Assessment of Product Carbon Footprint Reduction Potential Using Lightweight Rotor Components for Electric Traction Motors

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Abstract. The mobility sector is currently undergoing one of the most profound transformation processes in its history. With ambitious climate targets on the horizon, there is a pronounced shift towards electric traction drives. However, in comparison to drivetrains with internal combustion engines, electric drivetrains and batteries have a larger carbon footprint during manufacturing. Thus, product innovations become important to reduce the carbon emissions associated with the traction motor. Among these innovations are lightweight components such as rotor shafts, balancing disks, and magnetic fixations. This study compares three novel components with spring behavior designed for lightweight rotors in terms of their carbon footprint, contrasting them with state-of-the-art electric traction rotors. Given the substantial carbon footprint resulting from the use of rare earth magnets in rotors, efforts are directed towards highest value preservation. With regard to the potential of lightweight components, carbon emissions can be reduced during the electric motor operation. This paper discusses a life cycle assessment of electric traction rotors using lightweight components. A hotspot analysis shows that the environmental impact of the components can be significantly reduced by avoiding the use of chrome steel and by recycling of permanent magnet materials.

Keywords: Permanent Magnet Synchronous Machine · Life Cycle Assessment · Electric Mobility

1 Introduction

1.1 Motivation

Comparative life cycle assessments oftentimes come to the same conclusion when tackling different drivetrain solutions. Regardless of methodology or assumptions, battery electric vehicles (BEVs) enter the use phase with higher emission numbers as compared to internal combustion engine vehicles (ICEVs) [2, 9]. While research in the development of ICEVs is focused on reducing driving emissions, there is a significant need for cleaner and more circular production of BEVs [19]. Without a doubt, the battery significantly

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contributes to the lifecycle emissions of BEVs, accounting for 40 - 60%. However, this study focuses on the environmental impact of electric traction motors, which are essential for every electric drivetrain concept and can be optimized for specific applications [16]. These motors comprise the rotor shaft, a lamination stack, balancing disk, and permanent magnets, which pose substantial environmental risks due to their material composition. This issue is exacerbated by the limited availability and resource constraints of these critical materials [13]. One of the most critical resources for electric traction motors, rare earth elements (REE), are still not commonly recycled or reused, with a recycling rate below 10% in the EU [15]. Given that material costs are estimated to account for 73% of the cost of permanent magnet synchronous machine (PMSMs), a circular economy presents significant potential due to these scarce resources [16]. This study emphasizes the potential of three key components of PMSMs to reduce emissions.

2 Innovation Rotor

The key difference in emissions can be achieved during the production of these electric drivetrain components. Hence, this study compares the cradle-to-gate (C2G) emissions of a state-of the-art rotor and an innovative rotor concept using spring-loaded rotor components (see Fig. 1). These spring-loaded components are designed to facilitate weight reduction and require alternative manufacturing processes, compared to the manufacturing of state-of-the-art rotors.

Fig. 1. Innovative rotor components.

2.1 Spring-Loaded Rotor Shaft

The three-part structure of the rotor shaft is a novel design feature. It enables continuously thin wall thickness and a larger inner diameter of the lamination stack package, which contributes to weight savings. The core of the rotor shaft consists of a drawn polygonal tube, which exhibits radial spring action. This design enables a joining process of the rotor shaft and lamination stack at room temperature, while also ensuring the transmission of a consistently high torque when the lamination stack expands under temperature and rotational speed. At the same time, the polygonal tube exhibits low sensitivity to deviations in the inner diameter of the lamination stack, allowing for larger manufacturing tolerances in this regard. Furthermore, the three-part construction of the rotor shaft provides ample design flexibility in selecting the outer diameter, without significantly affecting the volume to be machined [17].

