Rare Earth Free e-Drives Featuring Low Cost Manufacturing

ReFreeDrive

Collaborative Project
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Abstract:

This report describes the progresses and achievements of ReFreeDrive project in the period from 01.07.2018 (M10) to 31.07.2019 (M22). In this period several management procedures have been carried out, such as risk management, open data management, reporting to the EC, monitoring of the project progress, etc. Design of induction motor, pure synchronous reluctance motor and permanent magnets assisted reluctance motor has been carried out, ensuring the accomplishment of the Key Performance Indicators defined in the project proposal. Power electronics and control algorithm for all motor topologies have been developed. Some integration activities have also been made. The first draft of the techno-economic evaluation and results exploitation is summed up, as well as the first iterations of the Life Cycle Analysis. Although the information is individualized for each Work Package, interactions between them are also considered. All the Work Package Leaders have participated in the writing of this report.

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REVISION TABLE		
Document version	**Date**	***Modified sections - Details***
V1	05.09.2019	First draft of the report
V2	13.09.2019	Added contributions from WP leaders
V3	19.09.2019	Added contributions from ECI, IFPEN and CSM-RINA

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Abbreviations

ATF: Automotive Transmission Fluid

AUR: Aurubis

BEM: Boundary Element Method

BOM: Bill of Materials

CAN: Controller Area Network

CFD: Computer Fluid Dynamics

CID: Fundación Cidaut

CPU: Control Power Unit

CR: Copper Rotor

Cu-ETP: Copper Electrolytic Tough Pitch

DRV: Drivers

GA: Grant Agreement

ECI: European Copper Institute

ECU: Engine Control Unit

EV: Electric Vehicle

EWG: Ethylene-Water-Glycol

FE: Finite Element

FEA: Finite Element Analysis

FEM: Finite Element Method

GO: Grain Oriented

HMI: Human-Machine Interface

IFPEN: IFP Energies Nouvelles

IGBT: Insulated Gate Bipolar Transistor

IM: Induction Machine

IPR: Intellectual Property Rights

IR: Inner Rotor

JLR: Jaguar Land Rover

KPI: Key Performance Indicator

LCA: Life Cycle Assessment

MAV: Mavel

MDL: Motor Design Limited

MOS: Metal-Oxide Semiconductor

NGO: Non-Grain Oriented

OD: Outer Diameter

OEM: Original Equipment Manufacturer

OR: Outer Rotor

PCB: Printed Circuit Board

PM: Permanent Magnets

PMA Synrel: Permanent Magnets Assisted Synchronous Reluctance Motor

PRI: Privé

PSU: Power Supply Unit

SG: Spiral Groove

SynRel (SyncRel): Synchronous Reluctance

UAQ: Università dell'Aquila (University of L'Aquila)

WJ: Water Jacket

WLTP: Worldwide Light Vehicle Test Procedure

WP: Work Package

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Executive Summary

This document reports the project progress during the period from M10 (July 2018) to M22 (July 2019). It reviews the technical achievements of the Work Packages (WPs), the work carried out and the coming activities for the next period. The main objective of this deliverable is to provide a summary of the work done so far and reflect the project current status from a global perspective:

- WP3 and WP4 have optimized the designs of their respective technologies, Induction Machines (IM, WP3) and Synchronous Reluctance machines (SynRel, WP4) with respect to the preliminary analysis shown in D1.1 (M9). Different motor configurations have been studied for each technology from an electromagnetic, mechanical and thermal point of view, in order to ensure the accomplishment of the Key Performance Indicators (KPIs) defined in the proposal stage, as well as their right operation in their final application. Downscaling procedure from 200kW to 75kW has been defined.
- WP5 has been kicked off in advance (M9) to follow the progress of the motor designs. This WP has defined the most suitable motor control algorithms for IM and SynRel motors using simulation platforms (D5.1), the motor electronic control unit and power electronics for the High Power Range Electric Drive (D5.2) and for the Medium Power Range Electric Drive (D5.3).
- WP6 has defined single actions for each manufacturing activity planned. Sub-contractors have also been identified, who will deal with some processing and motor assembling activities. The risks deriving from the prototyping steps and the mitigation actions have also been highlighted.
- WP8 covers the exploitation of the technological solutions developed within the project, for which a first Intellectual Property Rights (IPR) draft and a business plan have been defined. A technological watch of the main Electric Vehicles (EVs) markets and electric motor technologies has been performed.

This D1.2 deliverable has fully met its objectives. No deviations have been found in the deliverable or in the project progress in content, time or impacts, as set out in the Grant Agreement (GA).

1 Project Objectives 2nd year review

The main aim of this project is to develop rare earth-free traction technologies beyond their current state-of-art, with a strong focus on industrial feasibility for mass production, targeting lower costs with higher specific torque and power density.

The vision is to contribute to a greener European transport, by offering new solutions non dependant on critical sources and making use of the vast electric motor manufacturing capabilities in Europe.

In order to reach this challenging objective, several scientific and technological objectives have been defined:

- To explore, optimize and compare motor designs in two rare earth-free motor technologies: copper rotor induction machines and synchronous reluctance machines. In the case of IM two sub-avenues will be explored for comparison and optimization purposes: fabricated and die casted copper rotors. In the case of SynRel machines also two sub-avenues will be explored: pure and ferrite permanent magnet (PM). As a result, four designs will be obtained for each of the two power range settings under study in this project: 75kW (some candidates are Iveco Daily, Mercedes Sprinter, Isuzu, Ford Transit and Nissan Cabstar, or a Land Rover Defender) and 200kW (Jaguar Land Rover vehicle).
    - ✓ During this period optimized designs of both technologies have been carried out, taking into account electromagnetic, mechanical and thermal performance of the motors under operation conditions. The analysis of the induction machine has already been reported in D3.1, D3.2 and D3.3, whereas the analysis of the synchronous machines is reported in D4.1, D4.2 and D4.3. Both work packages have included designs for 75kW and 200kW using the requirements outlined in WP2.
- To design, prototype and test four high speed (maximum speed of 45.000 rpm) motors (one for each technology) that will increase the specific torque by 30%, and reduce the motor losses by 50%, compared to the project benchmark (Tesla S60 motor). To achieve these ambitious targets the project will tackle a number of innovations that are further defined later in this document.
    - ✓ During this period the work has been focused on the design and optimization of the different motor technologies considered, as well as the power electronics, according to the Boundary Conditions and the KPIs defined in WP2. Also the first steps in integration and manufacturing activities were given, as will be described later on this document.

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- To achieve an ambitious cost objective. ReFreeDrive electric powertrain can reach a cost reduction foreseen in at least 15% against solutions with equal performance characteristics, due to exhaustive work on optimized designs of motor and power electronics, proper selection of materials, implementation of better mass-manufacturing process and advanced motor control solutions and cooling system. This conclusion was achieved after a deep benchmark carried out against the Tesla S60 electric traction system.
    - ✓ The current cost estimations made in WP8 as part of the first draft of the business plan indicate that with the current optimized motor configurations it is possible to achieve the proposed cost reduction.
- To develop the power electronics needed for each power setting, increasing the power density by 50% compared to current systems which are being used in the electric vehicles, by means of not only adoption of wide bandgap semiconductor technology, increasing efficiency and reducing the weight of the cooling system, but also adoption of advanced gate drivers and efficiency optimized control strategies. To reach this objective a key work is to achieve an integrated design of the power electronics together with the different motors topologies within the project.
    - ✓ During this second year control algorithms for IM and Synrel motors have been developed, and the power electronics have been designed, as reported in D5.1, D5.2 and D5.3. Also preliminary activities have been started concerning the in-vehicle integration of the power units for the demonstrator.
- To define, prototype and test a cooling system that complies with the performance targets set above based on a novel technology, which will use an internal oil spray cooling method.
    - ✓ Two different cooling system configurations have been investigated, based on Ethylene-Water-Glycol (EWG) and oil spray as cooling fluids respectively. The former leads to acceptable results according to the requirements set, while the latter leads to higher hot spot temperature than the limit of 180º. Moreover the solution with oil spray is less conventional and brings some uncertainties from an integration point of view. For this reason, the first option is preferred.
- To validate the motor technologies by obtaining an integrated powertrain, including all the powertrain systems (batteries, gear box, etc.) that will be tested in real driving conditions in the full electric vehicles customized by PRIVÉ (e.g. Iveco Daily, Mercedes Sprinter)
    - ✓ This objective has not been addressed during this period.

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- To present the obtained results and boost their commercial exploitation to encourage the use of rare earth free motor technologies in Europe, demonstrating their feasibility with mass production industrial manufacturing support.
    - ✓ In this period dissemination and communication actions have been planned and carried out in order to pave the way and raise the awareness needed on the project results, which will later enable a wide audience for the demonstration of the feasibility of the project results. In particular during this period, a joint GV04 workshop has been organized in Brussels, presenting the innovations so-far being developed by the three H2020-funded projects, as well as contributions from the Project Officer and European Green Vehicles Initiative association.

2 Explanation of the work carried out per WP

In the following sections the technical progress done by each of the work packages (WPs) is reviewed. For Management and Dissemination and Communication actions, please see PPR1.

