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European Initiatives Addressing High Efficiency and Low-Cost Electric Motors for Circularity and Low use of Rare Resources

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Abstract

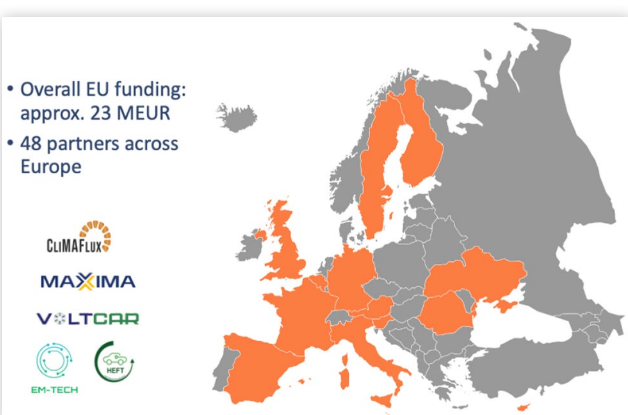
The automotive industry is amidst an unprecedented multi-faceted transition striving for more sustainable passenger mobility and freight transportation. The rise of e-mobility is coming along with energy efficiency improvements, greenhouse gas and non-exhaust emission reductions, driving/propulsion technology innovations, and a hardware-software-ratio shift in vehicle development for road-based electric vehicles. Current R&D activities are focusing on electric motor topologies and designs, sustainability, manufacturing, prototyping, and testing. This is leading to a new generation of electric motors, which is considering recyclability, reduction of (rare earth) resource usage, cost criticality, and a full product life-cycle assessment, to gain broader market penetration. This paper outlines the latest advances of multiple EU-funded research projects under the Horizon Europe framework and showcases their complementarities to address the European priorities as identified in the 2Zero SRIA. Target of this paper is to introduce a family of European projects (EM-TECH, HEFT, MAXIMA, VOLTCAR and CliMAFlux), all following the target of high efficiency and low-cost electric motors for circularity and low use of rare resources. Especially, this paper will describe the latest advances of the respective projects as well as their complementarity to address the 2Zero strategy.

Introduction

The automotive market is subject to a major transition, on one side driven by major societal challenges to reduce greenhouse gas emission ("European Green Deal" [1], a bundle of policy initiatives including "Fit for 55" [2] aiming to reduce greenhouse gas emissions by at least 55% by 2030, the "Paris Agreement" [3] as international climate treaty to limit global warming) and to improve road safety (Road Safety Initiative "Vision Zero" [4] with the ambition to achieve on European roads as close to zero fatalities as possible by 2050), on the other side enabled by the update of digital technologies. In order to structure this transition, the co-programmed partnership "Towards zero emission road transport (2Zero)", funded under the Horizon Europe programme, aims at accelerating the transition towards zero tailpipe emission road mobility across Europe and has recently published its Strategic Research and Innovation Agenda (SRIA) [5] summarizing the required innovation steps to support this transition. This transition is characterized by two main complementary technology trends: (a) the shift toward e-mobility and battery electric vehicles, and the uptake of digital solutions enabled by smart components, innovative control strategies and data platforms. Focus of this paper is to present the 5 European programs granted under the call HORIZON-CL5-2022-D5-01-09, all fostering the development of high efficiency and low-cost electric motors for circularity and low use of rare resources. The action is cumulating more than 50 partners for a funding of more than 23Mi€ European funding (see Figure 1). The ambition of the five projects is the following:

EM-TECH (*Innovative e-motor technologies covering e-axles and e-corners vehicle architecture for high-efficient and sustainable e-mobility*) The state-of-the-art showcases advancements in e-Gear systems of in-wheel motors [6], axial flux machines, direct cooling [7], and virtual sensing, each targeting efficiency, compactness, and reduced reliance on rare earth materials [8]. EM-TECH aims to surpass these innovations with cost-effective designs, AI-driven sensing, multi-physics modeling, innovative component and vehicle control strategies as well as sustainable manufacturing, achieving transformative powertrain performance.

FIGURE 1 European community around EM-TECH, HEFT, MAXIMA, VOLTCAR, and CliMAFlux projects.



HEFT (*Novel concept of a low cost, high power density and highly efficient recyclable motor for next generation mass produced electric vehicles*): Many research are focused on use less coercivity magnets [9,10,11] and others to reduce the magnet volume [12]. Few research is focused on design approaches enabling an easy magnet dismantling after EoL. Regarding the design methodology, the advanced tools based on Emag/Thermal/Structural FEM multiphysics simulations are well established, but the effects of intrinsic geometric and material tolerances need to be managed from the design view. HEFT deals with the designing and manufacturing of electric motors equipped with re-used/recycled permanent magnets.

MAXIMA (*Modular axial flux motor for automotive*): Most electric vehicles still rely on radial flux electrical machines. Among them, permanent magnet radial flux electrical machines were chosen by most car manufacturers and suppliers as traction motors, either using the interior permanent magnet radial flux or the permanent magnet assisted synchronous reluctance topology. The design as well as the mass production manufacturing is well known event though there are still scientific and technical challenges. An in-depth analysis of the technology of axial flux EM shows that a great potential of increasing the performances of the electric powertrain still exists [13]. Besides continuing to improve the performance in terms torque/power density and efficiency [14], the main challenges that are to be faced by PM axial flux EM are linked to the scarcity of rare earth PMs and to mass production manufacturing costs which are still too high to address the automotive core market (50 kW-120 kW). The ambition of MAXIMA is to design and develop a low-cost modular PM axial flux EM for the automotive core market, with improved performances, integrating CRM less strategies and with a low environmental impact.

VOLTCAR (*Design, manufacturing, and validation of ecocycle electric traction motor*): Current electric traction motors rely heavily on rare earth materials, specifically Neodymium Iron Boron (NdFeB) permanent magnets (PMs) [15]. The amount of NdFeB magnets in these motors varies from 1.5 kg up to 4 kg [16]. Given the massive demand and localized sources of these materials, it is crucial to reduce the amount of NdFeB used in all applications to balance demand with availability in the coming years. VOLTCAR investigates radial flux permanent magnet motors with the aim to ensure required performance, various sustainability criteria, as well as cost, reliability, and integrability issues. The objective of NdFeB reduction is pursued through novel ecodesign approaches, innovative motor topologies, advanced recycling and reuse approaches, and other technological solutions. The projects' activities are very well aligned with the European Commission's "Critical Raw Materials Act" [17], which aims to ensure a secure and sustainable supply of critical raw materials for Europe's industry. This alignment supports the Act's goals of reducing dependencies, increasing preparedness, and promoting supply chain sustainability and circularity. By focusing on reducing the use of rare earth materials and enhancing recyclability, the projects contribute to the EU's objectives of strengthening domestic supply chains and fostering sustainable practices.

