Rare Earth Free e-Drives Featuring Low Cost Manufacturing

Collaborative Project
Grant Agreement Number 770143

Start date of the project: 1st October 2017, Duration: 42 months

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

Deliverable no.: D1.3

Title of the deliverable: Third Progress Report

Contractual Date of Delivery:	31.03.2021
Actual Date of Delivery:	20.04.2021
Lead contractor for this deliverable:	CIDAUT
Period covered by this deliverable:	From 01.08.2019 to 31.03.2021
Author(s):	Jorge Velasco (CID), Giuseppe Fabri (UAQ), Tomas Jezdinsky (ECI), Luciano Albini (CSM), Misa Milosavljevic (IFPEN), Miguel Carrero (PRI), Cleef Thackwell (JLR), Matteo Benedetto (MAV), Manuel González (CID)
Participants(s):	All project partners
WP contributing to the deliverable:	WP1,WP2, WP3, WP4, WP5,WP6, WP8, WP9
Nature:	PUBLIC
Version:	03

Abstract:

This report describes the progress and achievements of the ReFreeDrive project in the period 01.08.2019 (M23) to 31.03.2021 (M42). Several management procedures have been carried out during this period, as well as numerous dissemination and communication activities. The development of the power electronics has been completed. And the manufacturing of the power electronics for the two power ranges and their integration has been carried out.

In addition, the performance of the motors has been characterised and the correct functioning of the developed engines in a real vehicle has been validated.

The techno-economic evaluation and exploitation of the results, as well as the life cycle analysis, have been completed. Although the information is individualised for each work package, the interactions between them are also considered. All those responsible for the work packages have been involved in the drafting of this report.

REVISION TABLE		
Document version	**Date**	***Modified sections - Details***
V1	13/04/2021	First draft
V2	16/04/2021	Merging of individual contributions & Review
V3	19/04/2021	Quality and format updates

Table of Contents

ABBREVIATIONS 5
EXECUTIVE SUMMARY 6
1 PROJECT OBJECTIVES 3ND YEAR REVIEW 8
2 EXPLANATION OF THE WORK CARRIED OUT PER WP 11
2.1 WP5: e-Drive Design 11
2.1.1 Task 5.4 – High Power powertrain integration 11
2.1.2 Task 5.5 – Medium Power powertrain integration 13
2.2 WP6: Prototypes manufacturing 14
2.2.1 Task 6.1 – IMs manufacturing 15
2.2.2 Task 6.2 – SynRel motors manufacturing 17
2.2.3 Task 6.3 – Power electronics manufacturing 20
2.2.4 Magnetic characterization of M235-35A material for Prototypes Manufacturing 23
2.3 WP7: Powertrain Testing, Vehicle integration and Validation 24
2.3.1 Task 7.1 – Motor Testing 25
2.3.2 Task 7.2 – Integrated Powertrain Testing 37
2.3.3 Task 7.3 – In Vehicle Integration 40
2.4 WP8: Techno economic evaluation and exploitation 42
2.4.1 Task 8.1 – Techno economic evaluation 42
2.4.2 Task 8.2 – Life Cycle Asssessment (LCA) 45
2.4.3 Task 8.3 – Exploitation of the technological solutions 49

Abbreviations

4WD: Four Wheel Drive

BP: Battery Pack

BEV: Battery Electric Vehicles

BOM: Bill of Material

BOP: Bill of process

CAN: Controller Area Network

CID: Fundación Cidaut

CRMs: Critical Raw Materials

CSM: Centro Sviluppo Materiali

DC-IM: Die Cast - Induction Motor

GA: Grant Agreement

ECU: Engine Control Unit

EIS: Electronic Ignition System

EMF: ElectroMotive Force

EV: Electric Vehicle

HMI: Human-Machine Interface

IC: Information Cluster

IFPEN: IFP Energies Nouvelles

ILCD: International Life Cycle Data system

IM: Induction Machine

IPR: Intellectual Property Rights

JLR: Jaguar Land Rover

KER: Key Exploitable Result

KPI: Key Performance Indicator

LCA: Life Cycle Assessment

NGO: Non Grain Oriented

MDL: Motor Design Limited

PE: Power electronic

PM: Permanent Magnets

PMa Synrel: Permanent Magnets assisted Synchronous Reluctance Motor

PRI: Privé

SiC: Silicon Carbide

SynRel (SyncRel): Synchronous Reluctance

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

WBG: Wide Band Gap

WLTP: Worldwide Harmonized Light Vehicles Test Procedure

WP: Work Package

Executive Summary

This document reports the project progress during the period from M23 (August 2019) to M42 (March 2021). It reviews the technical achievements of the Work Packages (WPs) active during this period (WPs inside the red dashed box in Figure 1) and the work carried out until the project end. 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:

- **WP5** was devoted to develop the Power Electronics (PE) and the control strategies needed for 75kW and 200kW power levels. In parallel, off-the-shelf solutions were sought for all other powertrain systems needed for the integration of the prototypes into a commercial vehicle, such as batteries, gearbox or auxiliaries. This last period of the project focused on the latter objective, analysing the integration strategy of the 200kW high power electric drive in a Jaguar Land Rover (JLR) vehicle (Task 5.4) and carrying out all the integration activities needed to allow the installation of the 75kW motors in a Mercedes Sprinter (Task 5.5)
- **WP6** concerned the manufacturing of the prototypes of the motors and power electronics for the two power ranges. In line with the two motor avenues explored within the project, Task 6.1 involved the manufacturing of the Induction Motors (IM) (die-cast and fabricated options), Task 6.2 involved the manufacturing of the Synchronous Reluctance (SynRel) motors, both pure and assisted by ferrite magnets, and finally Task 6.3 covered all aspect related with the manufacturing of the power electronics.
- **WP7** covered all testing steps needed to characterize the motors performance and ensure a proper operation of the motors developed within a real vehicle, demonstrating at the same time their suitability to meet expected market requirements through the accomplishment of the Key Performance Indicators (KPIs). Following an incremental level of components integration, Task 7.1 involved the testing of the motors and the power electronics either integrated or in standalone mode. Task 7.2 served as an intermediate integration step, where some of the powertrain components were added to the testing setup. Task 7.3 finalized the full integration of the motors with all powertrain systems into a commercial van and tested them on a circuit to validate it.
- **WP8** elaborated the exploitation strategy of the technological solutions developed within the project, for which an Intellectual Property Rights (IPR) plan and a commercialization strategy were defined (Task 8.4). A techno-economic analysis of all developed solutions as well as a technological watch of the Electric Vehicle (EV) market was performed (Task 8.1). This analysis was supported with a Life Cycle Analysis (LCA) of the different motor technologies for both power levels (Task 8.2), that assessed their environmental impact in comparison with the current benchmark motors, namely NdFeB Permanent Magnets (PM) motors.

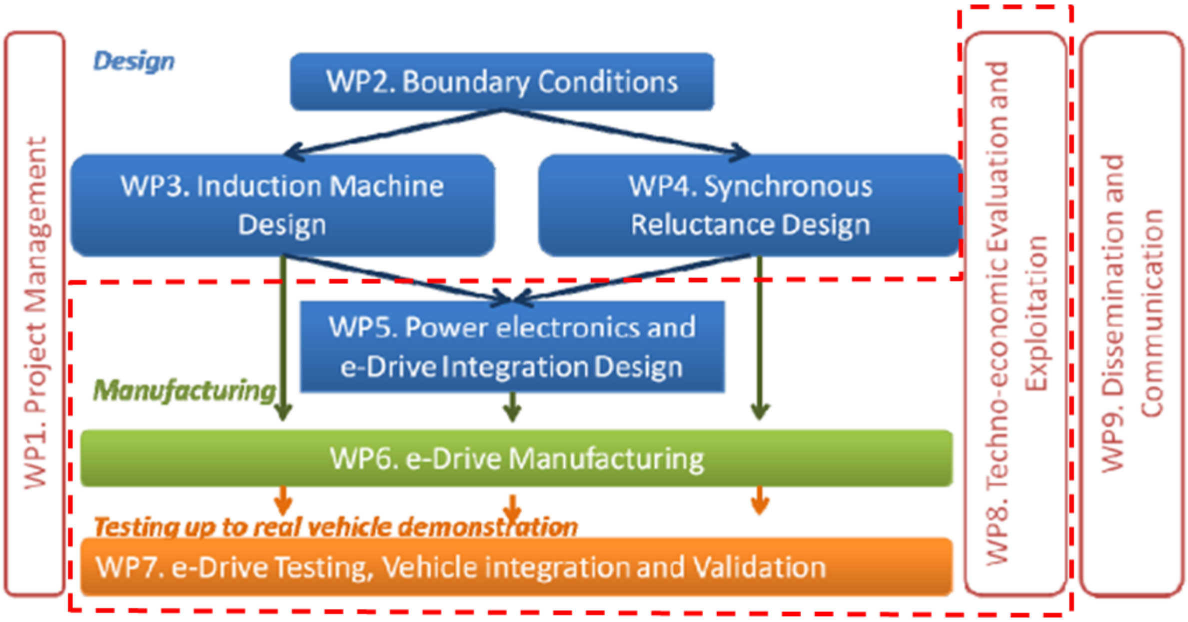

Figure 1. Scope of the Third Progress Report

This D1.3 deliverable has fully met its objectives. No deviations in content or impacts (either to the herein described tasks or to the overall project implementation) have been found in this deliverable compared with what was stated in the Grant Agreement (GA). There is a slight deviation on time, mainly caused by the nature of the document. Being D1.3 a summary of the activities carried out in the different project WPs, it is justified that the delays experienced by some WPs, namely WP6 and as a consequence also WP7 and WP8, impose a delay on D1.3 release date.

1 Project Objectives 3rd 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 Induction Machine (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 assisted. 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).

  ✓ The complete design of the motors and the power electronics was accomplished in the period before this report.

- 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).

  ✓ During this period, 8 motors representing 4 topologies in two power ranges (75 and 200 kW) have been manufactured. One motor topology, the fabricated rotor induction motor, was not ready for testing before the end of the project. The testing results confirm that the ambitious KPIs set at the beginning of the project are met by the prototypes designed and manufactured.

- 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.

- ✓ A cost-benefit analysis has been derived from the measured performance data and the estimated machine costs. SynRel motors meet comfortably the expected cost targets for both power ranges, showing their appropriateness to be used as main traction units. On the other hand, induction motors struggle to meet the expectations. 200kW induction motors are quite close to the target, but are affected by the need of additional battery capacity in order to meet the same range as NdFeB PM motors. 75kW induction motors show the same disadvantage and furthermore their PE is optimized for the operation at 200kW. Therefore, at this stage, induction motors are best suited for being used as secondary traction units.

- 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 period the integration strategy of the 200kW high power electric drive in a JLR vehicle was defined. The 75kW powertrain integration (components selection and integration) that allowed the motors installation within a commercial van was also carried out.

- 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.
    - ✓ This objective was accomplished in the period prior to this report.

- 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 (PRI) (e.g. Iveco Daily, Mercedes Sprinter)
    - ✓ During this period both technologies (Induction and SynRel) have been fully tested and validated. The performance of the motors with all powertrain

systems was first validated in laboratory conditions (test bench) and finally tested into a commercial van on a real circuit.

- 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, the barriers and risks have been updated considering the Covid-19 pandemic. Specifically, the lack of physical events has been recognized as a barrier for the increased difficulty in reaching the target audience of the campaign. Webinars have been organized and article on magazines written as a countermeasure.

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 Final Report.

2.1 WP5: e-Drive Design

WP5 intended to research and develop the power electronics and control strategies needed for each power range. This means that both traction technologies share the same power electronics and control algorithms for each use case (medium power range, high power range). Besides, WP5 analysed and selected 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.

During August and September 2019 partners focused their efforts on the final released of D5.4 (*Technical High Power Powertrain Integration Description Document)* and D5.5 (*Technical Medium Power Powertrain Integration Description Document*). Tasks 5.1 (*Development of control algorithms for IM and SynRel motors),* 5.2 (*High Power Range Electric Drive Design*) and 5.3 (*Medium Power Range Electric Drive Design*) ended in June 2019 (check D1.2 for further information).

2.1.1 Task 5.4 – High Power powertrain integration

Task 5.4 focussed on the integration of the 200kW high power electric drive units designed within the ReFreeDrive project in a JLR vehicle. The results were based on simulations that rely on datasets which have been provided by Motor Design Limited (MDL) in WP3, IFP Energies Nouvelles (IFPEN) and University of L'Aquila (UAQ) in WP4 and complemented by specific datasets related to mechanical and gearbox losses provided by JLR. As the gearbox development was not part of the ReFreeDrive project, JLR provided a dataset for this specific subcomponent based on the assumed gear ratios and gearbox layout corresponding to the target vehicle with the boundary conditions described previously within WP2. Vehicle performance calculations were generated with a JLR-internal vehicle model. Efficiency calculations were generated by the workflow described in Figure 2.

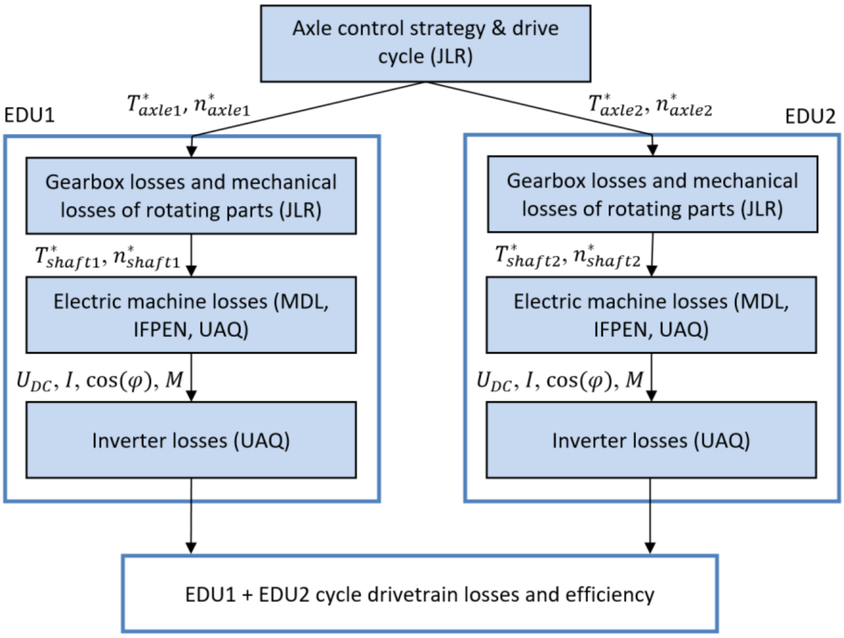

Figure 2. Workflow for generation of drivetrain losses over representative drive cycle and subsequent drive unit efficiency determination

The different outputs highlighted the performance of the three rare-earth free motor topologies at system level when used as dual-axle four Wheel Drive (4WD) propulsion system for high performance battery electric vehicles (BEV).