2.1 WP3: Induction machine design

Work package 3 (WP3) has four tasks to address within ReFreeDrive project.

Task 3.2 – Electromagnetic design of CR-IM design

A brief description of Task 3.2 is given in this section for each objective in part.

Selection of materials

A. Copper Alloys

Two options are considered for the rotor cage of Copper Rotor – Induction Motor (CR-IM): die-casted and fabricated copper alloys.

Based on the properties, a copper-silver alloy (CuAg0.04) has been selected. The decision on soldering and welding will be analyzed during the next period. This information was provided by Aurubis (AUR) – partner in ReFreeDrive project.

For die-cast copper solution, the alloy Copper-Electrolytic Tough Pitch (Cu-ETP) is selected.

The difference between various solutions for the cage rotor material is related to the rotor equivalent resistance.

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B. Electric Steels

Four Non-Grain Oriented (NGO) electrical steels, silicon-iron type, have been considered for CR-IM. Tests on the steel samples have been performed by RINA – CSM. Magnetization curve and core losses characterization tests have been carried out on:

- Material 1: M235-35A (thickness: 0.35 mm)
- Material 2: NO30-15 (thickness: 0.30 mm)
- Material 3: NO20HS (thickness: 0.20 mm)
- Material 4: M290-50K (thickness: 0.50 mm)

A fifth material, the Grain Oriented (GO) M85-23P electrical steel 0.23 mm in thickness, has been selected for the characterization to be used by UAQ in the Finite Element Method (FEM) simulations for the 2 pole SynRel Rotor design:

- Material 5: M85-23P (thickness: 0.23 mm)

A summary of the performed characterization is reported in the following.

1. *NGO Magnetic Characterization at 50Hz, according to the standard EN10106 (Finished materials), EN10341 (Semi-Finished Materials), EN 10107 (Finished GO materials)*
2. *Preliminary Magnetic Characterization of NGO and GO materials cut by laser, in order to select 3 of the 5 preliminary selected materials (0°, 45°, 90° - 50 Hz, 400 Hz, 1000Hz)*

Based on such measurements three materials were selected (n° 1, 2, and 5) and subjected to the following more accurate characterizations:

3. *Magnetic Characterization at 800 Hz of the selected materials cut by laser (0°, 45°, 90°).*
4. *Magnetic characterization of the selected materials cut by shear (0°& 90° - 50, 400, 800, 1000 Hz).*
5. *Other Laboratory activities & characterizations on selected materials:*
    - Evaluation of magnetic saturation Js
    - Resistivity measurements
    - Chemical analysis
    - Mechanical characterization
6. *Optimization of the Stress Relief Annealing treatment (SRA) of the selected material M235-35A.*
7. *Magnetic characterization after SRA of M235-35A samples cut by laser.*

An overview of the material characterization results carried out at RINA-CSM is reported in the following figures.

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In Figure 1 and Figure 2 a comparison in terms of magnetization curves and core losses curves, is reported at frequencies of 50, 400 Hz, a similar characterization has been performed at 1000 Hz.

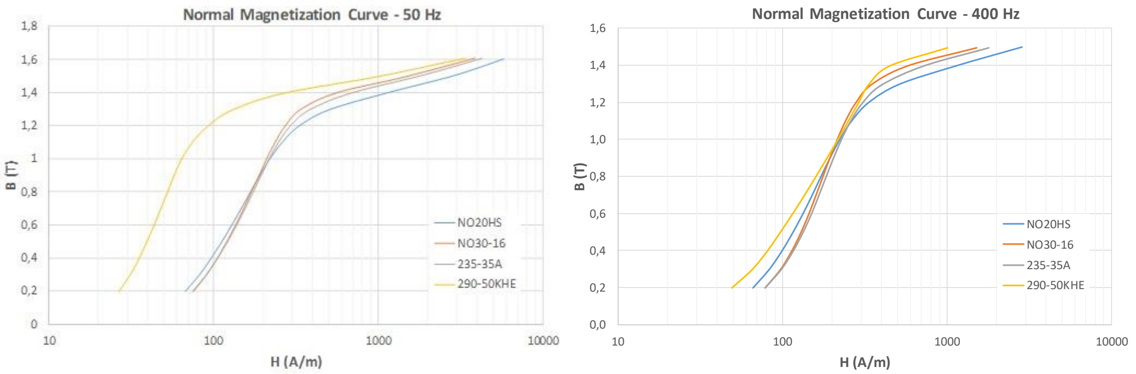

Figure 1: Magnetization Curve - 50% RD+ 50% TD @50-400 Hz - NGO Materials cut by laser

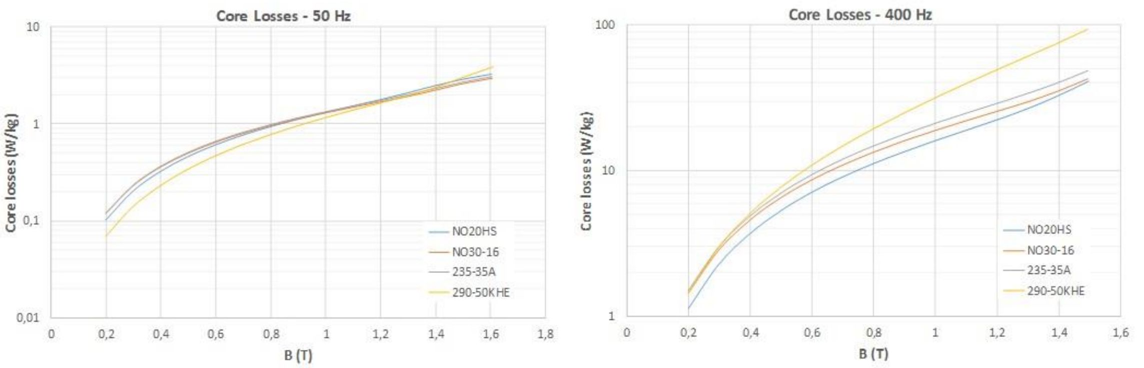

Figure 2: Core Losses Curve - 50% RD+ 50% TD @50-400 Hz - NGO Materials cut by laser

Standard tensile test specimens (UNI EN ISO 6892-1:2016 Type A) have been used to evaluate the strength and of the material in the rolling (L) and transversal directions (T). In Figure 3 the experimental engineering stress strain curves for the selected material M235-35A is reported. Similar characterization has been carried out for the NGO material NO30-15 and GO material M85-23P.

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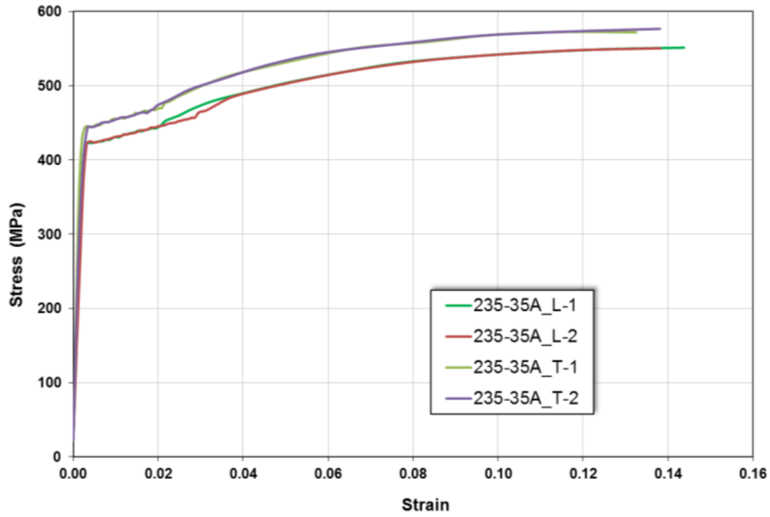

Figure 3: Stress-strain curve for M235-35A material

The magnetic properties measured have been used by the motor designers to model and design the motors. The induction up to 1.6T was extrapolated by Motor Design Limited (MDL) to 2.1T in modelling CR-IM.

The results from the materials characterisation and analysis performed for the designs selected at Task 3.1 for inner CR-IM and outer CR-IM lead to the following conclusions:

- Best choice will be M235-35A, considering cost/performance ratio.

Scaling

The selected designs for both Inner Rotor (IR) and Outer Rotor (OR) configurations can be scaled and used for various power levels, by just changing the power and control unit. This means, that the same motor can be used as an electro-mechanical converter for power levels between 75kW and 200kW.

3D FEA modelling

The validation of the initial 2D Finite Element Analysis (FEA) model designs is done using also 3D FEA models. This work was performed by UAQ. The comparison between 2D and 3D FEA models for IR design has been performed for operating at points 6000rpm and 20000rpm respectively. The two models agree with sufficient accuracy in all cases.

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Mechanical analysis

A modal analysis was performed on the new IR-IM design to ensure the first rotor natural frequency is still below the maximum operating frequency. The shaft length (bearing to bearing distance), the shaft diameter at ends and the bearing stiffness were varied to assess their impact on the natural frequency. This parametric analysis is important for two reasons: first to know how much space can be allocated to end-windings and secondly to select the right bearing for the ReFreeDrive application.

