Rotor	3,7545kBq	12,08%
Steel Stacks	0,68643 kBq	2,21%
Copper	2,5327 kBq	8,15%
Copper Bars	2,0011 kBq	6,44%
Copper End Plates	0,5316 kBq	1,71%
Shaft	0,24134 kBq	0,78%
Cooling Housing	20,995 kBq	67,58%

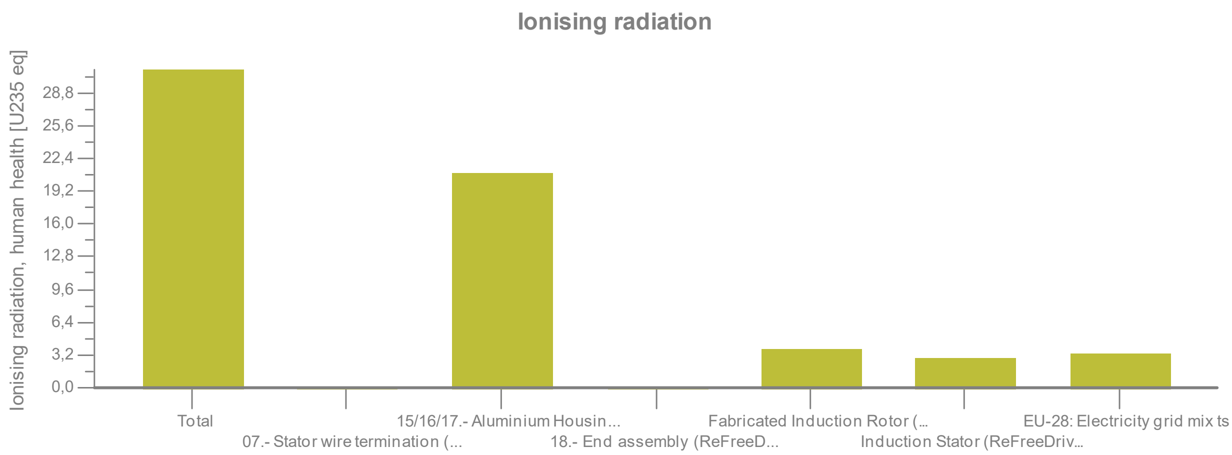


Figure 125: Ionising radiation, human health - Fabricated Rotor Induction Machine (REFREEDRIVE)

5.2.8 Photochemical Ozone Formation

5.2.8.1 Reference (PM SynRel)

Table 103: Reference (PM SynRel) environmental impact – Photochemical Ozone Formation

Photochemical Ozone Formation (Impacts ILCD/PEF) [kg NMVOC Equiv.]	75 kW		200 kW	
Reference (PM SynRel)	**0,6760 kg**		**1,514 kg**	
Steel Stacks (Stator & Rotor)	0,1717 kg	25,40%	0,3657 kg	24,15%
Copper Winding	0,01032 kg	1,53%	0,01677 kg	1,11%
Permanent Magnets on Rotor	0,2513 kg	37,17%	0,5376 kg	35,51%

Steel Rotor Shaft	0,01335 kg	1,97%	0,04409 kg	2,91%
Cooling Housing	0,2061 kg	30,49%	0,51046 kg	33,72%

