

Sustainable EDU Solutions

- AVL's pathway forward to support e-Mobility with power dense, efficient, sustainable and cost attractive
Electric Drive Unit (EDU) solutions -

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ABSTRACT: The e-mobility market is projected to continue its growth, leading to increasing production volumes annually. Consequently, the 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 (CO_{2e}) 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 CO_{2e} 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 CO₂ reduced future, many countries and territories have already stated their target on CO₂ 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 CO₂ 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 CO₂e neutrality. Nevertheless, the CO₂e neutrality is influenced by many boundary conditions and factors. The increasing need for energy security may be contradictory to the CO₂e 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 CO₂e 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 CO₂e 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 CO₂e impact of powertrain components, thus contributing to a more sustainable and environmentally friendly future for electric mobility.

3. DESIGN TO CO₂E OVER THE PRODUCT LIFE CYCLE

In product life cycle modelling, it is important to know the qualitative patterns of CO₂e influenceability, determination of and the actual occurrence to define appropriate optimization measures at the right times.

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 CO₂e decreases significantly during later phases in the product lifecycle. Although the majority of CO₂e 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 CO₂e footprint.

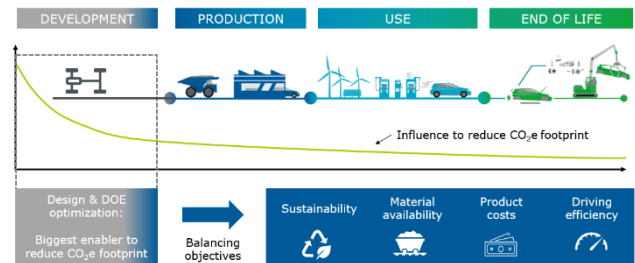


Figure 1 Model of the product lifecycle with qualitative evaluation of CO₂e influenceability⁽⁵⁾

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 CO₂e 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.

CO₂e footprint is important with regards to CO₂ targets. It also has an impact on product cost. For example a 80kWh battery comes with a production CO₂e footprint of 4t to 7t depending how and where it is produced. If you can cut that CO₂e footprint by 50%, you can reduce product cost by 300 to 500 EUR assuming a 150 EUR/t CO₂ certificate price in the EU once the price cap on CO₂ certificates is withdrawn in the EU in 2027. Thus, designing for low CO₂e in production is also influencing cost competitiveness.

4. DESIGN TO CO₂e METHOD IN PRODUCT DEVELOPMENT

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 CO₂e 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 CO₂, Recycling, 2nd Life applicability. This phase often requires multiple iterations to achieve the target verification, resulting in an achievable CO₂e value.

Following this, we enter the Supplier nomination phase, where we discuss CO₂e targets with suppliers based on their quotations. This phase may involve target offsetting to meet the desired CO₂e levels, culminating in the actual CO₂ equivalent for production.

In the final phase of CO₂e optimization we focus on the production optimization using increased portion of primary data for final assessment of the CO₂e 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 CO₂e phase. The data backbone evolves from relying on secondary data in the early stages to incorporating primary data as we approach production.

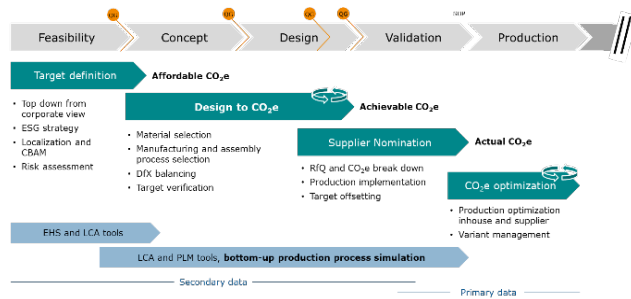


Figure 2 Design to CO₂e in Product Development

5. IMPACT OF TECHNOLOGY SOLUTIONS ON PRODUCT LIFE CYCLE CO₂E

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.

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.

$$P_{mech} = \omega \times M$$

$$M \sim d^2 \times l^{(4)}$$

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.