Optimisation

An optimisation process was setup for the IR-IM in optiSLang, a software developed by Dynardo. Motor-CAD is called via the so called ActiveX connection.
These results show that a compromise can be found between the reduction of the length (that directly impact the cost of the machine) and the continuous performance while satisfying the constraints (maximum temperatures, nominal power, peak power...).

Task 3.3 – Thermal analysis and cooling system optimisation of CR-IM

A brief description of Task 3.3 is given in this section for each objective in part.

Updated KPI

Table 1 summarizes the KPIs values for the low (75kW) and high (200kW) power range applications. Note that the specific power and specific torque values for the 200kW motor correspond to an increase of 30% compared to the baseline TESLA 60S. Also, it is worth mentioning that all data are valid for the electromagnetic design only as they refer to peak performances and active parts of the machine.

Table 1: KPIs for the low and high power range applications

KPI	Unit	Reference TESLA 60S	ReFreeDrive Goals		Comment
			75kW	200kW	
Specific power	kW/kg	3.31	> 1.6	> 4.3	Peak value, active parts only
Power density	kW/l	-	> 5.4	> 8.0	Peak value, active parts only
Specific torque	Nm/kg	6.32	> 2.5	> 8.2	Peak value, active parts only
Torque density	Nm/l	-	> 8.0	> 15.4	Peak value, active parts only
Weight	kg	60	< 44.6	< 44.6	Active parts only
Efficiency	%	92%	96%	96%	Peak value

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Final optimised CR-IM design

The optimization problem is multi-objective and is subjected to various constraints including performance requirements over the full speed range of the machine together with minimum dimensions for manufacturing feasibility.

Final 3D FEA validation

The design was validated in 3D FEA using ANSYS Maxwell. All simulations were performed by UAQ.

Final mechanical analysis

A 2D mechanical stress analysis was performed with Ansys Mechanical on the die-casted and fabricated rotors at 20% overspeed (24 krpm) and at the maximum acceptable temperature (180°C).

Thermal analysis

1. ***Cooling system n°1***. Housing Water Jacket (WJ) and shaft Spiral Groove (SG) cooling systems coupled in parallel, using EWG mixture as a coolant.
2. ***Cooling system n°2***. Housing jacket and hollow shaft cooling systems coupled in parallel, with oil spray through nozzles placed on the shaft and the housing, using Automatic Transmission Fluid (ATF) as a coolant.

Task 3.4 – Mechanical Analysis and Design Lead

A brief description of Task 3.4 is given in this section for each objective in part.

Noise, vibration and harshness analysis

The estimated noise and vibration effects at one operating point are briefly discussed

The electromagnetic forces in the rotor are calculated by means of FEA simulation. The analyzed operating point is fully described in Deliverable 3.3, Section 2.4:

- Torque = 350Nm
- Current = 500Arms
- Rotational speed = 6000rpm

The modal analysis results show that a few vibration modes appear between 1400Hz and 5000Hz.

The results of boundary element method (BEM) show that there is an important directivity pattern. The highest pressure is found at 400Hz, about 85 dB in X direction. And maximum values of 70dB are found for 1250Hz in X and Y; for 800Hz in X and for 1600Hz.

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Only two modes (x2) are present in analyzed frequency range, at 1411Hz and 1943Hz. It can therefore be concluded that the acoustic response is mainly due to electromagnetic loading.

CAD Drawings Set for Manufacturing

Table 2 below describes the list of draft drawings needed for manufacturing.

Table 2. CAD drawings set for CR-IM motor manufacturing

Assembly	Component
Stator	Lamination
	Laminated pack
	Winding
	Housing
	Full stator assembly
Rotor	Lamination
	Laminated pack
	Rotor cage pack
	Shaft
	Full rotor assembly
Motor	Full general assembly

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Summary of final design

This section contains a short description of final CR-IM inner rotor topology that is going to be prototyped. Table 3, Table 4, Table 5, Table 6 and Table 7 summarize the final design dimensions, materials, winding, parameters and cooling system.

Table 3. Dimensions final CR-IM design

Parameter	Unit	Final Design
Stator slots	-	36
Pole pairs	-	2
Rotor bars	-	50
Stator Outer Diameter (OD)	mm	190
Rotor OD	mm	116
Airgap	mm	0.8
Active length	mm	161
Active weight	kg	39

Table 4. Active materials final CR-IM design

<table>
<tr><th colspan="2">Active part</th><th>Material</th></tr>
<tr><td rowspan="2">Bars</td><td>Die-casted rotor</td><td>Cu-ETP</td></tr>
<tr><td>Fabricated rotor</td><td>CuAg 0.04</td></tr>
<tr><td colspan="2">Rotor laminations</td><td>M235-35A</td></tr>
<tr><td colspan="2">Stator laminations</td><td>M235-35A</td></tr>
</table>

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Table 5. Winding parameters final CR-IM design

Parameter	Unit	Final Design
Conductors/slot	-	4
Turns per coil	-	4
Layers per slot	-	4
Parallel path	-	1
Coil pitch	slots	9
Wire width	mm	5.81
Wire height	mm	3.56

Table 6. Scaling results for final design inner CR-IM

Rated peak power [kW]	Peak torque [Nm]	Maximum efficiency [%]	Maximum DC voltage [V]	RMS line current [Arms]	Maximum speed [rpm]
200	378	96	720	500	20000
75	192	95	350	275	13000

Table 7. Main characteristics for the final cooling system

Parameter	Unit	WJ	SG
Fluid inlet temperature	°C	75	75
Fluid outlet temperature	°C	83.38	79.26
Fluid flow rate	l/min	5.75	4.25
Pressure drop	kPa	10.42	-
Channel number	-	10	1
Channel width	mm	12.06	-
Channel height	mm	8.05	4.09

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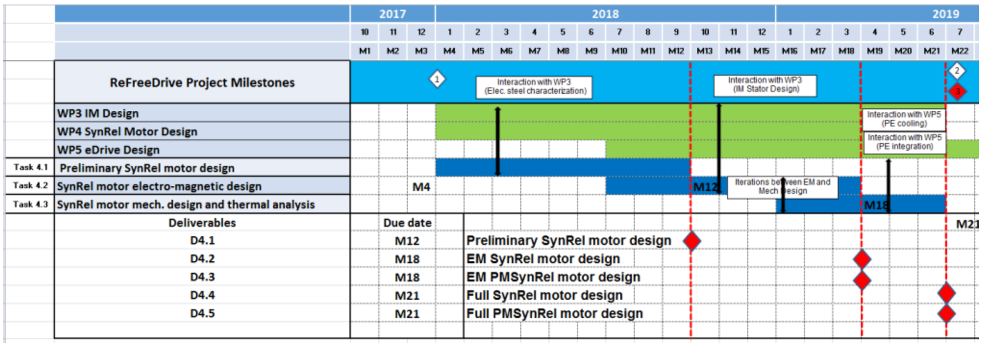
2.2 WP4: Synchronous reluctance machines

The main objective of Work Package 4 (WP4) is to design low cost rare earth free Synchronous Reluctance motors fulfilling the requirements defined within the WP2 for the 200kW and 75kW motor applications. According to the WP4 planning, the work carried out within the WP4 during the period M10-M22 has been focused on the task 4.1 (Preliminary SynRel Motor Design), 4.2 (SynRel motor electromagnetic design) and 4.3 (Mechanical design and thermal analysis SynRel Motor design).

Figure 4 shows an overview of the WP4 activities including tasks, deliverables (with due dates for each one of them) and interactions with other WPs.

Figure 4: WP4 overview.



According to the ReFreeDrive Grant Agreement document the objectives are:

- *to identify the key factors in SynRel motor design that lead to an increase in power/torque density and lower cost*. This objective is fulfilled within subtask 4.1.1 with no deviation on content or time. Several stator/rotor configurations have been investigated in order to find the best trade-off between performances and costs. For the thermal analysis, conventional water jacket cooling has been considered.
- *to select the materials for SynRel high speed motor applications avoiding rare earth content and lowering costs*. This objective is fulfilled within subtask 4.1.2 with no deviation on time and the following limitations:
    - The electrical steel characterization was limited to commercially available products. It was not possible to test high strength electrical steels for high speed rotors due to unavailability of samples.
    - Only commercially available ferrites have been considered as rare earth free permanent magnets as their characteristics are well known.

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- *to propose an optimal and cost effective design for SynRel and PMA SynRel motor based on preliminary results.* Following accomplishments were carried out with no deviation:
    - A specific rotor geometry optimization.
    - A specific stator design using the winding configuration.
    - The investigation on the demagnetization of the selected Permanent Magnets (PM) for Permanent Magnets Assisted Synchronous Reluctance Motor (PMA SynRel).
    - The investigation on scalability aspects (to derive the 75 kW motor design).
- *to perform advanced thermal and mechanical analysis with a focus on high speed impact on mechanical stress*.
    - Water cooling is mainly considered here bear in mind the high level of requested performances for the 200kW motors. 75kW motors will share through scalability the same housing architecture in order to decrease manufacturing costs.
    - Mechanical stress and deformation analysis and its impact on the EM performances have been quantified.

