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Sustainable EDU Solutions

AVL's pathway forward to support e-Mobility with power dense, efficient and cost attractive EDU solutions

Wilhelm Vallant[1], Mathias Deiml[2], Gernot Fuckar[3], Martin Rothbart[4]
[1]*AVL List GmbH, Hans-List-Platz 1, 8020 Graz, Styria, Austria*
E-mail: wilhelm.vallant@avl.com
[2]*AVL Software and Functions GmbH, Im Gewerbepark B29, 93059 Regensburg, Deutschland*
E-mail: mathias.deiml@avl.com
[3]*AVL List GmbH, Hans-List-Platz 1, 8020 Graz, Styria, Austria*
E-mail: gernot.fuckar@avl.com
[4]*AVL List GmbH, Hans-List-Platz 1, 8020 Graz, Styria, Austria*
E-mail: martin.rothbart@avl.com

Executive Summary

The e-mobility market is projected to continue its growth, leading to increasing production volumes annually. Consequently, demand for materials such as copper, magnets, semiconductors, and metal sheets is substantial, potentially putting the transition to green mobility at risk. It is the automotive industry's responsibility to navigate this path carefully, making informed decisions to manage the demand for critical raw materials. This paper explores various technological approaches to enhance the sustainability of electric powertrains. A product lifecycle CO_2e evaluation is employed to assess the impact of individual technologies. Solutions such as the implementation of high-speed e-motors with high power density and/or state-of-the-art energy-efficient e-axle systems are described and analyzed. The CO_2e footprint over the application lifetime serves as the primary criterion for comparing different technical solutions. Additionally, measures to further improve the CO_2e footprint through increased integration and the use of recycled materials are discussed.

KEY WORDS: EDU, e-Axle, high-speed, high-efficiency, lifecycle CO_2e

1 Introduction

The global shift towards e-mobility has seen some setbacks lately but driven by the urgent need to reduce greenhouse gas emissions and combat climate change it is necessary to further proceed with the transition. As electric vehicles (EVs) become more prevalent, the automotive industry faces the dual challenge of scaling up production while minimizing the environmental impact of manufacturing processes. This growth in the e-mobility market has led to a significant increase in the demand for critical materials such as copper, magnets, semiconductors, and metal sheets. Managing this demand sustainably, both ecologically and economically, is crucial to ensuring a successful transition to green mobility.

Electric powertrains, the heart of EVs, offer a promising solution to reduce the carbon dioxide equivalent (CO2e) footprint across the product lifecycle. By leveraging advanced technologies, the automotive industry can enhance the efficiency and sustainability of electric powertrains, thereby reducing their overall environmental impact. This paper delves into various technological innovations that can be applied to electric powertrains to improve their sustainability. Through a comprehensive product lifecycle CO2e evaluation, we assess the impact of these technologies and identify the most effective solutions.

2 Life cycle view of CO_2e emissions

Thriving for a CO_2 reduced future, many countries and territories have already stated their target on CO_2 neutrality. The European Union as well as Japan have defined 2050. China set a 2060 target, whereas the USA have set the goal to reduce their output of CO_2 equivalents (CO_2e) by 50 % until 2030. According to a recent study by International Energy Agency (IEA)[1], the -1.5°C goal is still in reach if all nations stick to their target and announce milestones towards achieving CO_2e neutrality. Nevertheless, the CO_2e neutrality is influenced by many boundary conditions and factors. The increasing need for energy security may be contradictory to the CO_2e reduction targets around the globe.

Considering the complete life cycle as a system with certain limits is essential for a valid analysis. Automotive manufacturers can influence most scope 1 and 2 emissions according to the Greenhouse Gas (GHG) Protocol Corporate Standard[2] and have certain but not full control of the upstream scope 3 emissions of the supply chain, as well as the scope 3 emissions downstream in the usage and recycling phases.[3]

STRATEGIES FOR CO2E REDUCTION: To mitigate the CO_2e emissions associated with the production of powertrain components , several strategies can be employed:

SUSTAINABLE MATERIAL SOURCING: Prioritizing materials with lower environmental impact and ensuring responsible sourcing practices.

ENERGY-EFFICIENT MANUFACTURING: Implementing energy-efficient technologies and processes, in particular in battery production, to reduce energy consumption and CO_2e emissions.