CliMAFlux (*Circular design and manufacturing techniques for next-generation highly-efficient integrated axial flux motor drives for electric vehicles*), innovates the design and manufacturing processes of axial flux motors towards improved range, performance, circularity, and reduced costs. This innovation with respect to the state of the art include composite rotor technologies with reversible permanent magnet retention, hybrid excitation systems to reduce permanent magnet mass, and alternative aluminum winding materials with advanced insulation for high-voltage applications.

The five projects have been designed to address the research priorities identified in the 2Zero SRIA [5]. Hence, this document has been prepared with a large group of stakeholders who represent the diverse areas covered by the partnership and includes a description of some of the research and innovation activities needed to achieve a climate-neutral road transport. It further details the technical and specific objectives, sets milestones and provides a timeframe for such R&I activities and their expected outcomes. The five projects are developing complementary approaches to develop high efficiency and low-cost electric motors for circularity and low use of rare resources, finally supporting the transition toward sustainable mobility. Figure 2 illustrates the coverage of the 5 projects toward the research needs from the 2Zero SRIA. Intuitively, all projects are addressing the research needs "Vehicle technologies and vehicle propulsion solutions for BEV and FCEV" and "LCA and Circular economy" – with different emphasis on the underlaying R&I areas. The areas of "powertrain modularity and integration" as well as "methods and tools for LCA/LCC" are key pillars for all projects, which are then selectively combined with "thermal management," "digitalization enabled design methods," "efficient control of vehicle operations," respectively different aspects of circular economy. This highlights the importance of multi-disciplinarity to support the uptake of innovative e-Motor technologies for efficient, financial- and environmentally sustainable e-mobility. In the remaining of the paper, the innovation driven by the 5 projects are introduced.

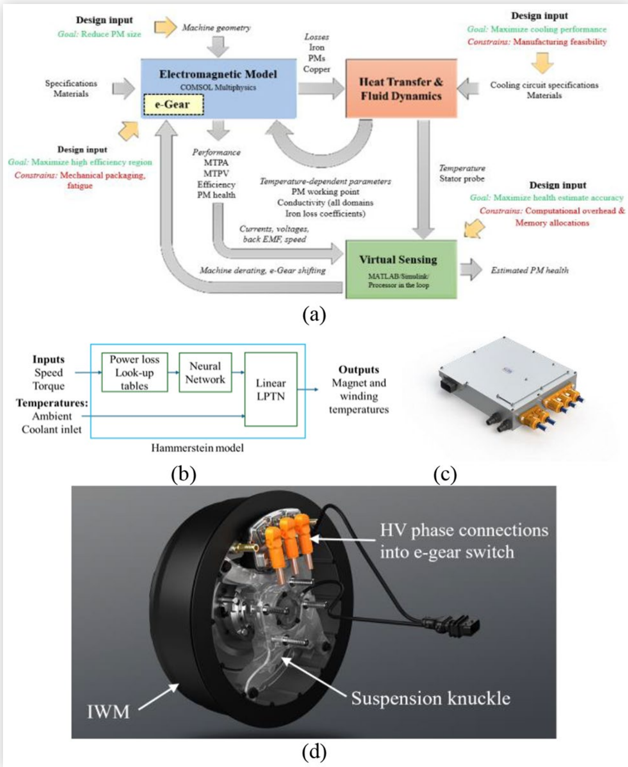
The EM-TECH Project

The "Innovative e-motor technologies covering e-axles and e-corners vehicle architectures for high-efficient and sustainable e-mobility" (EM-TECH) project aims to enhance electric motor (e-Motor) technologies for the next-generation electric vehicles (EVs), targeting both electric axle (e-Axle) and electric corner (e-Corner) powertrain architectures. The project seeks to improve the efficiency, performance, and sustainability of these propulsion systems through the development of numerous critical improvements. This encompasses i) sophisticated direct and active cooling systems; ii) virtual sensing for real-time management of the EV systems; iii) control strategies that mitigate design conservatism; iv) the adoption of reconfigurable windings to achieve electric gearing (e-gear) thereby enhancing operational flexibility and energy efficiency; v) digital twin-based optimization that incorporates life cycle analysis and costing; and vi) the utilization of recycled permanent magnets, intended to reduce the environmental impact linked to motor production, thereby emphasizing sustainability. EM-TECH aims to substantially diminish energy losses in electric traction motors, specifically targeting a 35% reduction in In-wheel motors (IWMs) for e-Corner architectures and a 25% reduction in Axial Flux Motors (AFMs) for e-Axle applications, compared to existing state-of-the-art

FIGURE 2 Complementarity of the 5 projects to address the 2Zero SRIA priorities.

Research Need	CliMAFlux	VOLTCAR	MAXIMA	EM-TECH	HEFT
Vehicle technologies and vehicle propulsion solutions for BEV and FCEV					
advanced lightweight design for zero emissions			sec		core
digitalisation enabled advanced design methods	sec	core	core	sec	sec
efficient control of vehicle operations	core	sec	sec	core	
powertrain modularity and integration	core	core	core	core	core
thermal management		core	core	sec	sec
LCA and Circular economy					
Life cycle inventory database			sec	sec	
track and trace of products and their use over life-time	sec		core		
method and tools for LCA/LCC	core	core		core	core
social LCA for the transport sector			core	sec	
methods, tools and processes for CE		core		sec	sec
system-wide LC and CE strategy modelling				core	
CE strategies for ZEVs			sec		

FIGURE 3 (a) Multi-physics modeling workflow; (b) Hammerstein model; (c) SiC Based 800V motor controller; (d) IWM with e-gear reconfigurable winding.



technologies, along with the improvement of torque density and specific torque in IWMs to surpass 150 Nm/l and 50 Nm/kg, respectively. Additionally, the initiative seeks to reduce the utilization of rare earth resources by over 60% through the implementation of recycled permanent magnets.