The final designs are in agreement with KPI specified within WP2, and executive drawings were delivered for active parts manufacturing.

Task 4.1 – Preliminary SynRel Motor Design

Material selection for the electric motors active parts has an impact on both, the cost and the performances; making this parameter a common concern for all motor designers involved within the ReFreeDrive project. Electrical steel characterisation by RINA-CSM guided the partners to a standard M235 electrical steel common choice based on the cost to performance criteria.

The starting point for both motor topologies was a techno-economic evaluation based on the cost to power ratio which has been used in order to select the best topology to be optimized in the following tasks.

PURE SYNREL MOTOR

The designs of the pure SynRel motor with flux-barriers have been carried out by a sizing procedure that allows determining the motor dimensions and any other geometrical data by adopting simplified relationships between geometrical and physical motor data in order to meet the motor specifications.

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Several pair pole number, electrical steels and flux barrier shapes have been tested and the results clearly indicate that the 6-pole, 54-slots design is the best topology for Pure SynRel motor, with a limited volume and satisfactory performances at rated and peak power.

The current density values of the preliminary design are reasonable for the liquid cooled machines.

PMA SYNREL MOTOR

200kW motor initial design used for techno-economic evaluation is based on a 10 pole design with distributed windings and an asymmetrical rotor. Demagnetization of ferrites and mechanical/thermal aspects are considered to be technological locks for the high power density ferrite motors (very high current) and are addressed in the following tasks.

Alternative solutions, including pair pole number variation, PM quantity, concentrated or fractional slot winding have been investigated and compared to the reference design. The conclusion is that the 10 pole design with distributed winding configuration exhibits the highest output power and lowest ripple. An additional configuration is proposed in order to improve the performances especially at high speed. This is accomplished with a "Full magnet design", which uses 7 magnets per pole. Two winding configurations were also explored, namely fractional and concentrated winding distributions. It was shown that the distributed winding has overall better performances than the previously mentioned winding alternatives.

Using scalability, the 10 pole and 200 kW design can be used for the 75kW design by reducing the active length and increasing the number of coils (800V towards 350V DC).

Task 4.2 – SynRel motor electromagnetic design

Based on the conclusions, in task 4.2 the reference designs are refined and optimized in accordance with technological locks identified in the preliminary investigations and KPI defined in WP2.

PURE SYNREL MOTOR

The 800V, 200 kW and 6-pole design has been optimized using specific algorithms interfaced with Finite Elements (FE) tools. Different design strategies have been chosen for the rotor geometry shape with the aim to verify the effects on the motor performance in terms of efficiency, torque and ripple. The optimized design has also been analysed by thermal and mechanical analyses in order to test the motor behaviour in the critical operating conditions.

The following design strategies have been chosen and particularly:

1) SynRel motor with radial ribs in the rotor core;
2) SynRel motor without radial ribs and flux barriers filled with epoxy adhesive resin.

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The aim was to verify which of those two solutions could guarantee better motor performances in terms of efficiency, torque and ripple.

The final design with 6 poles and 54 slots presents a rotor with "fluid shaped" flux barriers without radial ribs in order to improve the motor performance: as this choice is challenging for the mechanical strength of the rotor core, it was decided to fill the flux barriers with epoxy adhesive resin. This design brings very high electromagnetic performances potential.

The 350V, 75kW machine has been scaled from the optimized 6-pole and 200 kW design by only changing the stator winding and the stack length: good power levels can be obtained with the same material quality and radial dimensions.
Final designs are in agreement with KPIs specified within WP2 and summarized in Table 8.

Table 8: KPI* compliance for PURE SynRel 75 and 200kW Motors

CL-KPI	SynRel (UAQ)			
	Spec	Achievement	Spec	Achievement
	75kW	75kW	200kW	200kW
Specific Peak Power (kW/kg)	> 2.52	4.04	> 4.3	5.3
Peak Power Density (kW/ liter)	> 8.75	13.1	> 19.7	20.8
Specific Peak Torque (Nm / kg)	> 8.2	8.23	> 8.2	8,4
Peak Torque Density (Nm/l)	> 28.2	26.6	>37.7	32.6
Motor Dimensions Length (mm)	< 310	180	< 310	310
Motor Dimensions Diameter (mm)	<250	220	<250	220
Active parts weight (kg)	< 30	22	<47	46
Maximum speed (krpm)	12	12	15 - 18	18
Peak efficiency (%)	>97	95	>96	96

**KPIs consider the active parts only: stator and rotor lamination, copper wires and slot insulation.*

PMA SYNREL MOTOR

Based on the preliminary investigation about number of pole pairs and stator architecture, an optimisation of the 800V, 200kW PMA SynRel Motor topology was accomplished in terms of torque ripple, ferrite demagnetization and power at very high speed in order to comply with guidelines provided by Jaguar Land Rover (JLR) as end user. Thus, updated KPIs defined in WP2 have been used, and additional vehicle performances, as acceleration time and average efficiency over the Worldwide Light Vehicle Test Procedure (WLTP) cycle were considered. The major difference with respect to the preliminary design is the 220 mm rotor diameter.

As the coercivity value (Hcb) for ferrite magnets is much lower than the one of the neodymium magnet, the risk of demagnetization due to high flux-weakening angle or short-

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circuit is more important in this case than for synchronous motors with rare-earth magnets. Motor design was optimized in order to minimize the risk of ferrite damage at highly loaded operation.

Among the main performances obtained for the 200 kW PMA SynRel, it is noticeable that the peak power (226 kW) exceeds the required value (200 kW). That was necessary in order to limit the power drop in the speed region corresponding to the 80-120km/h vehicle speed and therefore ensure the vehicle acceleration performances specified by the end user.

Design of the 350V, 75 kW motor has been carried out using the same stator/rotor geometry as the 200 kW motor, by reducing the active length and the maximum phase current. In this case, the theoretical maximum speed of the motor is close to 17500 rpm but it will be limited to 12000 rpm to be compatible with the integration in the vehicle demonstrator.

Final designs are in agreement with KPI specified within WP2 and summarized in Table 9.

Table 9: KPI* compliance for PMA SynRel 75 and 200kW Motors

CL-KPI	PMA SynRel Motors			
	Spec	Achievement	Spec	Achievement
	75kW	75kW	200kW	200kW
Specific Peak Power (kW/kg)	>2.52	4,8	>4.3	4,9
Peak Power Density (kW/l)	>8.75	17.9	>19.7	22,8
Specific Peak Torque (Nm/kg)	>8.2	8.3	>8.2	8.8
Peak Torque Density (Nm/l)	>28.2	30.7	>37.7	41
Motor Dimensions Length* (mm)	<185	75	< 310	200
Motor Dimensions Diameter* (mm)	<250	220	<250	220
Active parts weight (kg)	<30	19	<47	46.1
Maximum speed (krpm)	12	12	15 - 18	17.5
Peak efficiency (%)	>96	95	>96	96

KPI: Active part mass is considered only (stator and rotor steel, copper and magnets).*

Task 4.3 - Mechanical design and thermal analysis SynRel Motor design

PURE SYNREL MOTOR

As the proposed SynRel motor without radial ribs presents an unusual rotor shape compared to those typically reported in literature, a deep mechanical analysis has been carried out at high speed operation. For this study, the 2D Mechanical FE software has been used and the rotor core has been modelled taking into account the material properties of the electrical steel and the epoxy adhesive resin. The mechanical analysis points out that the rotor structure with resin is able to withstand mechanical stress at high speeds even if some

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critical points are highlighted inside the flux barriers. That could cause the resin to detach from the wall with consequent weakening of the rotor structure. Therefore, design measure is being studied to reduce the critical issues and this could result in a slight change of the presented rotor shape. Mechanical rotor deformation impact on the air gap at very high speed operation was accomplished also with conclusion that the impact is acceptable.

Finally, the thermal behaviour of the liquid cooled SynRel motor has been analysed considering the water jacket designed and proposed by MAV and shared with PMA SynRel motor. The analysis has pointed out that the current design is valid for the targeted application and that low cost standard potting should be used.

PMA SYNREL MOTOR

Mechanical rotor stress was another optimization topic. Mechanical validation at maximal speed, over speed (21000 rpm) as well as the air gap variation impact was accomplished in order to ensure safe motor operation. Mechanical fatigue was also investigated. The defined criteria were respected in most of regions of the lamination. Although, some very small areas are not compliant with the criteria but the maximum operating speed will be lower than 18000 rpm.

Finally, complete thermal analysis has been performed through Computer Fluid Dynamics (CFD) and MotorCAD. The conclusion is that 70kW at 17500rpm is a harshest operating condition for the motor. Cooling system developed by MAV is validated and the low cost standard potting will be used in order to ensure the safe motor operation.

2.3 *WP5: e-Drive Design*

WP5 intends to research and develop the **power electronics and control strategies needed for each power range**. This means that both traction technologies will share the same power electronics and control algorithms for each use case (medium power range, high power range). Besides, WP5 will analyse and select off the shelf solutions for the rest of the **powertrain systems needed from an integration** point of view, such as batteries, gear box, electric and electronic integration as well as cooling systems and testing systems.