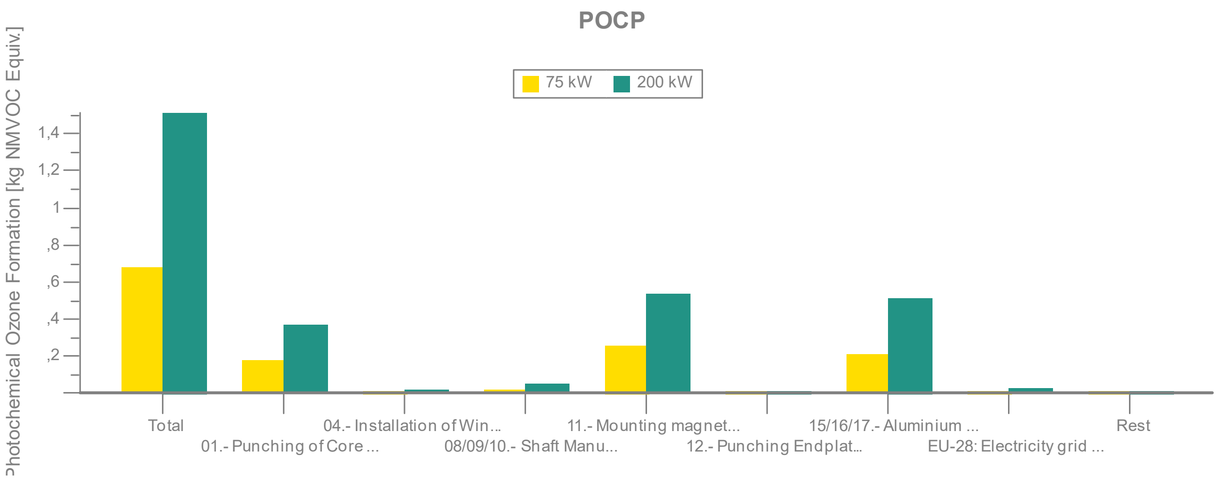


Figure 126: Photochemical Ozone Formation - Reference (PM SynRel)

5.2.8.2 PM assisted SynRel (REFREEDRIVE)

Table 104: PM assisted SynRel (REFREEDRIVE) environmental impact – Photochemical Ozone Formation

Photochemical Ozone Formation (Impacts ILCD/PEF) [kg NMVOC Equiv.]	75 kW		200 kW	
PM assisted SynRel (REFREEDRIVE)	**0,44349 kg**		**0,70117 kg**	
Stator	0,1098 kg	24,76%	0,2431 kg	34,67%
Steel Stacks	0,07443 kg	16,78%	0,1985 kg	28,31%
Copper Winding	0,009587 kg	2,16%	0,01619 kg	2,31%
Resin	0,022 kg	4,96%	0,023 kg	3,28%
Rotor	0,13061 kg	29,45%	0,25568 kg	36,46%
Steel Stacks	0,070 kg	15,78%	0,1877 kg	26,77%
Ferrite Magnets	------	-----	------	-----
Aluminium End Plates	0,01312 kg	2,96%	0,01312 kg	1,87%
Shaft	0,04346 kg	9,80%	0,04557 kg	6,50%
Cooling Housing	0,19313 kg	43,55%	0,19313 kg	27,54%

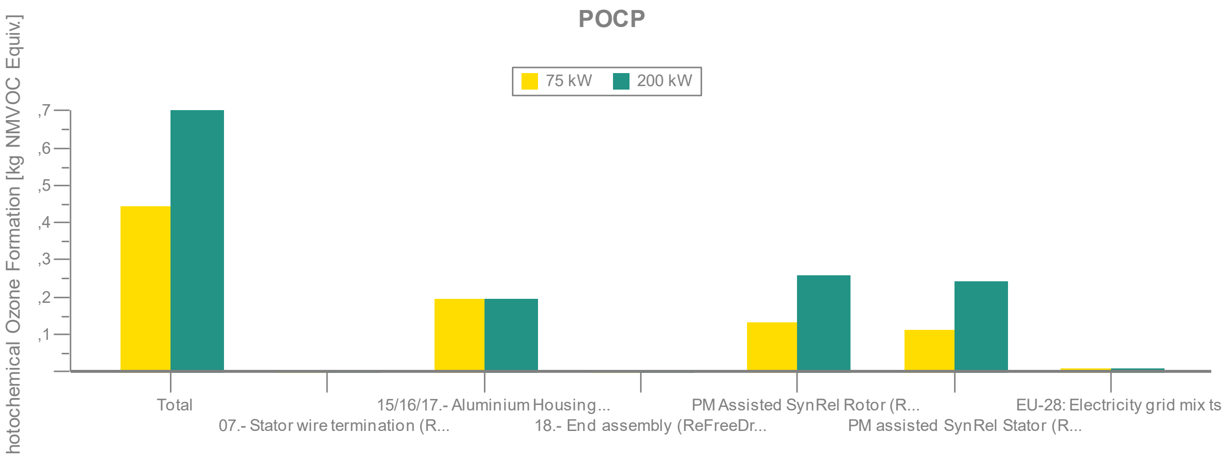


Figure 127: Photochemical Ozone Formation - PM assisted SynRel (REFREEDRIVE)