To achieve these goals, EM-TECH utilizes unique model-based design methodologies for both AFMs and IWMs (see Figure 3a), incorporating features such as multi-domain models that integrate electrical and thermal physics using finite element and CFD methods. These models, with varying levels of complexity, enable the assessment of system performance, such as power loss, coolant flow, and thermal behavior. Additionally, simplified or surrogate models can be coupled with vehicle models to evaluate vehicle-level performance, such as power consumption, for different powertrain configurations. Alongside hardware advancements, EM-TECH investigates (i) sophisticated control algorithms and (ii) AI-based virtual temperature sensors to enhance motor management by monitoring real-time conditions. The research has demonstrated that on-board electric powertrains can enhance ride comfort and longitudinal vehicle dynamics through preview-based control of motor torque, accounting for road irregularities [18]. Furthermore, the swift torque responsiveness of direct-drive in-wheel motors enables sophisticated control functions, including anti-lock braking system (ABS) torque modulation (currently under investigation), and is essential for enhancing vehicle safety in adverse driving conditions. Control solutions for enhancing energy savings, such as brake blending and shifting strategies for the e-gear system, are also being investigated by the University of Surrey. Specifically, the investigation into e-gear shifting solutions ranges from rule-based to optimal approaches which also include pulse-and-glide (PnG) techniques. i.e., an eco-driving where the vehicle first accelerates (pulse) and then freewheels (glide) over a continuously repeating period, while tracking a desired average speed, which also increases the overall energy saving.

The e-gear reconfigurable winding system is developed by the University of Bath and allows the motor windings to be reconfigured between a series-star and a parallel-star arrangement, the former achieving high torque and the latter achieving higher speed. The design is based on a mechanical switch arrangement, rather than a semiconductor solution. This approach is taken in order to achieve extremely low losses (so as not to negate the efficiency benefit of the technology) and to evaluate the cost of such a system, which is likely to be cheaper than a semiconductor-based equivalent. The compromise is with the changeover (reconfiguration) time, but it is expected that a total torque interruption of <100ms is achievable, and very likely <50ms. This is comparable to the gear change time of a high-performance mechanical transmission, and on the edge of what would be perceived by a human driver. The e-gear is integrated directly onto the IWM and packaged according to constraints imposed by suspension geometries (Figure 3(d)).

For the design of the magnet virtual temperature sensing method, the Politecnico di Torino has designed a reduced-order lumped parameter thermal network (LPTN) improved with a Hammerstein model, intended for real-time temperature applications. The proposed Hammerstein model is based on Neural Networks (see also Figure 3b) which correct the inputs though the use of training data to improve the overall temperature estimation. Temperature profiles and inverter signals were obtained experimentally utilizing a custom driving cycle for a two-wheel drive SUV on a baseline in-wheel motor at diverse inlet coolant temperatures. Due to the limited data, the model generalization performance was assessed using a cross-validation technique. Previously, the parameters of the LPTN were identified using a particle swarm optimization algorithm that minimizes the quadratic temperature error considering a linear parameter varying system. Then, the LPTN was linearized through auxiliary temperature sources that model the speed- and temperature dependence, since the Hammerstein model requires a linear time-invariant block of the system. The inputs to the model are the motor speed and torque required to estimate the power losses from look-up tables. Additionally ambient and coolant inlet temperatures are directly inputs to the LPTN, as shown in Figure 3b. The outputs are the magnet and winding hotspot temperatures. Results of this hybrid approach show a promising improvement in the temperature estimation compared with a single LPTN. Ongoing work is towards the real-time implementation and validation in an in-wheel drive demonstrator in collaboration with Elaphe Propulsion Technologies.

Regarding the development of a novel cooling solution for IWMs, the Politecnico di Torino has been carried out an extensive modeling work with respect to a coupled electromagnetic and thermal model in COMSOL Multiphysics. Electromagnetic phenomena are simulated exploiting a 2D model of the machine, conserving a reasonable computational effort. Losses in key components of the machine such as the stator, windings, and magnets are propagated to the thermal model for temperature computation. Due to the dependency of several electromagnetic parameters on temperature, an iterative computation is necessary, along with the machine's thermal response. Indeed, thermal phenomena are simulated exploiting a 3D model that considers heat transfer and laminar fluid flow. Simulation of the Multiphysics model is carried out over several iterations, terminating when the temperature difference computed between iterations remains below a threshold value. The development of the novel cooling system has been largely informed by the modeling process, where critical design decisions were made according to the results obtained numerically. Another EM-TECH innovation aimed at reducing energy losses by 20-25% and lowering the overall costs of electric drivetrains consists of the Ideas & Motion silicon carbide (SiC)-based power inverter optimized for axial flux motor driving (see also Figure 3c). The 800V SiC motor controller currently under development shows promising features in terms of power density and offers a lean internal structure that facilitates an easy assembly process and a higher reparability rate, making the project both economically and environmentally advantageous. Furthermore, Politecnico di Torino's expertise in digital twin technologies and life cycle analysis has supported Ideas & Motion in enhancing the circularity and sustainability of their motor controllers.

EM-TECH employs a variety of validation methodologies, ranging from virtual simulations and Model-in-the-Loop (MiL) simulations to distributed X-in-the-Loop (XiL) platforms for testing the proposed innovations. Within this framework, a vehicle simulation toolchain based on the AVL VSM simulation platform has been developed to host surrogate models of EM-TECH components and assess their impact at the vehicle level across different vehicle segments. Additionally, EM-TECH aims to assess and experimentally demonstrate e-axle components, utilizing the dSpace Scalexio Rapid Prototyping device at the University of Ilmenau to run a customized virtual vehicle model in the XiL environment for control evaluation and refinement while the AFM, operated via the Ideas and Motion controller, will be installed and tested on the University of Surrey's test rig. A secure VPN connection through routers has been established between the dSpace systems at both universities to control and manage the two test rigs, with initial tests conducted to measure the round-trip time. Moreover, the integration of IWMs into the smart e-corner at the University of Ilmenau, along with the deployment of an IWM prototype on the powertrain test rig, is planned. The benefit of using two interconnected test rigs is the ability to evaluate and optimize the performance of the IWM and AFM systems under various conditions while enabling real-time data exchange. This setup allows for synchronized testing and comprehensive analysis of system behavior across different scenarios.

