

Design and material based Sustainable Mobility – Copper vs. REE

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Abstract. Carbon neutrality by 2050 is one of the greatest challenges of our society. Hence, the electrification of the mobility sector belongs to those to focus on, due to their high carbon intensity, when based on combustion engines. Therefore, electrification of power train is seen as a solution. Different alternative concepts with different materials exist to achieve the above-mentioned goal of decarbonisation of mobility. To provide a good basis for decision making in the automotive industry to support their sustainability goals for electric vehicles, the environmental impacts related to the manufacturing process of different types of electric motors (induction machines with copper rotor and also ferrite assisted and pure synchronous reluctance machines) in the typical power range of electric vehicles (75 kW and 200 kW) have been assessed. The work was carried out within the European Commission (EC) funded REFREEDRIVE (RFD) project (REFREEDRIVE – Rare Earth Free e-drives featuring low cost manufacturing). This paper intends to give some key facts which help answer some of the questions raised by stakeholders on sustainability, while comparing different concepts, the Induction Motors (IM) and the Synchronous Reluctance Motors (SynRel), both in different configurations.

1 Introduction and Objectives

Discussion around decarbonisation of our society leads to the fact that mobility has become a hotspot that we need to tackle. Hence, electrification of mobility has been intensified all around the world. For designers, tier 1 and automotive original equipment manufacturers (OEMs) the question remains: which materials to use and which way to go? Different alternative concepts of traction technology exist. While copper appears to be the material of choice for many electrical applications, alternative materials e.g. REEs (rare earth elements) are used as reference in rotors for electric vehicle motors.

To provide a good basis for decision making in the automotive industry to support their sustainability goals, the environmental impacts related to the manufacturing process of different types of electric motors (induction machines and also low-cost Ferrite magnet

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assisted and pure synchronous reluctance machines) in the typical power range of electric vehicles (75 kW and 200 kW) have been assessed.

REFREEDRIVE project (REFREEDRIVE –Rare Earth Free e-drives featuring low cost manufacturing [1]) was focused on contributing to avoid the use of rare earth magnets through the development of a next generation of electric drivetrains. Along the REFREEDRIVE project, two solutions for the power traction system of electrical vehicles were simultaneously developed: Induction Motors (IM) with fabricated and copper die-cast rotor and Synchronous Reluctance Motors (SynRel) (pure and assisted by Rare Earth Free Permanent Magnet (PM)).

In the project, the 200 kW e-motors in different variants (copper rotor and SynRel variants) were optimized (REFREEDRIVE machines – RFD [3, 4, 5]) and the physical prototypes were compared against reference REE PM-e-motors designed with NdFeB (SynRel machines for automotive) [2].

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

2 Process Mapping and design

LCA performance within the REFREEDRIVE project was focused on the manufacturing and assembly processes of the electric motors, from a “cradle-to-gate” approach, for all the studied machines (PM SynRel as reference, and the four technologies of the REFREEDRIVE project (Induction and SynRel machines)), in their different configuration. The approach covered the life cycle from resource extraction (cradle) to the factory gate (**Figure 1**).