The analysis results concern the identification of suitable power modules for the target application:

- Different suitable Power electronics modules were analysed for the target application (both Metal-Oxide Semiconductor (MOS) Silicon Carbide and Insulated Gate Bipolar Transistor (IGBT) Technology).
- The best available solution in the market in terms of power ratings and efficiency is the module FMF800DX-24A (Manufactured by Mitsubishi) as seen in Figure 5.

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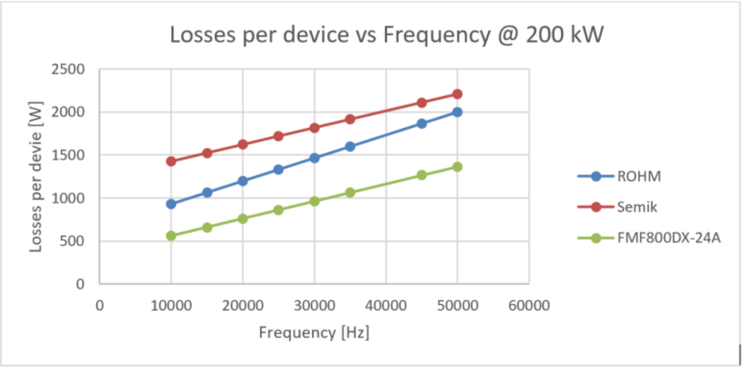

Figure 5: Losses vs frequency at target maximum power (BSM600D12P3G001, blue; SKM350MB120SCH17, red; FMF800DX-24A, green)

From the previous analysis, considering the modules price, the Mitsubishi module FMF800DX-24A has been definitely chosen.

About the activities on the control strategies, the partners carried out studies on the control strategies of Synchronous and Induction motors, aimed to enhance the efficiency at low torque.

Task 5.1 – Development of control algorithms for IM and SynRel motors

UAQ has been working on the development of the most suitable motor control algorithms for Induction and SynRel motors using simulation platforms. The model is the one shown in Figure 6. This model can be used also to check the impact of the motor performance on the vehicle performance.

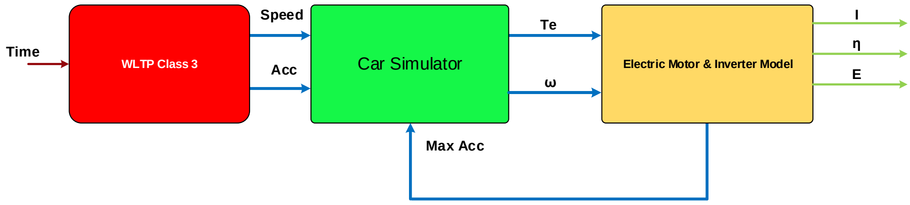

Figure 6: Vehicle simulation model

Main activities carried out are:

- **Task 5.1.1** Design and Setup of a dedicated simulation environment.
- **Task 5.1.2** Design of a control algorithm for IM Motors.
- **Task 5.1.3** Design of a control algorithm for PM SyncRel Motors and Pure SyncRel Motors.

The main results of the task 5.1 are reported in the followings.

Task 5.1.1: three models have been developed to simulate respectively the power electronics, the vehicle performance and the detailed motor-drive behaviour. The model of the power electronics has been used to select the most adequate Silicon Carbide components by evaluating current ratings, power losses and thermal behaviour. The model of the vehicle has been used to evaluate the impact of the KPI on the motor-drive design

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and the impact of the motor-drive performance on the vehicle one. The detailed multi-physics model of the motordrive has been developed by mean of the co-simulation approach by using different cooperating tools: Matlab, Simplorer, Ansys Maxwell. The model accurately simulates the dynamic performance of the motor-drive including the non-linearity of the motor and the effect of the control strategy on it. It has been used to check the effectiveness of the control strategies in task 5.1.2 and 5.1.3.

Task 5.1.2: The theory of the control strategy of IM has been analysed and customized for the target motors. The non-linearity has been taken into account by mean of co-simulation. Optimum control strategies have been formalized to optimize the motor performance in terms of maximum toque per ampere, maximum efficiency per torque. The control scheme integrating speed control loop, torque control loop and current control loop have been defined for the further integration on the target hardware.

Task 5.1.3: The theory of the control strategy of SyncRel and PMa SyncRel has been analysed and customized for the target motors. The non-linearity has been taken into account by mean of co-simulation. Optimum control strategies have been formalized to optimize the motor performance in terms of maximum toque per ampere, maximum efficiency per Torque. The control scheme integrating speed control loop, torque control loop and current control loop have been defined for the further integration on the target hardware.

Task 5.2 – High Power Range Electric Drive Design

Task 5.2 concerns the design of the motor electronic control unit and power electronics for the high power range e-Drive, while increasing the power density and lowering costs. The design is sought to share the same mechanical design as the motor in the power electronics design to enable an easier mechanical integration.

The main goals of these activities consist in:

- Proposing power architecture solution according to the requirements
- Designing the High Power Range e-Drive
- Selecting components (power modules and technology, sensors, capacitors, mechanical connections, etc…)
- Studying the Mechanical Integration of the High-Power Range e-Drive with the motor housing

During this period, IFPEN work was focused on calculations and design of the main components (DC capacitors, gate drivers power, max current, sensors, diagnostic, etc.). Besides schematics, placement and routing phases according to mechanical constraints were also studied.

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The high power range inverter is based on the development of three main electrical boards, which are: a gate Drivers board (DRV board); a Control Power Unit board (CPU board); and a Power Supply Unit board (PSU board).

A mechanical integration has been proposed (Figure 7). In order to increase the capacitors number and fulfil the maximum space between the power modules, the CPU and PSU boards should be placed over the capacitors as presented in the same Figure 7.

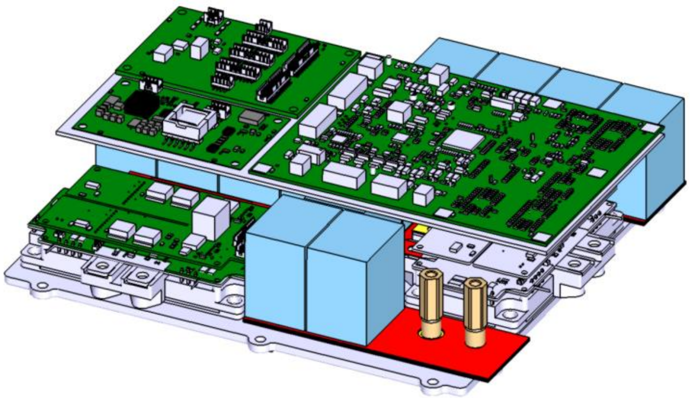

Figure 7: Mechanical integration of the inverter's boards on the machine casing.

Task 5.3 – Medium Power Range Electric Drive Design

As the previous task aims to design the motor control circuit and power electronics for the Medium Power Range e-drive

During this period, UAQ and R13 have been working on the control electronics and power electronics design, considering the mechanical design and integration in the motor assembly.

In cooperation with IFPEN, the main task achieved is the power components sizing and selection. Meanwhile, the control board architecture has been defined and some tests on an Inverter IGBT based were performed. The schematics, placement and layout of electrical boards are still ongoing. The first block has mainly the aim to achieve all the action required to control and protect the power electronics and the motors. The microcontroller of Texas Instruments called TMS320F28377S performs these features:

- Compute electric motor control algorithms.
- Safety functions (overvoltage, overcurrent, overtemperature).
- Elaborate electric and position measurements.

The communication and diagnostic block has the purpose to supervise the motor control microcontroller and manage all communication between the inverter and the outside world.

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Furthermore, it allows the inverter to interface with a debugging system, crucial to tuning the overall system. A block diagram of the electrical boards can be seen in Figure 8 below.

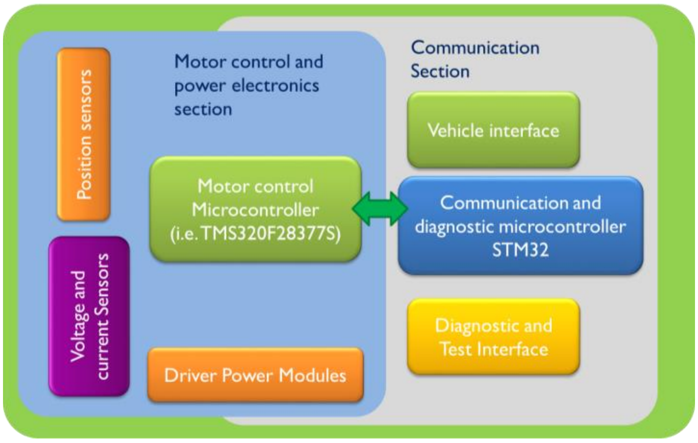

Figure 8: Block diagram of electrical boards.

The power electronics design concerns the choices of the main components of power electronics, to meet the electrical and mechanical requirements from motor and integration designers:

- Power electronics modules;
- Gate drivers;
- Current measurements sensors;
- DC link capacitors;
- Busbar;
- Communication interfaces;

One of the concerns for the Original Equipment Manufacturer (OEM) is the reduction of the cost of DC bus capacitors. To correctly size the capacitors and minimize the costs, a DC-bulk capacitors study has been carried out.