5.2.8.3 Pure SynRel (REFREEDRIVE)

Table 105: Pure SynRel (REFREEDRIVE) environmental impact – Photochemical Ozone Formation

Photochemical Ozone Formation (Impacts ILCD/PEF) [kg NMVOC Equiv.]	75 kW		200 kW	
Pure SynRel (REFREEDRIVE)	**0,4141 kg**		**0,6200 kg**	
Stator	0,1192 kg	28,79%	0,2552 kg	41,16%
Steel Stacks	0,1036 kg	25,02%	0,2341 kg	37,76%
Copper Winding	0,00767 kg	1,85%	0,01129 kg	1,82%
Resin	0,00448 kg	1,08%	0,004895 kg	0,79%
Rotor	0,09178 kg	22,16%	0,1624 kg	26,19%
Steel Stacks	0,05932 kg	14,33%	0,12944 kg	20,88%
Shaft	0,03197 kg	7,72%	0,03179 kg	5,13%
Cooling Housing	0,19313 kg	46,64%	0,19313 kg	31,15%

5.2.8.4 Die Cast Rotor Induction Machine (REFREEDRIVE)

Table 106: Die Cast rotor Induction Machine (REFREEDRIVE) environmental impact – Photochemical Ozone Formation

Photochemical Ozone Formation (Impacts ILCD/PEF) [kg NMVOC Equiv.]	75 kW / 200 kW	
Die Cast Rotor Induction Machine (REFREEDRIVE)	**0,6248 kg**	
Stator	0,20428 kg	32,70%

Steel Stacks	0,18303 kg	29,29%
Copper Winding	0,01704 kg	2,73%
Rotor	0,13388 kg	21,43%
Steel Stacks	0,08607 kg	13,78%
Copper	0,013122 kg	2,10%
Shaft	0,03307 kg	5,29%
Cooling Housing	0,27339 kg	43,76%

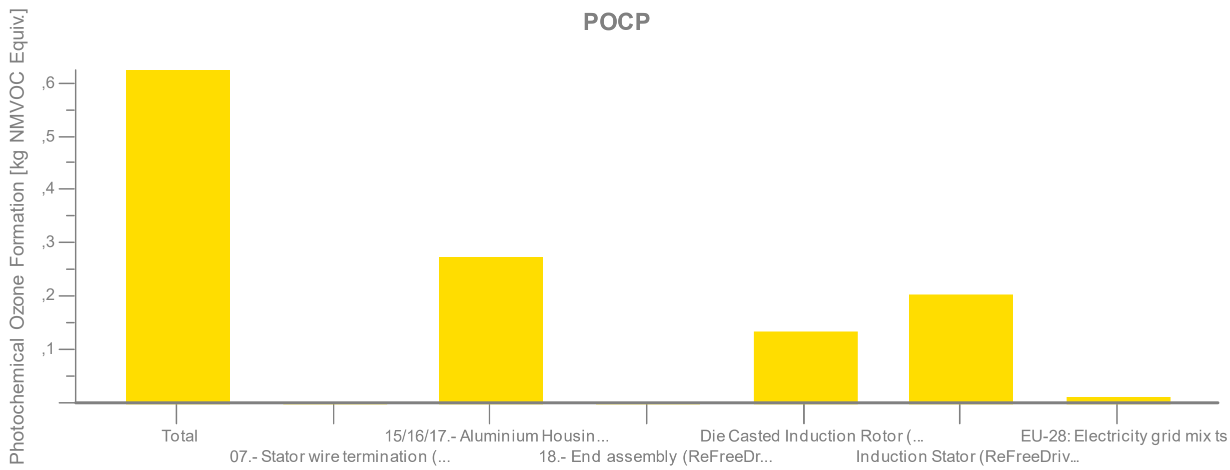


Figure 128: Photochemical Ozone Formation - Die Cast Rotor Induction Machine (REFREEDRIVE)