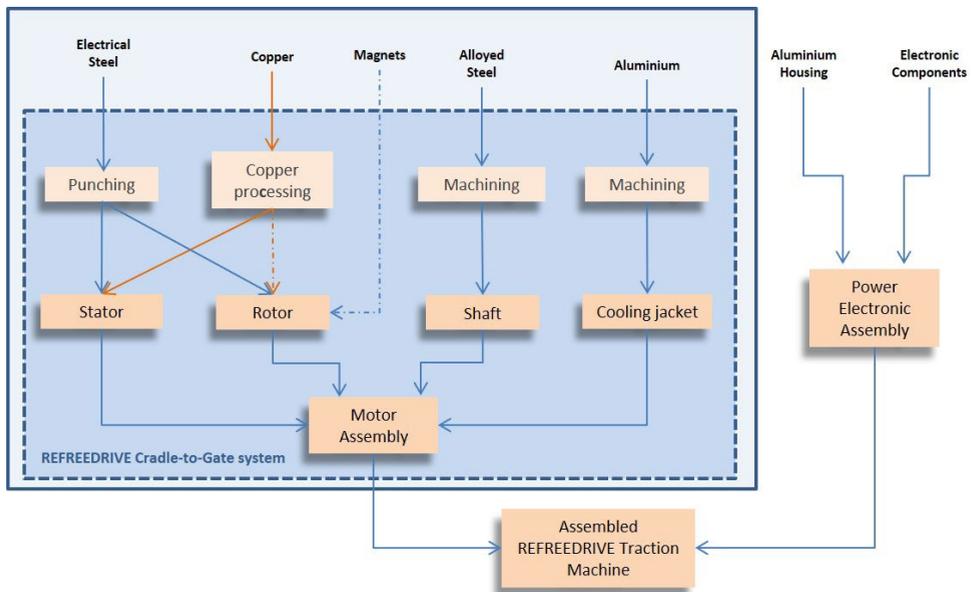


Figure 1: System Boundaries for the REFREEDRIVE Life Cycle Assessment

In figure 1, background processes are included into the area limited by the continuous dark blue area, but out of the area bordered by the dashed dark blue line. Here are included the manufacturing processes of the needed materials to manufacture electric motors, which are not under the direct control of the REFREEDRIVE partners, but nevertheless, they have huge relevance on the environmental impact of the product under analysis. Background data were taken from GaBi Professional Database and LCA motors models were merged in a life cycle inventory software (GaBi) [6] to obtain a full model of each REFREEDRIVE machines.

System boundary (see **figure 1**) was chosen considering that the use phase and end-of-life scenario for all the configurations of the REFREEDRIVE machines can be assumed as quite similar, not showing relevant differences among them: efficiency, which defines the consumption of energy during its use phase, is quite similar for all the REFREEDRIVE electric drives, and the reuse/recycling strategies for the REFREEDRIVE solutions are the same in each configuration on base of the used materials. In the REFREEDRIVE project, efficiency of the developed electric drives was characterized. However, this information was not available for the electric machines taken as reference. This issue does not allow making a comparison study about the use phase of the REFREEDRIVE machines against the reference one (state of the art) - reason why it has not been carried out.

Therefore, the production stage was the step of the life cycle where the study was focused, to determine the environmental impact of traction systems developed in the project, and more specifically, for the e-motors. For each motor technology, the production process of the different motor parts (stators, rotors and cooling system) were modeled individually. Manufacturing steps in the REFREEDRIVE LCA cover the production of the active parts of the electric motors (rotor, stator and shaft), but also the cooling jacket. Rotor and stator are mainly joined stacks of electrical steels. Stator also includes copper, either as winding or hairpins, depending on the type of motor. Rotor of induction machines has got copper, casted or in bars (**figure 2**). SynRel motors do not use copper (**figure 3**). One of the REFREEDRIVE SynRel motor uses ferrite magnets (see **figure 3**).

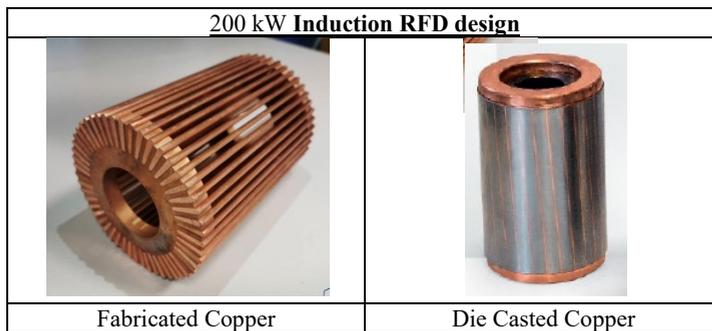


Figure 2: RFD Induction rotor designs with copper

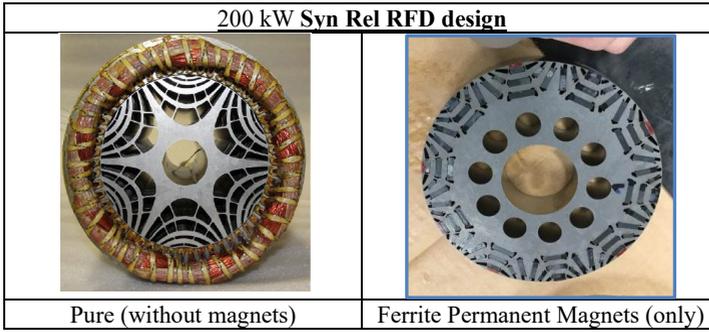


Figure 3: RFD SynRel designs without magnets and with ferrite permanent magnets

Charts in **figure 4** show the materials distribution and weight breakdown for a 200 kW motor employed as reference, in comparison with the machines developed within the REFREEDRIVE project.