The HEFT Project

Novel concept of a low-cost, high-power density and highly efficient recyclable motor for next generation mass produced electric vehicles (HEFT) project considers that an energy efficient rare-earth synchronous motor is the best option for next generation high-power primary axle traction EVs [19]. It focuses on a set of innovation challenges on electric synchronous motor configuration based on SiC inverters (direct cooling of rotor and stator, advance insulation for high voltage, multibarrier rotor topology, stator manufacturing based on continuous windings [20]) and advanced materials (advanced GBD magnets, epoxy for magnet fixation, composite for motor housing, insulation resin). These innovations will result in a high-efficient and low-cost solution that will be validated on two e-Motor for different vehicle segments, which compared to two main references automotive IPM commercial motors in Europe (the e-Motor of the Fiat 500e and the e-Motor of Volkswagen ID4 have been chosen as benchmark e-Motor for segment A+B and segment C+D respectively) will lead to next impacts:

- Motor insulation for voltage >800V,
- 20% reduction motor losses,
- >7 kW/kg power density,
- 28% cheaper,
- 50-66% material savings,
- 60% reduction of REE content,
- >80% REE recyclability rate.

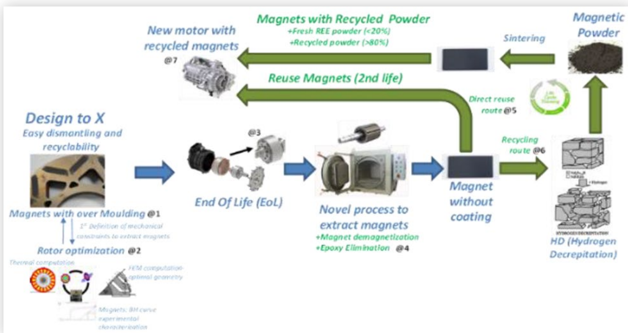
HEFT will be aligned with the ERMA action plan towards a circular economy market of rare earth permanent magnets and suggests: one alternative magnet route (Cerium based) for A+B e-Motor and two REE recycled routes together with policies promotion towards the foundation of a European rare earths industry, capable of delivering 20% of EU demand by 2030. The strategy is shown in Figure 4.

Objectives of HEFT Project

The general objective of HEFT is to develop and test two variants of lower cost, higher efficiency and power density permanent magnet eMotors for mass produced cars and vans. The two main technical objectives are:

- Development of lower cost, higher efficiency and power density electric motors for mass produced

FIGURE 4 Development of a resilient long-term strategy to face rare earth CRM (Critical Raw Material) supply chain possible issues.



cars and vans. HEFT innovations: (i) Advanced configurations (SiC inverters, advanced direct cooling systems on rotor and stator, advanced electrical insulation, IPM multibarrier rotor topology, much higher operating speeds, novel hairpin configurations, higher operating voltages); (b) Advanced materials (advanced Grain Boundary Diffusion (GBD) magnets, advanced compound materials for a high resistance magnets fixation inside the rotor, new composite materials for structural motor housing, advanced insulation resin for the slots molding).

- Development of a resilient long-term strategy to face rare earth CRM (Critical Raw Material) supply chain possible issues. In HEFT project, high saving rates (>60%) of primary rare earth CRM will be achieved by developing very compact IPM motors. At the same time, it is recognized the need to develop resilient long-term strategies to face rare earth CRM material supply constraints. HEFT project, aligning with the EU Call for Action “Rare Earth Magnets and Motors.”

e-Motor Design for A+B Vehicle Segment

A new motor design for the A+B segment has been already done, based on the methodology shown in Figure 5. In the first stage the design constraints are set. Among the different constraints the magnets grade is a key point, and a N38H grade is chosen, lower than the one used in the benchmark motor, in order to reduce the content of Heavy rare earths elements (HREE). Then the stator design is done, the stator geometry is defined considering the magnet saturation and manufacturing aspect, as continuous winding will be utilized. Once the stator is defined the rotor design is carried out. Six different rotor layouts are analyzed during the preliminary sizing stage. To reduce the mass, the stack length is fixed, and the dimensions of the rotor are obtained considering the magnet volume, working temperature and demagnetization as criteria.

FIGURE 5 Flow chart of the applied design process.

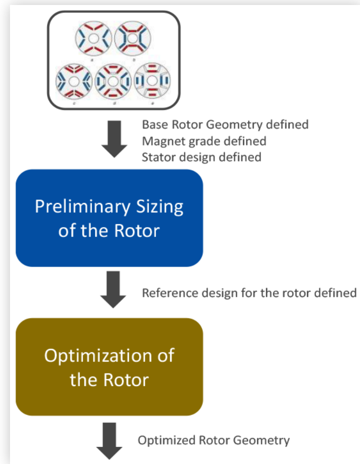


TABLE 1 Comparison of performance of motor and targets in topic HORIZON-CL5-2022-D5-01-09.

	Call Target	Obtained Results
Power density (kW/kg)	>7 kW/kg	7.32 kW/kg
Power density (kW/l)	>23kW/l	24.47 kW/l
Torque density (Nm/kg)	>20 Nm/kg	34.25 Nm/kg
Torque density (Nm/l)	>50 Nm/l	132.62 Nm/l
REE Saving	>60%	60%

Finally for the optimization of the rotor, two strategies have been carried out, one of them to maximize the power density and minimize the demagnetization, whereas the second strategy includes the minimization of magnet volume too. Both strategies provide the same results, being the best option the V-block rotor layout alternative, considering the mechanical performance and accomplish of all KPI. Cooling system is based on two different systems. Firstly, oil through the haft and sides of the inner layer of the magnets. Finally, spray cooling directly applied to the end winding.

