B R&D Challenges: Battery Electric Vehicle 2024+

In summary, the following specific research needs for product development for the European and global market (to strengthen the European competitiveness and the European exports) can be identified for the years 2024+:

- Energy Storages
  - (Structural) Battery Integration from cell to pack to battery system
  - Advanced Lithium-Ion Batteries 3rd and 4th generation as well as advanced Battery Technologies
- Electric Components
  - Electric Motor and matching inverter technology and manufacturing for high voltages and supply chain independence warranty (Heavy Rare Earth Free designs)
  - Vehicle-, Motion-, Drive- or Powertrain-Control components & systems (Software & Hardware)
  - Converter, inverter and Power Electronics with new architecture for higher integration levels and lower costs
  - New design guidelines to guarantee disassembling and remanufacturing to fulfill sustainability regulations.
- Charging Technologies
  - Ultra-fast charging technology
- Thermal Management and Energy Management on BEV Level
  - More efficient Technologies and system integration

B.1 Position

Battery-powered electric vehicles (BEV) represent an outstanding opportunity to make mobility more energy-efficient, to decarbonize, to move away from fossil energy carriers (requiring that electricity is produced sustainably) and to reduce pollutant emissions.

Although this position paper focuses on the automotive sector with on- and off-road vehicles including non-road mobile machinery, other mobility sectors such as aviation and inland/maritime shipping will also benefit from the research addressed in this section.

Technologies currently used in series production still need innovation to achieve lower cost, higher efficiency, performance and solutions for circular economy. Further research and developments are required regarding the functionality and efficiency of the drivetrain components as well as for manufacturing technologies and production processes to be able to deliver competitive and sustainable products with high efficiency, low resource consumption, high reliability and durability as well as low costs.

Modern development processes start with virtual prototyping to save time, money and unnecessary iterations, especially in this currently still imperfect field of expertise. Therefore, simulation tools, continuous validation in mixed development and simulation environments (SIL, MIL, HIL, VIL)[6] and advanced development methods and tools (e.g. co-simulation, data analytics, AI, ML) are used to reach these high-level goals.

The Austrian research landscape needs to develop the methods and data from component to system level including the necessary hardware technologies to bring advanced products onto the market safely, cost efficient and sustainably.

B.2 Requirements on Technology Development and Research Demand

B.2.1 Energy Storages

The **major challenge** in the development of electrified vehicles is the **rapid change in battery technology** and the resulting effort and increasing risk with regard to the key aspects for the Austrian

[6] Software in the Loop (SIL), Model in the Loop (MIL), Hardware in the Loop (HIL), Vehicle in the Loop (VIL)

supplier industry: the safe integration of new battery cell technologies, the early detection and avoidance of critical errors in the battery system and drivetrain, the necessary expertise (cell chemistry, manufacturing process, cost structure, low environmental impact) and infrastructure (test benches for electrical but also abuse, misuse and environmental tests) for the development of optimal battery management. This also enables the necessary industrialization competence and the associated quality management to be established.

The **success of battery electric vehicles (BEVs)** in the automotive sector strongly depends on the **development of safe high-energy batteries at competitive prices**. Therefore, the Austrian supplier industry must focus on the development of methods, tools and components to increase the operating range, reliability and safety of BEVs, and to lower their costs in €/kWh and their ecological footprint.

The **objective of the R&D portfolio** covers the improvement of existing batteries, as well as further research regarding the next generation of battery technology – thus covering materials of generation 3a, b (dominantly NMC (Nickel Manganese Cobalt) based cathodes, but also higher voltage solutions such as NMO (Nickel Manganese Oxide) materials for cells voltages above 4.5V; Si-graphite composite based anodes and pure silicon anodes) as well as 4 (solid-state dominated) and 5 (post-Lithium chemistries e.g. Na-Ion).

In addition to the focus on the development and manufacturing of modules or packs, the **opportunities also lie in battery cell, module and pack production**. New cell types and technologies allow much higher variation and optimization of battery modules and packs. Therefore, it is essential to expand the necessary skills and competencies in Austrian industry and research in this area as well. Battery technology needs to enable fast charging capability to achieve charging times comparable to ICE refueling, in the range of 5-10 minutes. This includes the reduction of the carbon footprint of the cell production in particular, which has major opportunities to lower energy demand as well as the need for (toxic) organic solvents.

B.2.2 Electric Components

B.2.2.1 (High) Voltage Level BEV System

High-voltage systems with voltage levels post 800 V and above enable a significant increase in performance. Additionally, high-voltage systems enable the **implementation of ultra-fast charging** of BEVs – getting close to refueling a vehicle with an internal combustion engine. A higher voltage level can generate added value: At constant power level, the current is reduced by increasing the voltage level, with the advantage of lower losses in the DC link and in the supply lines. This means that high-quality conductor material can be saved.