The results showed that each type of motor technology has a different impact on the behavior of the inverter and the gearbox thus directly impacting the overall system. The ReFreeDrive motors integration potential is described and proven in section 2.1 of D5.4.

In conclusion, T5.4 gave an overview of how the different motors and the inverter designed within the ReFreeDrive project would behave when integrated into the powertrain of the JLR target vehicle. It showed that the different motors all influence the behavior of the other components such as the inverter and the gearbox differently. Implementing the rare-earth free motors with a 0/100 torque split, or only operating in 4WD when necessary will benefit the system efficiency the most. Base on that torque split, powertrain efficiencies between 85.8 % and 88.7 % can be achieved.

2.1.2 Task 5.5 – Medium Power powertrain integration

Task 5.5 was focused on the activities of vehicle integration that have been performed in order to allow the Medium Powertrain integration and the demonstration of the new ReFreeDrive motors on the Mercedes Sprinter demo.

The activities of this task have been divided (check D5.5) in 3 different macro areas and therefore divided in sub groups each one related to sub components of the vehicle.

1- **Component Selection.** This section describes the activities related to the analysis of the requirements for each specific sub group of component (Figure 3) fulfilling the requirements specified in WP2, the discussion with different suppliers until the final decision has been taken.

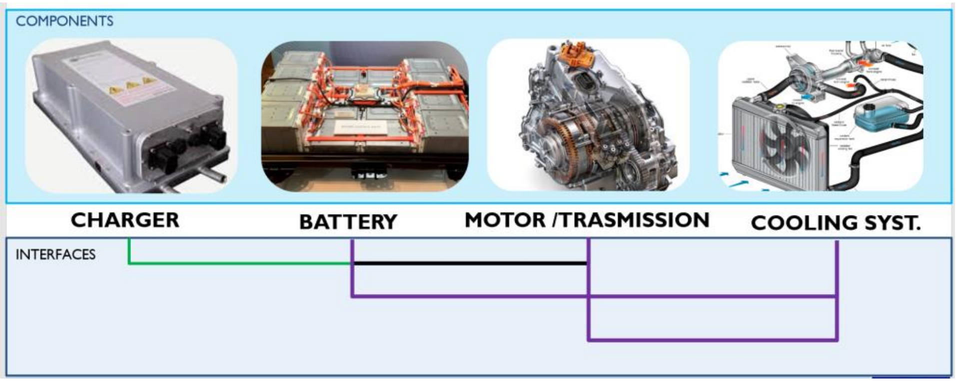

Figure 3. Main component to consider for the in-vehicle integration of ReFreeDrive e-drives

2- **Component Integration.** This section describes the detailed design of different sub components such as the Battery Pack (BP) or the activity of integration of purchased parts inside the vehicle.
3- **Powertrain Integration.** This section has a specific focus on the activities performed at a system level and involves the communication and the integration of different components in order to obtain a complete working vehicle.

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.

The proposed architecture for the final system included **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 Information Cluster (IC) and provide a USB interface for the Human-Machine Interface (HMI). It may also send the ignition signal from the modified Electronic Ignition System (EIS) ECU, and translate the gear selection switch. Figure 4 shows the proposed two ECU architecture scheme.

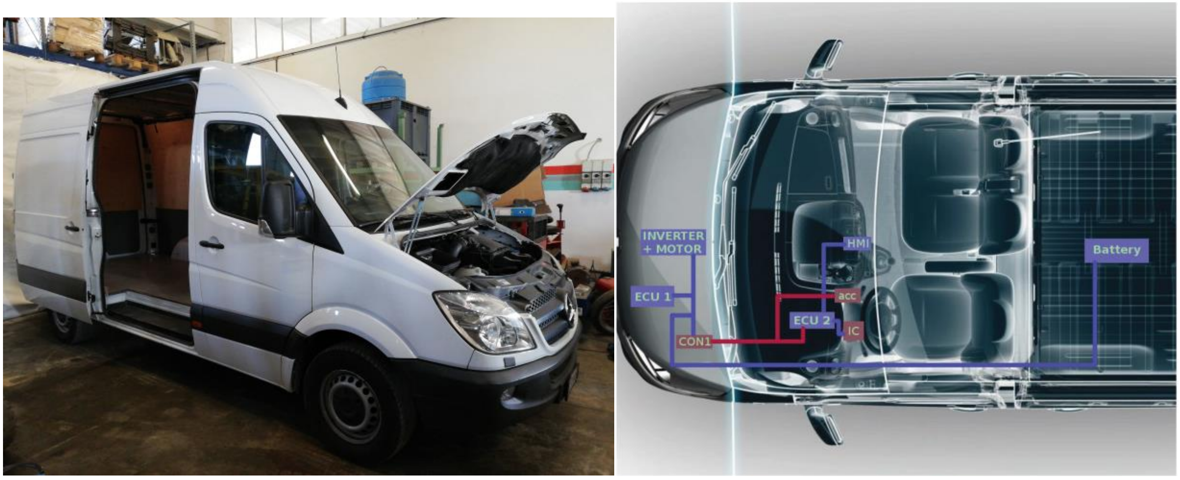

Figure 4. Vehicle disassembly and proposed ECU architecture scheme

2.2 *WP6: Prototypes manufacturing*

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

- 2 prototypes of Induction motors with fabricated copper rotor;
- 2 prototypes of Induction motors with die-cast copper rotor;
- 2 prototypes of pure Synchronous Reluctance motors;
- 2 prototypes of PM-assisted Synchronous Reluctance motors;
- 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 5):

- Task 6.1 – IMs manufacturing;
- Task 6.2 – Synchronous Reluctance (SynRel) motors manufacturing;
- Task 6.3 – Power electronics manufacturing.

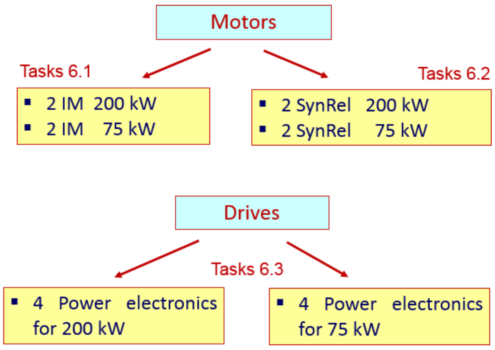

Figure 5. Prototypes of motors and power electronics

For this activity, the single actions were defined for the manufacturing of the prototypes. Sub-contractors were identified who dealt with some processing and motor assembling.

The prototypes will now be illustrated in detail.

2.2.1 Task 6.1 – IMs manufacturing

The actions related to the construction of the 75 and 200 kW Induction motors are shown in Figure 6.

The main goals concerned:

- Stator and rotor cores manufacturing by laser-cut
- Stator winding manufacturing with hairpin windings and flat wires
- Copper rotors, either die-cast and fabricated
- Manufacturing of cooling jacket, external housing and flanges
- Final assembly

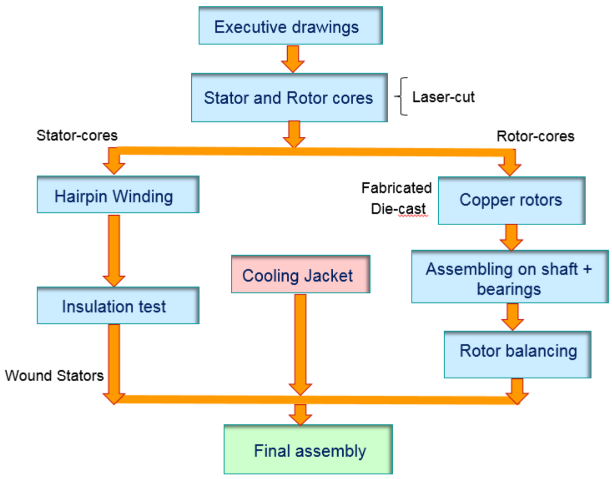

Figure 6. Actions for the Induction motors manufacturing

The stator and rotor cores were manufactured by laser cutting and the chosen electrical steel is M235-35A: the same material has been used for the cores manufacturing of the SynRel motors.

The manufacturing goals were fulfilled with a large deviation in time that is in major part attributable to the stops of the productions activities, due to the Covid-19 pandemic.

Figure 7 shows the wound stator and Figure 8 the copper rotors. The final motor assembly is presented in Figure 9.

Figure 7. Wound stator with hairpin technology

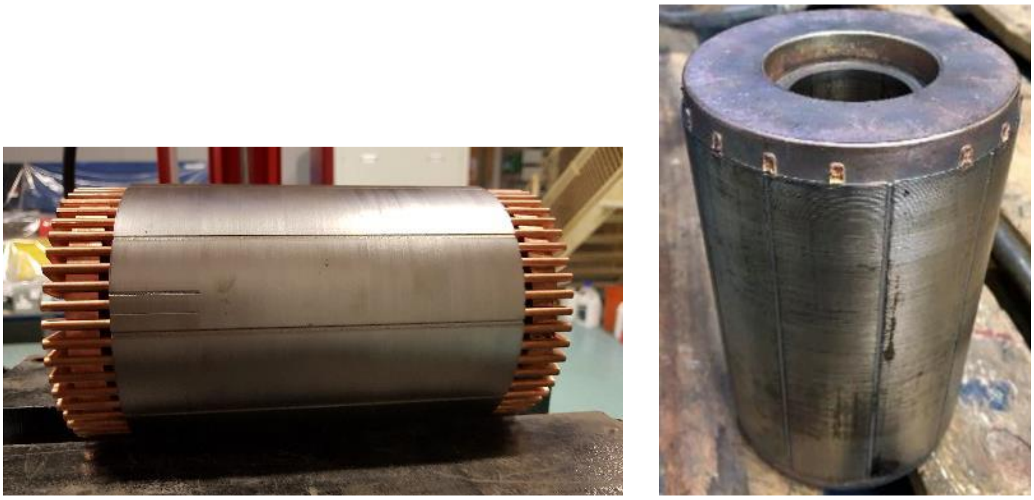

Figure 8. Fabricated copper rotor (left) and die-cast copper rotor (right)

Figure 9. Induction motor complete assembly

2.2.2 Task 6.2 – SynRel motors manufacturing

2.2.2.1 Pure SynRel Motors

The actions related to the construction of the 75 and 200 kW Pure SynRel Motor are shown in Figure 10.

The main goals concerned:

- Stator and rotor cores manufacturing by laser-cut
- Stator winding manufacturing with round wire
- Manufacturing of cooling jacket, external housing and flanges
- Final assembly

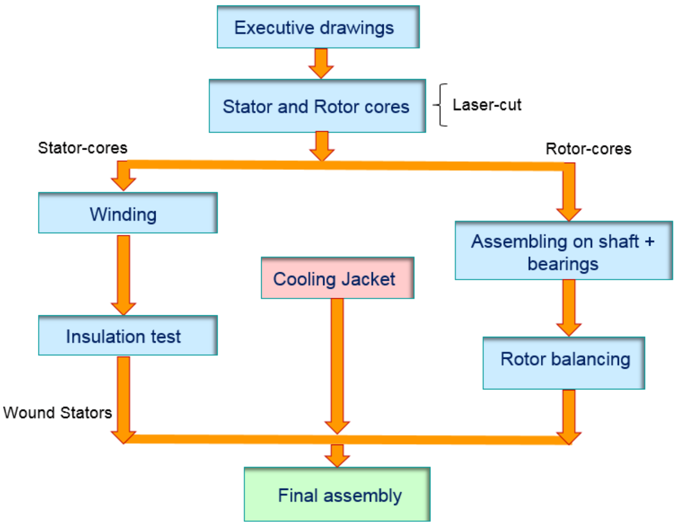

Figure 10. Actions for the Pure SynRel motors manufacturing

The objectives were fulfilled and the deviation in time was in major part due to a slight delay in the construction of the cooling jacket and mechanical parts.

Figure 11 shows the wound stators and the rotor cores of the 200 kW and 75 kW Pure SynRel motors and Figure 12 shows the final motor assembly.

Figure 11. Pure SynRel motors: wound stators and rotor cores

Figure 12. SynRel motor complete assembly

2.2.2.2 PM-assisted SynRel Motors

The steps related to the construction of the 75 and 200 kW PM-assisted SynRel motors are shown in Figure 13.

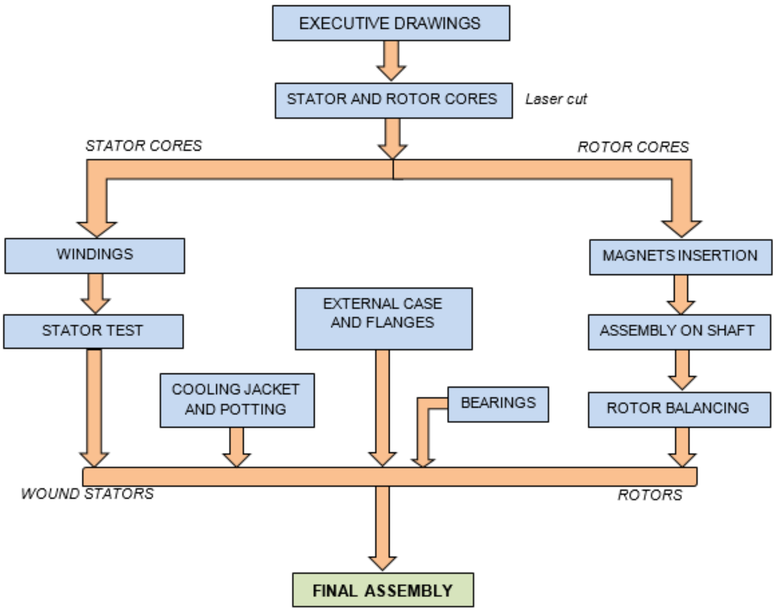

Figure 13. Actions for the PM-assisted SynRel motors manufacturing

The main goals concerned:

- Stator and rotor cores manufacturing by laser-cut
- Stator winding manufacturing with round wire
- Insertion of the permanent magnets in the rotor cores;
- Manufacturing of cooling jacket and potting, external housing and flanges
- Final assembly

The objectives were fulfilled and the deviation in time (if we consider September 30th 2019 due date) was mainly due to supplier delays.