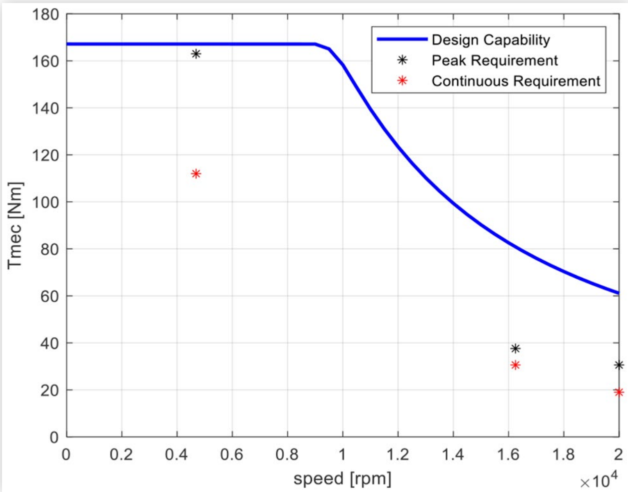
In Table 1 the comparison between the performance results of motor for A+B segment and the targets initially defined in the topic HORIZON-CL5-2022-D5-01-09 from the call HORIZON-CL5-2022-D5-01 (Clean and competitive solutions for all transport modes) is presented. The torque and power curves for the optimized e-Motor is shown in Figure 6. HEFT will develop optimized rotor designs for eMotor variant, with a design to X approach, enabling the magnet dismantling and reducing the Neodymium and Dysprosium use.

The MAXIMA Project

Overall Presentation of MAXIMA

MAXIMA aims to design a high-performance, cost-effective axial flux PM-less EM for automotive applications,

FIGURE 6 Peak envelope of the mechanical torque.



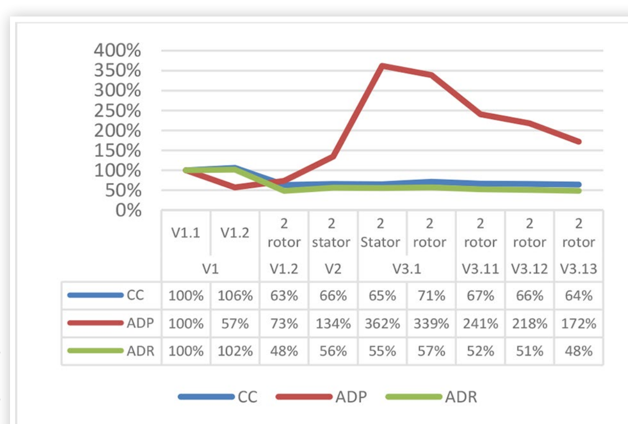
with a focus on minimizing environmental impact. The inputs for MAXIMA will include functional specifications (such as driving cycles and efficiency maps) and organic specifications (including volume and voltage) defined by experts in the automotive industry (OEMs), electric motor manufacturing, and life cycle assessment (LCA) from academia. To achieve its objectives, MAXIMA is built on three key pillars: (i) EM design: compactness, a critical factor for high performance, demands pushing magnetic materials to their operational limits. A multiphysics approach will be employed to account for the strong interactions among various phenomena, including electromagnetic, thermal, and mechanical effects. The design process will adopt a holistic approach that addresses all these factors; (ii) Digital Twin (DT): high performance as well as life increase require a perfect understanding of the magnetic and thermal states of the EM which can be facilitated by a DT. The DT enables exploitation up to the limit without damaging the EM. A DT will be developed by combining a physical reduced model with artificial intelligence based on experimental data for maximum accuracy as well as compatibility with real-time control; (iii) Manufacturing/recycling process flow: the final cost of a product highly depends on the cost the cost of raw materials and the optimization of the manufacturing process flow. Additionally, the end-of-life phase of the EM will be taken into account, particularly focusing on the recycling of permanent magnets made with CRMs. The LCA will be addressed through a transversal axis which will provide the tools and the expertise to analyze the environmental impact of the different solutions in terms of design, manufacturing and recycling proposed within MAXIMA. By the end of the project, prototypes will be manufactured to test, assess, and validate the new concepts developed in MAXIMA, including both the EM design and its manufacturing and recycling process flow. In the following, the focus will be set on how LCA is integrated from the very start of the electric machine design process, as well as the role of the digital twin in enabling optimal control of the machine.

Life Cycle Assessment (LCA) for Ecodesign in MAXIMA

LCA is a recognized method to assess how to reduce the environmental impacts of EM considering all life cycle stages. It avoids transferring impacts from one life cycle stage to another. For example, reducing the amount of certain materials may lead to a reduction of the EM efficiency. It means that while the impacts from the production may reduce, the impacts from the electricity consumption may increase. Therefore, trade-offs can be observed in between life cycle stages with LCA. In MAXIMA, the tool has been implemented from the beginning of the project. The process is iterative with recurrent exchange of data on the bill-of-materials of the design versions and the production processes and end-of-life treatment. Implementing LCA from the beginning of the project allows to preliminary quantify the impacts of the MAXIMA EM. Several versions of the EM designs have been developed to which attributional LCA has been applied. Ecoinvent 3.9.1 [21] is used as the background database. The system boundaries are based on cradle-to-gate including life cycle phases from raw material extraction to the assembly of the machine. The functional unit is the production of one EM. The impacts assessed are Climate Change (CC) [22], Abiotic Depletion (AD) [23] and Average Dissipation Rate (ADR) [24]. While AD investigates the effect of using a material on the reduction of its reserves, ADR investigates the loss of material at end-of-life, meaning that it becomes inaccessible for future applications. It gives different perspectives for the use of mineral resources.

Figure 7 shows the results of the LCA on CC, AD and ADR on different structures of electrical machines along the time. The results are given as relative difference with the first design established. For both CC and AD, the impacts have been reduced compared to the V1. This is due to the amount of Permanent Magnet (PM) that is reduced compared to V1 which is the main burden for both indicators. For all indicators, the reduction from V3.1 is due to the reduction of copper and active materials,

FIGURE 7 Results of the LCA of the production of the different designs' versions on different indicators.



while the amount of PM stays the same. Finally, for AD, copper mining is the main sources of burden. It is noteworthy that although AD is recommended by the Joint Research Center, the rare earth elements from the EM are not characterized in this method. The increasing impacts between V1 and V3.1 is therefore due to an increasing amount of copper needed for the newer designs. However, the increase of copper weight is needed to meet the targets on efficiency which impacts the use phase environmental performances. This is why the further steps for the LCA task is to evaluate the impacts on the use phase and end-of-life from the new designs.