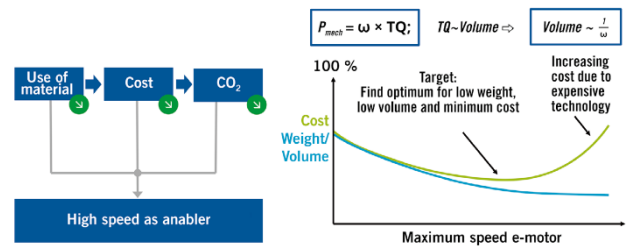


Figure 3 Basic evaluation visualizing the influence of e-motor speed vs. component cost.⁽⁴⁾

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⁾

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.

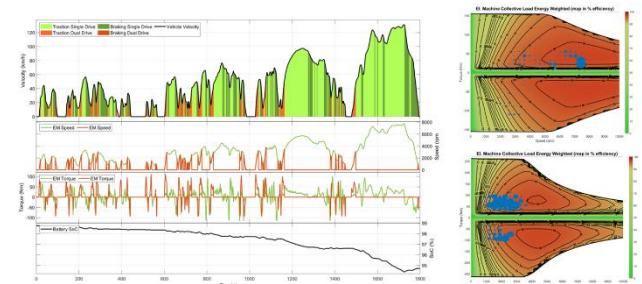


Figure 4 Operating strategy and E-Motor characteristics applied

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.

The need 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 has 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 is pumped along the stator slots. Thus, the copper losses are very efficiently cooled. An air gap tube keeps

the oil away from the rotor space, so no friction or splashing losses are present.

The transmission is not directly cooled with the same fluid, because of pollution by metal abrasion. The transmission has a lubrication circuit with an own oil pump. Transmission fluid cooling is realized by spraying lubrication oil against the cooled housing towards the e-machine.

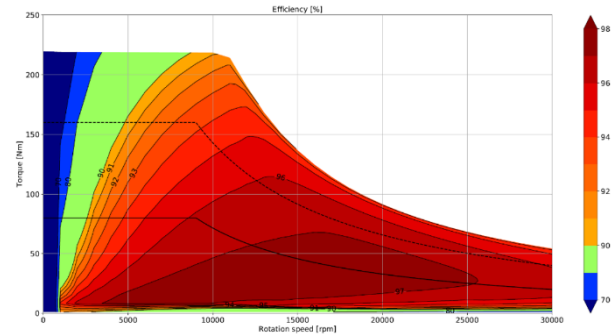


Figure 5 High Speed E- Machine Performance and Efficiency

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 balanced. This is shown in the map in FIGURE 5 which is generated for 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

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 $\frac{AC_{loss}}{DC_{loss}}$
- cooling with best-in-class effectiveness, combined with the inverter
- mechanical rotor stability up to $1,2 * n_{max}$

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 aimed at significantly improving the energy efficiency of battery electric vehicles. 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 CO₂e footprint, furthermore it shall increase efficiency in the life cycle. "Design-to-CO₂e" 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 CO₂ equivalent over the life cycle⁽⁴⁾. The total life cycle includes production, use and end-of-life, including recycling or second life.

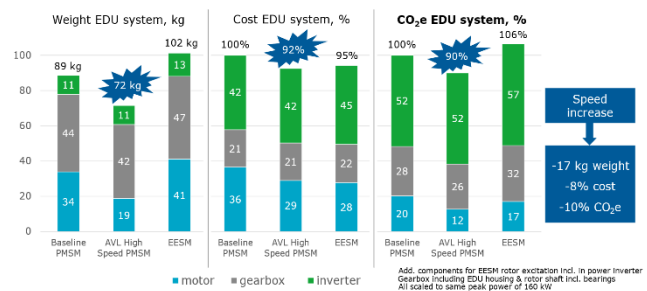


Figure 6 Weight, cost and CO₂e evaluation of the electric drive unit
COST, WEIGHT AND CO₂E COMPARISON

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 CO₂e of active motor parts, power inverter, and transmission, considering additional components like rotor shaft, bearings, and motor housing. Rotor excitation for the EESM system is considering cabling, sensors, and rotor interfaces

part of the power inverter. Collector ring and copper bars/wires to the rotor windings are already considered within the e-motor 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 CO₂e emissions showed an advantage of 10 % with the highspeed PMSM System. The EESM system indicates a potential increase in terms of CO₂e emissions of up to 6 %.