Figure 14 shows the rotor core and the stator insertion in the internal cooling jacket of PM-assisted SynRel motor; Figure 15 presents the final motor assembly.

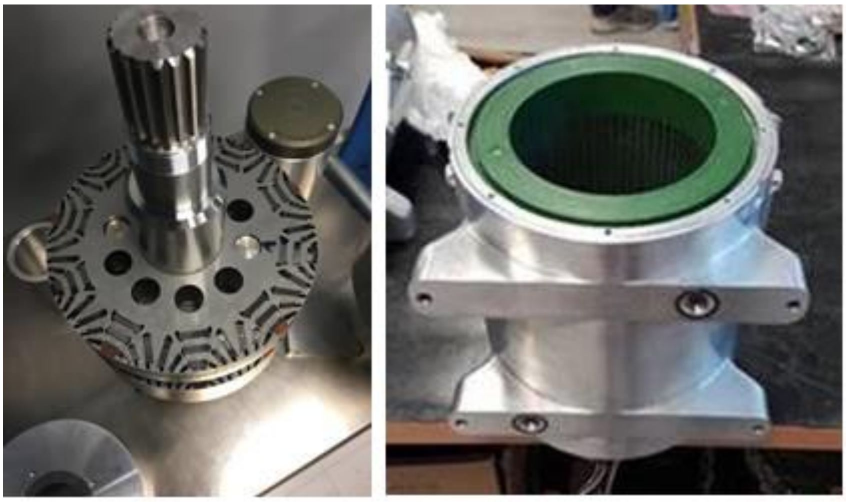

Figure 14. PM-assisted SynRel motors: rotor core and stator

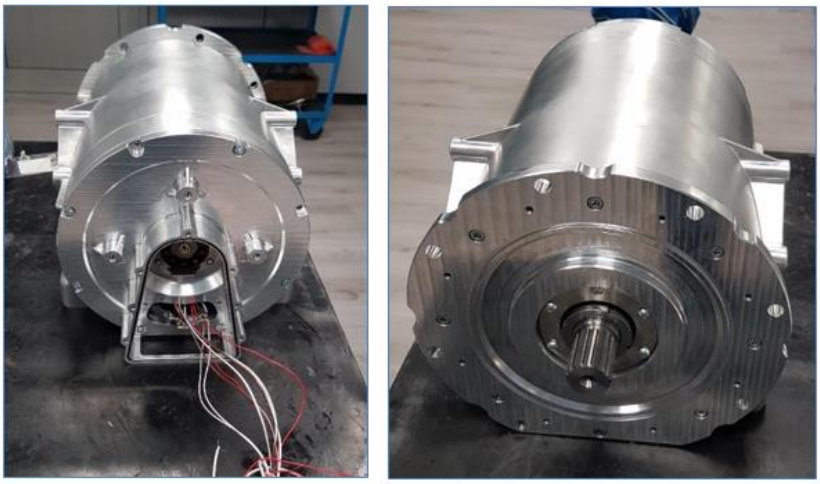

Figure 15. PM-assisted SynRel motor complete assembly

2.2.3 Task 6.3 – Power electronics manufacturing

About the power electronics manufacturing, the objectives are:

- to manufacture 4 prototypes for the 75kW power range for testing and in-vehicle integration.
- to manufacture 3 200kW power range prototype for test bench validation of the high power setting drivetrain (1 prototype complete spare parts was left available for repairing in case of faults)

The manufacturing of the power electronics started with the refinement of the mechanical designs to assure the proper dimensions to fit the motor housing and to define the proper shape for the AC bus bars connecting the Power Electronics with the motor phases.

Concerning the control electronics for the 75kW power settings, a customized control board has been developed. The customizations include the board dimensions and electrical interfaces to allow for vehicle integrations. Figure 16 shows the manufactured boards before assembling while Figure 17 reports a picture of the fully assembled control board. Layout design, component assembly and preliminary testing have been carried out by R13.

Figure 16. Control Board V2 for the 75kW power range before assembling.

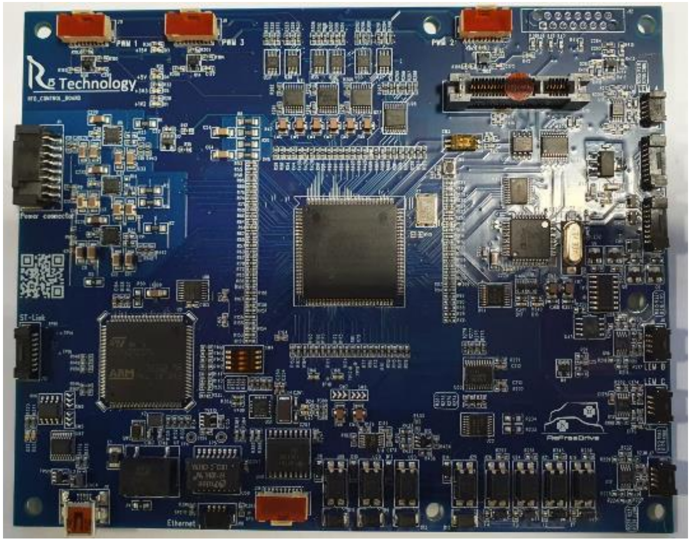

Figure 17. Control Board V2 fully assembled for the 75kW power range.

For what concern the 200kW power setting a proper control electronics have been developed by IFPEN, considering the higher voltage ratings of the PE (up to 800V) the driver has been properly designed to assure efficient safe operations for the SiC transistors. Prototypes under preliminary test operations are shown in Figure 18.

Figure 18. First assembling for testing of the control and driving electronics for the 200kW power range.

Almost in parallel the layout and the manufacturing of laminated DC bus bars were carried out, including the installation of the DC capacitors. The laminated Bus Bar is designed to be adopted on both the power settings to enhance scalability.

Figure 19 reports two of the manufactured prototypes along with Silicon Carbide (SiC) mosfets power modules while Figure 20 shows the fully assembled 75kW Power Range. The integrated PE on the 75kW IM prototype is shown in Figure 21.

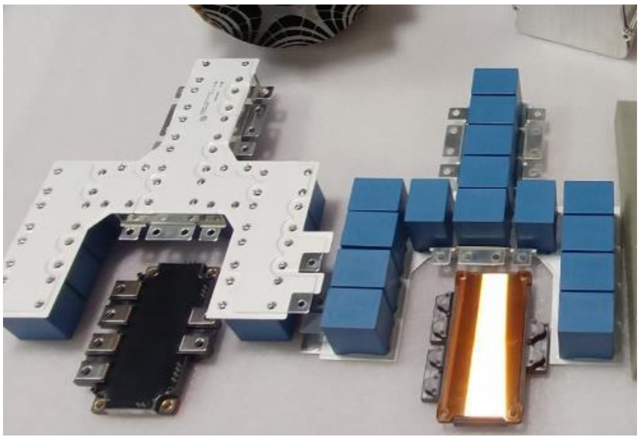

Figure 19. DC bus bars with SiC components.

Figure 20. Assembled 75kW PE.

Figure 21. 75kW PE integrated on the 75kW IM.

The task was fullfiled without deviation in time. Some minor manufacturing defects found on the cooling housings required a slight adjustment.

2.2.4 Magnetic characterization of M235-35A material for Prototypes Manufacturing

According to the final motor design and project requirements the material choice focused on the M235-35A grade. This material has been acquired for the prototypes manufacturing with two types of coating, C5 and Back Lack, as indicated in each motor design.

Due to fluctuations of magnetic properties of Non Grain Oriented (NGO) materials within the same grade, the properties of M235-35A, characterized in the motor design phase, are expected to be not completely coincident with those of the material acquired on the market for the prototypes manufacturing. For this reason, in the framework of the 18M General Assembly Meeting it has been decided to perform also the magnetic characterization of both the M235-35A used for prototypes.

The aim of this characterization is to provide a complete comparison between the magnetic properties of the material selected in the motor design phase and the materials used for the prototypes manufacturing. In Figure 22 the plan of the magnetic characterization performed on Epstein Frame (IEC 60404-2, IEC 60404-10) is shown:

Materials:

- M235-35A with C5 Coating
- M235-35A with Back-Lack

Cut method: Laser, Shear

Cutting Direction:

- 50%L+50%T (standard @ 50 Hz)
- 100% @ 0°, 45°, 90° with respect to RD

Frequencies: 50, 400, 800, 1000 Hz

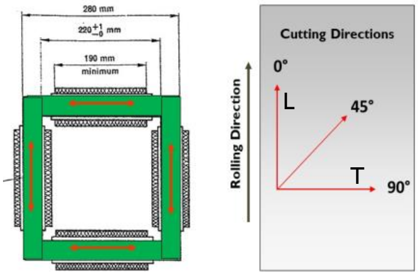

Figure 22. Magnetic characterization plan for the material used for the prototypes manufacturing

The results of such a characterization show that at low magnetic field strength, materials acquired for prototypes show higher inductions and slightly lower core losses compared with the reference material (M235-35A selected in motor design phase); at high H levels, M235-35A with C5 coating used for the prototypes show slightly lower induction. Furthermore, M235-35A with Back Lack coating show slightly better magnetic properties in terms of Core Losses in all the investigated conditions (Induction, Frequency). Last, for both M235-35A used for prototypes the reduction on P_{10} core losses, in case of shear cut with respect the laser cut, is in the range 18-21% at 50Hz, 9-11% at 400Hz and 3-7% at 1000Hz. The reduction on P_{15} is about 8-10%, at 50Hz and 3-4% at 400Hz. Therefore, despite unavoidable fluctuations expected within the same grade of NGO, magnetic properties of the materials used for prototypes manufacturing are compatible with those of the reference material (M235-35A selected in motor design phase).

2.3 WP7: Powertrain Testing, Vehicle integration and Validation

The objective of WP7 is to test and gather experimental evidence of the developed motor technologies, validating the proposed design methodologies and proving the motors performance with a series of test campaigns that incrementally added powertrain components up to the full vehicle integration. According to this testing strategy, the motors with their respective power electronics (integrated or in standalone configuration), control and cooling systems were tested in first place within Task 7.1 following JLR recommendations; secondly, in Task 7.2 the performance of the motors and the power electronics in different driving scenarios (such as accelerations) was tested and an intermediate integration of component was made; and finally the full integration of the 75kW e-Drives in a commercial van was achieved within Task 7.3.

The outbreak of Covid-19 pandemic coincided in terms of schedule with the start of WP7 tasks. Hence, lockdowns and travel restrictions both on project partners and on some subcontracted activities have had great impact on WP7 causing unexpected delays of different duration. Although measures to mitigate these impacts have been defined dynamically since April 2021, delays affected in some unavoidable ways and at different extents to WP7 Tasks and to the prototypes to be tested therein. These impacts will be explained individually in each Task below, although it is convenient to remark that the difficulties to manufacture the Fabricated IM made it not possible to test it within WP7 either the 75kW or 200kW versions, as it was eventually delivered with no time left for any testing activity.

2.3.1 Task 7.1 – Motor Testing

The main objective of the Task 7.1 is to validate and characterize on the IFPEN bench 8 motors with associated PE, control and cooling systems manufactured within the WP6 framework. This experimental activity is supported by UAQ for the control of Pure SynRel motor, Fabricated IM and Die-cast IM, while Permanent Magnet (ferrite) assisted Synchronous-Reluctance motor (PMa-SynRel) control is implemented by IFPEN. This in order to provide experimental evidence of the developed technologies, validating the followed design methodologies and proving the motors performance (Key Performance Indicators (KPI) and JLR test requirements). COVID pandemics have had an impact on the task 7.1 with namely WP6 induced delays and impossible partner travel in order to support mid power range PE validation and motor testing. In agreement with Cidaut and partners a plan B was activated with IFPEN assuming complementary activities in order to minimize the deviation in time and content.

With respect to items listed in the Grant Agreement WP7 description, the work carried out during the task includes:

- Validation and characterization of 3 high power and 3 medium power range motors out of 4 with their cooling systems.
- Validation and characterization of the High power range PE with dedicated control to each motor topology and track (350 V-75 kW and 750 V-200 kW).
- Experimental results analysis and share with the partners.

2.3.1.1 Experimental facility and testing protocol overview

Two fully equipped test benches were used at IFPEN for the electric motor and power electronics testing (Figure 23):

- Mid-Power test bench for the characterization of the 75 kW motors and PE

- Hi-Power test bench for the characterization of the 200 kW motors and PE

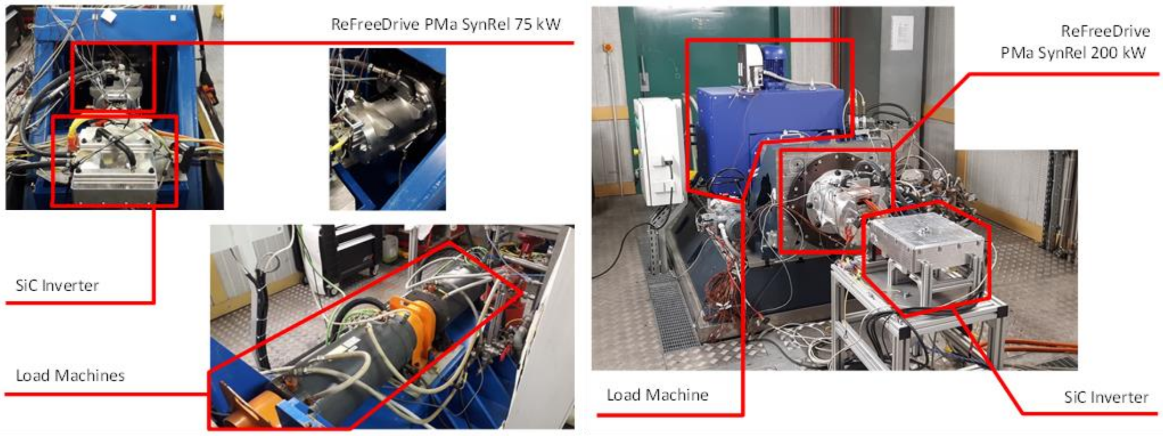

Figure 23. Mid (left) and High (right) Power range test benches overview

The testing time budget was used through focused tests in order to produce KPI and "must have" results in priority. Also, 75kW motors were given the priority in order to maximize the T7.2 and 7.3 activity time.