These are the main criteria followed:

- Maximize the capacitance and current ratings per volume ratio;
- $\Delta V < 5$ % at maximum current;
- Minimize the costs;
- Fulfil the JLR dimensions requirements;

To reduce the overall cost, the design choice was to use off-the-shelf capacitors; the different solutions are summarized in Table 10.

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The strict electrical features to fulfil for target application are the high current capability and the volume constraints.

The main mechanical issue encountered is related to the maximum height of the power electronics box, so the capacitor must have a low profile. The available free space between the modules has also a dimension constraint to be considered, as shown in the following Figure 9.

The solution B, that concerns 10 or more B32776G0226K000 capacitors manufactured by TDK, has the better the capacitance and current ratings per volume ratio and the lowest cost.

Table 10. Main capacitors investigated.

	Solution A	Solution B	Solution C
Part Number	B32778J0207K000	B32776G0226K000	B32778G0606K000
Single Capacitance	200 µF	22 µF	60 µF
Number of Capacitors	3	10	6
Total required	600 µF	220 µF	360 µF
Current Capability	198 Arms	210 Arms	180 Arms
Volume required	1.3 L	0.66 L	0.93 L
ΔV @ 800 A	1.8 %	4.96 %	3 %
Cost	≈150 €	≈50 €	≈80 €

Starting from the JLR dimensions requirements, different integration proposals have been analysed to evaluate the effective volume to install the capacitors, taking into account modularity. In the next Figure 9, one possible solution is shown to highlight the integration issues of the power converter.

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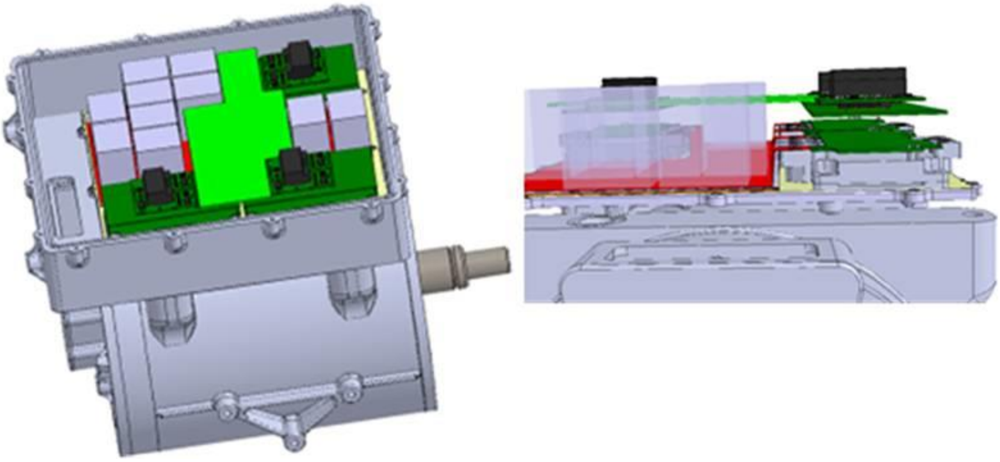

Figure 9: Mechanical views of the power electronics box

To reduce the risk of project we have developed an IGBT based power converter to perform functional and reliability tests.

Task 5.4 & 5.5 –High Power powertrain integration and Medium Power powertrain integration

Task 5.4 (*High Power powertrain integration*) and **Task 5.5** (*Medium Power powertrain integration*), preliminary activities have been started concerning the in-vehicle integration of the power units for the demonstrator.

PRI has been working on the selection of the main components (Figure 10) fulfilling the requirements specified in WP2.

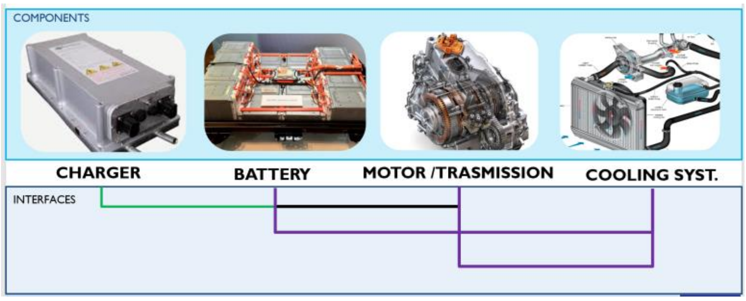

Figure 10: main component to consider for the in-vehicle integration of ReFreeDrive e-drives

Another main activity was the disassembly of the vehicle where ReFreeDrive motor prototype will be integrated. In this first phase PRI studied the vehicle with its original engine, to find possible problems and have a general understanding of the vehicle architecture. Parts studied where: Engine Control Unit (ECU) connector, accelerator pedal, gear/power switch, power braking, power steering, DC/DC and cooling.

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The proposed architecture for the final system includes **two separate ECUs.** ECU1 will supervise and adapt communication between the electric powertrain and the rest of the vehicle, simulating relevant Controller Area Network (CAN) messages from the old engine ECU. It will also provide and translate relevant signals to the motor inverter. ECU2 will filter CAN messages to the IC and provide a USB interface for the Human-Machine Interface (HMI).

2.4 WP6: Prototypes manufacturing

The main objective of the WP6 is to manufacture the prototypes of the motors and power electronic for two power sizes: 200 kW and 75 kW. Particularly:

- n.2 prototypes of Induction motors with fabricated copper rotor;
- n.2 prototypes of Induction motors with die-cast copper rotor;
- n.2 prototypes of pure Synchronous Reluctance motors;
- n.2 prototypes of PM-assisted Synchronous Reluctance motors;
- n.8 prototypes of Power electronics.

According to the WP6 planning, this work package has been divided in three tasks, two for each track technology and an additional task for the prototyping of the power electronics (Figure 11):

- Task 6.1 – IMs manufacturing;
- Task 6.2 – SynRel motors manufacturing;
- Task 6.3 – Power electronics manufacturing.

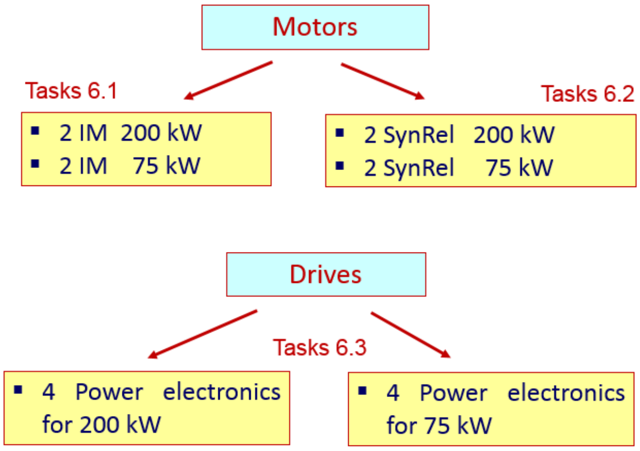

Figure 11: Prototypes of motors and power electronics

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For each activity, the single actions have been defined that will lead to the constructions of the prototypes.

The stator and rotor cores for the IMs and SynRel motors have been manufactured by laser cutting and the chosen electrical steel is M235-35A. These cores have made with the material taken from the same coil for a better comparison of the motors performance.

The actions related to the construction of the motors and the power electronics will now be illustrated in detail.

Task 6.1 – IMs manufacturing

WP3 has allowed defining the final drawings of the stator and rotor shapes and the winding data. Starting from these results, the induction motors will be realized.

This task includes the stator and hairpin windings with flat wires, the rotor, either die casted or fabricated, cooling system, sensors and all the other components of the induction motor. These actions are listed in the following Table 11.

The construction of the cores and the realization of prototyping tooling for the hairpin winding have been completed and the activity is now focused on the realization of hairpin winding and the cooling jacket.

Table 11: Actions for the manufacturing of the Induction Motors

Nr.	Activities
1	Stator and rotor lamination supplying and cutting
2	Stator and rotor stacking
3	Material and commercial parts supplying, with specific redundancy in order to reduce failure risks
4	Hairpin winding
5	Die-cast rotor realization
6	Copper bars and end rings welding for fabricated rotor
7	Assembly on shaft + bearings (fabricated and die-casted)
8	Rotor balancing (fabricated and die-casted)
9	Cooling jacket, including housing & mechanical system required
10	Final assembly

Task 6.2 – SynRel motors manufacturing

Starting from the final drawings of the stator and rotor shapes and the winding data (from WP4), the PMA SynRel motors and the Pure SynRel motors will be manufactured.

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This task includes the stator and round wire windings, the rotor, the insertion of the PMs (for the PMA Synrel solution only), cooling system, sensors and all the other components of the induction motor. These actions are listed in the following Table 12 and Table 13.

The construction of the stator and rotor cores has been completed and the activity is now focused on the insertion of the round wire winding and the construction of the cooling jacket.

