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Comparative Life Cycle Assessment for Permanent and Externally Exited Drive Systems

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Executive Summary

For battery electric vehicles the drive system has the third highest environmental impact, after battery and chassis. This study compares the global warming potential (GWP) between a drivetrain with a permanent synchronous machine (PSM) and an external exited drive system (EESM) by applying the life cycle assessment (LCA) methodology. Life cycle stages are considered from cradle-to-grave excluding OEM manufacturing and end of life. The functional unit is to drive 200,000 km with a C-class vehicle the speed trajectory of a specific drive cycle. The results show, on the one hand, that the EESM inverter has a higher GWP attributable to the additional module for external excitation and thus the larger housing. On the other hand, the magnets of the PSM contribute to a higher GWP for the machine. Although the EESM doesn`t need to apply field weakening during operation, the PSM has less losses. Nevertheless, the electricity grid mix for charging the vehicle has the biggest impact on the use stage. In the future, the most environmentally friendly drive system will be determined by the development of the electricity grid mix in the world.

1 Introduction

Sustainability is currently the greatest challenge of humanity and therefore an essential success factor for the future. As a responsible member of the society, Vitesco Technologies focuses on developing sustainable powertrain solutions, which are in line with the environmental requirements. For this reason, we apply extensive life cycle assessments on new and existing products over the entire life cycle.

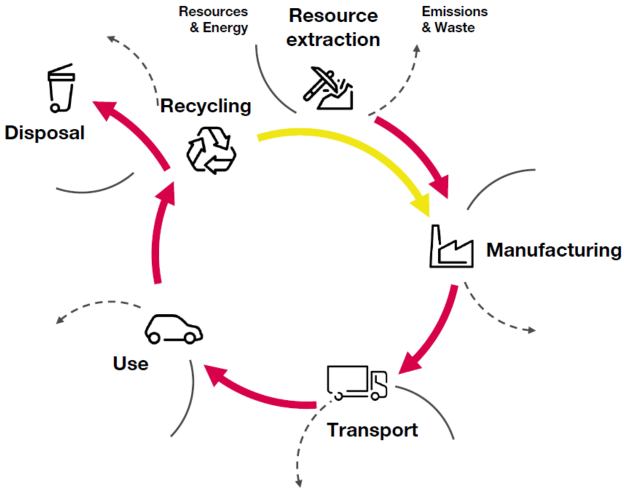

Figure 1: Life cycle of a product, material, or service

Vitesco Technologies is an international leader in electrified drive systems for sustainable mobility. After battery and chassis, the powertrain of battery electric vehicles (BEV) has the third highest global warming potential (GWP) in the manufacturing stage [1]. However, multi motor concepts for better efficiency, all-wheel drives, or safety reasons for autonomous driving can increase the environmental impact during the manufacturing stage. Additionally, the powertrain has the highest effect on global warming potential (GWP) in the use phase of the BEV. Life Cycle Assessment from Hyundai stated that the electric powertrain has the highest Abiotic Depletion Potential of all vehicle components [2].

Due to the mentioned focus of Vitesco Technologies, this paper emphases permanent- (PSM) and externally exited synchronous machines (EESM) as well as the regarding inverters for the electrified drive system. The gearbox of the drive system is out of scope. To achieve a valid comparison the diameter and the active length of the rotor is kept the same for both machine types. Within the product life cycle in Fig. 1 the stages resource extraction until use are taken into consideration. The end of life treatment of the drive system is not in scope.

2 Comparative Life Cycle Assessment for Drive Systems

The technology comparison of the PSM and EESM drive system is based on the latest CML (Centrum voor Milieukunde University Leiden) method for the impact category GWP over 100 years. The unit of the GWP is kilogram carbon dioxide equivalents (kg CO_2-eq). To calculate the corresponding mass of kg CO_2-eq, the Life Cycle Assessment (LCA) methodology, according to the standards ISO 14040:2006 [3] and ISO14044:2006 [4], is applied. LCA is an iterative process, which includes goal & scope definition, inventory analysis, impact assessment, interpretation, and review as shown in Fig. 2.