5.2.8.5 Fabricated Rotor Induction Machine (REFREEDRIVE)

Table 107: Fabricated rotor Induction Machine (REFREEDRIVE) environmental impact – Photochemical Ozone Formation

Photochemical Ozone Formation (Impacts ILCD/PEF) [kg NMVOC Equiv.]	75 kW / 200 kW	
Fabricated Rotor Induction Machine (REFREEDRIVE)	**0,67656 kg**	
Stator	0,20428 kg	30,19%
Steel Stacks	0,18303 kg	27,05%
Copper Winding	0,01704 kg	2,52%

Rotor	0,18625 kg	27,53%
Steel Stacks	0,08607 kg	12,72%
Copper	0,06620 kg	9,78%
Copper Bars	0,05498 kg	8,13%
Copper End Plates	0,01122 kg	1,66%
Shaft	0,033069 kg	4,89%
Cooling Housing	0,27339 kg	40,41%

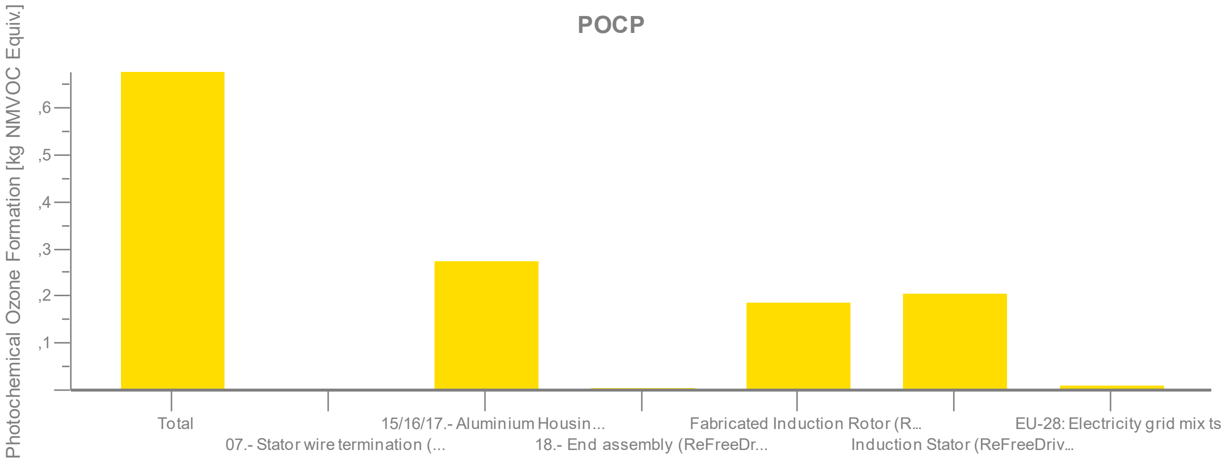


Figure 129: Photochemical Ozone Formation - Fabricated Rotor Induction Machine (REFREEDRIVE)

5.2.9 Acidification

5.2.9.1 Reference (PM SynRel)

Table 108: Reference (PM SynRel) environmental impact – Acidification

Acidification (Impacts ILCD/PEF) [Mole of H+ eq.]	75 kW		200 kW	
Reference (PM SynRel)	**1,4953 mol**		**3,3532 mol**	
Steel Stacks (Stator & Rotor)	0,2352 mol	15,73%	0,5009 mol	14,94%
Copper Winding	0,0228 mol	1,52%	0,03726 mol	1,11%
Permanent Magnets on Rotor	0,6576 mol	43,98%	1,4067 mol	41,95%
Steel Rotor Shaft	0,01692 mol	1,13%	0,05586 mol	1,67%