Digital Twin of an Electrical Machine for Optimal Control

A DT of the electric machine is the central element for an improved thermal and integral control strategy for Permanent Magnet Synchronous Motors (PMSM). DTs are real-time digital replicas of physical assets, modeled and continuously recalibrated using real-time measurements [25]. The DT model that will be used in MAXIMA, is based on low-order coupled electromagnetic and thermal models extracted from high-fidelity models, enabling accurate and local calculation of losses and temperatures. These models will also be associated with Artificial Intelligence (AI) combined with experimental data for recalibration. The DT must accurately and locally determine temperature, allowing for a refined prediction of losses in ferromagnetic materials. This integration provides several key advantages for optimizing motor performance: i) monitoring the internal temperature during operation, ii) evaluating the risk of permanent magnet (PM) demagnetization, and iii) diagnosing faults promptly to schedule repairs during downtime, thus preventing breakdowns [26]. The DT also applies thermal derating to respect the motor's thermal limits. Building on this digital infrastructure, the control strategy is based on field-oriented control (FOC), which generates current references from the magnitude and angle [27]. A voltage control loop is included to extend the operating range in field weakening mode, improving high-speed performance. A trajectory selection algorithm optimizes between Maximum Torque per Ampere (MTPA), Constant Torque (CT), and Maximum Torque per Voltage (MTPV), considering the variation of dq-axis inductances and semiconductor losses to increase the efficiency of both the motor and the overall powertrain. This comprehensive approach, combining digital twin technology and optimized control strategies, will significantly enhance the performance, reliability, thermal management, and efficiency of PMSM drives in electric powertrains.

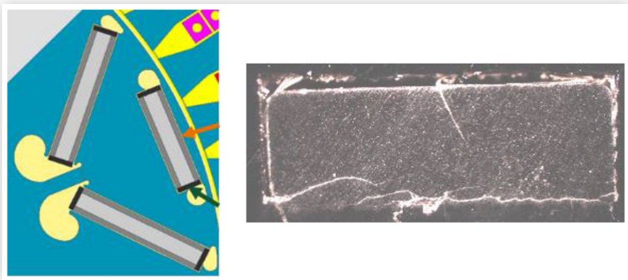
The VOLTCAR Project

Recent developments have resulted in cleaner and more efficient options for electric transportation. Whilst related technologies have evolved over a couple of generations, certain challenges continue to persist. On the part of the electric traction motors the specific issues include 1) how to reduce the dependency on the critical and strategic materials while simultaneously improving the most important performance criteria; 2) how to maintain the leading position of European car manufacturers also in the mass manufacturing segments and consequently, enhance the competitiveness of whole Europe; 3) how to increase the overall attractiveness of the electric vehicles. In response to the identified challenges, Horizon Europe project "Design, manufacturing, and validation of ecocycle electric traction motor", VOLTCAR, aims at developing a next generation high-speed electric traction motor that meets the strictest performance requirements (power density, energy efficiency), sustainability criteria (recyclability, circularity and low use of rare resources and copper) and the expectations of the automotive sector (cost, reliability, integrability). This major goal is supported by introducing digital design and optimization methodologies that can assess the life cycle costs, energy consumption, and carbon footprint in the early phase, guiding the outcomes towards maximized sustainability with reduced use of rare materials and efficient recycling and repurposing patterns. The 50-kW and 120-kW VOLTCAR motor prototypes and related technologies are experimented according to relevant standards, presenting a XiL experimentation environment. With this initiative, VOLTCAR aims to provide the automotive industry with competitive solutions, foster the creation of green jobs in Europe, and enhance the appeal of electromobility for everyone. The VOLTCAR project brings together key European automotive Tier 1/2 suppliers, companies, and research partners.

Major steps have been taken towards the key objectives. First, the manufacturing of the 50-kW electric traction motor prototypes has begun. This task has necessitated a balance among the competing objectives of reducing and recycling rare earth permanent magnets (PMs), enhancing energy efficiency, and reducing the motors' physical size. Optimization of the 120-kW motor prototypes towards 7 kW/kg and 20% reduction of losses is in good progress as well. The motor design tasks have engaged multiple project partners in conducting multiphysics computations and analyses, thorough material and manufacturing assessments, and computer-aided integration of various motor components, including both active and supporting elements, as well as the direct liquid cooling of the windings [28]. Complete motor assemblies include an 800V SiC inverter and a reduction gear, along with the necessary external cooling system arrangement.

To date, the key technical accomplishments in ecodesign and sustainability include the comprehensive life cycle analysis (LCA) and life cycle costing (LCC) of selected VOLTCAR motor designs. The findings have provided insights into how decisions at various stages affect overall performance, cost, and sustainability, leading to significant enhancements in the designs of the 120-kW motors from one version to the next. A motor analysis application has been developed, too. With this application, it is possible

FIGURE 8 Cross-sectional geometry of a design variant with encapsulated magnets and result of first practical experimentation of magnet encapsulation [30].



to benchmark various commercial designs very efficiently and reliably and compare those against our own VOLTCAR designs and produce the necessary input data for the LCA and LCC. To improve the circularity of rare earth PMs and minimize the reliance on virgin materials [29], initial samples of encapsulated magnets have been created for easy removal and subsequent reuse in, e.g., another application. The cross-sectional geometry of an early design variant with encapsulated magnets (left) and the initial practical experimentation to produce the encapsulation for a rare earth magnet (right) are illustrated in Figure 8.

The principles of the VOLTCAR digital platform have been established, and the digital threads that make up the entity have been specified. Digital threads encompass the VOLTCAR electric traction motor and other powertrain components and vehicle dynamics. The platform and its components are being actively developed to explore the intricate connections between the state of manufacturing tools, part quality, and ultimately, motor lifespan. Reduced order modeling can be applied to provide sufficient accuracy with reasonable computational effort [31].

Since the VOLTCAR motor prototypes are on their way, testing and validation activities have so far included planning and executing tests on parts and subassemblies, planning the motor and complete motor experiments (motor back-to-back and complete motor with gear both with SiC inverter) and also, implementing initial test setups to validate the feasibility of our XiL simulation concepts. The VOLTCAR digital platform supports the XiL simulation, and selected digital threads are intended to the applied for the virtual inspection of the motor condition.