RENEWABLE ENERGY INTEGRATION: Utilizing renewable energy sources in both the manufacturing and use-phases of electric vehicles to lower the overall carbon footprint.

ADVANCED RECYCLING TECHNIQUES: Developing and adopting advanced recycling methods that are less energy-intensive and more effective in recovering valuable materials.

By focusing on these aspects, the automotive industry can significantly reduce the CO_2e impact of powertrain components, thus contributing to a more sustainable and environmentally friendly future for electric mobility.

3 Design to CO_2e over the product life cycle

IIn product life cycle modelling it is important to know the qualitative patterns of CO_2e influenceability, determination of and the actual occurrence to define appropriate optimization measures at the right times.

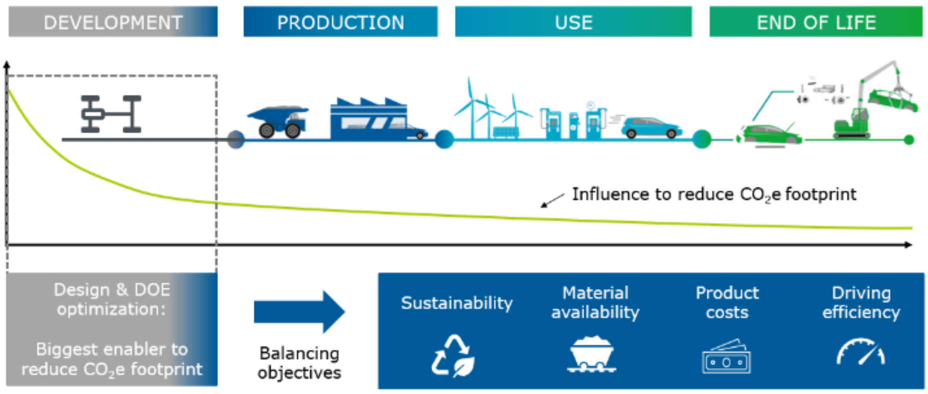

Figure 1 Model of the product lifecycle with qualitative evaluation of CO_2e influenceability[5]

FIGURE 1 shows a typical pattern for the product life cycle of a Battery Electric Vehicle (BEV) assuming an European 2023 electricity mix in the production and in-use phase.[1] It is shown that the possibility to influence CO_2e decreases significantly during later phases in the product lifecycle. Although the majority of CO_2e emissions occur during the production phase and typically need to be offset during the in-use phase when compared to other powertrain technologies, the development phase has the most significant impact on the CO_2e footprint.

By integrating life cycle assessment (LCA) methodologies and sustainability criteria from the outset, developers can evaluate and compare the environmental impacts of various powertrain technologies. This proactive approach enables the identification of technologies that not only meet performance and cost requirements but also minimize CO_2e emissions throughout the product's life cycle. Consequently, making informed decisions early in the development process ensures that the chosen technology aligns with sustainability goals, leading to a more environmentally friendly product

4 Design to CO2e method in product

With reference to FIGURE 2, we have structured our development process into distinct phases.

The first phase is the target definition phase, where we establish an affordable carbon footprint value based on our organization's environmental, social, and governance strategy. This phase involves risk assessments and considerations of localization and the carbon border adjustment mechanism.

Next is the Design to CO_2e phase, which focuses on material selection, manufacturing, and assembly process modeling, aiming for optimal DFX balancing. That means balancing of Design for Manufacturing (DfM), Assembly (DfA), Cost (DtC), Quality as well as CO_2, Recycling, 2nd Life applicability. This phase often requires multiple iterations to achieve the target verification, resulting in an achievable CO_2e value.

Following this, we enter the Supplier nomination phase, where we discuss CO_2e targets with suppliers based on their quotations. This phase may involve target offsetting to meet the desired CO_2e levels, culminating in the actual CO_2 equivalent for production.

In the final phase of CO_2e optimization we focus on the production optimization using increased portion of primary data for final assessment of the CO_2e footprint out of the production.

Throughout these phases, we utilize various tools, including commercially available LCA (Life Cycle Assessment), environment health and safety software in the early stages, as well as production process simulations in the design to CO_2e phase. The data backbone evolves from relying on secondary data in the early stages to incorporating primary data as we approach production.