- For this reason one motor was tested with both, PE integrated on the motor housing and PE in standalone configuration in order to have system efficiency temperature impact between two configuration but also inverter and motor individual efficiencies. Other motors were tested with PE in standalone configuration in order to focus on KPI and motor efficiency.
- Also, for the motors which were tested without any time consuming tasks, it was possible to test at 690 and 750V DC voltage to quantify the impact of the voltage drop when used with the car electric battery.
- Finally, a rationalized number of testing points was necessary in order to keep an equivalent testing time for all motors. For those purposes a method was established through vehicle simulation over the driving cycle to identify the zone of interest for on driving cycle mean efficiency evaluation.

Moreover, each motor topology having its own particularities, the protocol and the testing time were adapted to the specific need and motor/inverter capacities. For instance PMa-SynRel motor needed back- electromotive force measurements, Pure-SynRel available time was used to test the reverse speed and torque operation while Die Cast-Induction Motor (DC-IM) has had extended coolant circuit validation.

Experimental facility mesurmement layout is given in Figure 24. It is composed of bench instrumentation as well as inverter mesurments. All data was gathered in an unique test report.

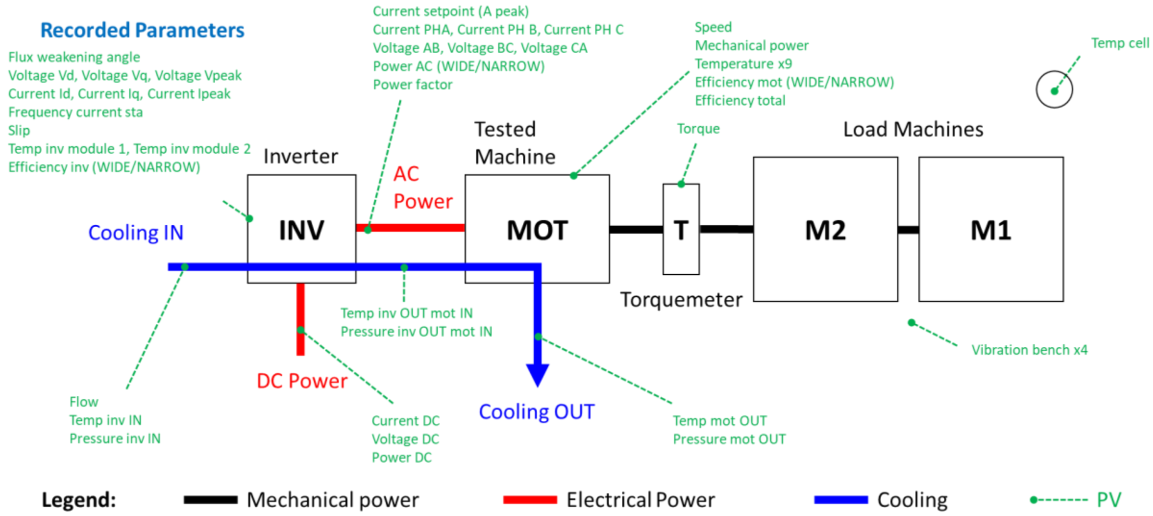

Figure 24. Experimental facility – Measurement layout

Thermal boundary conditions are kept identical for all motors except when motor or inverter capability do not allow it. Coolant flow rate is constant (10 L/min) except for IM motors which, inherent to their design (shaft cooling system) and manufacturer recommendation, is lower (4 L/min) and variable with the speed. Coolant temperature is constant (65 °C) at PE cooling circuit inlet.

2.3.1.2 Power Electronics validation and characterization

In order to validate the different motor technologies, a new generation Wide Band Gap (WBG) based inverter has been entirely designed to meet high power density and high efficiency requirements. The design of both high and medium power ranges PE was based on implementation of the same new Full-SiC semiconductors modules from Mitsubishi Electric. Compared to conventional Silicon-based power semiconductors, WBG devices lead to an increasing of several key parameters such as switching speed, thermal performances and efficiency. The selection of Mitsubishi modules contributed to meet the project requirements for two power levels (75 kW / 200 kW) according to their respective DC-link voltages (350 V/750 V). The PE were tested first in laboratory in order to validate the design choices and capabilities. Then the complete high power range PE was tested with the motors.

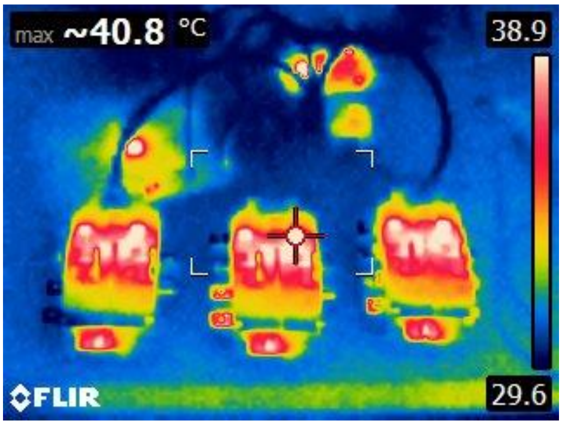

Figure 25. Thermal evaluation of the three gate drivers during high-switching frequency operation

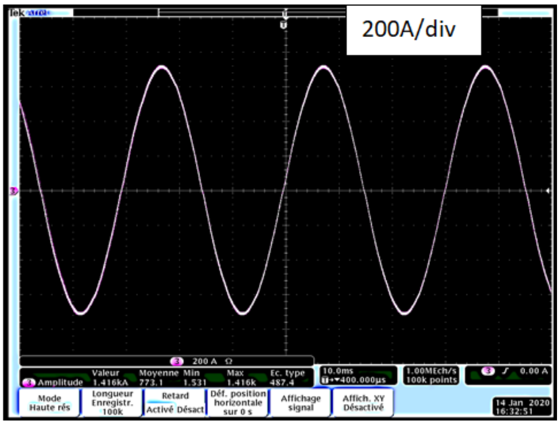

Figure 26. Motor phase current waveforms at 700 A and 750 V_{DC}

2.3.1.2.1 Preliminary validation

Main PE functions (power supply board, gate drivers, control board, etc.) were validated in laboratory and if IFPEN bench prior to before the testing phase on the tests bench with RFD motors. Gate drivers thermal behavior and gate-to-source voltage have been evaluated as presented in Figure 25. Motor current waveforms are presented in Figure 26 and validate high-current inverter performances.

2.3.1.2.2 Final validation and characterization

High power range inverter was used in standalone as well as integrated to the motor to validate and characterize 3 medium and 3 high power range motors. The achieved PE performances and KPI are given in Table 1.

Table 1. PE achieved KPI

PE KPIs	200kW baseline	RFD goals	200kW inverter
Specific Power (kW/kg)	10-12	13.7	20
Power density (kW/liter)	10-12	12.9	27
Efficiency (%)	95-97	98-99	99.2

The following figures (Figure 27 and Figure 28) show inverter efficiency maps obtained for the 75 kW and the 200 kW applications tested on the PMa-SynRel motor (performances are similar whatever the motor topology). The SiC-based PE reaches an efficiency higher than 95 % over the entire operating range of the motor. Optimization in the low-speed (<2000 rpm) region might be achieved by reducing the switching frequency.

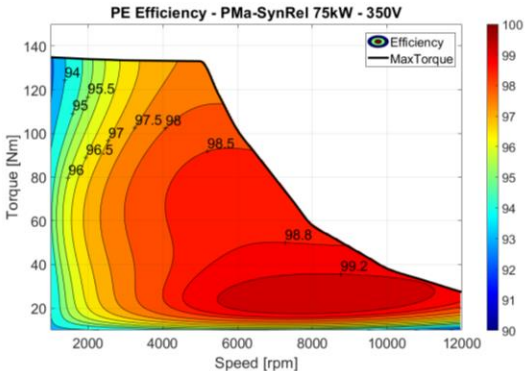

Figure 27. PE efficiency map for PMa-SynRel 75 kW (350 V) application

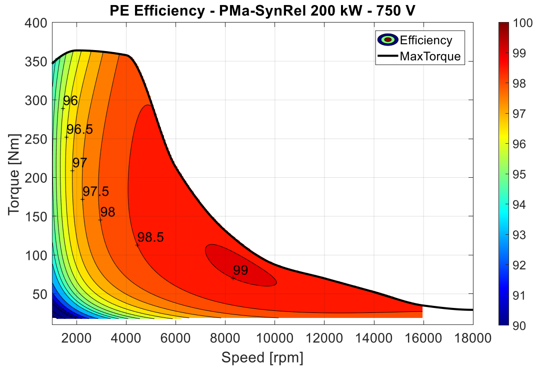

Figure 28. PE efficiency map for PMa-SynRel 200 kW (750 V) application

The results show very good performances over a large operating area. The achieved performances are in agreement with simulation results with 99 % maximal efficiency and wide operating zone with over 95 % efficiency for the 350 V and 750 V voltage applications. Moreover, the variable frequency should allow increasing its efficiency at low motor speeds. ReFreeDrive project target KPI are achieved with experimental evidence.

2.3.1.3 Motor validation and characterization

8 motors representing 4 topologies in two power ranges (75 and 200 kW) were developed in the ReFreeDrive project of which 3 topologies following two tracks were tested. The last motor topology was not ready for testing before the end of the project. Each motor undewent preliminary validation tests either at IFPEN or at UAQ or at Denis Ferranti Group in order to break-in the bearings and ensure the good behaviour of the stator windings. The main experimental results overview is given in the following.

2.3.1.3.1 Permanent Magnet assisted SynRel motors (75 and 200kW)

Preliminary verifications concern the bearings break-in and some mesurements on the stator windings which validate the stator conformity (resistance measurement and isolation performances). The measured phase resistance is in accordance with the design estimation with less than 3 % deviation.

Ferrite based PMa-SynRel motors have been as well qualified in terms of back-electromotive force (back-EMF) which gives an idea of the performances of the ferrite magnets. The measurements highlight 15 % (75 kW motor) and 20 % (200 kW motor) deviation in comparison with design phase simulations based on datasheet PM charcteristics provided by the supplier. The difference between measurements and simulation is due to a deviation between the PM characteristics given in the datasheet and those of the ferrite samples used in the motor. This observation prognosticate luck of motor performances in comparison with design phase simulations.

Table 2. PMa-SynRel motors performances

Parameter	Unit	PMa-SynRel 75 350V	PMa-SynRel 200 750V
Peak torque	Nm	136	363.9
Peak power	kW	71	174.8
Power at max speed	kW	34	57
Motor peak efficiency	%	96.3	96.3
System eff. on driving cycle	%	90.6	89.8

Table 2 presents motor performances at currents and voltages given in the design phase without compensation of luck of performances of the magnet samples. Figure 29 and Figure 30 show efficiency maps for 75 kW and 200 kW respectively with wide area higher than 94 % which should contribute to the energy losses decrease on the vehicle. Peak efficiency is slightly above 96 % for both motor power ranges.

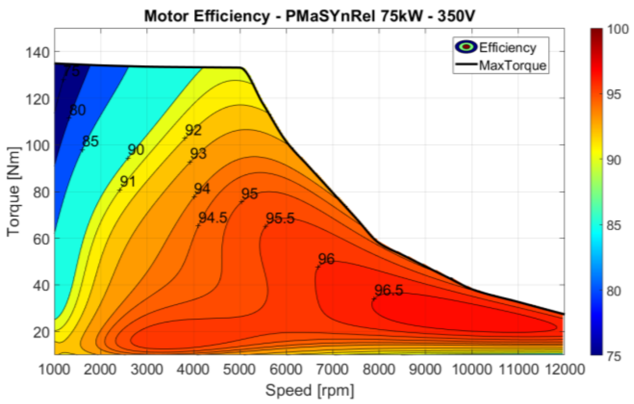

Figure 29. 75kW – 350V Motor Efficiency map

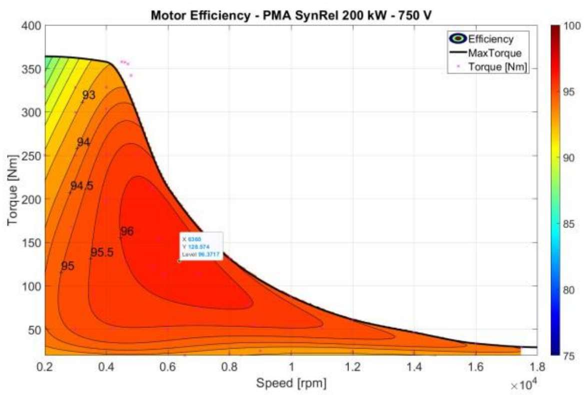

Figure 30. 200kW – 750V Motor Efficiency map

In addition to the torque, power and efficiency characterization tests, thermal validation tests were conducted. Results show good thermal performtances of the motors which stator is potted. Indeed the highest stator temperature is under 160°C even on the harsh 30 secondes max power test after 1 hour at continuous 70 kW operation (Figure 31).

Finally, Table 3 sum-ups targeted and achieved KPI by both PMa-SynRel motor tracks. Medium power motor reaches all KPI targets demonstrating thus the motor scalability based on the same industrial tooling while winding modification, source voltage and active part length leads to rescaled power range.