Since high-voltage systems have the inherent attribute of producing EMC relevant electromagnetic fields, it is essential to consider design and testing methods to design high-voltage systems properly.

The necessary **cost-efficient insulation systems** and adjacent cooling system, to optimize package and enable higher integrated sub-components, still **needs to be developed** for the automotive industry.

Further innovation activities must be focused on highly automated manufacturing and assembling processes (e.g. winding technologies), alternative E-Motor technologies (e.g. SSM), power electronics, control algorithms and alternative materials (e.g. plastic).

B.2.2.2 E-Motor, Power Electronics, Gear Box and Electric Drive Unit (EDU)

The choice of the machine type (asynchronous, synchronous, reluctance motors, etc.) and the design depends on the respective application and, among other things, on cost, volume (package on vehicle level), sustainability and cycle efficiency requirements. An important aspect is the **avoidance of critically materials** (avoiding monopoles, etc.). The **highest levels of efficiency** guarantee the optimal use of the battery load and therefore driving range. **E-Motor research** applies to classic machines such as internal rotors with the highest possible speed or external rotors with high torque, but also to innovative technologies (e.g. separately excited synchronous motor, HRE (heavy rare earth) free PSM, in-wheel motor or axial flux machine). The development of directly cooled (high-speed) machines with a particularly high power-to-volume ratio is crucial. All conflicting aspects of cost, cycle efficiency, power density, sustainability and supply chain resilience (e.g. HRE free design) must be addressed to gain an economy of scale effect for a successful BEV implementation.

The R&D efforts include not only the optimization of the E-Motor but also of the inverter and -control and communication. To assure a defined reduction from the future very high-speed E-Motor designs the Gear Box must incorporate novel technologies for sealings, bearings, NVH cover, and gear flank run off geometries. Manufacturing and assembling excellence is necessary to hit the cost target and guarantee together with smart design future sustainability regulations (re-use, re-manufacturing, second live).

Other tasks in the area of transmission belong to smooth actuation (with several gear ratios), loss minimization, torque vectoring and single cooling circuit (of the rotor and stator shared with the gearing). E-Motors must have particularly good controllers at speeds of around zero up to highest levels. High dynamic torque vectoring capability, the generated vibrations and the resulting noise-level are especially important for the end-product. Therefore, proper simulation, testing methods, sensor systems and tools are very essential for the construction of new E-machines.

In the field of **power electronics**, the **use of alternative semiconductor materials** such gallium nitride (GaN) and the construction of integrated power modules is of high interest. It's higher switching speeds and better thermal performance allows for higher operating temperatures as well as **lower losses** especially in partial load conditions, thus enabling **new (cheaper) cooling** system solutions as well as more **highly integrated powertrain concepts** with an overall cost benefit. Also, the aging and reliability of power electronic components is a particularly important aspect to be considered when designing and developing new inverters, charging systems, auxiliary power sources or test systems. The perfect match of the passive components to the new electronic circuit performances needs further development of them.

The amount of **auxiliary power electronic components** in the vehicles is rapidly increasing. DC-DC converters, Onboard Chargers, HVAC, comfort devices, devices for automated driving etc. play an increasing role in vehicle developments. To compensate the energy demand of the devices, the **efficiency** of all **power electronic components** in the vehicle must be increased and synergies between power electronic components must be exploited. Modeling & simulation is necessary to develop **lean code for all power electronic control** units to reduce the energy consumption needed for complex calculations.

The integration of the power electronics, control, E-machine and gearbox into electric drive units (EDU) is necessary to allow **highly integrated powertrain concepts** and further improve energy and cost efficiency at high levels of functional safety and (cyber) security. The vast R&D amount to tackle and secure the 9R concept will be explained in a separate capital of this paper.

Last but not least, R&I efforts must cover necessary functional safety and system (cyber) security aspects too.

B.2.3 Charging Technologies

As the **focus** of this Position Paper **is the Vehicle**, the R&D requirements listed here refer to charging from vehicle perspective including the connection of a vehicle with the charging station but not the electric grid.