Figure 2 Design to CO_2e in product developmen

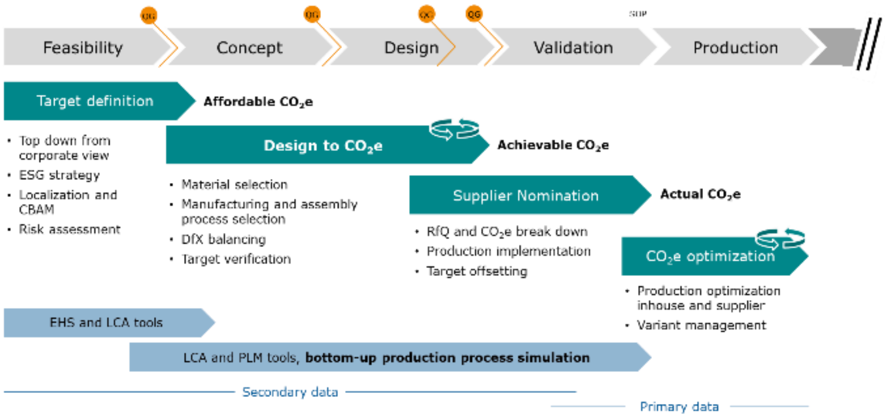

Figure 2 Design to CO_2e in Product Development

5 Impact of technology solutions on product life cycle CO_2e

In the quest for reducing the Product Carbon Footprint (PCF), optimizing key elements of the electric powertrain like electric motor design, inverter technology and transmission arrangement are crucial. The challenge is to select the right technology that can significantly lower cost and material usage without compromising performance.

5.1 Speed and sustainability

Electric motors, such as PMSM based machines widely used for automotive applications, consist of high masses of expensive materials like dynamo sheet metal, magnets and copper. Reducing the size of the motor reduces these costs. Scaling down motor size means to reduce its torque.

$$Pmech = \omega * M;\ M \sim d2 * l$$ [4]

d: diameter; l: lamination length

To maintain the power rating the rotational speed needs to be increased when reducing motor dimensions. An increase of factor 2 in motor speed results in a reduction of active motor material by a factor of 2. Provided that special or expensive technologies in motor and transmission can be avoided there is a substantial cost saving in the motor possible. Weight and size of the motor can be reduced accordingly and are additionally beneficial for vehicle features and again costs.

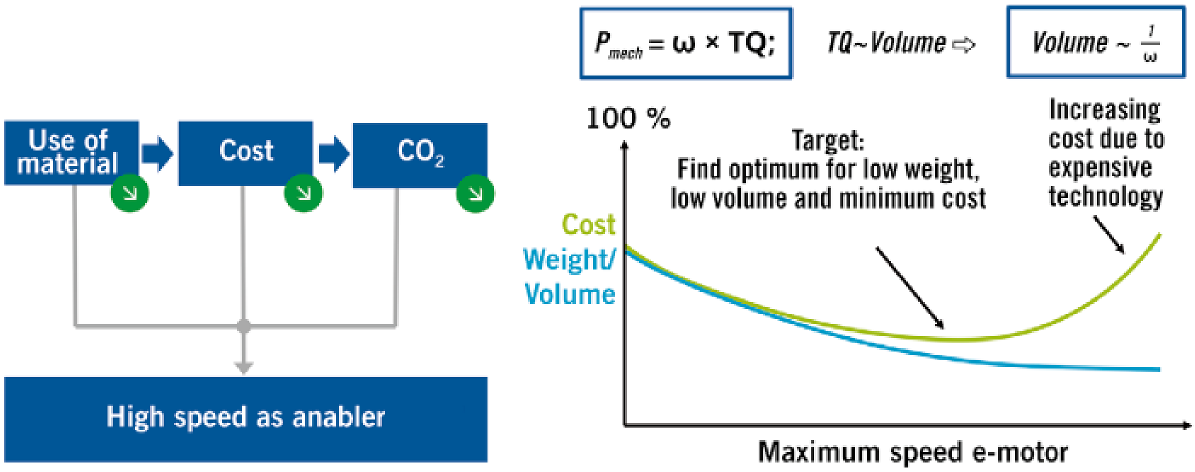

Figure 3 Basic evaluation visualizing the influence of e-motor speed vs. component cost[4]

These relations between speed and weight/volume/cost are shown in FIGURE 3. Engineers were looking for the optimal speed, at which weight and cost are both low.[4]

5.2 Energy efficiency and sustainability

Addressing the applications use phase a high-efficiency EDU, has been specially developed to maximize energy efficiency, resulting in an average WLTC efficiency rating of over 94 %. The design combines two PMSM technology e-motors on a single-stage reducer transmission paired with a self-developed, super-compact, and efficient planetary differential.