Cooling Housing	0,5167 mol	34,55%	1,281 mol	38,20%

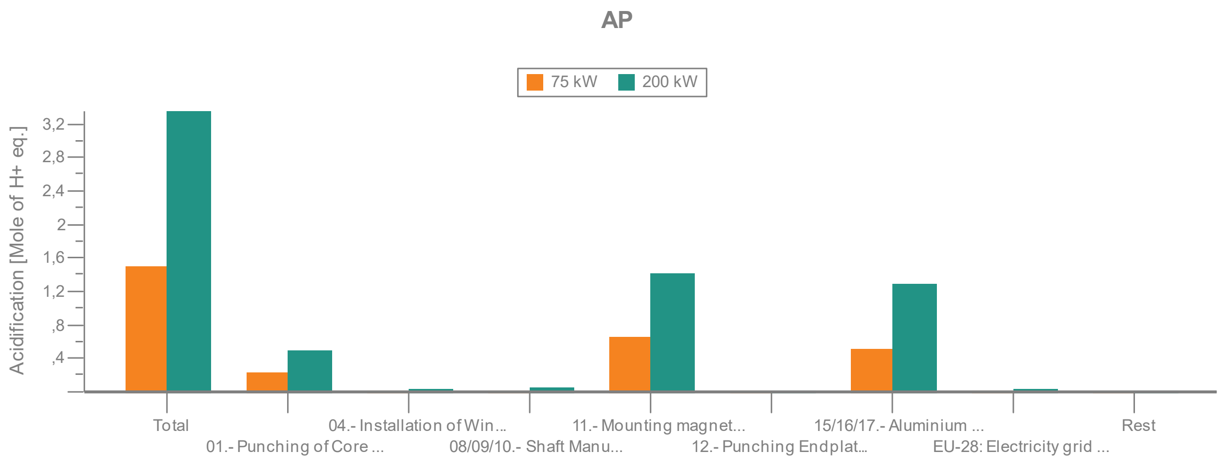


Figure 130: Acidification - Reference (PM SynRel)

5.2.9.2 PM assisted SynRel (REFREEDRIVE)

Table 109: PM assisted SynRel (REFREEDRIVE) environmental impact – Acidification

Acidification (Impacts ILCD/PEF) [Mole of H+ eq.]	75 kW		200 kW	
PM assisted SynRel (REFREEDRIVE)	**0,84221 mol**		**1,2013 mol**	
Stator	0,1501 mol	17,82%	0,3391 mol	28,23%
Steel Stacks	0,10196 mol	12,11%	0,27188 mol	22,63%
Copper Winding	0,02314 mol	2,75%	0,03908 mol	3,25%
Resin	0,01955 mol	2,32%	0,01955 mol	1,63%
Rotor	0,18966 mol	22,52%	0,3608 mol	30,03%
Steel Stacks	0,09604 mol	11,40%	0,2571 mol	21,40%
Ferrite Magnets	-----	-----	-----	-----
Aluminium End Plates	0,03293 mol	3,91%	0,03293 mol	2,74%
Shaft	0,05505 mol	6,54%	0,05773 mol	4,81%
Cooling Housing	0,4840 mol	57,47%	0,4840 mol	40,29%