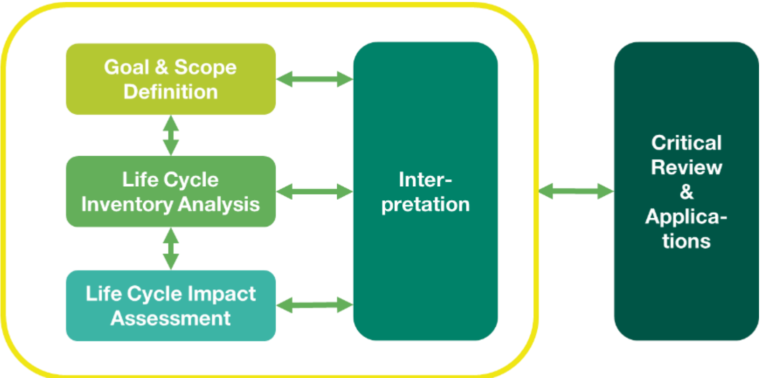

Figure 2: Illustration of the LCA process

The functional unit is: “The usage of an electric drive system in a C-class vehicle driving 200,000 km in WLTC (Worldwide harmonized Light vehicles Test Cycle)”. The addition “comparative” means, that just the technical differences and the resulting various efficiency maps between PSM and EESM are evaluated.

The cut-off criteria for mechanical components is < 10 g for every material group on sub-component level based on the internal bill of materials (see Table 1). For example, if the EMC-Filter has 10 sealings made of the same material with 1 g each it is regarded as a material group of 10 g, but if it has one single sealing with 9 g it is neglected. All electrical components were considered, as far as correspondingly scalable data sets are available in GaBi (LCA software provided by Sphera). This leads to the fact, that 99 % of the mass for mechanical components of machine and inverter are regarded. In addition, 97 % of all electrical components are considered for the inverter.

Table 1: Data Source for the different life cycle stages

Life Cycle Stage	Resource	Supplier	Manufacturing	Transport	Use
Data Source	Internal Bill of Material	1. Supplier Data 2. Literature Values	Internal Measurement Data	Internal Data	Simulation

For the manufacturing steps taken place within Vitesco Technologies internal measurement data were collected. For upstream manufacturing, supplier information has been preferred; however, if it was not available, the life cycle inventory of the case study "Life Cycle Assessment of Permanent Magnet Electric Traction Motors" proceeded by A. Nordelöf at the Chalmers University of Technology has been used, scaling the data accordingly for the machine [5] and the inverter [6]. The data for the use stage were obtained by computing simulations. The impact assessment was performed with the software GaBi. The following chapters show the LCA results for the resource extraction and manufacturing stage, which correspond to the cradle-to-gate analysis and a separate use-stage study for the machine. For the analysis in chapter 3 and 4 the highest GWP will always be the reference.

3 Cradle-to-Gate Analysis

The main part of the resource extraction and manufacturing takes place in China. The environmental impact of the up-stream transport was assigned to the supplier products.

3.1 Inverter

The inverter of the EESM contains an additional external excitation module for the power supply of the rotor windings. It is a step-down converter and connects the DC-link with the excitation busbar. These additional electronics including the corresponding cables increase the installation space. For this reason, the inverter housing is larger. Fig. 3 shows, that the aluminum housing has the highest contribution to the GWP, followed by the power module.

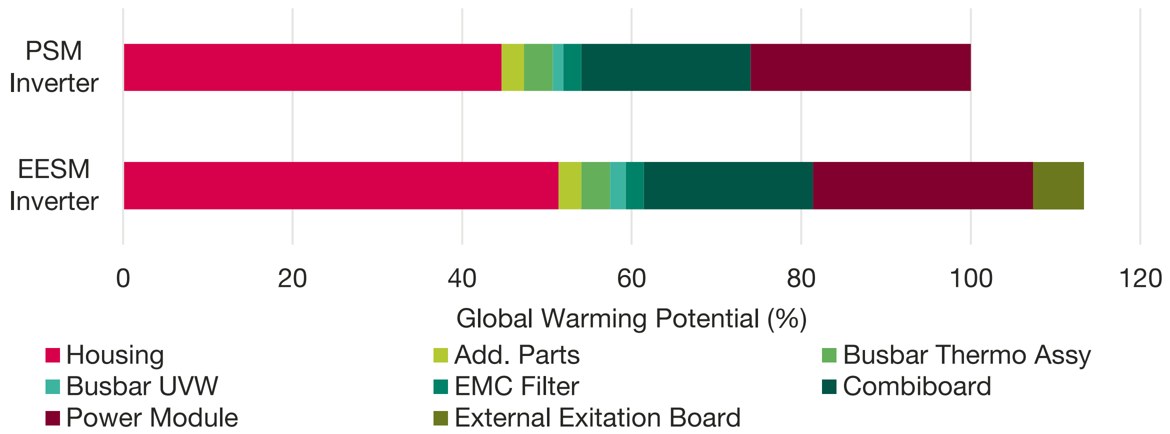

Figure 3: GWP of the inverter

The EESM inverter has the benefit, that during error events, the rotor can be demagnetized. Resulting in reduced safety requirements for the power module, the capabilities of the power electronics can be decreased. This effect was not considered in this study. As a result, the GWP of the EESM inverter is 13 % higher as of the PSM inverter.