2.2 Spring-Loaded Balancing Disk

Traditional balancing disks often require additional tension rods to create axial preload on the lamination stack. However, the introduction of spring-loaded balancing disks eliminates the need for these rods. These thin-walled disks, through their resilient behavior, serve the dual purpose of balancing the rotor and reducing weight. A non-ferromagnetic material lacking chromium and nickel, offering high cost efficiency, is utilized. The plate spring design allows for axial pre-tensioning of the lamination stack as well as a force-locking connection with the rotor shaft [6, 17].

2.3 Spring-Loaded Magnet Fixations

At the end of its lifecycle, a waved spring strip enables the disassembly of the rare-earth magnets. These magnets can be reused or separated from the remaining materials and recycled to a high standard. The force-locking, detachable fixation within the magnet pocket of the lamination stack needs no modification of the typically cuboid-shaped magnet pockets. The gap previously required for material-locking fixation in the magnetization direction can be filled by the spring strip. It thus not only serves the function of fixation but also facilitates the conduction of magnetic flux and provides thermal bonding of the magnets to the lamination stack. This allows for an increase in efficiency of 0.1% across different operating points of a traction drive compared to transfer molding [7, 17].

2.4 Manufacturing Innovations

On the production side, balancing through mass application or redistribution aims to reduce the amount of material needed for a conventionally subtractive balancing process. The previously thermally assisted joining process of the shaft-hub connection can now be reliably conducted at room temperature due to the resilient behavior of the rotor shaft. The resilient magnet fixation also does not require any thermal curing processes. Unlike conventional rotor shafts, the polygonal tube does not require additional machining in the press fit area, thus reducing manufacturing times. As the radial preload between the shaft and balancing disk occurs only at the end of the joining process, joining at room temperature is possible here as well [17].

3 Comparison of Rotor Components

3.1 Cradle-to-Gate Comparison

Both the innovative rotor as well as the reference rotor have been modeled in openLCA software utilizing the ecoinvent database and primary data. The reference rotor has a global warming potential (GWP) of 265.9 kg CO_2 eq in the C2G assessment, while the innovative rotor reduces this by 4.38% to 254.2 kg CO_2 eq without magnet recycling.

For the innovative rotor, 98.5% of the emissions are caused by the rotor components, and only 1.5% are attributable to the joining processes. The permanent magnets are responsible for 54% of the emissions, followed by the lamination stack with 25%, the rotor shaft with 16.5%, and the balancing disks with 3%. The balancing disk reduces emissions compared to the reference rotor by 8.6 kg CO_2 eq, while the rotor shaft achieves a reduction of 2.5 kg CO_2 eq (Table 1).

Table 1. Environmental impacts of rotor production.

Impact	Innovation	Reference	Unit
Acidification	1.042	1.101	kg SO_2 eq
GWP_{100}	254.247	265.896	kg CO_2 eq
Ecotoxicity: freshwater (FAETP)	645.385	686.201	kg 1,4-DCB eq
Ecotoxicity: terrestrial (TETP)	1.350	11.042	kg 1,4-DCB eq
Eutrophication	0.498	0.520	kg PO4 eq
Human toxicity	484.859	764.037	kg 1,4-DCB eq

All impacts are calculated according to the CML v4.8 2016 assessment method. The greatest differences can be found in the terrestrial ecotoxicity (89.7% reduction) and the human toxicity (36.5% reduction). This can be attributed to the avoided use of chrome steel in the balancing disks compared to the reference (Fig. 2).

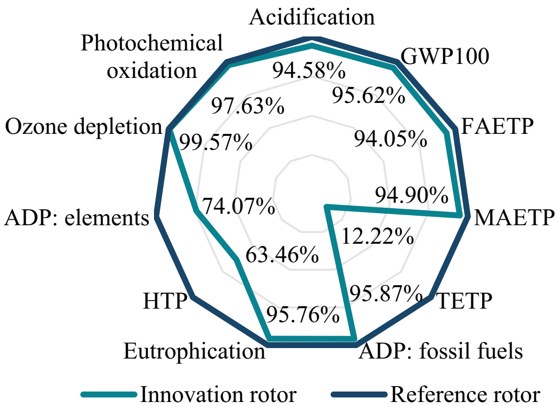

Fig. 2. Environmental impacts of rotor production processes.