Regarding the potential impact, the VOLTCAR project is proposing state-of-the-art electric traction motor designs that meet the strictest requirements, with reduced amount of rare earth PMs. All research and development steps are conducted with the potential for larger-scale application in mind. Target is to leverage the best practices in mass manufacturing of electric machines without adding many extra processing steps, ensuring the further exploitation of the VOLTCAR results. Furthermore, sustainability at large should be an integral part of the developments. VOLTCAR has potential to introduce new practices to the ecodesign of traction motors. First, we employ the LCA and LCC to guide the motor developments. Second, we aim to enable the reuse of PMs after the motors' first life. Hence, there is the potential to generate information on the future sources of the PM materials and, also, on the prerequisites of efficient, less energy intensive recycling of the magnets. In the process, data on the quality of the magnets when installed and after removal is also produced, which can help in identifying the fittest use cases and applications for the recycled magnets. Third, modeling and simulation are at the heart of modern product development and manufacturing processes to reduce the costs and time for the actions. VOLTCAR aims to elevate the state-of-the-art by introducing a digital platform that would allow assessing the motor's performance during its lifetime. The VOLTCAR platform and the first use cases are under intensive development and planned to be demonstrated during the second half of the project. Last, to prove the benefits of the VOLTCAR outcomes, practical experiments need to be carried out. The measurements of the VOLTCAR prototypes are scheduled for the second half of the project. The whole purpose of the extensive testing campaign is to show how far the set targets are reached and also to provide material for the communication, dissemination, and exploitation of the results and hopefully, for promoting and advancing clean electrification.

The CliMAFlux Project

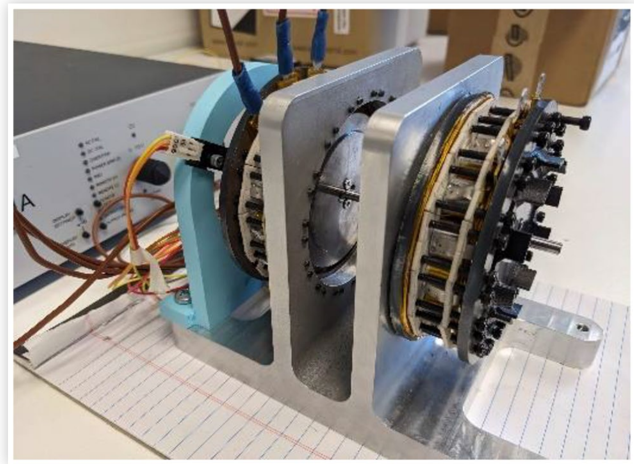
CliMAFlux develops novel rotor, winding and integration concepts for more performant axial flux motors. Innovative designs and manufacturing processes will provide a 35% energy loss decrease in driving cycles, ensure cost competitiveness up to 50% costs reduction as compared to benchmarked electric vehicle motors reaching ~€5/kW at mass production level and demonstrate >23 kW/l of continuous power densities and >7 kW/kg of specific power, while reducing the need for rare earth materials by 60%, enhance circularity over the lifetime including >70% recyclability at the end of life. The CliMAFlux on-board axial flux motor in the range of 50-to-120 kW continuous power is integrated with the high-efficiency single-speed mechanical transmission system and an 800V SiC-based power electronic inverter into a single integrated drive unit. Deriving from the CliMAFlux axial flux traction motors, a new series of axial flux motors, optimized for the highly-efficient and responsive actuation of electrified chassis systems and ancillaries for passenger cars and vans will be developed. In particular, the CliMAFlux introduces fractional power axial flux motors for an electro-mechanical active suspension actuator powered by compact GaN-based power electronic inverter. CliMAFlux will create a digital-twin-based optimization framework for axial-flux motors and integrate drive units to improve performance, energy efficiency, and reduce costs and environmental impact. This framework will be customized for specific electric vehicle applications, such as B-segment passenger cars or vans. The optimization will focus on motor geometry, material selection, cooling systems, and operating parameters, using advanced high-fidelity multiphysics models and will focus in particular on the CliMAFlux axial-flux integrated drive unit concepts to achieve these improvements. The resulting electric drives will be managed by robust predictive controllers based on the CliMAFlux digital twins, including artificial intelligence -based prediction models, which will also facilitate novel functionalities in vehicle systems, hereby exploiting the full capability of the complete electrified drivetrain. CliMAFlux develops an axial-flux rotor that uses a reversible retaining mechanism to secure permanent magnets, enabling their easy recycling. Also, the stator design will allow easy extraction of windings without the use of resins or varnishes. Optimizing the magnet shape and motor geometry will reduce rare earth content by over 60% compared to current motors, while improving efficiency. Hybrid rotor excitation systems, combining permanent magnets and excitation windings will further reduce or replace permanent magnet usage. A focus on recyclability and environmental impact aims for a >70% recyclability rate and integration of sustainable materials and processes in manufacturing. The individual axial-flux motors and integrated drive unit will be benchmarked over a wider range of vehicles, in terms of both performance and environmental impact, on virtual such as X-in-the-Loop with digital twin, and hardware test platforms up to TRL7 i.e., a representative B-segment test vehicle.

Axial-Flux Integrated Drive Unit Innovations

The CliMAFlux project covers a wide range of specific axial-flux machine design innovations. The project builds upon the extensive expertise and know-how of the CliMAFlux consortium partners on the Yokeless And Segmented Armature (YASA) axial-flux motor technology. For the rotors, two innovations are being investigated: composite rotor technologies and hybrid excitation. Composite rotor technologies, featuring a reversible permanent magnet (PM) retaining mechanism, will be implemented based on lessons and design methodologies derived from literature on conventional radial flux (RF) machines [32, 33, 34]. However, these will be applied and adapted for the first time to the innovative CliMAFlux axial flux YASA traction motor topology, given its completely different rotor layout. The hybrid excitation system will combine the advantages of PM excitation, which creates a bias magnetic field, with a field winding to increase or decrease the magnetic field as needed.

This approach significantly reduces the required PM mass, as demonstrated in studies [35, 36, 37], and will be introduced for the first time in yokeless AF traction machine prototypes. Similar to the rotor development, novel winding assembly and extraction methods are being explored, aiming to facilitate ease of manufacturing, enhance functional recyclability, and reduce or eliminate the use of bonding techniques. Additionally, conventional enameled copper wire will be replaced by aluminum

FIGURE 9 Low-voltage fractional-power YASA motor using anodized aluminum foil winding.