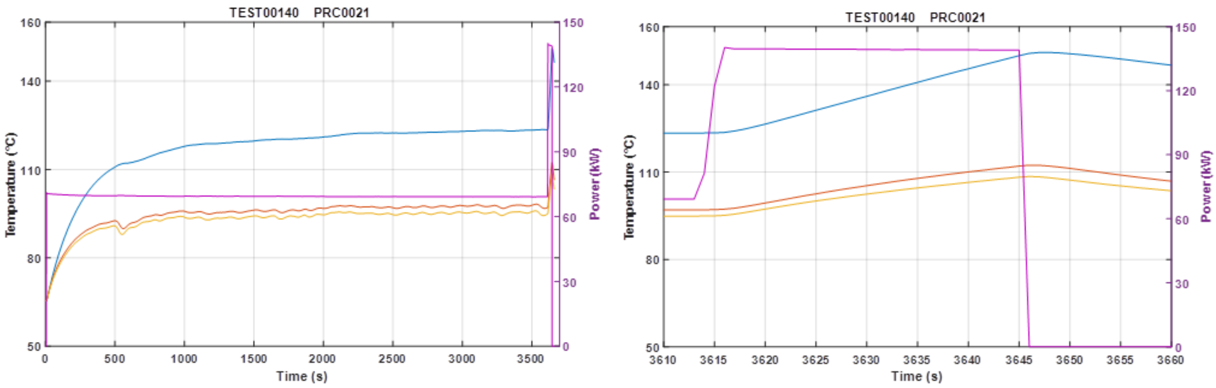

Figure 31. Continuous power test – 200 kW-750 V: 70 kW during 3600 s then high power during 30 s

High power range motor reaches efficiency and volume power density targets while mass performance density is under the target considering previously mentioned magnet discrepancies.

Target performances could be achieved by increasing the current and voltage for instance, nevertheless the goal was to give experimental evidence of design methods with the same boundary conditions. For the market production, the magnet supplier should be integrated in the production workflow.

Table 3. PMa-SynRel motors KPI

Parameter	Unit	PMa- SynRel 75kW – 350V		PMa- SynRel 200kW – 750V	
		Spec	Achiev	Spec	Achiev
Specific peak power	kW/kg	>3.1	3.6	>4.3	3.8
Peak power density	kW/L	>5	13.8	>8	17.7
Specific peak torque	Nm/kg	>5	7	>8.2	7.9
Peak torque density	Nm/L	>9	26.5	>15.4	36.8
Active parts weight	kg	<47	19.5	<47	46.3
Peak efficiency	%	>96	96.3	>96	96.4

2.3.1.3.2 Pure-SynRel (75 and 200kW)

Pure-SynRel motors preliminary validation and software verification took place at UAQ and R13 Technology facilities. Stator winding phase resistance was measured with values in agreement with the design phase estimation (<4,4 % deviation).

This motor topology is highly robust as the active parts are composed mainly of stator copper and stator/rotor magnetic steel. Thus, taking into account the precise magnetic steel characterization by Centro Sviluppo Materiali (CSM), medium and high power range motors show good agreement with the predicted performances (Table 4). Medium power range reaches 80 kW while high power range motor achieves more than 218 kW peak power. Clockwise and counter clockwise rotation operations were tested in order to qualify the rotor asymmetry impact. The motor indeed has a preferred rotation sense in what torque is concerned, however the difference is not significant (<3 % of torque).

Table 4. Pure-SynRel motors performances

Parameter	Unit	Pure-SynRel 75 350V	Pure-SynRel 200 750V
Peak torque	Nm	176.4	305.7
Peak power	kW	80.2	218.3
Power at max speed	kW	22.3	58.7
Motor peak efficiency	%	94.2	96
System eff. on driving cycle	%	87.5	87.6

Figure 32 and Figure 33 depict medium and high power range Pure-SynRel motors efficiency maps respectively. 200 kW motor has a wide efficiency zone over 94 %. Moreover 96 % peak efficiency is reached.

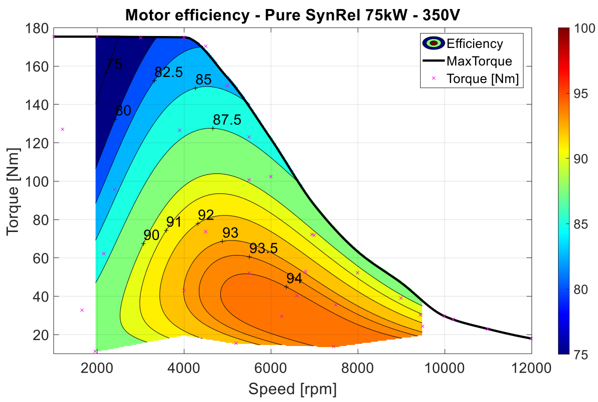

Figure 32. 75kW – 350V Motor Efficiency map

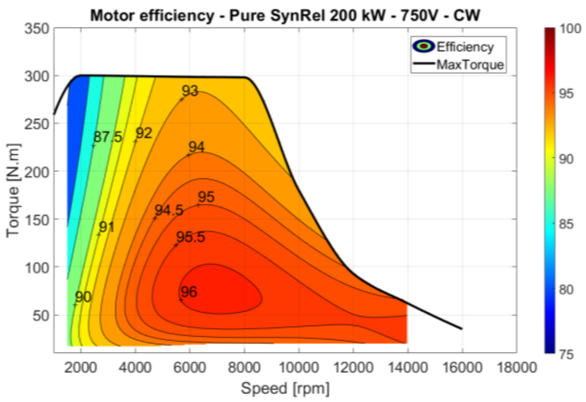

Figure 33. 200kW – 750V Motor Efficiency map

The maps are limited at 14000 rpm because of very few tested points at higher speeds limiting the graphical interpolation. High power range motor was tested up to 16000 rpm while medium power motor up to specified 12000 rpm.

Medium power range motor derived from high power range active parts is as well in agreement with predicted performances. Though, 96 % peak efficiency was not reached as the motor architecture was optimized for 200 kW – 750 V application. Though, active parts scalability and industrial compliant design was proven.

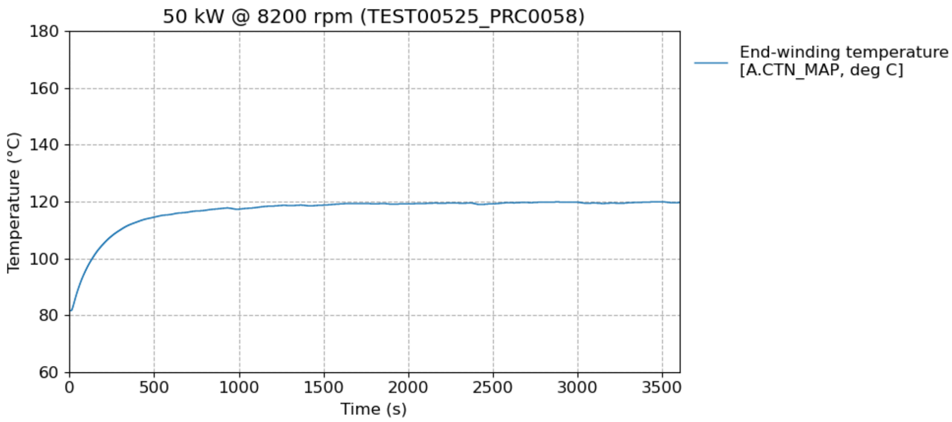

Figure 34. Continuous power test - 50 kW at 8200 rpm during 3600 s

In addition, thermal performances of the Pure-SynRel motors were characterized (Figure 34) with maximum winding temperature of 120°C at 50 kW – 8200 rpm continuous power which indicates that the 200kW motor is able to produce continuously more than 50 kW. The hot spot of the motor concerns the phase cables which reach 180 °C at the maximal torque operation. This is a minor aspect to be addressed when industrial exploitation is concerned.

Table 5. Pure-SynRel motors KPI

Parameter	Unit	Pure- SynRel 75kW – 350V		Pure- SynRel 200kW – 750V	
		Spec	Achiev	Spec	Achiev
Specific peak power	kW/kg	> 1.6	3.9	> 4.3	5
Peak power density	kW/L	> 3	13.6	> 19.7	22.1
Specific peak torque	Nm/kg	> 3	8.6	> 8.2	6.9
Peak torque density	Nm/L	> 6	29.9	> 15.4	30.9
Active parts weight	kg	< 47	20.4	< 47	44.1
Peak efficiency	%	> 96	94.2	> 96	96.0

Finally, KPI table for both Pure-SynRel motor performance ranges (Table 5) show that all targets are reached except efficiency and mass torque density for medium and high power range respectively. Indeed, the high power range motor design simulation considers 800 Ap phase current while during the tests the PE maximal current was limited to 700 Ap in order to limit the risk of damage.

2.3.1.3.3 *Die cast Induction Motor (75 and 200kW)*

Both DC-IM power ranges use the same active parts and scalability proof is done through voltage and current adaptation to targeted application. Preliminary tests took place at Denis Ferranti Group for bearing and shaft sealing validation while software verification was done at UAQ and R13 Technology facilities. Stator winding phase resistance was measured with values close to the design phase estimation (<8 % deviation).

During the tests, maximal speed and coolant mass flow rate were limited in comparison with SynRel motors in order to match the prototype rotor cooling system characteristics and limit the risk of damage at the early stage of development. Table 6 highlights DC-IM achieved high level performances with 88 kW for medium, and 214 kW peak power for high power range motor. 200 kW motor performances are nevertheless limited by the coolant flow rate capacity having an impact on PE and motor operation. Consequently torque and power in the production version of the motor would be higher than those shown in Table 6.

Table 6. DC-IM performances

Parameter	Unit	DC-IM 75 350V	DC-IM 200 750V
Peak torque	Nm	204.6	306
Peak power	kW	88.4	214.6
Power at max speed	kW	27.7	127.9
Motor peak efficiency	%	94.0	92.7
System eff. on driving cycle	%	86.4	79.2

Figure 35 and Figure 36 depict medium and high power range DC-IM efficiency maps respectively. Medium power range DC-IM reaches 94 % of peak efficiency with a wide zone over 90 % of efficiency. High power range motor performs unexpectedly with lower efficiency in comparison with medium power range motor. This result is due to software parameters which were implemented and will be corrected for further motor use. Consequently the expected efficiency for high power range IM should be at least equivalent to medium power range IM (>94 % peak).

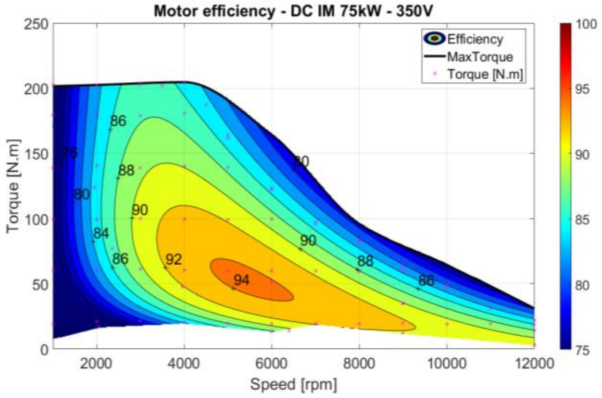

Figure 35. 75kW – 350V Motor Efficiency map

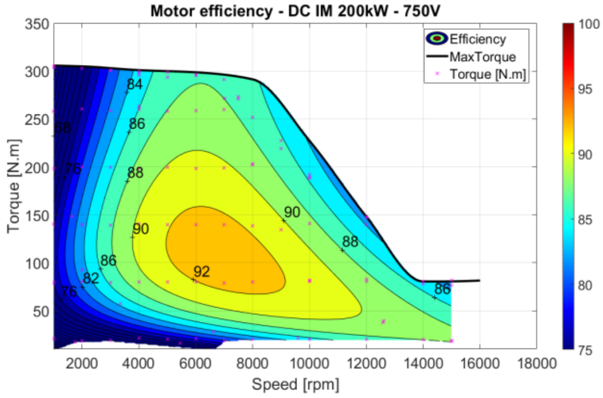

Figure 36. 200kW – 750V Motor Efficiency map

DC-IM has an hairpin winding in the stator and an integarted rotor cooling system which should allow good thermal performances of the motor. All previous consideration taken into account, 200kW motor was able to produce 120 N.m during 150 seconds (Figure 37). The test was stopped when stator temperature reached 165 °C (4 L/min coolant flow). This performance should be highly increased when industrial exploitation will be foreseen by using adapted rotor gasket (the current prototype is equiped by off the shelf gasket to limit cost and delay for the 1st prototype).

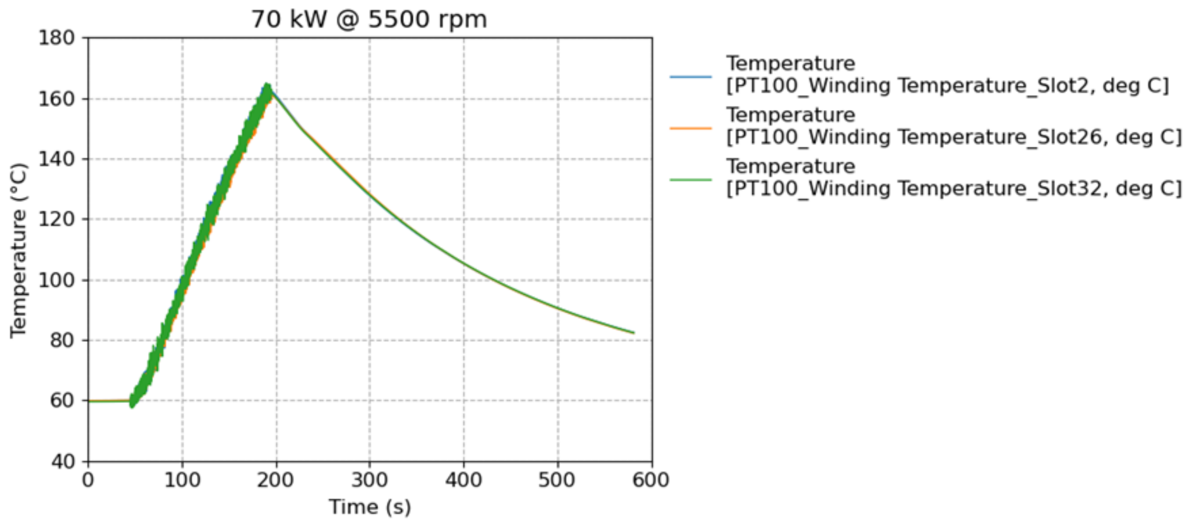

Figure 37. Continuous power test - 70 kW at 5500 rpm during 3600 s

Finally, KPI table for DC-IM performances (Table 7) show that all targets are reached except peak efficiency and mass torque density for high power range motor.