As seen above, terrestrial ecotoxicity (TETP) is immensely improved. TETP studies how environmental pollutants affect land organisms and their environment. It involves three elements: a pollutant source, receptors, and exposure pathways and is especially highlighted when working with various metals [3, 10]. A holistic view of the different impact categories is very important to avoid shifting emissions between different categories [4, 14]. It is important to clarify that, at this point, improvements in environmental impacts are primarily attributed to the different production processes and materials used. In the following sections, the potential of lightweight design for reducing production emissions as well as the immense recycling potential for permanent magnets, are highlighted.

3.2 Lightweight Design Improvements

To reach the design goal of a lightweight rotor, the innovative rotor components enable a weight reduction of 0.25 kg in the lamination stack by removing additional tension rods and about 1 kg in the rotor shaft. This decreases the amount of raw materials and energy required for production resulting in lower emissions of 14.32 kg CO_2 eq without affecting performance during the use phase. Although the weight reduction compared to the reference rotor is notable, the approximately 1 kg difference is a small contribution to the energy consumption of a two-ton electric vehicle.

3.3 Magnet Recycling

Environmental improvements for BEVs are constrained by high emissions during raw material extraction and the limited application of recycling possibilities [1]. Over 90% of total energy consumption for permanent magnet production is needed for mining and refining of REEs with about 50% of the material being lost in the process [15]. Preparation processes of REEs have to be repeated several times using high amounts of chemicals and energy to gain the required purity [12]. Figure 3 shows the distribution for permanent magnet production, as modelled in openLCA. The annual consumption of REE magnets is expected to increase, making recycling crucial to avoid shortages and supply risks and enable a transition away from fossil fuels. The mining of REEs is highly centralized, with China holding a monopoly position at 83% leading to high import-dependency of 100% for the EU and price volatility [15, 18].

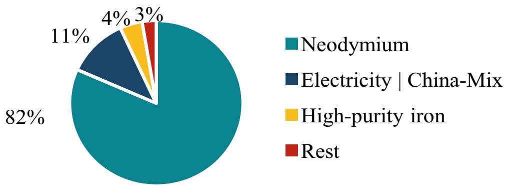

Fig. 3. Emissions in permanent magnet production according to the manually modelled openLCA system.

Three different routes can be used for magnet recycling: Functional recycling, elemental recycling, and direct reuse, each utilizing different amounts of primary material. While the former focuses on extracting the permanent magnet alloys or the REEs, the focus of this paper is on the direct reuse enabled by the enhanced magnet fixation for the innovative rotor. This provides a range of possible improvements through the recycling of magnets. Lixandru et al. prove the concept of magnet-to-magnet recycling with up to 100% of magnetic properties possible to be restored [11]. Accardo et al. estimate a 33% GWP reduction potential in (NdDy)FeB magnet production by using a hydrogen decrepitation recycling process with 60% recycled material [1]. This would correlate to 45,3 kg CO_2 eq reduction or 17,8% of the overall GWP of the innovative rotor. Zakotnik et al. adopt a magnet-to-magnet recycling which incorporates only 1.9 wt % of Nd-Pr hydride additive and enables energy savings of around 95% [18]. This recycling route removes the costly mining and purifying of the REEs and replaces them with demagnetization and hydrogen decrepitation. Adopting such a procedure for the innovate rotor would reduce the GWP by 124.9 kg CO_2 eq or 49.1%. Jin et al. also explore the possibilities of magnet-to-magnet recycling, reaching a potential GWP improvement of 80% [8] (Fig. 4).