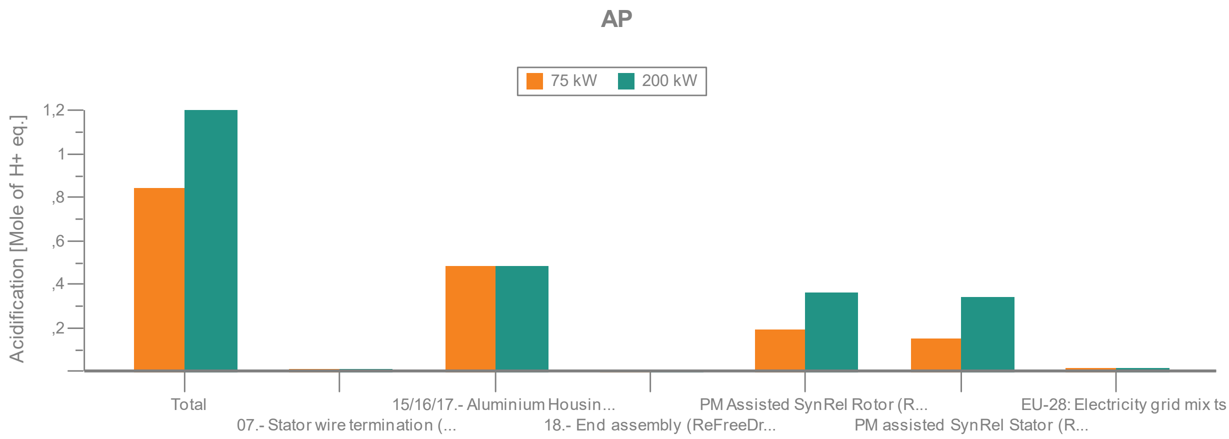


Figure 131: Acidification – PM assisted SynRel (REFREEDRIVE)

5.2.9.3 Pure SynRel (REFREEDRIVE)

Table 110: Pure SynRel (REFREEDRIVE) environmental impact – Acidification

Acidification (Impacts ILCD/PEF) [Mole of H+ eq.]	75 kW		200 kW	
Pure SynRel (REFREEDRIVE)	**0,79365 mol**		**1,0789 mol**	
Stator	0,16871 mol	21,26%	0,35843 mol	33,22%
Steel Stacks	0,14185 mol	17,87%	0,32065 mol	29,72%
Copper Winding	0,01851 mol	2,33%	0,02725 mol	2,53%
Resin	0,00403 mol	0,51%	0,00436 mol	0,40%
Rotor	0,1225 mol	15,44%	0,21912 mol	20,31%
Steel Stacks	0,08127 mol	10,24%	0,17731 mol	16,43%
Shaft	0,04028 mol	5,08%	0,04028 mol	3,73%
Cooling Housing	0,48403 mol	60,99%	0,48403 mol	44,86%

5.2.9.4 Die Cast Rotor Induction Machine (REFREEDRIVE)

Table 111: Die Cast rotor Induction Machine (REFREEDRIVE) environmental impact – Acidification

Acidification (Impacts ILCD/PEF) [Mole of H+ eq.]	75 kW / 200 kW	
Die Cast Rotor Induction Machine (REFREEDRIVE)	**1,20007 mol**	
Stator	0,29771 mol	24,81%

Steel Stacks	0,25072 mol	20,89%
Copper Winding	0,04112 mol	3,43%
Rotor	0,1939777 mol	16,16%
Steel Stacks	0,1179 mol	9,82%
Copper	0,031673 mol	2,64%
Shaft	0,04189 mol	3,49%
Cooling Housing	0,68548 mol	57,12%