3.2 Motor

The highest share of the GWP in the PSM rotor is attributable to the permanent magnets. They contain rare earth metals, which are scarce in the ore of the mines. Thus, high efforts are required to extract the oxides and reduce them to pure metal. This leads to high gravimetric prices, which is currently the basis for the allocation procedure, resulting in high gravimetric GWP values for these metals.
On the one hand, the EESM has the huge advantage, that these rare earth magnets are replaced by copper coils. On the other hand, this lengthen the rotor for the same active length. In addition, the slip rings extend the rotor shaft. Nevertheless, the EESM rotor has an 54 % reduced GWP compared to the PSM rotor (see Fig. 4).

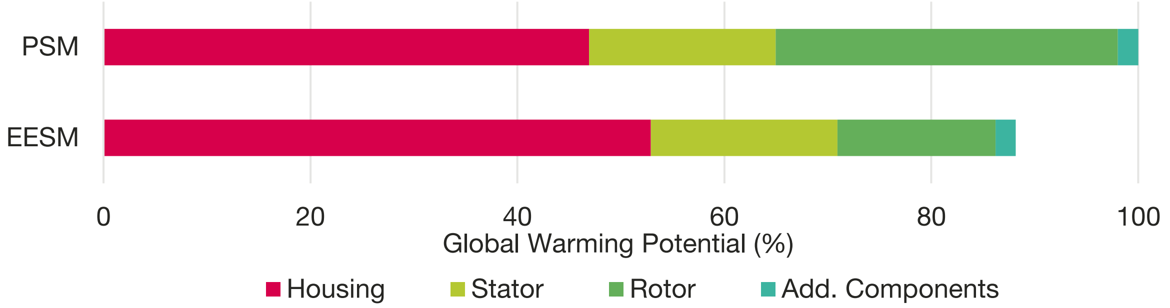

Figure 4: GWP of the electric machine

The lengthened EESM rotor needs an also an enlarged housing, causing a 13 % higher GWP. The entire EESM has 12 % lower GWP regarding the PSM.
Aluminum is the material with the highest contribution to the GWP. Different shares of secondary materials are analyzed for open loop recycling with the cut-off approach. The effect of recycling is strongly dependent on the applied approach. Figure 5 shows a reduction of 44 % in GWP when using 100 % recycled material.