Table 7. Pure-SynRel motors KPI

Parameter	Unit	DC-IM 75kW – 350V		DC-IM 200kW – 750V	
		Spec	Achiev	Spec	Achiev
Specific peak power	kW/kg	> 1.6	2.2	> 4.3	5.4
Peak power density	kW/L	> 5.4	12.6	> 19.7	30.6
Specific peak torque	Nm/kg	> 2.5	5.1	> 8.2	7.7
Peak torque density	Nm/L	> 8	29.1	> 15.4	43.6
Active parts weight	kg	< 47	40	< 47	40
Peak efficiency	%	> 96	94.2	> 96	92.7[1]

2.3.1.4 Motor testing observation

Task 7.1 was achieved despite deviation in time due to COVID lockdown. A complete set of 6 out of 8 motors was characterized providing experimental evidence of the developed technologies, validating the followed design methodologies and demonstrating the motors performance. Motors and PE were tested considering Grant Agreement (GA) engagements as well as following JLR recommendations.

The most of KPI are met with the 1st prototypes validating the chosen approaches to meet the requirements (Motor, PE and software). Some exceptions leading to performance deviation were observed, analyzed and explained. None of those exceptions led to technological locks which would question the developed technologies. More particularly, 200 kW motors have all a deviation in mass torque density compared to the target. This deviation is due to cooling (DC-IM and Pure-SynRel) and ferrite magnet (PMa-SynRel) performances which should be corrected for B-sample specimens (afterward the current project). The scalability of the developed technology in terms of power range keeping the same industrial tooling was as well proven with complete performance KPI compliance except for peak efficiency.

PE benefiting Full-SiC modules and a very compact electronics and mechatronics design, achieves the expected performances with 45% better power mass density and 100% power volume density. 99 % efficiency target being asymptotic was achieved.

[1] Software parameters impact on the efficiency. Expected efficiency for high power range IM is at least equivalent to medium power range IM (>94 % peak).

Finally, Task 7.1 tests served to identify early in the project the prototype related problems and correct them upstream integrated e-Drive tests (Task 7.2) and in vehicle Technology Validation (Task 7.3).

2.3.2 Task 7.2 – Integrated Powertrain Testing

The aim of Task 7.2 was to incrementally include different powertrain components to the motor and inverter tested in Task 7.1 to assess the overall system performance and to make possible an early detection of malfunctions and points to improve, both from a hardware and software point of view, in order to be ready for the on-road testing within Task 7.3. Therefore, Task 7.2 was conceived as an intermediate step to bridge the gap between the motor and inverter testing activities and the validation of the prototypes after being installed in a commercial vehicle.

The main activities carried out within this Task can be organized as follows:

Experimental facility setup: the first step of this Task consisted on preparing the test bench at Cidaut Foundation (CID) in order to carry out the tests. This included the installation of the accelerator, the batteries or the reduction gearbox, among others. The impact of Covid-19 on this subtask was severe, caused both by the unavoidable delays on previous (mainly WP6 and Task 7.1) and parallel activities (mainly Task 7.3), and by the inability of the partners to travel and give in-person support for the integration. As a consequence, some components of the testing facility had to be set out again with respect to what was envisioned at the beginning of the project so as to be in position to end the Task on time.

Initially it was planned to install the batteries built by PRI at CID test bench. This option was discarded in order not to threaten the completion of Task 7.3. In its place a couple of power source concepts were explored. In first place a single power source was employed, which was discarded after comprehensive analysis of CID and UAQ as it was unable to provide the power as requested by the motors under dynamic operation (e.g. accelerations). After that a set of four 15 kW power sources connected in parallel was installed, hence being able to provide up to 60 kW, more than enough for validating the correct operation of the drivetrain.

Regarding the reduction gearbox, initially installed at CID, it had to be returned to PRI because of the simultaneity of Task 7.2 and Task 7.3 after the restart of the project activities. Higher priority was given to Task 7.3 as in-vehicle validation was considered a key result for the project, hence having higher priority. The test bench had to be consequently redesigned and re-manufactured to fit the motors without the reduction gearbox.

Finally, all other hardware (accelerator, cooling circuits, CAN bus) and software (motor control firmware) was added to the setup. The full testing setup used for the powertrain integration tests is shown in Figure 38 below.

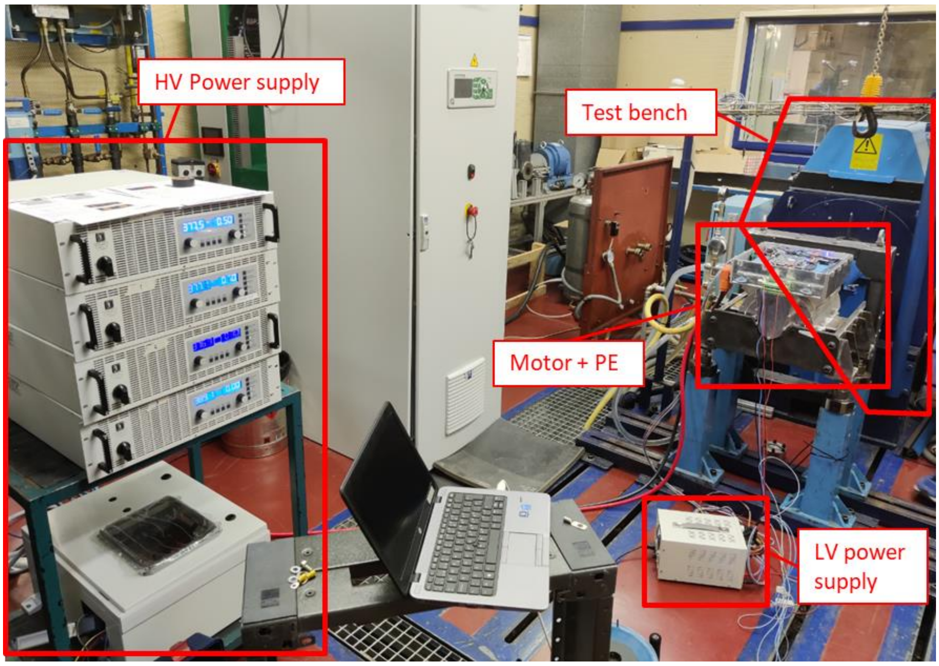

Figure 38. CID's testing facility setup

Systems integration and tuning: in this stage the objective was to achieve a proper functioning of all installed devices, to ensure that the testing facility had the capability to carry out the envisioned e-drive tests. Main efforts were devoted to guarantee an optimal motor response to variable and abrupt accelerator pedal inputs (Figure 39), to this end the firmware that controls the motor response was iteratively enhanced and motor power output was progressively unlocked, achieving a satisfactory pedal response.

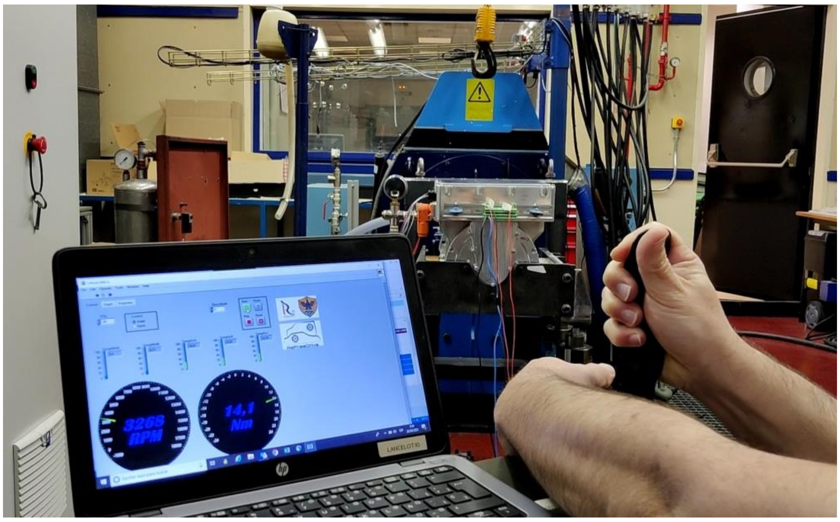

Figure 39. Accelerator pedal tuning tests

E-drive test results: once the individual elements were added and validated in standalone and integrated modes in the previous subtask, the prototypes were tested under different driving scenarios: constant velocity operation, response to accelerations and simplified driving cycle simulations. These test aimed at validating the proper operation of the powertrain components (Figure 40).

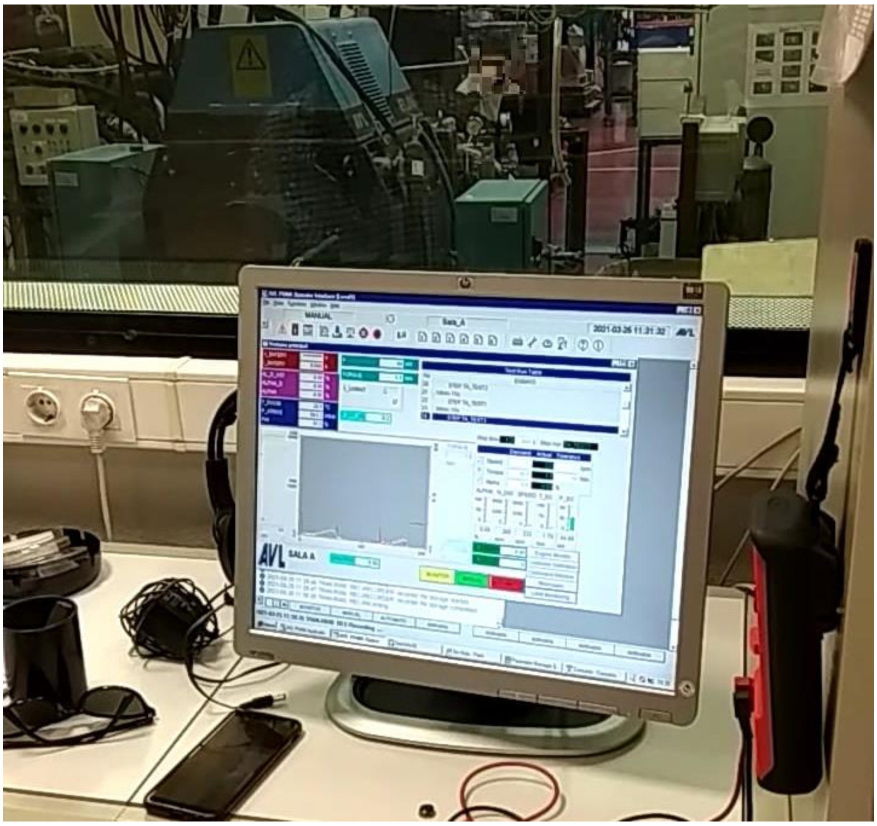

Figure 40. e-drive testing.

Acoustic characterization: a whole assessment of the integration of a powertrain within a real vehicle needs to take into account the effect of motor vibrations both from a mechanical (vibrations that might compromise the structural integrity of the powertrain) and comfort (excessive noise perceived by the vehicle occupants) points of view. Taking advantage of the capabilities and the experience of CID in noise and vibration analysis, a preliminary acoustic assessment of the motors was carried out. The aim of this activity was to highlight potential noise issues that may arise during motor operation. An overview of the test setup is shown in Figure 41.

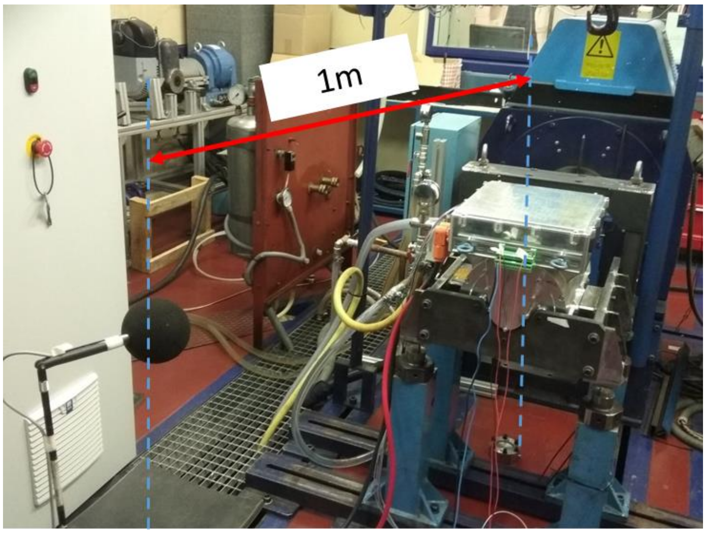

Figure 41. Accoustic assessment setup.

2.3.3 Task 7.3 – In Vehicle Integration

The goal of Task 7.3 was to provide a description of the activities that have been carried out on the Mercedes Sprinter demonstrator after the end of WP5. For simplicity PRI have divided them into three main areas:

1- **Integration**: it is the group of tasks that followed the deliverables 5.4 and 5.5 and consisted in the assembly of the components on the vehicle according to design guidelines already defined. In particular these activities had as a main focus the creation of the High Voltage and Low Voltage harness and the installation of the motors in the van (Figure 42).

Figure 42. Battery Pack installed in the vehicle and HV routing

2- **Test at component level**: before and during the final integration in the vehicle the main components of the powertrain have been tested in stand-alone conditions or on a bench tests specifically designed for those activities (Figure 43). This allowed a quicker debugging phase on the vehicle and reduced risks of failures of component when tested with high currents.

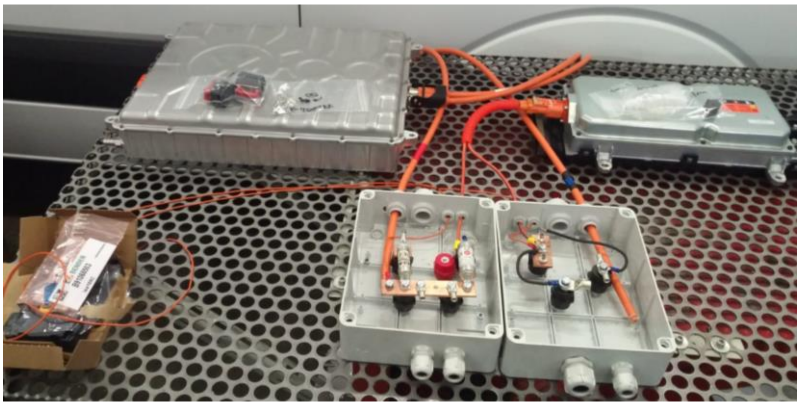

Figure 43. Test bench with charger, DC/DC, power distribution box

3- **Test at vehicle level**: after the functioning of all the components have been assured in the previous sub tasks and the preliminary debugging has been carried out two different types of motors and inverter have been tested on road (Figure 44).