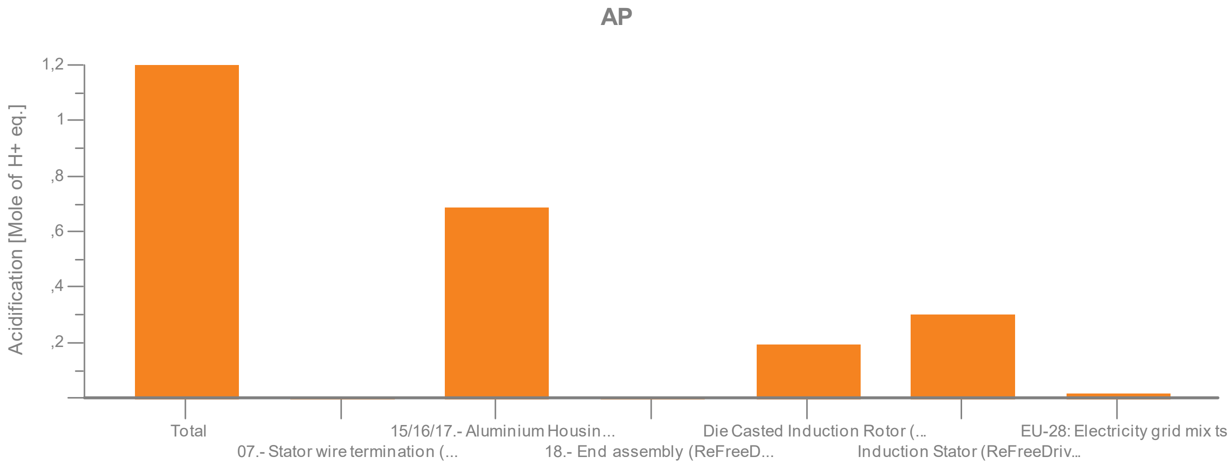


Figure 132: Acidification - Die Cast Rotor Induction Machine (REFREEDRIVE)

5.2.9.5 Fabricated Rotor Induction Machine (REFREEDRIVE)

Table 112: Fabricated rotor Induction Machine (REFREEDRIVE) environmental impact – Acidification

Acidification (Impacts ILCD/PEF) [Mole of H+ eq.]	75 kW / 200 kW	
Fabricated Rotor Induction Machine (REFREEDRIVE)	**1,3495 mol**	
Stator	0,29771 mol	22,06%
Steel Stacks	0,25072 mol	18,58%
Copper Winding	0,041123 mol	3,05%
Rotor	0,34342 mol	25,45%

Steel Stacks	0,11790 mol	8,74%
Copper	0,1821 mol	13,50%
Copper Bars	0,15156 mol	11,23%
Copper End Plates	0,030564 mol	2,26%
Shaft	0,04189 mol	3,10%
Cooling Housing	0,68548 mol	50,80%

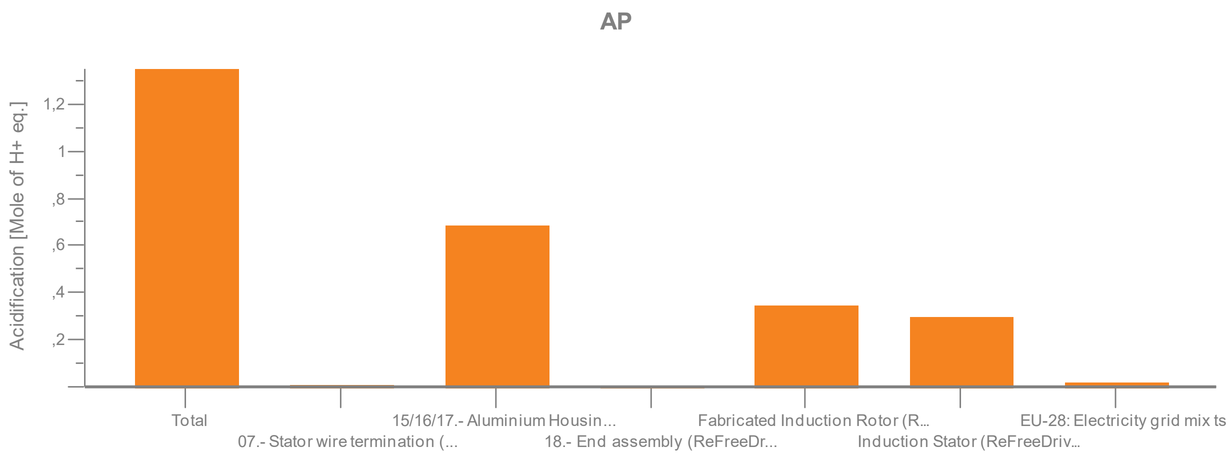


Figure 133: Acidification - Fabricated Rotor Induction Machine (REFREEDRIVE)

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