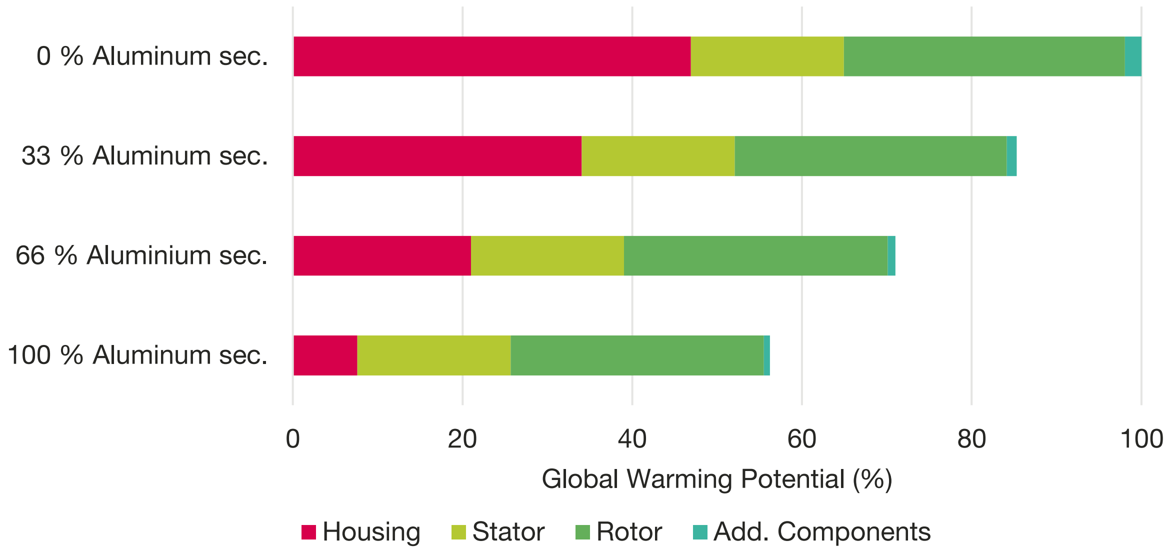

Figure 5: GWP of the electric machine

3.3 Comparative LCA Results Gradle-to-Vitesco Technologies Gate

The rare earth magnets in the PSM rotor have such a huge impact on the overall drive system, that it overcompensates the copper windings, bigger housings, and the additional excitation module for the EESM. The GWP of the EESM is 6 % lower.

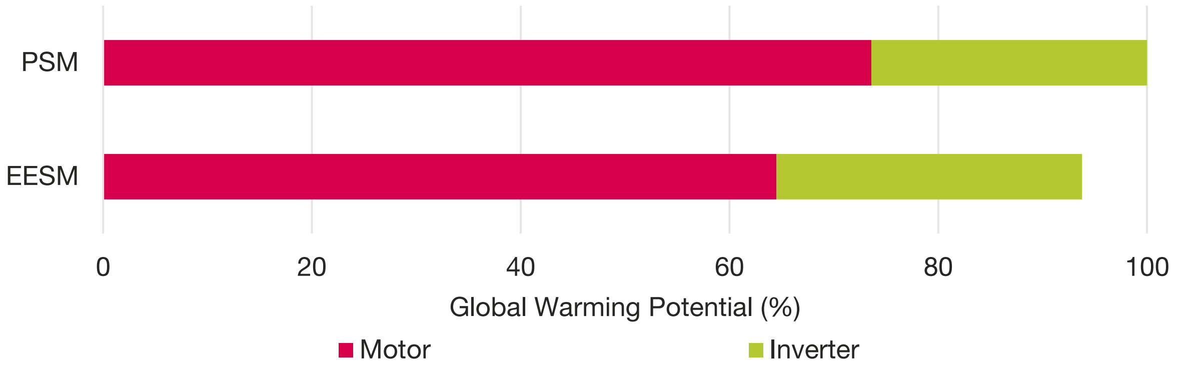

Figure 6: GWP of the electric drive system

4 Use Stage

The use stage of electric driven vehicles has the greatest influence on the GWP over the entire life cycle [7]. It is calculated for PSM in a C-segment vehicle over the distance of 200,000 km WLTC. For the use stage, the direct machine losses and an allocated share of the driving resistances by mass are considered. Charging losses are out of scope for this investigation. Different electric grid mixes in Europe have been considered for modelling the power generation (see Fig. 7).