This phase has been executed in two parts. The first one has had as a main concern the debugging of the vehicle parameters and the optimisation of the interaction of all the components. In the second part the final tests have been carried out aiming at the collection of the data that have been used for the final comparison between each motor and electronic.

Figure 44. ReFreeDrive demo vehicle ready for the test on road

2.4 WP8: Techno economic evaluation and exploitation

WP8 was devoted to evaluating the motor technologies developed within ReFreeDrive project from a technical, economic and environmental perspective, in order to assess the market potential and quantify the environmental impact of each one of them compared with the current benchmark technologies (rare earth NdFeB PM SynRel motors).

In line with the general WP8 objectives, Task 8.1 focused on assessing the costs of each technology avenue in different manufacturing scenarios, linking it with the technical performance of the motors either obtained experimentally or by simulations (for the Fabricated IM). Task 8.2 involves the Life Cycle Analysis of the motor technologies, considering all relevant elementary flows, product flows and waste flows. Finally, Task 8.3 manages the exploitation strategies within the Consortium, including the definition of a commercialization strategy and the monitoring of Intellectual Property Rights (IPRs)

2.4.1 Task 8.1 – Techno economic evaluation

The main objectives of this task were, once the optimal design options have been defined, to analyse possible manufacturing avenues and their cost implications and to derive a full assessment of cost of materials and manufacturing costs for the motor and electric drive – based on the weight and choice of materials and related process costs.

- Furthermore, to include assumptions on systems costs including transmission and battery capacity (as systematic approach).
- Then, to combine these cost data with performance data (torque, power, losses, etc.) under the operational considerations such as power or thermal limits.
- Finally, to derive some recommendations for the adoption of the proposed technologies in different vehicle categories and profiles and show their overall markt potential as alternatives to current rare-earth PM motor solutions.

The following approach has been used to derive the final motor should-costs:

- Bill of Material (BOM) definition for the considered motor based on exact materials and assemblies used for prototyping, with associated weights. From a detailed BOM, assembly-level data is summarised into:
    - Stator assembly
    - Rotor assembly
    - Motor passive parts
    - Power electronics (same assumption for all motor variants)
- Bill of process (BOP) definition for the considered motors based on exact choice of manufacturing technology and assembly assumptions.
- Should-cost derived from the BOM and the BOP for two production volumes to highlight potential savings gained through economies of scales:

- 30,000 units per annum (Figure 45)
- 100,000 units per annum (Figure 46)

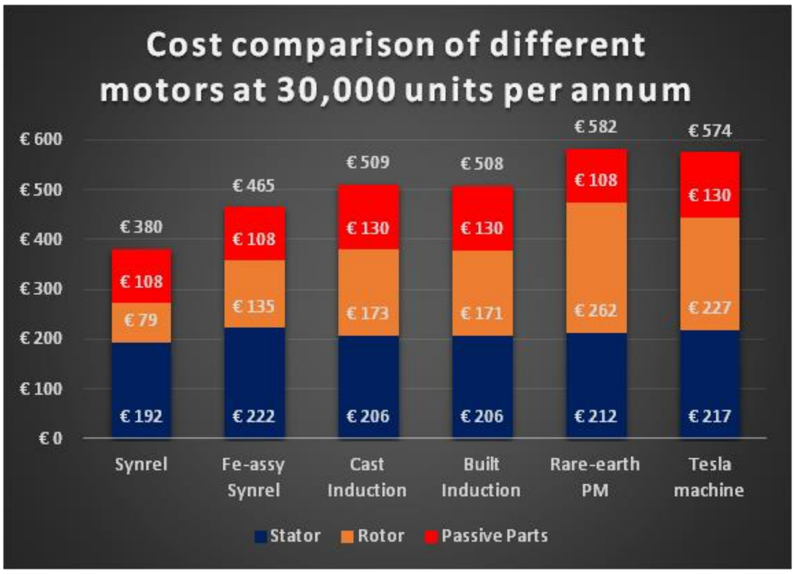

Figure 45. Should-cost summary of ReFreeDrive motors, rare-earth benchmark and Tesla Model S induction motor for 30,000 units per annum

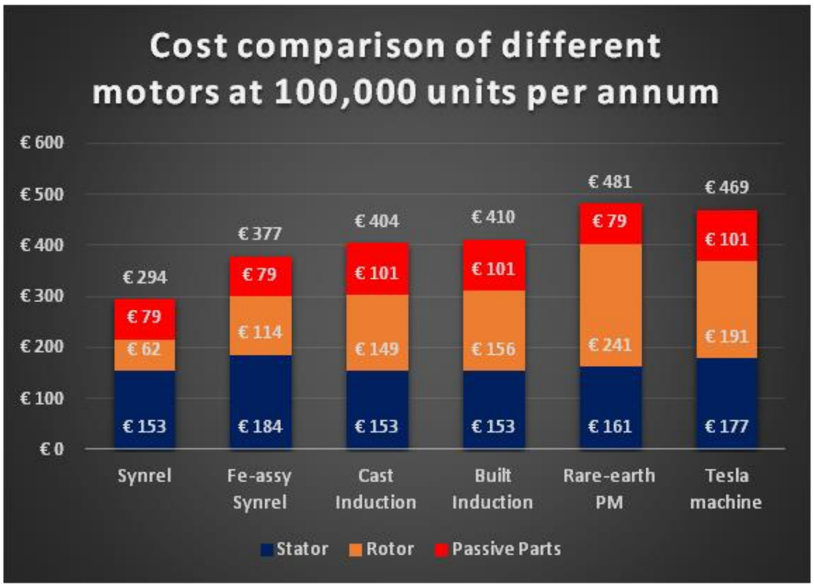

Figure 46 Should-cost summary of ReFreeDrive motors, rare-earth benchmark and Tesla Model S induction motor for 100,000 units per annum

All the machines designed within the ReFreeDrive project are cheaper than the benchmark Tesla Model S induction motor and enable a significant cost saving compared to the rare-earth benchmark, which is based on a rare-earth motor of similar specification and size as the ReFreeDrive machines.

As the gearbox and the battery pack are not part of the ReFreeDrive project, in this present exercise analysis we have added those two key elements as “simulated assumptions” based on internal JLR data. An internal battery cost is used to quantify the potential cost savings through different cycle energy-consumption of the motors and to derive a representative overall powertrain cost.

Then these cost summaries have been combined with performance metrics (both simulated design performance as well as measured performance data from previous tasks of the project) of the different ReFreeDrive motors to create a comprehensive overview of the benefits of each key technology as a traction machine used within automotive applications

The weight targets are achieved for all motor variants, same as are the peak torque density targets and the peak power density targets in Nm/L and kW/L.

The energy consumption of the motors over the Worldwide Harmonized Lightweight Testing Procedure class 3 (WLTP3) drive cycle is used to derive the required increase in battery capacity i.e. in battery cost in order to achieve the same range as the most efficient motor, which in this case is the Rare-earth PM motor (not part of the ReFreeDrive project).

It was obvious that our ReFreeDrive motor alternatives will never surpass the rare-earth PM motor total driving efficiency for a given powertrain configuration (assumed same gearbox and battery size).

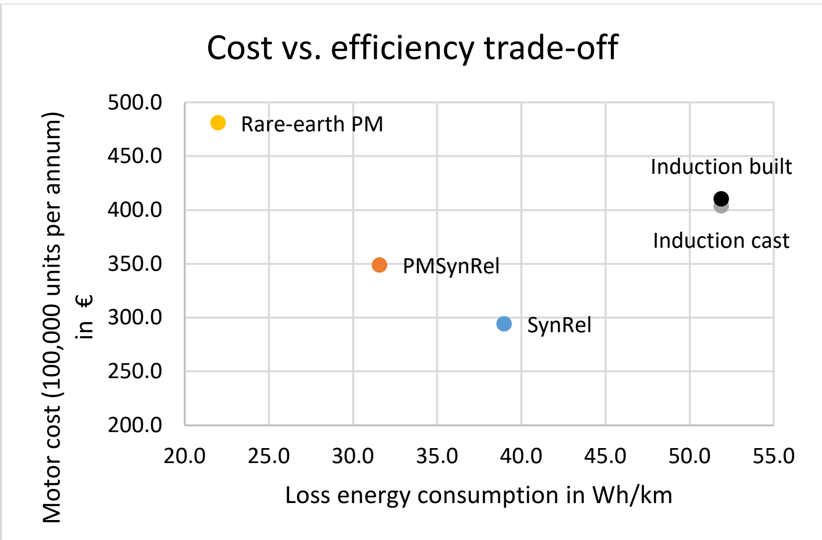

Figure 47 Cost vs efficiency trade-off between the different technologies

However, the cost advantage of our motors compared to rare-earth PM motor can become a relevant criterion of choice for future automotive use cases (Figure 47). As the battery price expected to decrease in some years, the cheaper motor solutions as developed in our ReFreeDrive project (induction motor and synchronous reluctance motor) will become more viable economically, when the efficiency lost by switching to a cheaper motor technology can be offset through a higher battery capacity.

Given the massive uptake of BEV production beyond 2025, and the expected demand for rare-earth based PMs also in other end-uses beside E-mobility, we see a huge potential for series application of the ReFreeDrive drivetrain proposals with their adequate performance, whenever ultimate power density can be traded-off for other goals as cost reduction, local supply guarantee and ease of recyclability.

There was only a small deviation - a laguna - in the content compared to the Document of Agreement, as we could not use any real measured performance data for the variant of “induction motor with fabricated rotor”. Given the logistic problems due to Covid-19 and other issues at the sub-contracted supplier in the United Kingdom, the fabricated IM could not be produced, assembled and shipped to the testing facility in time to allow any testing during the official course of the already extended project lifetime. This was a clear knock-on effect from WP6 and WP7 (more details on the respective reasons see deliverables of WP6 & WP7, [1] and [2]. This caused also a small delay on 2 weeks in final submission of this delivery, as the real test results of the “induction motor with die-cast rotor” were affected by a wrongly calibrated software control, and hence our last hope – until virtually last minute- was to wait to fix software issues and test again the IM with the second variant of the “fabricated rotor” to prove targets on the bench.

Nevertheless, we then could use a combination of simulated design performance and real test performance to provide an overview on both motor topologies here.

Furthermore, as a surplus to the GA, we added a comparison in some aspects to the rare-earth PM motors, which indicates relevant directions to potential users of our ReFreeDrive solutions for possible substitution scenarios in future automotive applications.

These additional comparisons provide relevant information to assess the potential contribution of our ReFreeDrive alternatives in the context of the European Union Commission’s Green Deal and particularly within its new Circular Economy Action Plan.

2.4.2 Task 8.2 – Life Cycle Asssessment (LCA)

The aim of this task was to perform a LCA analysis of the developed technologies within the ReFreeDrive project (Induction and SynRel machines), comparing them against electric motors already in the market as representative state-of-art (NdFeB permanent magnets SynRel) in automotive.

In the period of time concerning this report the Life Cycle Assessment has been finished. The last iterations were carried out within the Life Cycle Inventory phase, in order to tune up the processes mapping, identifying the production processes and the incoming and outgoing flows in each stage, achieving definitive flows quantification (raw materials, energy, emissions, wastes, etc.).

Additionally, Life Cycle Interpretation also was carried out. An estimation of the potential environmental impacts related to the manufacturing process for each ReFreeDrive electric motors (75 kW and 200 kW) was performed, taking into account the different technologies employed during the project (Induction machines and also PMa and Pure SynRel machines).

The use of NdFeB Permanent Magnets significantly marks the environmental impact of the manufacturing process for the reference motors (Figure 48), despite its small contribution to the overall motor weight (just 3%). Therefore, the lack of this material (NdFeB magnets) in the manufacture of ReFreeDrive motors makes its environmental impact significantly lower than impact of reference motors.

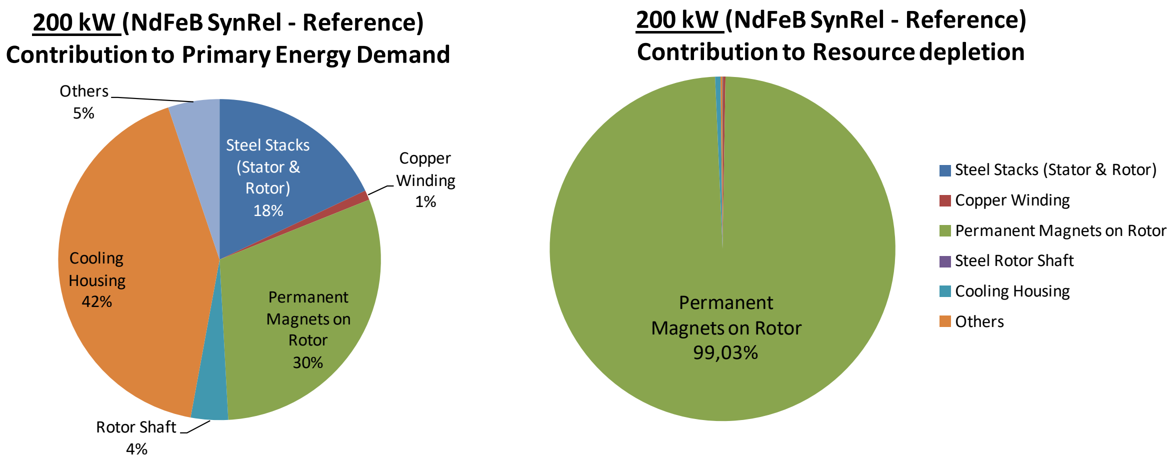

Figure 48. Contribution to "Primary Energy Demand" and "Resource Depletion", of main parts of reference motor (NdFeB PM SynRel machines).

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 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 NdFeB permanent magnets use**.

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 49 (200 kW motors) and Figure 50 (75 kW motors). In these graphs a comparison between ReFreeDrive PMa and Pure Synrel motors, and the reference motors, is introduced, for the different impact categories analyzed and related with the International Life Cycle Data (ILCD) system method used on the LCA. 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, 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.