9. IMPACT OF RECYCLING MATERIALS ON CO₂E FOOTPRINT

The typical motor used in an electric vehicle has a continuous output power of approximately 150 kW. This conclusion was reached through a comprehensive analysis of all models on the market in 2023, which involved a systematic evaluation of the average output power in relation to the number of sales and the number of models. The resulting data indicates that the total average output power falls within the range of approximately 150 kW.

To achieve compatibility across the different machine types, the results of an optimization design study were scaled down to 150 kW output power via the machine length and volume. This resulted in six machines with identical diameters, peak speeds and voltage levels as well as comparable corner speeds. One PMSM, EESM and IM for 400V and 800V DC link voltage. The shaft and housings have been approximated to derive the overall material amounts used in the different machines. It should be noted that the EESMs and IMs are generally less power dense, resulting in longer machines that require more material for their housing and shaft. The PMSM and EESM are comparable in terms of their total steel lamination weight and the quantity of copper required for the stator. Regarding the rotor, the IM was designed with a copper squirrel cage, and both machines the EESM and the IM require a similar amount of copper for their rotor construction. However, the IM stands out significantly in the amount of copper and steel lamination required for the stator, which is considerably higher than the EESM and PMSM.

To quantify the greenhouse gas (GHG) emissions associated with distinct production phases and the manufacture of materials, the CO₂ equivalent (CO₂e) values have been utilized. Wherever available, the GWP100 values in accordance with the IPCC 2021

guidelines were employed as a life cycle impact assessment method.

To assess the emissions associated with our various machines, we concentrated our analysis on the components that contribute the most to the overall carbon footprint. These include permanent magnets, electrical steel, copper hairpins/wires, steel shafts, and aluminum housing.

In order to approximate the true carbon footprint of the individual components, the emissions associated with energy-intensive production steps, as well as the raw material production, were taken into account. The results demonstrate that the IM generates the highest CO₂e emissions due to the considerable quantity of copper required, followed by the PMSM and then the EESM, which produces the lowest amount of CO₂e in its manufacturing. The discrepancy between the PMSM and EESM can be traced back to the significant environmental impact associated with the production of the permanent magnets.

The utilization of recycled raw materials has the potential to significantly reduce the overall CO₂e emissions as shown in FIGURE 7. The discrepancy between the least and most environmentally friendly machines produced from primary raw elements is approximately 15%. When primary raw materials are replaced with recycled ones, the emission reduction potential for all machine types is greater than 75%. It is reasonable to assume that the same relationship applies to the emissions of other components as well.

Emission by Component: Virgin vs Recycled Materials (400V PMSM)

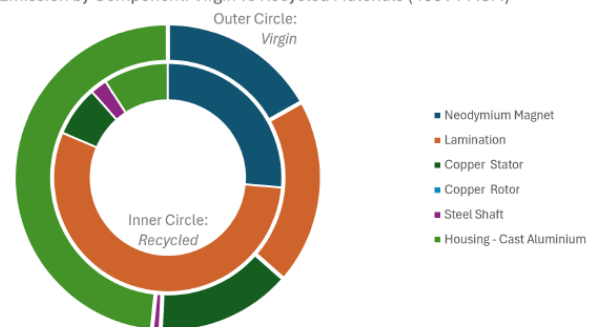


Figure 7 Weight, cost and CO₂e evaluation of the electric drive unit

Using this potential for CO₂e reduction is unfortunately currently not economically viable for most of the materials involved, as it would require alloy-to-alloy recycling or generally higher quality scrap metal. Although all the processes involved are technically feasible, there would be significant up-front costs to introduce these supply chains and product-specific recycling. Nevertheless, some of the processes are already in use and companies such as GM have announced that they will introduce

alloy-to-alloy recycling of their production scrap. With relevant legislation such as CO₂e pricing and product passports, there is an opportunity for this potential to be fully harnessed in near future.⁽⁶⁾

10. CONCLUSIONS

In conclusion, the integration of advanced technologies in electric powertrains presents a significant opportunity to reduce the CO₂e 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.

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