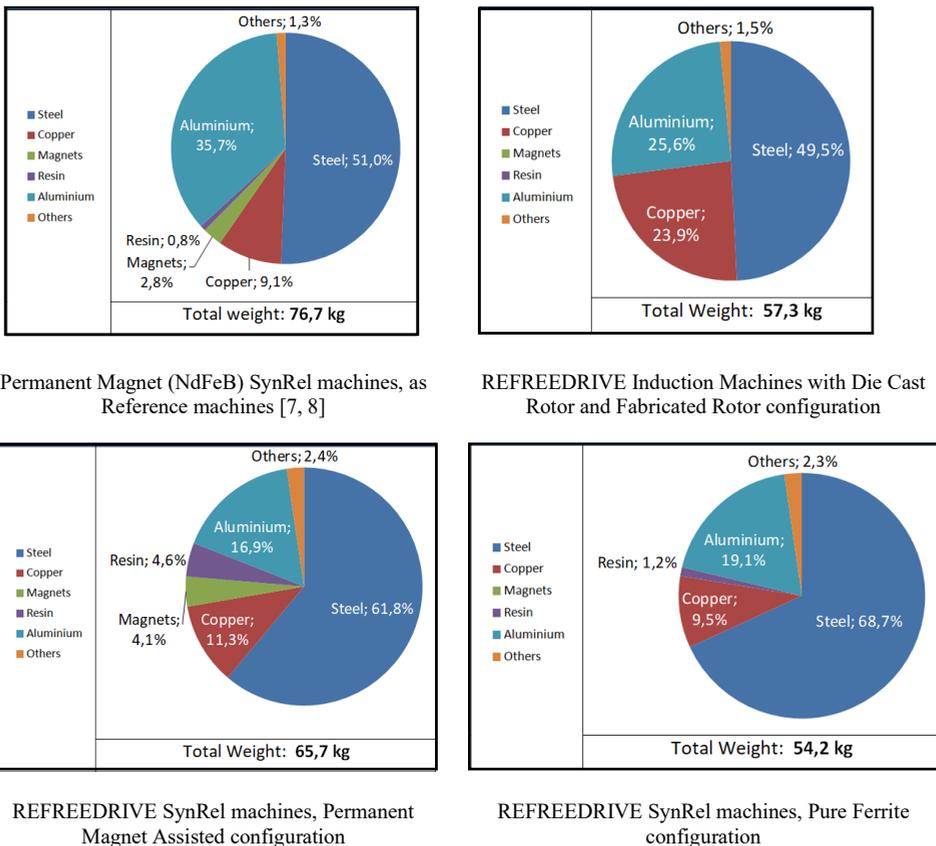


Figure 4: Mass configuration of different electrical machines

Steel:

The main active machine parts, the rotor and the stator cores, generally consist of electrical steel (stacked electrical steel laminations) in order to concentrate the magnetic flux, and thus

to minimize flux leakage to the surrounding air, which would not contribute to the torque production.

Electrical steel laminations, used in the stator and rotor cores of electrical machines, are typically obtained by cutting through punching or laser, from steel sheets. The next manufacturing step after cutting core laminations is the stacking process. There are several methods for stacking core laminations. Along the Life Cycle Assessment within REFREEDRIVE project, both welding process and bonding process were used, for different motor configurations. Therefore, reference SynRel motors and RFD induction motors had got welded their steel stacks (for stators and rotors). On the other hand, RFD SynRel motors used a bonding technique for the stacking process (varnish “Backlack” technique).

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

Aluminium:

In order to protect and contain the stator and rotor packages, housing is needed. For automotive powertrains, aluminium is a common material. Together with the steel employed in the stator and rotor stacks, which is usually the main contributor to the overall weight of the motors, the cooling system casing is usually the other main contributor, despite being manufactured using a light alloy (aluminium) (See Figure 4).

Copper:

A third material hugely used in the motor manufacturing is copper, but according to the handled technical literature, ever in less amount than steel (stator and rotor) or aluminium (cooling casing), as shown in figure 4. In motors developed within the REFREEDRIVE project, copper was used for the manufacturing of the stator winding in all technologies (SynRel and Induction), and additionally, for the rotor in induction machines.

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

Magnets:

The task of the rotor is to produce a torque which can be transmitted to the wheels. By providing a magnetic field which interacts with the magnetic field of the stator windings, it converts magnetic power to mechanical power. In the case of Permanent Magnets (PM) SynRel machines (see **figure 3**), the rotor field is generated by permanent magnets (as in the case of the reference machine for the comparison with the REFREEDRIVE machines).

The electric motors with permanent magnets embedded in the rotor, used a few of magnets manufactured and employing different materials, depending on the performance to achieve. Currently, rare earths are usually employed in the manufacturing of these permanent magnets, obtaining as example, different formulations of NdFeB magnets, which are vastly employed in automotive traction. The amount of rare earth material in the magnets, most used in motor manufacturing, varies with magnet grade, which is usually a ternary alloy containing mainly Nd (28%), Fe (70%) and B (1%)

The NdFeB magnets only mean a low contribution to the overall weight of the motor (around 3%). However, its contribution to the environmental impact is relevant in comparison with

other materials, as shown in following sections, when reference motors are analysed from an environmental point of view.