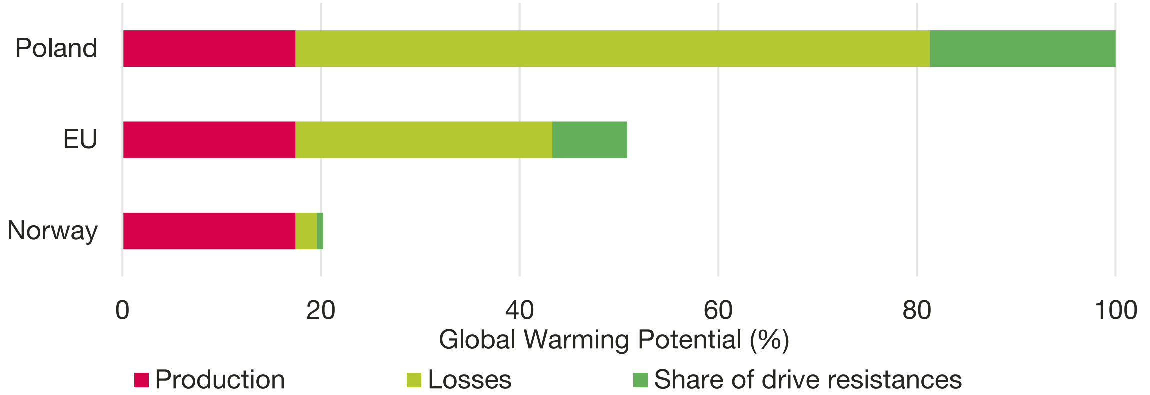

Figure 7: GWP of the use stage for PSM in different regions

Contrarily to the PSM that benefits from the permanent magnets to generate the rotor magnetic field, the EESM generates its magnetic field with an electro-magnet that consumes energy for that purpose. Yet, the EESM has the advantage that it does not need to compensate for the high magnetic field of the permanent magnets when the machine is rotating at high speed. This results in higher efficiency at low rotation speed for the PSM, whereas the EESM has higher efficiency at high rotation speed. In a nutshell, the EESM has higher energy consumption for the use stage. Currently, the high grid mix emissions lead to a higher GWP of the EESM in comparison to the PSM, even though the EESM has a lower GWP during the resource extraction and manufacturing stage. Fig. 8 depicts its potential impact on the future until 2050.

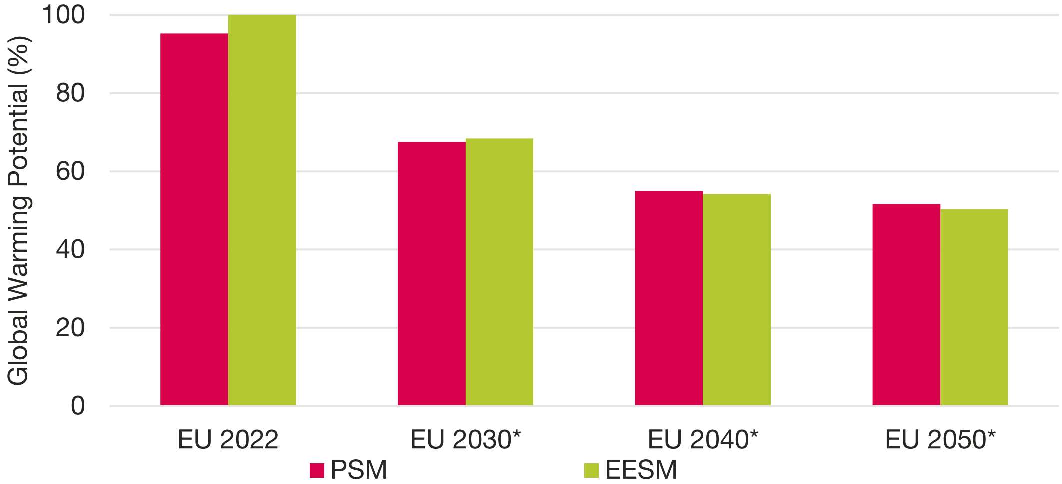

Figure 8: GWP trend for different electric machines   *EU Reference Scenario [8]

In the timeframe from 2030 until 2040, the most sustainable electric machine technology based on the GWP will shift from PSM to EESM. It must be stated that the difference between both machine types is very small and deviations in the assumptions or boundary conditions can change the picture. If the study is expanded to inverter and reducer, the benefit for the EESM is going to shift further in the future. This is due to the higher manufacturing efforts of the EESM inverter as shown in chapter 3.1. The second reason consists in additional losses of the external excitation module during the use stage. But if end of life is considered, the copper of the EESM rotor is quite simple to recycle compared to the rare earth magnets of the PSM. In addition, there is no established large- scale recycling industry for these magnets [9].