Table 12: Actions for the manufacturing of PM-assisted SynRel motors

Nr.	Activities
1	Stator and rotor lamination supplying and cutting
2	Stator and rotor stacking
3	Material and commercial parts supplying, with specific redundancy in order to reduce failure risks
4	Round wire winding manufacturing
5	Rotor parts assembling (PMs into rotor stack)
6	Assembly on shaft + bearings
7	Rotor balancing
8	Cooling jacket, including housing & mechanical system required
9	Final assembly

Table 13: Actions for the manufacturing of Pure SynRel motors

Nr.	Activities
1	Stator and rotor lamination supplying and cutting
2	Stator and rotor stacking
3	Material and commercial parts supplying, with specific redundancy in order to reduce failure risks
4	Round wire winding manufacturing
5	Assembly on shaft + bearings
6	Rotor balancing
8	Final assembly

Task 6.3 – Power electronics manufacturing

This activity has been divided in the following tasks:

- Task 6.3.1: Preliminary Design, Bill of Materials (BOM) and Selection of the Suppliers;
- Task 6.3.2: E-drive Mechanical Assembly Design;
- Task 6.3.3: Manufacturing Ordering and Assembling.

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During the Task 6.3.1, innovative Printed Circuit Board (PCB) solutions will be analyzed and the delivery timesheet for the preliminary BOM will be verified, planning additional suppliers for critical components. The layout development will be followed with a close relationship with the 3D tool to make the design very compact. Mock-ups and demonstration boards will be developed if needed to give feedback to the design tasks. 3D printing and rapid prototyping techniques will be adopted to minimize the risk of the projects. Signal integrity, power integrity and thermal verification will be made after PCB preliminary design with dedicated software tools, with the use also of particular techniques like as copper filled vias to increase thermal conductivity; copper's high thermal conductivity attracts this heat, keeping it away from critical areas of the PCB,

In the Task 6.3.2, the final assembly design will be refined based on the studies performed in WP5 about the electric drive integration with the electric motor. Boards' geometries along with mechanical integration and wiring design will be carried out. Besides, a final PCB, probably a multi-board structure, design and BOM will be carried out.

The Task 6.3.3 foresees PCBs manufacturing, the supplying of the BOM and the assembly of the power electronics and control unit boards. To ensure a professional assembly with low risk of errors, it will be performed using a precision manual stencil printer to spread the soder paste evenly on the PCB, a semi-automatic pick & place system for the placement of surface mount device components and finally a Lead-Free reflow oven to make a perfect and temperature controlled soldering. Also mechanical assembly related to the boards will be finalized.

2.5 WP8: Techno economic evaluation and exploitation

The first objective of this work package is to evaluate the test results coming out of WP7 and relate them to the costs of the different technologies, performing a Life Cycle Assessment (LCA). The second objective is the management of the exploitation strategies within the Consortium, including the definition of a business plan and the monitoring of IPR.

Task 8.1 – Techno economic evaluation

The techno-economic evaluation will analyse the technical and economic performance of the different electric drive units developed within WP3, WP4 and WP5 to evaluate the feasibility and likelihood of the deployment of the different technologies at larger scale within the considered automotive powertrains compared to other motor topologies and configurations used for the same purpose. The technical performance outputs will be based on the measurement results of the different drive units within WP7. Cost-benefit assessments and detailed bill of materials of each developed component will complement the study.

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Task 8.2 – LCA

The aim of this task is to perform a LCA analysis of the developed technologies, comparing both technologies (IM and Synrel machines), and comparing them against electric motors already in the market as well.

The environmental performance will be included in the study of the emissions related to the powertrain manufacturing (manufacturing phase), environmental effect due to the powertrain electrification (use phase), the impact of the maintenance labors (use phase) and the treatment at the end-of-life of the e-Drives (end-of-life phase).

In the period of time concerning this report, the manufacturing phase of under development machines have been updated, in order to improve preliminary processes mapping to support the Life Cycle Inventory. Technical workshops were carried out with partners from WP3 and WP4, in order to tune up the processes mapping, identifying the production processes and the incoming and outgoing flows in each stage, as previous step before flows quantification (raw materials, energy, emissions, wastes, etc.). The LCA activities carried out during these months were summarized in Figure 12.

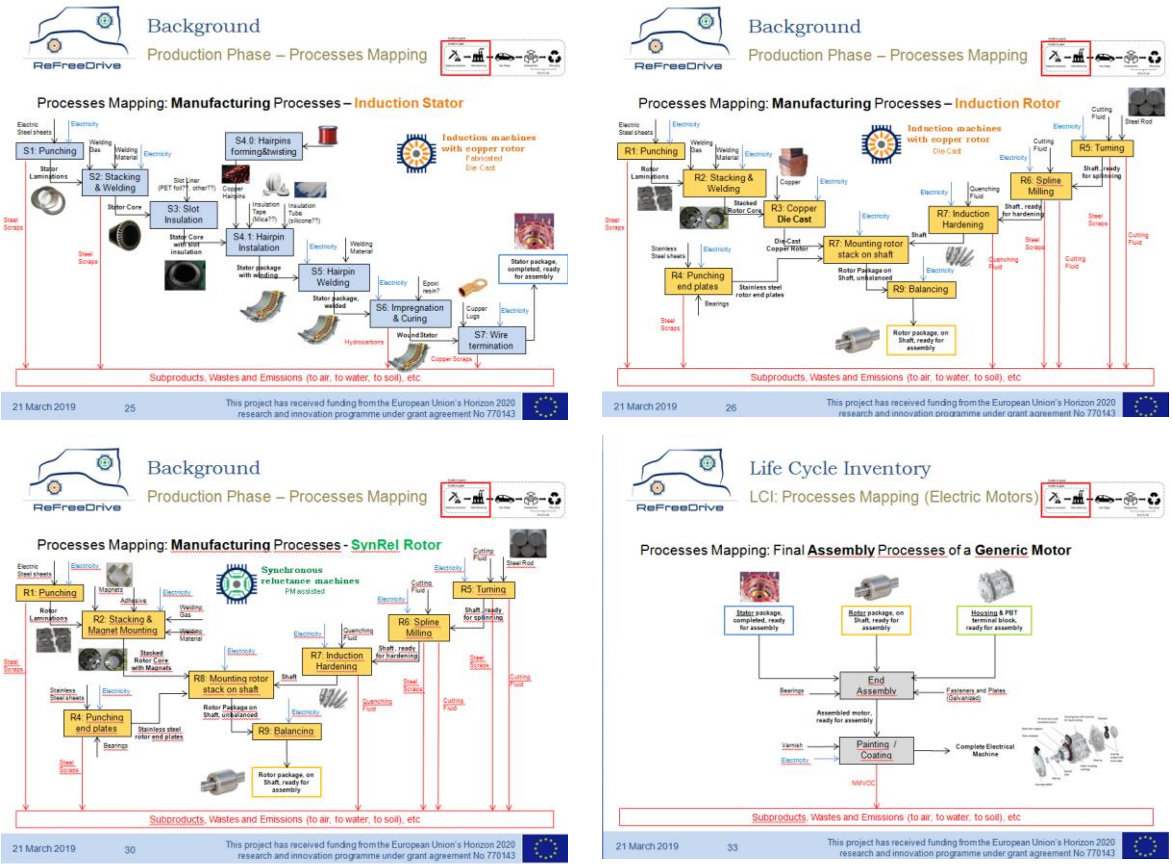

Figure 12: LCA activities overview

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Recently, individual communication among CID and the others partners involved in the electric traction machines definition were carried out in order to update the information linked with each production processes, quantifying the amount of input/output. That updated information has been employed to feed the LCA models, Figure 13.

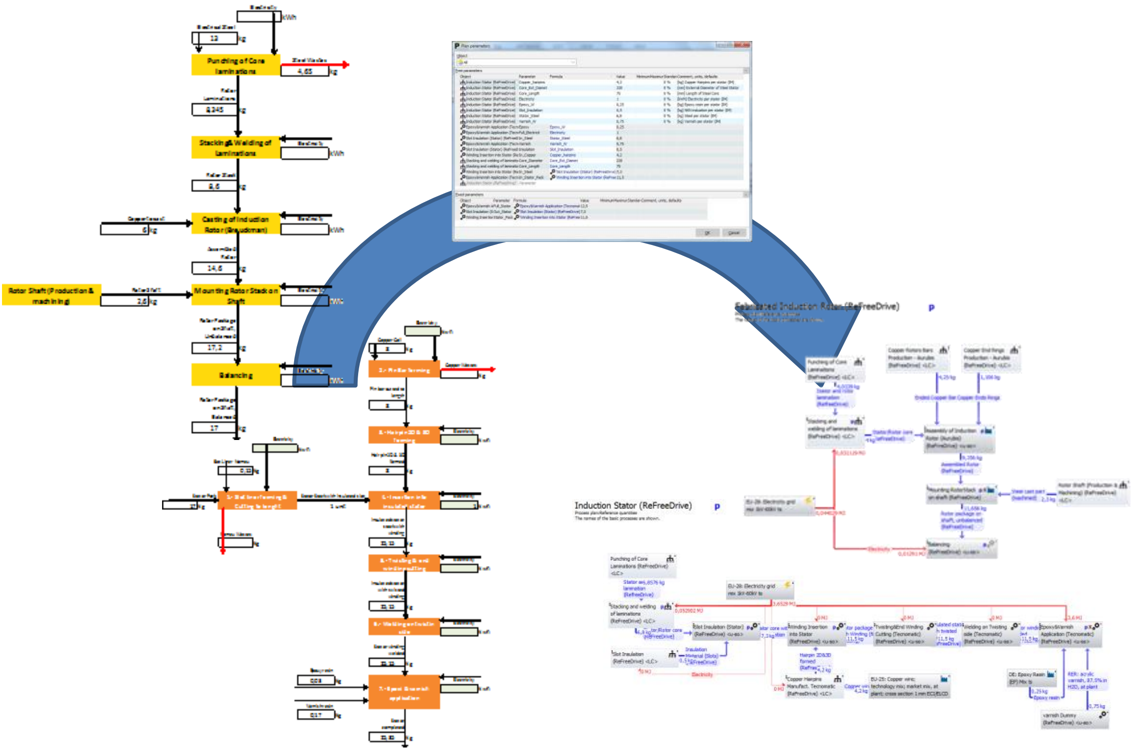

Figure 13: LCA models

During the prototyping stage within WP6, a new data update will be carried out, which will improve the data employed in the LCA models, in a new iteration of the Life Cycle Assessment method.