Vehicle traction batteries are charged with DC voltage. BEVs have AC and/or DC charging interfaces. AC charging typically takes place at lower power levels (<22kW), mostly in a private environment or at the workplace (during longer vehicle standstill periods). Thereby, an on-board charger converts AC to DC for battery charging. When vehicle traction batteries are currently charged fast, energy with high power (>> 50 kW) is transferred via a suitable interface using direct current (DC voltage). DC charging usually takes place on the road – at parking lots or service/filling stations – to obtain the necessary energy to reach the destination. Suitability for daily use and user-friendliness are essential for acceptance on the market: **short charging times**, **increased convenience** in the charging process (partially automated or robot-supported conventional charging cables, inductive charging, and vehicle to grid-functionality), standardized, interoperable interfaces and software protocols, simple authentication, and billing. This consequences in a high R&D demand on the one hand and demand for harmonization on the other hand.

The charging time of a car and truck is a relevant parameter and will become more important in the future. High-performance personal car DC charging systems are expected to reach power levels of 1MW – new solutions for power electronic modules with multiple specific features will allow to reduce the footprint of such systems. A draft of the charging interface MCS (Megawatt Charging System) for trucks was presented in 2022 and is expected to enable a charging capacity of almost 4MW. For personal car and truck systems, there is a particular need for research into system configuration/integration. Future high-performance charging interfaces must be further developed. The extremely high charging currents require innovative solutions to avoid high conductor/power-line cross-sections and thus increasing costs and weight. Furthermore, solutions for cooling these conductive charging systems need to be researched.

Demand-oriented charging and a corresponding electric power distribution infrastructure (including solutions for load management) will be essential to ensure a scalable and stable energy supply infrastructure that enables the high share of battery electric mobility in the future.

B.2.4 Thermal Management and Energy Management

Thermal consideration is highly essential both for the battery electric propulsion system and for the overall vehicle management. The latter aspects can be found in Chapter E R&D Challenges: Advanced Vehicle Concepts 2024+.

Batteries, power electronics, and E-Motors for require complex thermal management to perform in cold and hot conditions (e.g. during fast charging) without damage (reduced service life, early shutdown etc.). There is an increasing demand from customers and OEMs for fast charging. This requires new ideas for efficient cooling using innovative heat exchangers and new manufacturing processes. In addition, new safety regulations must be met, which call for new component solutions. Waste heat can be used via suitable technical processes (e.g. heat pumps). Heat storage concepts must be developed (especially using new chemical latent heat storage devices that reduce heat losses). Especially innovative cooling concepts (e.g. direct cooling of battery modules) will be more and more in the focus. To use these concepts effectively, highly precise simulation methods and new measurement methods for simulation validation are necessary.

This results in a high need for research on thermal control issues. It is essential to include all relevant components: In addition to the energy storage and drive system, these include air conditioning, cooling, and the related operating strategies. The formerly independent subsystem controls must either be integrated to form a central control unit or have to be increasingly communicating with one another.

Predictive models must be used to anticipate thermal events and react in advance.

In addition to intelligent heating and cooling concepts, also modular thermal architectures at the system and component level have to be developed, which meet different e.g. country-specific, performance, or comfort requirements. To enable effective thermal system design, there is a high need for R&D in scalable thermal models for all relevant components of an electrified powertrain (E-Motor, inverter, battery, and cables).

With increasing EV numbers, real-life fleet data must be used to enable an update of battery performance and degradation models, typically used for the remaining useful life (RUL) prediction. Specifically, ageing prediction models parameterized with lab data can be improved significantly. A cloud-based digital twin of the battery can help to mitigate degradation, predict/prevent failure and extend battery life.

B.3 Essential Legal Framework

Creation of an EU-wide legislative framework and directives for rapid implementation of an efficient and climate-neutral mobility allowing the EU-industry the introduction of new technologies because of R&D activities described in this position paper.

An important topic is the legal framework for the reuse, disposal and recycling of batteries as well as for the handling and transport of damaged batteries especially in emergency situations. Based on the new EU Battery Regulation[7] the supplement documents (Delegated Acts), which describe the technical requirements for circular economy tasks, must be developed in cooperative joint research (lead: EC JRC). Thus, must be supported by industrial actors with deep technical knowledge reg. EV and HVB (High Voltage Battery) business together with the downstream Waste Management & Recycling Tech companies to have at the end a practical 9R'[8] process to be established on the European markets. In this context the consequences of this regulation for integrating a HVB into a vehicle and the efficient implementation of the technical details for the battery passport shall be addressed.

De-escalation of thermal runway effects require deep understanding and cross functional R&D efforts to ensure health and safety, environmental protection and economically acceptable procedures after accidents of BEVs fostering acceptance of e-mobility solutions.