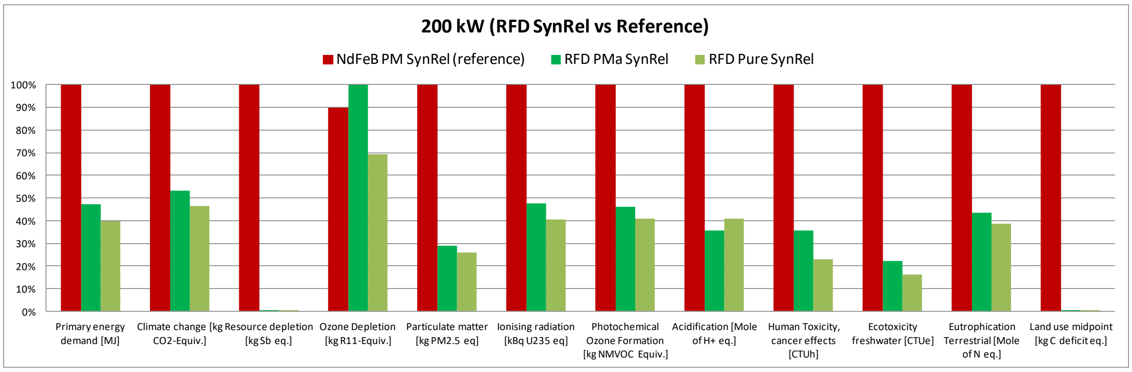

Figure 49. Comparison of SynRel motors developed within ReFreeDrive project, against reference (NdFeB PM SynRel) – 200 kW

For the 75 kW ReFreeDrive 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 50).

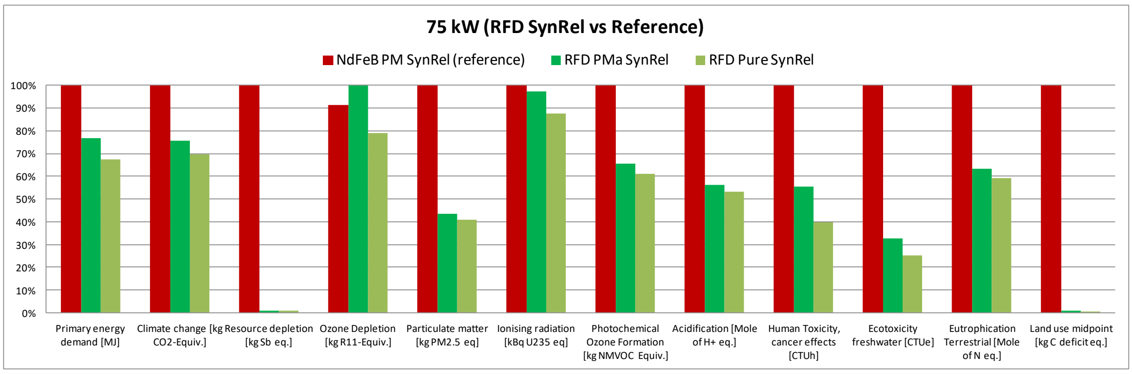

Figure 50. Comparison of SynRel motors developed within ReFreeDrive project, against reference (NdFeB PM SynRel) – 75 kW

Like the ReFreeDrive SynRel motors developed, the new **200 kW ReFreeDrive 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 51. 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.

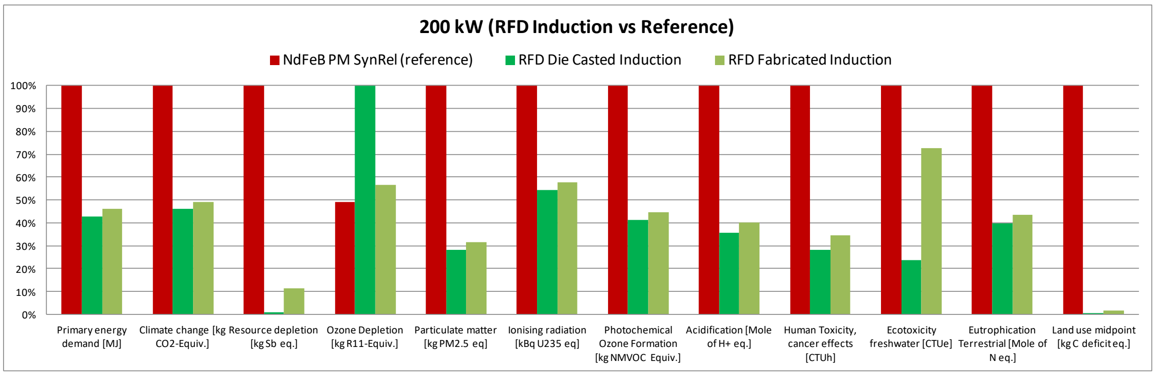

Figure 51. Comparison of Induction motors developed within ReFreeDrive project, against reference (NdFeB PM SynRel) – 200 kW

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 52.

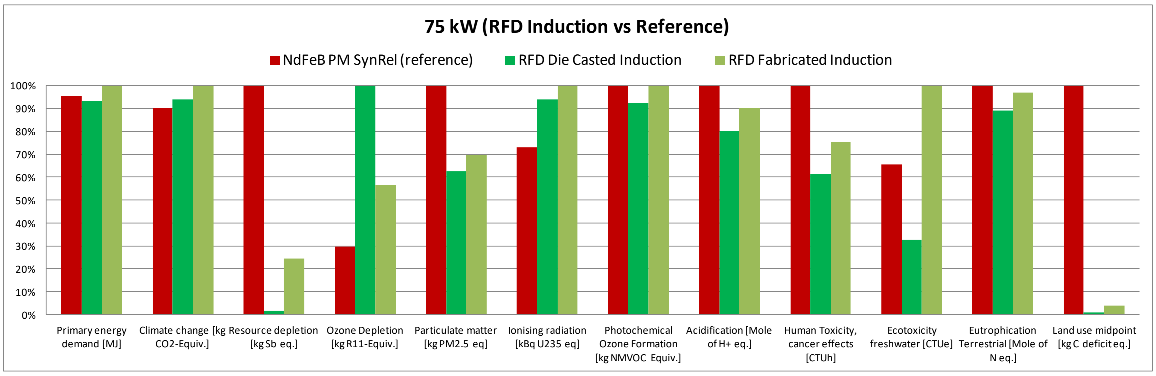

Figure 52. Comparison of Induction motors developed within ReFreeDrive project, against reference (NdFeB PM SynRel) – 75 kW

2.4.3 Task 8.3 – Exploitation of the technological solutions

The main objectives of this task were all activities related with the exploitation and commercialization of the technological solutions developed during the project. D8.4 takes as starting point the First version of the ReFreeDrive Exploitation Plan (D8.3) already delivered in M18. This Final Exploitation Plan provided:

- A more comprehensive market analysis, covering the EV market evolution and prospects for the next decade; the trends of customers' needs and the solutions provided by potential competitors; and a review of the Critical Raw Materials (CRMs) availability from a European perspective, with a special focus on Rare Earth elements used in PM.
- An IPR strategy, which ensures that all relevant Intellectual Property information is tracked, hence guaranteeing that any dissemination or exploitation action carried out after the project will not result in conflicts between the interested partners.
- A summary of the techno-economic analysis developed within Task 8.1, comparing each motor technology with the current benchmark technology (NdFeB PM magnets) in terms of performance (extracted from WP7 tests) and cost (taken out from WP6 – prototypes manufacturing) under different market uptake scenarios.
- A Commercialisation strategy looking for the best pathways to market after the project.
- An Exploitation plan which gathers, for each partner, the exploitation interests of the different assets (either physical or intellectual) generated during the project in fields such as research, academy or industry.

Concerning the market analysis, the most expanded motor solutions currently rely on PM technology, using rare-earth magnets. However, the high and volatile cost of raw materials for magnets makes uncertain their long term availability. Therefore, it has become mandatory to find alternative solutions, that include rare earth free machines or reduced rare-earth PM machines. Several types of motors have been under study for propulsion applications, including low-cost PM, induction, switched reluctance and synchronous reluctance motors. ReFreeDrive research has demonstrated that the induction motors, ferrite magnet assisted and synchronous reluctance motors represent valid alternatives, though care must be taken during the motor sizing and selection of electrical steel in order to satisfy the hard requirements and avoid an increasing on the system costs.

About ReFreeDrive IPR strategy, as stated in the Grant Agreement, D8.4 defined and implemented a methodology aiming at controlling the transfer of knowledge and IPRs from the beginning of the project (Figure 53). Hence the background and foreground knowledge were defined and managed in such a way that enables a favorable environment for the exploitation of results, described within the Exploitation Plan.

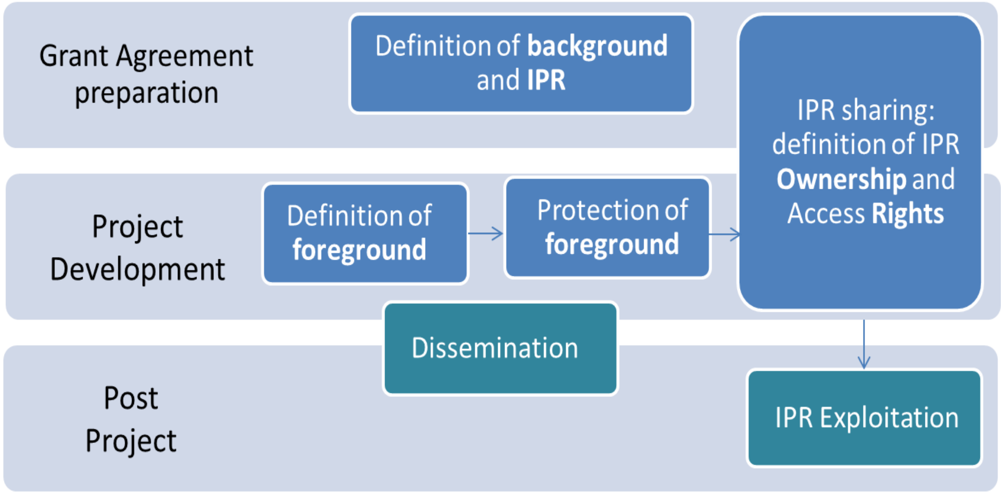

Figure 53. IPR management overview

IPR management was focused on the careful handling of IPR issues in the ReFreeDrive project, those that are of strategic importance to facilitate the exploitation of its solutions. It aims to create a favorable environment for the enforcement of IPR and to ensure a sound approach by ReFreeDrive participants, together with a permanent IPR management during the project (Figure 53). The IP information on the ReFreeDrive project, including both background and foreground, was prepared and made available to all partners, in order to check that post-exploitation actions do not contradict any form of IPR protection.

A commercialization strategy was also developed (Figure 54), in which different target markets according to the expertise of ReFreeDrive's partners have been defined. Starting from a comprehensive BOM and BOP for two production volumes (30000 and 100000 units per annum), a should-cost model for each motor technology and power level has been built. The techno-economic analysis of the ReFreeDrive motors was compared to a full rare-earth permanent magnet counterpart and the Tesla Model S induction motor reference. This study shows that the cost of the motors developed in the project have a lower production cost than the motors used as a reference. Attending to the findings from the techno-economic analysis, proposed ReFreeDrive scalable motor solutions (from 75kW to 200kW), either as single drivetrain or as booster machine in configurations with two e-machines in a car, one on each axle, would as a first guess fit for at least 30% of the EV production, hence 7 to 8 Mio drivetrain units, in 2030 as addressable market.

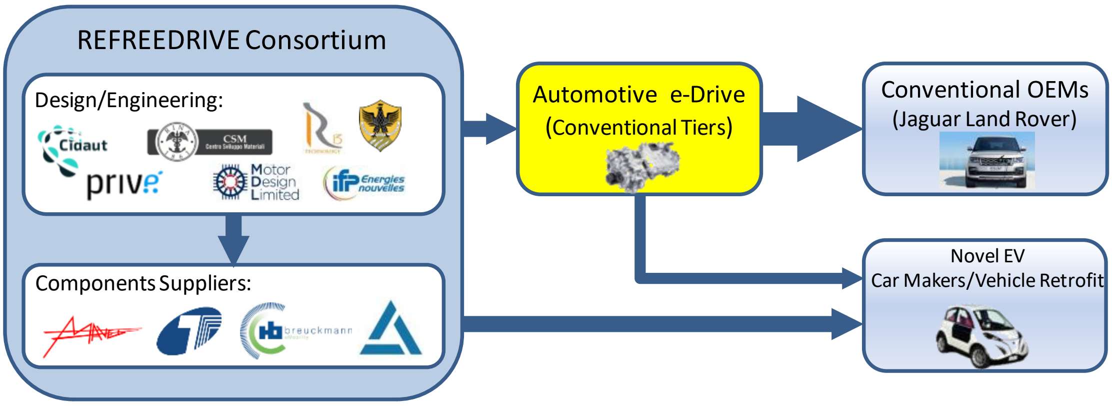

Figure 54. Players involved in the ReFreeDrive commercialization strategy.

On the other hand, the principal objective for exploitation in ReFreeDrive project was to implement an exploitation strategy to facilitate the successful exploitation and adoption of results and benefits within emergency services, research communities and policy advisers. Exploitation activities in the project aimed to ensure the longevity of the project's results through either policy uptake, further research or commercial applications.

A Exploitation Plan was designed to multiply the impact of the proposed solutions and to prepare the transition to industrial and commercial take-up in order to achieve the expected impact. The first step of the process was aimed to support the partners in identifying the exploitable results they are interest in and in defining their exploitation strategy. A specific data collection tool was designed for this purpose by the team in charge of the exploitation task (Mavel and CID) and shared with the other partners. This model table was shared in which each partner was able to enter the results obtained and specify which results they were interested in and what nature is the interest in exploitation. All exploitation of the results is defined upon request according to the consortium agreement.

Regarding the dissemination, that was the public disclosure of the results by any appropriate means, including by scientific publications in any medium. More detailed information is contained in document D9.6 "Communication and dissemination plan" developed by UAQ.

During the ReFreeDrive project seven Key Exploitable Results (KERs) were selected. The KERs selected by the ReFreeDrive consortium were included in Horizon Results Platform, created by the European Commission to increase the impact of the results of innovation actions.