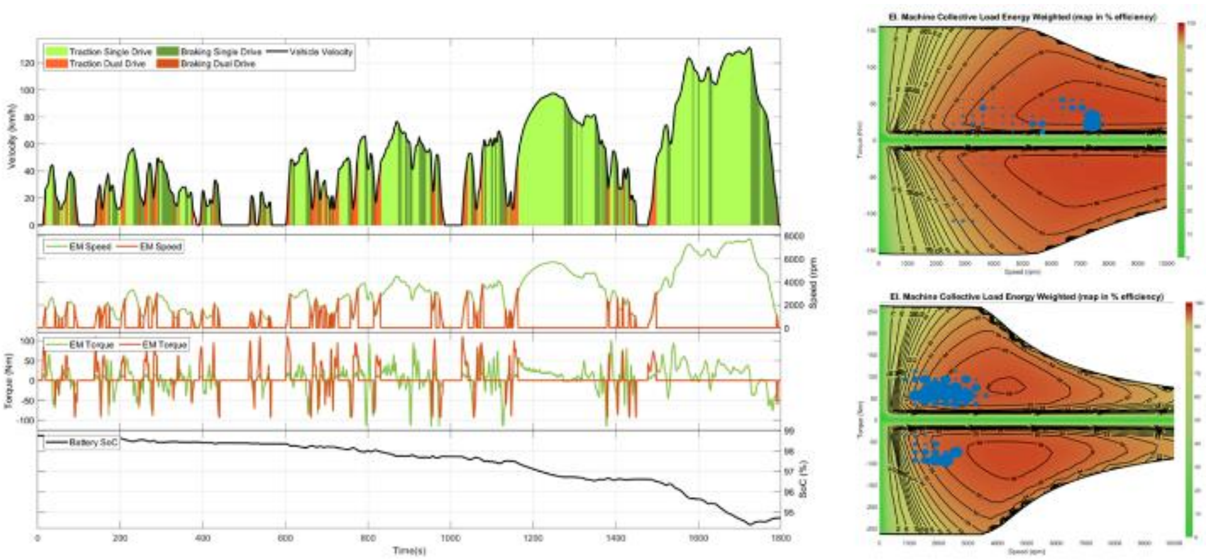

Figure 4 Operating strategy and E-Motor characteristics applied

As shown in the operating strategy in FIGURE 4 one motor is permanently engaged, the second one can be connected on demand by a clutch, thus it is only used during boost operation to provide a higher system performance in driving or regeneration. To operate the e-motors, AVL’s efficient and compact dual SiC inverter is applied, with high power density, efficient switching, and low electromagnetic emissions.

Modular electric drive unit (EDU) systems like the described high-speed EDU and high-efficiency EDU, are perfect examples of the industries commitment to push electric mobility to a next level. Excellence in complete system design and consequent application of the advanced development methodologies and development tools are the foundation for achieving technological excellence.

6 High speed e-machine development

To develop the aforementioned e-motor for the required 30.000 rpm without using expensive technology like cobalt lamination, the following challenges had to be overcome:

- Mechanical rotor strength due to high centrifugal forces
- Bearing technology at high rotational speed in partnership with SKF
- High frequency losses in copper windings
- Increased iron losses due to higher fundamental frequency of 1500Hz

The developed Solutions included new innovative designs for

- Hairpin Windings
- Cooling concept

A six-layer hair pin winding with bent copper on one side and copper forming and welding on the other side was chosen. A copper fill factor of 60% was achieved. This factor includes the oil channels for cooling as described in the cooling chapter. A slot-liner with only 0.1 mm thickness was used. The slot was optimized for coolant flow in combination with copper fill factor.

Theneed for resin in the slot has been avoided. Additional micro-oil channels along the copper improve coolant flow. Recycling of copper is facilitated by that the winding can be removed in one piece without shredding.