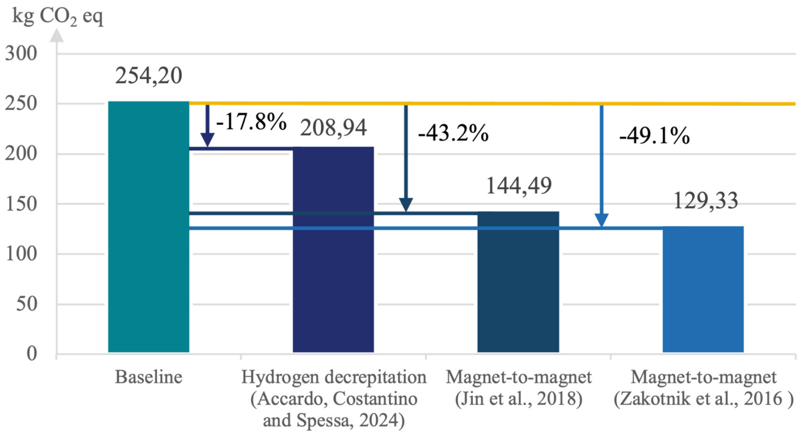

Fig. 4. GWP comparison of rotor production with different magnet recycling scenarios.

4 Conclusion and Outlook

In this paper, three major changes to the design of a rotor for an electric traction motor have been highlighted regarding their environmental benefits compared to a reference rotor. The product has been modelled in openLCA software to explore hotspots and ways of improvement. Results show, that through different manufacturing routes, lightweight design and enabled magnet recycling, the lifecycle emissions of the innovative rotor can be significantly reduced. The potential in GWP reduction lies especially in the possibility to reuse the highly critical permanent magnets. Figure 5 illustrates, how the individual improvements effect the GWP of the rotor.

As the demand for electric traction motors is projected to increase, the potential environmental benefits of widespread implementation of these innovative concepts, particularly magnet recycling is highlighted. With a projected growth of up to 47 million

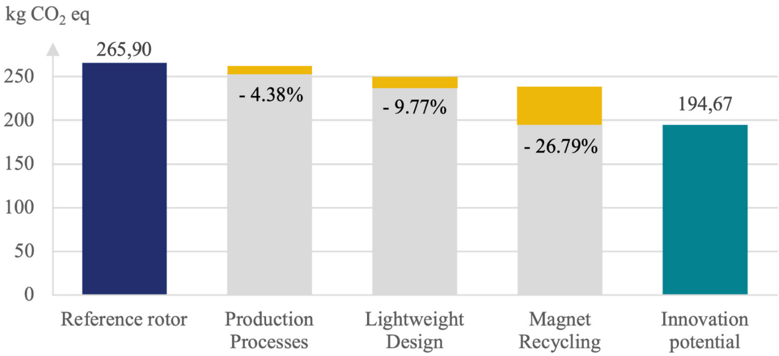

Fig. 5. GWP reduction potential via different innovations.

motors by 2035 [5], the potential savings can be significant, as illustrated in Fig. 6. The spring-based magnet fixations offer a first stepstone in a more circular economy but to capitalize on these opportunities, it is crucial that magnet-to-magnet recycling is further improved.

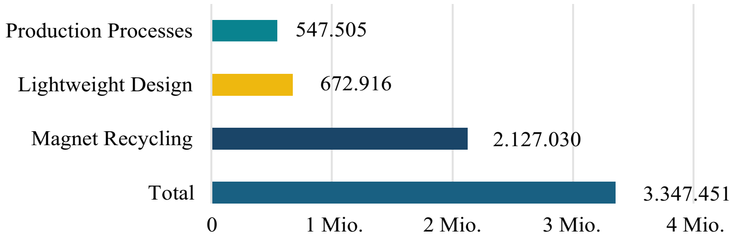

Fig. 6. Scenario analysis for CO_2 reduction potential by 2035 [t CO_2 eq].

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