Task 8.3 – Exploitation of the technological solutions

About the second objective, the exploitation of the technological solutions that were designed during the project and will be tested in WP7, the tasks are defined as following, according to the Grant Agreement.

- ***Market Analysis***: *"perform a continuous market analysis, analysing any change in the customer's' needs and potential competitors as well as identifying the trends and expected growth at European and international level will be carried out ..."*
- ***Business Plan***: *"define a Commercialisation Strategy and Business Plan that will be carried out by Mavel SRL (MAV) with the support of Fundación Cidaut (CID), based on*

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previous tasks and with a more detailed cost analysis. The Business plan will include a refined commercialisation strategy and a proposal for an investment policy."

- ***Event Attendance**: "participating in specialist fairs in Europe and throughout the world; the project partners will take part in specialist fairs and it is envisaged to book for a stand during the project final event in one of them, which will be selected during the project, and organized by Università dell'Aquila (UAQ)"*
- ***Exploitation:** "…focused on the industrial exploitation and marketing. A market and technological watch will be established to keep track of new competitors, initiatives as well as research results. This market and technological watch will be carried out jointly by the Project Technical Management Board during the whole project, reporting at the end of each project year"*
- ***IPR Management:** "monitoring of foreground and IPR issues, the project's IPR strategy, etc...*

Not all topics are due for M18 deadline, according to the original project planning. The tasks on which we worked are the following, while the rest will be included in the next deliverable D8.4, due at the end of the project, M36.

1. Market and Technological Watch.

The market trend is clearly lacking against expectations, if we consider the latter as defined in the main scenarios issued by government. These are related with reasonable targets (which are close to be strictly necessary), for example IEA 2DS scenario is defined in order to get a global warming not higher than 2°C, by the year 2050. Figure 14 shows this situation, to be compared by today's figure, which is a total worldwide stock of EVs of about 5.1 Million units.

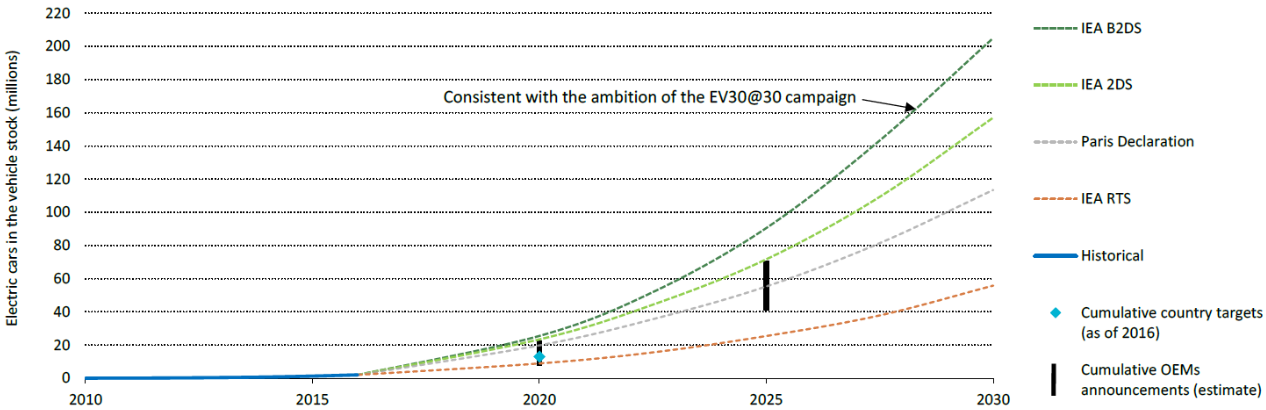

Figure 14: IEA scenarios – for the source, check the project deliverable

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In this situation, we can reasonably expect that EV sales will be supported more than today.

From the technological point of view, the report shows that PM motors are used in EVs. The only main player in Electric Car making which uses other technologies is the American company Tesla, which by the way recently switched to PM for its last (and cheaper) car, called model 3.

2. Trends in customers' needs and in competitors' solutions.

The customers' needs are defined by a joint brainstorming of all partners, technology ones, components manufacturers and car makes and it can be resumed as following:

- Cost/price.
- Reliability (operational expenses are an advantage, and we must be sure to keep it low).
- Range, which means high efficiency and low battery consumption.
- Easiness of recharging batteries.

As for the competitors' trends, in technological development, we clearly see a wide use of PM motors (today's benchmark) but, on the other hand, also many efforts to reduce the impact of rare earth materials inside these motors.

3. Critical materials: is a focus about the state of the art and the forecast request for critical materials in an electrical drivetrain. It focuses above all on rare earths.

It is clear that the use of Neodymium is a problem and will remain an issue even in the future, as shown in Figure 15. Today we could not yet find any definitive solution, among the many proposals in literature. Our project is proposing solutions by completely changing the technology of electric motors used in drivetrains.

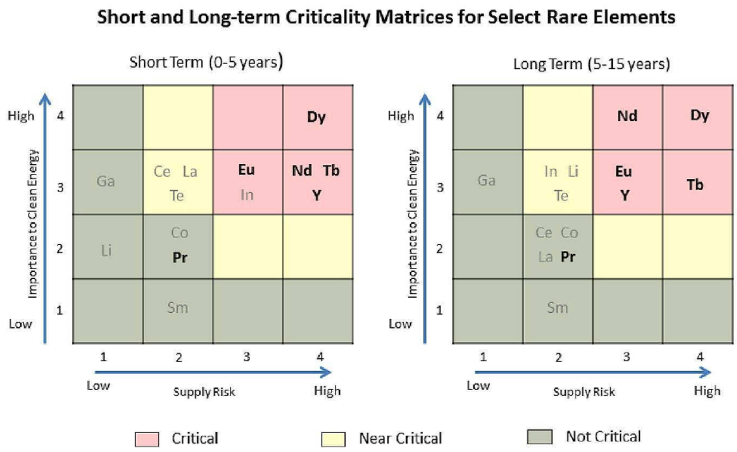

Figure 15: Critical Materials – for the source, check the project deliverable

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4. Intellectual Property Rights, setting up a methodology to allow all partners dealing with this throughout the whole project.

A table was defined and a procedure was shared among the partners in the project. Until today, no intentions for protection are presented by the partners, but a few potential intentions were found.

5. Commercialization Strategy and Business Plan definition; in this first draft deliverable, the assessment reported in the Grant Agreement and the assessment of the break-even are crosschecked, considering the forecast sales and the calculated costs of the products designed during this project.

The calculation shows that, even in the worst case, that is IM, which has the highest variable cost, we still meet the expectations described in the Grant Agreement and reported in Figure 16, what means that the evaluated costs of goods are within the expected one.

	kEuros									
	2020		2021		2022		2023		2024	
SALE INCOMES	2872,4	100,0%	6051,6	100,0%	12428,4	100,0%	25777,5	100,0%	54316,9	100,0%
R&D EXPENSES	200	7,0%	150	2,5%	105	0,8%	65	0,3%	40	0,1%
SALES EXPENSES (included investments	2722,77	94,8%	5736,42	94,8%	11781,20	94,8%	24435,08	94,8%	51488,19	94,8%
Cost of Goods	2344,68	81,6%	4939,86	81,6%	10145,25	81,6%	21042	81,6%	44338,5	81,6%
Selling Expenses (Marketing)	234,47	8,2%	493,99	8,2%	1014,53	8,2%	2104,20	8,2%	4433,85	8,2%
Overheads (Rental, Energy, …)	143,62	5,0%	302,58	5,0%	621,42	5,0%	1288,88	5,0%	2715,84	5,0%
EBITDA	-50,4	-1,8%	165,2	2,7%	542,2	4,4%	1277,4	5,0%	2788,7	5,1%

Figure 16: Incomes and expenses as reported in the Grant Agreement – for the source, check the project deliverable

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