The prototypes were manufactured using selective laser melting (SLM), a 3D printing process. This offers further advantages:

- Smaller winding heads
- Low cost for tooling
- Reduced electrical resistance compared to welding

Copper printing may be only the beginning, further optimizations like free shaping of very short winding heads can be realized in later steps. This manufacturing process is suitable for small series production. For large scale volumes welding is more cost effective. AVL's current design supports both manufacturing processes.

Direct oil cooling means that the coolant is directly in contact with the copper winding in the slots and winding heads. The stator is fully filled with oil, which flows along the stator slots. Thus, the heat from copper losses is removed very efficiently. An air gap tube separates the oil from the rotor space. Thus, no friction or splashing losses occur.

The transmission is cooled with a separate circuit because of pollution by metal abrasion of the gears. The transmission has a lubrication circuit with a separate oil pump. Transmission fluid cooling is realized by spraying lubrication oil on the cooled housing towards the e-machine.

The magnets are made of cost-effective material with low heavy rare earth content. Still the efficiency map shows a maximum of over 97% in a wide range. Due to NO20, segmented magnets and high copper fill factor the losses at high speeds are well balancedas shown in Fig. 2.

The map shown in FIGURE 5 is generated at 180°C copper temperature. Due to direct oil cooling, the copper temperature is typically at 90°C only, which results in even better efficiency.

The EDU design with the new e-Motor continued to focus on overall cost reduction, reduction of material usage and increased power density without sacrificing efficiency. Scalability and high-volume production were also key considerations. With these requirements the resulting concept is described:

EDU:

- dual motor, dual torque path to enable torque vectoring for premium segment
- central gearbox for optimal length of drive shafts in various vehicles
- low profile design to support flat chassis

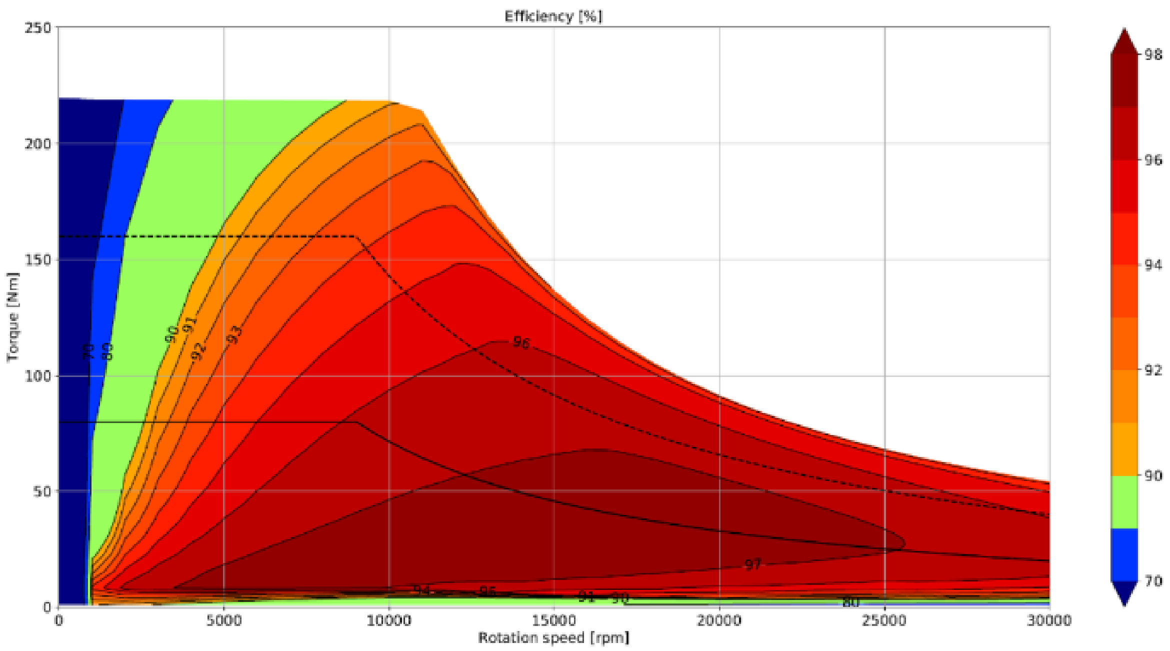

Figure 5 High Speed E- Machine Performance and Efficiency

HIGH SPEED MOTOR:

- standard materials for sheet metal and magnets
- PSM technology for best power density and system efficiency
- high frequency winding for low factor (AC_(_loss))/(DC_loss)
- cooling with best-in-class effectiveness, combined with the inverter
- mechanical rotor stability up to 1,2 * nmax

SIC INVERTER:

- high power density in complete package
- best efficiency, fast switching slopes, variable switching frequency
- combined DC link, interleaved switching, low EMC emissions

GEARBOX:

- 2 stage transmission, single speed
- lay shaft concept
- high efficient tooth geometry, optimal NVH tradeoff
- injection lubrication, separate fluid than motor

7 Development of highest efficiency for product use-phase co2e-footprint optimization

The development of a highly efficient Electric Drive Unit (EDU) aimed at significantly improving the energy efficiency of battery electric vehicles (BEVs). The investigation focused on enhancing the total efficiency of BEVs to extend driving range and reduce charging times.

The EDU is designed for B/C-Segment vehicles, which are common in the compact and mid-size car markets. This makes the technology applicable to a wide range of consumer vehicles, thus enhancing their appeal and usability.

The development process involved a structured approach to concept evaluation and initial sizing of key components, including the e-motor, transmission, and inverter. AVL utilized AI-supported Design of Experiments (DoE) to optimize the system. The EDU features: Two Permanent Magnet Synchronous Motors (PMSMs) on a single-stage reducer transmission. A self-developed, highly compact and efficient planetary differential. A dual SiC inverter with high power density, efficient switching and low electromagnetic emissions has been used.

With the described solution a vehicle energy efficiency of 10 kWh/100km and an average cycle efficiency of the EDU of over 94% in the Worldwide Harmonized Light Vehicles Test Cycle (WLTC) has been achieved when evaluated at the charging terminal. The system's performance was validated through hardware testing on a test bed.

The high-efficiency EDU offers the following advantages:

- Superior Energy Efficiency: Achieves over 94% average cycle efficiency in WLTC.
- Enhanced Performance: The dual-motor setup, with one motor permanently engaged and the second motor used on demand, provides higher system performance during driving and regeneration.
- Advanced Inverter Technology: The dual SiC inverter ensures high power density and efficient switching with low electromagnetic emissions.
- Modular Design: AVL’s modular EDU systems, including the high-speed and high-efficiency variants, exemplify the company's commitment to advancing electric mobility.

In summary, AVL's high-efficiency EDU represents a significant advancement in electric drive technology, offering substantial improvements in energy efficiency and performance for BEVs. This development supports the broader goal of making electric vehicles more cost-effective and appealing to a wider range of consumers.

8 CO2e footprint and comparison of other systems

Besides the already discussed technological and cost targets, a future proven EDU concept must also comply with a sustainable design for a reduction of the CO_2e footprint, furthermore it shall increase efficiency in the life cycle. “Design-to-CO_2e” as a holistic approach in the course of systems engineering meant a transition from an original focus on design-to-function and design-to-cost, to the additional dimension of CO_2 equivalent over the life cycle[4]. The total life cycle includes production, use and end-of-life, including recycling or second life.