B.4 Life Cycle Assessment and Circular Economy

Global differences in production technologies, energy supply, and waste treatment stress the necessity to consider country specific aspects when applying a Life Cycle Assessment (LCA) and required Product Carbon Footprint reporting. Regarding the fulfilment of diverse legal and taxonomy reporting requirements for Product Carbon Footprints, supply chain engagement, education and involvement for LCA, e.g. data collection, is of importance. LCA of BEVs, ideally applied already during the design phase, involves a large range of influencing factors, such as

- electricity supply (incl. intermediate storage of fluctuating renewable electricity) for BEV operation (to estimate emissions a robust model for electricity generation and change of its carbon intensity in the future is needed (e.g. based on IEA STEP[9] or EU RED[10] prognoses)
- energy supply for battery manufacturing (share of renewable energy sources vs. fossil or nuclear energy sources)
- cell chemistry and related extraction and refining of critical raw materials (e.g. Nickel, Cobalt, Lithium), including the increasing demand for secondary 'recycled' cell material (high quality black mass refined to recycled CAM precursors and cell material)
- production of materials for battery casing (e.g. Aluminum)
- E-Motor (e.g. rare earth metals).
- Electronics (PCBs, semi-conductor, Si-wafers and precious metals)

Also end-of-life (EoL) treatment of BEV (e.g. a better mandatory recovery of dismantling parts, like EV batteries or electric drive units) influences their life cycle performance. Especially in Europe, complete vehicle and battery recycling is an important element to (partly) close "critical" material cycles (EU CEAP, e.g. incl. ELV Regulation proposal, Critical Minerals Regulation, Battery Regulation). However, challenges such as (global) used-battery collection, the diversity of cell chemistries as well as metallurgical material recovery rates remain to be solved. A crucial topic is to characterize quality of EV waste streams before any other end-of-life treatment following the 9R' principles. Innovative solutions for repurpose, remanufacture or higher automated dismantling must be found. Direct recycling, defined as the recovery, regeneration, and reuse of battery components without breaking down the chemical structure, is another important end-of-life strategy that needs to be developed towards the target of a true circular economy in this field. Such new developed technologies and

[7] Regulation (EU) 2023/1542, https://eur-lex.europa.eu/eli/reg/2023/1542/oj, retrieved 10 March 2024

[8] Categorisation System for the Circular Economy; The 9 R's are: They are Refuse, Rethink, Reduce, Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle and Recover, https://circulareconomy.europa.eu/platform/sites/default/files/categorisation_system_for_the_ce.pdf, retrieved 10 March 2024

[9] IEA Stated Policies Scenario (STEPS), https://www.iea.org/reports/global-energy-and-climate-model/stated-policies-scenario-steps, retrieved 22 March 2024

[10] Renewable Energy Directive, https://energy.ec.europa.eu/topics/renewable-energy/renewable-energy-directive-targets-and-rules/renewable-energy-directive_en, retrieved 22 March 2024

solutions for EoL treatment of EV must be covered in automotive LCA. Activities and environmental impact for new repurpose applications or recycling technologies is currently rarely investigated in Europe.

B.5 Research Requirements

The research requirements listed below are expected to be most relevant within a short-term perspective (2024-2026).

A more extensive list of research requirements including mid-term (2025-2030) and long-term (2030+) topics can be found in the A3PS Roadmap "Austrian Roadmap for Sustainable Mobility – a long-term perspective, Version 2022 (https://www.a3ps.at/a3ps-roadmaps).

B.5.1 Energy Storages

B.5.1.1 (Structural) Battery Integration from cell to pack to battery system

- High Voltage (up to 1500 V) on pack level with Li-Ion (NMC, LTO, LFP) and higher voltage (more than 4.5V) at cell level
- "Stop thermal propagation" design & simulation
- Short circuit automatic release concepts of DC-separator (e.g. by smart, integrable current sensors)
- Battery management system and battery diagnostics
- Second life applications and design for reuse and recycling
- Optimized integration of real and virtual sensors and diagnostics
- C2S (Cell-to-Structure) integration concepts with higher energy density, long service life and improved re-usability/recyclability
- Structural battery cells (e.g. for aeronautic applications)
- Long service life → Low TCO
- Thermal management (reduced temperature sensitivity) of state-of-the-art batteries and new battery concepts

B.5.1.2 Advanced Lithium-Ion Batteries 3rd and 4th generation as well as advanced Battery Technologies