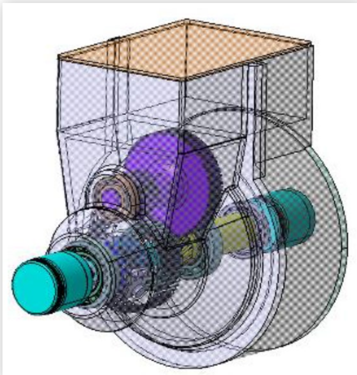


windings. For these aluminum windings, alternative insulation materials with improved properties to address partial discharge issues—an inherent problem in motors powered by 800V SiC inverters—will be investigated. In addition to organic insulation materials, alumina (aluminum oxide by anodization) will also be considered as an electrical insulator. The use of anodized aluminum foil windings was previously demonstrated in a low-voltage fractional-power YASA motor is presented in Figure 9. Building on this, the CliMAFlux project will extend this technology to the flat windings currently used in YASA machines and aim to increase the insulation resistance to make this technology viable for 800V motors.

The mechanical and cooling integration of the CliMAFlux machines will be combined with high-efficiency, low-cost mechanical transmissions. Detailed analysis of the significant, yet unexplored, efficiency improvements achievable through transmission redesign can be found in [38]. Additionally, the project will focus on the functional, mechanical, electrical, and cooling integration of the CliMAFlux machines with modular SiC-based high-voltage power electronics. A concept for the integrated drive unit is presented in Figure 10.

The development of an axial flux (AF) machine series for compact, efficient, and responsive chassis actuation systems and ancillaries—such as electric motors for electro-mechanical active suspension actuators [39]—will be integrated with GaN-based power electronics from the HighScape project. This extends the impact of the CliMAFlux yokeless AF motor technology, which has never been evaluated for these types of applications. Machine cost reduction will be addressed through material selection and optimization, particularly by evaluating different magnet materials with low rare-earth content. This will lead to a reduction in the total rare-earth mass of the machine by approximately 50% to 65% compared to the state-of-the-art L13 motor by Tesla and the P400 motor by YASA, for the same power rating. Further optimization will focus on the lamination of the electrical steel used in the axial-flux motor. Digital twinning will be employed for

FIGURE 10 One of the suggested integration concepts having a parallel shaft helical gear transmission, vertical inverter package.



application-based electric motor optimization. The baseline motor design will be tailored to specific electric vehicle applications and their typical driving cycles. The CliMAFlux optimization routines will build on methodologies recently presented in [40, 41, 42, 43, 44], including robust AI-driven machine and powertrain system optimization [45]. This will be done at a level of machine customization never attempted before. Moreover, for the first time, neural-network-based digital twins (DTs) will be systematically used for neural network model predictive control (NNMPC)—as demonstrated in a preliminary example of inverter control in [46]—and applied to powertrain, energy management, and active reliability control, ensuring mission completion through motor control. The life cycle assessment (LCA), life cycle cost (LCC), and recyclability of the machines will be addressed through innovative axial flux and integrated drive unit solutions, along with novel tooling for end-of-life machine disassembly. Additionally, a proposal for smart marking of electric motor components will be introduced to enhance sustainability and recyclability [47].

Conclusions

EU must increase its resilience amid global and local crises. The current dependence of the electric traction motors on the rare earth PM materials is problematic; the magnets are imported and expensive. A particular challenge in reducing the quantity or quality of magnets lies in the contradiction it poses to the objectives of enhancing power density and energy efficiency. By accepting a slightly lower specific power, the reduction or even elimination of the rare earth PM materials becomes significantly more feasible. The mission is to contribute to creating the key attributes and technologies for the future's mass market electric traction motors and building Europe's independence in component supply chains regarding next-gen electric traction motors.

The five European projects are tackling these challenges under different angles: This includes (a) the introduction of innovative axial flux motors for CliMAFlux, EM-TECH and MAXIMA with the target to reduce amount of rare earth while increasing performances and power density; (b) multi-physics based optimization of radial flux motor designs for VOLTCAR, HEFT and EM-TECH to increase efficiency while reducing rare earth content; (c) introduction of innovative e-Gear (EM-TECH) and optimized mechanical transmissions (CliMAFlux) to increase the high efficiency region; (d) introduction of innovative control strategies at e-drive and vehicle level (CliMAFlux and EM-TECH) to take advantage of the e-drive design capability such as fast torque activation of in-wheel motors; (e) usage of reused and recycled magnets (HEFT) and ecodesign approaches enabling the efficient dismantling of magnets (VOLTCAR and HEFT) to reduce environmental footprint.

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Definitions, Acronyms, Abbreviations

2Zero - Towards zero emission road transport

ABS - Anti-lock Braking System

AC - Abiotic Depletion

ADR - Average Dissipation Rate

AF - Axial Flux

AFM - Axial Flux Motor

AI - Artificial Intelligence

BEV - Battery Electric Vehicle

CC - Climate Change

CE - Circular Economy

CFD - Computational Fluid Dynamics

CRM - Critical Raw Material
CT - Constant Torque
DT - Digital Twin
EM - Electric Motor
EoL - End of Life
ERMA - European Raw Materials Alliance
EV - Electric Vehicle
FOC - Field-Oriented Control
FCEV - Fuel Cell Electric Vehicle
GaN - Gallium Nitride
GBD - Grain Boundary Diffusion
HD - Hydrogen Decrepitation
HREE - Heavy Rare Earth Elements
IPM - Interior Permanent Magnet
IWM - In-wheel Motor
KPI - Key Performance Indicator
LC - Life Cycle
LCA - Life Cycle Assessment
LCC - Life Cycle Costing
LPTN - Lumped Parameter Thermal Network
MiL - Model-in-the-Loop
MTPA - Maximum Torque per Ampere
MTPV - Maximum Torque per Voltage
NNMPC - Neural Network-based Model Predictive Control
OEM - Original Equipment Manufacturer
PM - Permanent Magnet
PMSM - Permanent Magnet Synchronous Motors
PnG - Pulse-and-Glide
REE - Rare Earth Elements
RF - Radial Flux
SiC - Silicon Carbide
SRIA - Strategic Research and Innovation Agenda
TRL - Technology Readiness Level
VPN - Virtual Private Network
XiL - X-in-the-Loop
YASA - Yokeless And Segmented Armature
ZEV - Zero Emission Vehicle

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