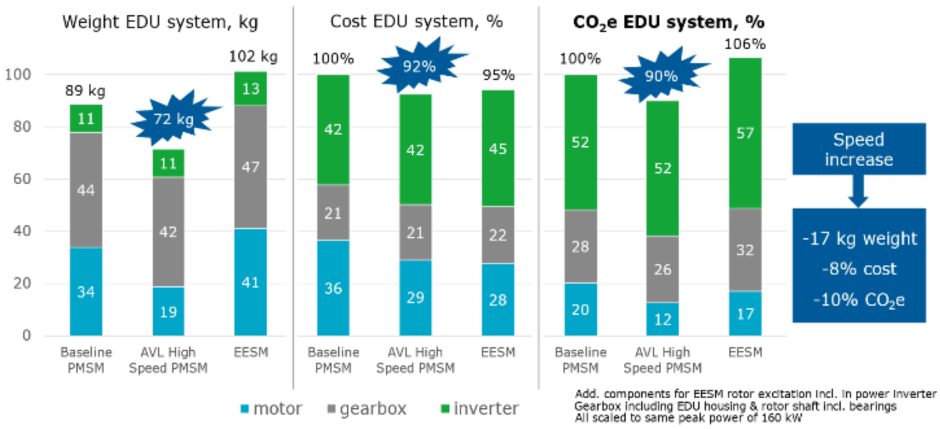

Figure 6 Weight, cost and CO_2e evaluation of the electric drive unit

COST, WEIGHT AND CO_2E COMPARISON

To compare the EDU system from AVL with other solutions, three systems with a peak power rating of 160 kW were evaluated: a baseline PMSM system, the new highspeed PMSM system, and an Externally Excited Synchronous Motor (EESM) system. For the comparison of the complete EDU system, the evaluation included weight, cost, and CO_2e of active motor parts, power in verter, and transmission, considering additional components like rotor shaft, bearings, and motor housing. Rotor ex citation for the EESM system is considering cabling, sensors, and rotor interfaceas part of the power inverter. Collector ring and copper bars/wires to the rotor windings are already considered within the emotor active parts.

By usage of the highspeed emotor 17 kg weight and 8 % cost can be saved, whereas the EESM shows a potential of 5 % cost saving, but the disadvantage of up to 13 kg in terms of system weight, FIGURE 6.

Evaluations on the sustainability of EDU systems by comparing calculated CO_2e emissions showed an advantage of 10 % with the highspeed PMSM System. The EESM system indicates a potential increase in terms of CO_2e emissions of up to 6 %

9 Conclusions

In conclusion, the integration of advanced technologies in electric powertrains presents a significant opportunity to reduce the CO_2e footprint across the product lifecycle. By employing high-speed electric motors with high power density and state-of-the-art energy-efficient e-axle systems, the automotive industry can achieve substantial improvements in efficiency and sustainability. The use of recycled materials and increased levels of integration further enhance these benefits, contributing to a more sustainable and environmentally friendly approach to e-mobility.

Looking ahead, future applications will focus on the development of highly integrated EDU systems with high-speed e-motors for small vehicle segments. These systems will leverage advancements in materials science and engineering to deliver superior performance in terms of cost, weight, packaging, and efficiency. The combination of these factors will not only reduce the environmental impact but also provide economic advantages, making electric vehicles more accessible and appealing to a broader market.

The continued evolution of electric powertrain technology will play a crucial role in the global transition to sustainable transportation. By prioritizing innovations that enhance performance, sustainability and improve cost, the automotive industry can lead the way in reducing greenhouse gas emissions and promoting a greener future.

References

[1] I EA (ed.): Net Zero Roadmap: A Global Pathway to Keep the 1.5 °C Goal in Reach. 2023 Update, Paris, Online: https://www.iea.org/reports/net-zero-roadmap-a-global-pathway-to-keep-the-15-0c-goal-in-reach, access: November 22, 2023

[2] GHG Protocol Secretariat (ed.): GHG Protocol Standards and Guidance Update Process. Online: https://ghgprotocol.org/ghg-protocol-standards-and-guidance-update-process-0, access: November 22, 2023

[3] T. Schmid, M. Rothbart, C. Sams, “Design-to-CO2eq – The Reality Check,” ATZ worldwide, Springer Verlag, pp 17-21, 2024

[4] M. Deiml, A. Simonin, P. Jafarian, “High Speed Electric Drive by AVL”, CTI Symposium Berlin, 2018

[5] A. Angermaier, M. Deiml, W. Vallant, G. Fuckar, “Electric drive units with high power density and sustainability through high speed and maximum efficiency”, 45th International Vienna Motor Symposium, 2024-09; Vienna, Austria, April 24-26, 2024

Presenter Biography

Wilhelm Vallant was studying Automotive Engineering at University of Applied Sciences in Graz and started his professional career in 2010. Since 2012 he has been working as a development engineer at AVL in the field of transmission and component testing. In recent years, he has dedicated himself to topics such as transmission hydraulics, test planning, and test management for complete transmissions as well as components and load collective creation, with increasing responsibility. In 2019, he transitioned from transmission development to the area of global business development, sales, and international business, focusing on electric drive systems and transmissions for passenger cars. In his role as Senior Product Manager, he is responsible for the further development and strategic alignment of the product area for the development of electric drive systems and transmissions. His tasks include market analysis, creation of the technology roadmap, planning of R&D activities, coordination of global markets, and coordination of promotional activities.