5 Conclusion and Outlook

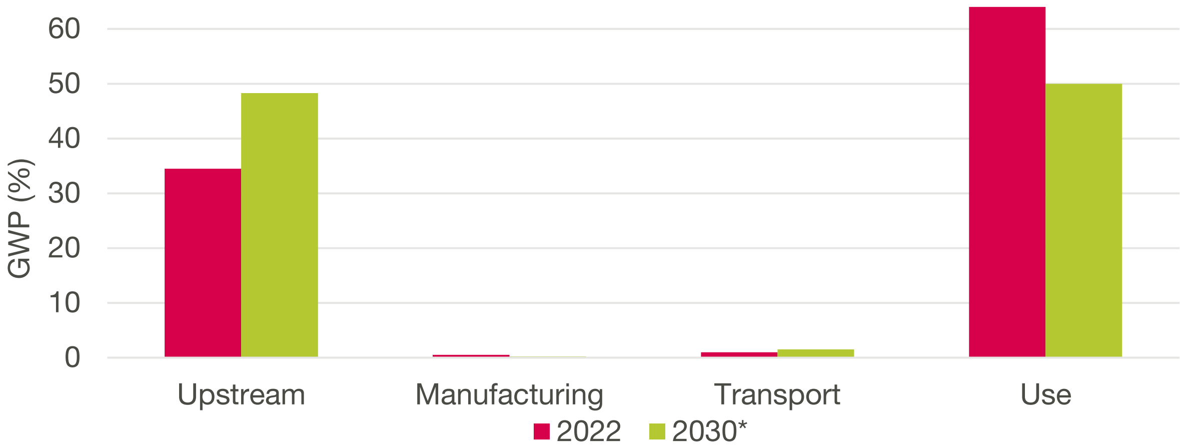

Figure 9: Impact of life-cycle stages on GWP   *EU Reference Scenario [8]

The upstream stage in Fig. 9 includes resource extraction, supplier manufacturing (see Tab.1) and transport to the Vitesco Technologies plant. At Vitesco Technologies the manufacturing of subcomponents and the final assembly takes place. For the production, the data has been measured and 10 % for general facility energy supply was added. In order to become more environmentally friendly, Vitesco Technologies procures 100 % of its external electricity from renewable energies. The transport stage consists of the shipment of the PSM from the Vitesco Technologies' plant in China to the warehouse in Europe, including truck transportation for the first and last mile including packaging. These values for 2022 show a very low deviation at the big levers (upstream and use stage) compared to the values published by Hyundai for the model Kona in their sustainability report 2021 [10]. The GWP for the OEM manufacturing is neglected in this investigation.

The upstream efforts are determined by the product design and the supply chain of Vitesco Technologies, while the product efficiency defines the use stage. It can be stated, that as the electricity grid mix will increase its renewable energy share in Europe, the impact of the use stage will decline. Assuming the positive influence of the electricity grid mix will be compensated by higher efforts for the resource extraction, the upstream stage becomes more important.
As shown in chapter 2 and 3, recycling and its evaluation approach is a big lever to reduce the GWP of the upstream stage. But this is just a first step in the huge field of new technical design solutions for electrified drive system to lower the GWP.

References

[1] D. T. Hänsel, „Umwelt und Nachhaltigkeit im funktionalen Bordnetz - Volkswagen", in Bordnetze im Automobil, Ludwigsburg, 2021.

[2] M. Song, W. Lee, J. Choung, D. Kim, G. Han und T. Hur, „Life Cycle Assessment of Electric Vehicles - Hyundai Motors", 30th Aachen Colloquium Sustainable Mobility, Aachen, 2021.

[3] International Organization for Standardization, „ISO 14040 - Environmental Management - Life Cycle Assessment - Principles and Framework", 2006.

[4] International Organization for Standardization, „ISO 14044 - Environmental Management - Life Cycle Assessment - Requirements and Guidelines", 2006.

[5] A. T. A. Nordelöf, „A scalable life cycle inventory of an electrical automotive traction machine-Part II:manufacturing processes", The International Journal of Life Cycle Assessment, 2017.

[6] A. Nordelöf, „A scalable life cycle inventory of an automotive power electronic inverter unit-part II: manufacturing processes", The International Journal of Life Cycle Assessment, 2018.

[7] R. Palm, A. Egeskog, K. Hagdahl, C. Krewer, I. Rade, L. Bolin und L. Dahllöf, „The Carbon Footprint of Volvo XC40 BEV and ICE – Presented with Transparency", 30th Aachen Colloquium Sustainable Mobility, Aachen, 2021.

[8] European Commission, „EU Reference Scenario 2016 – Energy,transport and GHG emissions – Trends to 2050", Brussels, 2016

[9] T. Elwert, D. Goldmann, F. Römer, M. Buchert, C. Merz, D. Schueler und J. Sutter, „Current Developments and Challenges in the Recycling of Key Components of (Hybrid) Electric Vehicles", Recycling, Bd. MDPI, 2015.

[10] Hyundai Motor Company, Road to Sustainability, Seoul, 2021.

Presenter Biography

After finishing his master studies "electromobility and grids" at the OTH Regensburg, Dr.-Ing. Florian Uhrig received his Ph.D. from the Technical University Chemnitz for the thesis "Evaluation of efficiency enhancing measures for automotive fuel cell powertrains with nested optimization" in 2020. He has been employed at Vitesco Technologies (former Continental Powertrain division) since 2015 and works for live cycle engineering at the technology and innovation department.