3 Results

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”). Primary energy demand (PED) and Climate Change were analysed as main environmental impact categories in the REFREEDRIVE Life Cycle Assessment, as shown in **figures 5** and **6**. In both categories, the reference motor shows a significant higher impact than any RFD machine. Proposed RFD e-motors show about half of the environmental impact in these commented environmental categories.

The use of NdFeB PM by the reference motors significantly marks the environmental impact of its manufacturing process. Therefore, avoiding the need to use that material (NdFeB magnets) in the manufacture of RFD motors, makes its environmental impact significantly less than that of the reference motor. Pure SynRel solution or PM-assisted SynRel one shows a better environmental profile than the reference motor with NdFeB “PM” (see **figure 5**).

On the other hand, with a good design as developed within the REFREEDRIVE, copper remains from a circular economy point of view, the best environmentally friendly choice for e-motors compared to NdFeB “PM SynRel” solutions [2] (**figure 6**).

Additionally, the ability to use less steel in the manufacture of the stator and rotor in the novel RFD motor designs, gives them an environmental advantage over the reference motor.

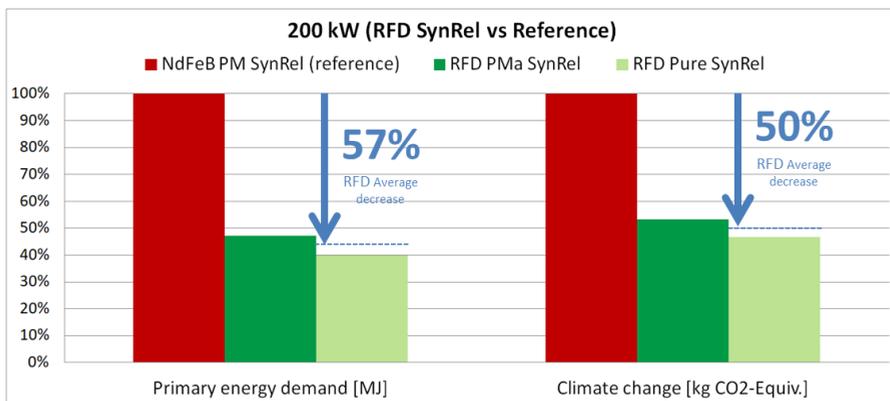


Figure 5: Environmental Impact comparison of REFREEDRIVE motors with “PM-assisted” and “pure ferrite” against current automotive electric motor (NdFeB permanent magnets SynRel)

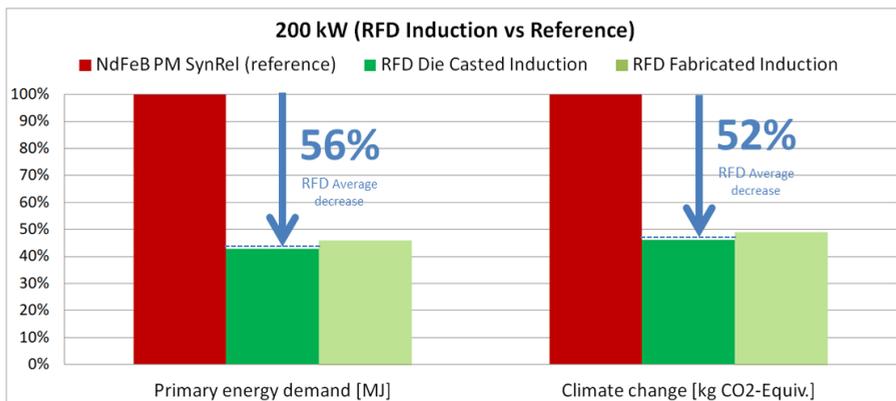


Figure 6: Environmental Impact comparison of REFREEDRIVE induction motors with copper against current automotive electric motor (NdFeB permanent magnets SynRel)

Therefore, reductions in the environmental profiles are mainly due to an optimized design, which results in a proper and efficient use of materials (less material needed, less environmental impact), but above all, to the reduction and elimination of the use of NdFeB permanent magnets [7, 8].

4 Conclusion

The study here showed that high-efficient motors can be designed with different materials than rare earth elements. One of those well-known materials by automotive designers is copper. The proposed REFREEDRIVE designs help limit or at least not increase the material mix in the automotive sector while transitioning to electrification of the power train. This can be seen as a key aspect for recycling and for the material circularity aspect.

The permanent magnet solutions as mostly used today with e.g. NdFeB “PM” have significantly high environmental impact, despite the small contribution of the magnetic material to the overall motor weight (magnets weight < 3%), compared, for example to copper based induction designed ones as shown in **figures 5 and 6**.

Further advantages in using copper are as follows:

- Copper solutions are cost effective.
- Copper solutions are environmentally not critical and have low supply risks [9].
- Copper solutions guarantee material circularity (mature recycling practice).

Acknowledgement

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