- Both generations
  - Avoiding toxic materials and scarce resources
  - Self-healing materials
  - Higher cell voltage (more than 4.5V)
  - Advanced cathodes & anodes (e.g. pure Si-anodes for 3rd gen.)
- 4th generation Solid State Batteries
- Cell design (material optimization, reproducibility, …)
  - Multilayer cells of several Ah
  - Interface investigation for ageing and Li dendrite growth
  - Manufacturing processes, research and production pilot lines
  - Adaptable processes to existing 3rd generation manufacturing processes
  - Material research (conductivity, electro-chemical stability, usable at temperatures below 60°C and up to and above 100°C, sulphide and halide solid state electrolytes)
  - Polymer based electrolytes with ceramic fillers
- Advanced Battery Technologies beyond Li – Cells and Modules
  - Multivalent and low-cost ion batteries (e.g. Mg-, Ca-, Na-, Al-ion)
  - Metal-oxygen (metal-air) batteries, Oxygen-ion batteries
  - Aluminum-Graphene batteries

- New Methods and Materials to Improve Performance, Cost and Environmental Impact
    - Assembly and joining process technologies
    - Improved electrical power connection and control (Conductor Materials, Copper Replacement with Aluminum)
    - Green manufacturing and reduction of carbon footprint and energy need during production
    - Highly safe batteries
    - Multiscale modelling (material, cell & system level, processing)
    - Battery design, processes & strategies for recycling and 2nd life

B.5.2 Electric Components

B.5.2.1 E-Motor

- Advanced materials and manufacturing technologies for cost effective and sustainable E-Motor designs
    - Advanced material designs for hard-magnetic materials insulation materials, light-weight conductor materials
    - New 3D magnet shapes and related manufacturing processes
    - Reuse / second use / recycling concepts (system/component analyses, standardization, simulation, assessment and testing, state-of-health tracking with digital twins)
    - Joining, winding and insulation technologies (up to 1500 V) as well laminating and sheet stamping technologies for HV E-Motor applications
    - Assembling and disassembling concepts (e.g. in line /closed loop/high automation processes, IIoT[11] concepts)
- Advanced models for powertrain simulation
    - Power electronic components
    - Multiphysics motor simulation (e.g. thermal, electromagnetic, mechanical)
    - Powertrain system optimization
    - Material data driven FEM (Finite Element Method) of components for second life or reuse applications
- Advanced E-Motor architectures and topologies and advanced transmission architectures
    - Functional safe designs for high speeds > 20.000 rpm
    - Novel magnetic encoders/polewheels/resolvers
    - Motors with non-critical materials, e.g. Heavy Rare Earth Element (HREE) free or non-permanent-magnet E-Motor topologies including Induction and electrically excited motor designs
    - Axial flux technology and in-wheel E-Motors
    - HF-PWM (High-Frequency-pulse-width-modulation) E-Motors (e.g. new insulation concepts for primary and secondary insulation)
    - NVH optimization
    - Single Speed with high reduction ratios and 2-speed & multi speed transmissions
    - Advanced cooling concepts (e.g. direct slot cooling, embedding, direct active part cooling or 2-phase cooling or single fluid)
- Advanced Testing and validation methods beyond current standards
    - Partial discharge testing of components and insulation aging
    - Effect of e.g. hairpin forming processes on insulation performance
    - Alternative Peel-off test methods round copper wire

[11] IIoT: Industrial Internet of Things

B.5.2.2 Inverter, Power Electronics

- Advanced materials (e.g. printed circuit boards, housings, capacitors) and advanced manufacturing technologies
  - Material and component design for reusability and recyclability
  - Joining technologies
  - High automation assembling technologies for high volume inverters and power modules including disassembling and recyclability (decrease cost, increase quality)
- Increase of performance and packaging density
  - PCB integration of electric components
  - miniaturize passive electronic components
- Advanced wide-bandgap semiconductors
- Improvement of electromagnetic interference and induction for achievement of EMC (electromagnetic compatibility) and reach efficiency goals
- Advanced complex control algorithms (e.g. self-learning adaptive algorithms, model-based controls)
- Passive components required for optimum utilization of new inverter design (e.g. SiC or GaN based inverters)

B.5.3 Charging Technologies

- Comfort charging and automated charging systems (conductive or inductive charging)
- High Power DC-charging up to 1000 kW (passenger vehicle), >1000 kW (heavy duty vehicle) @ high voltage up to 1500 V
  - compact cooling solutions
  - System integration/configuration
- AC Charging <50 kW (conductive)
  - Increase power density / combine functions of on-board-charger
  - Integrated charging
  - Vehicle-to-Home, “home-storage on wheels” – sector coupling
  - Charging authentication & payment PnC (plug-and-charge)
- Integration of electric cars into power grid as mobile energy storage device (V2L - vehicle-to-load)
  - Functional integration in Operating strategies

B.5.4 Thermal Management and Energy Management on BEV Level

- Access to relevant vehicle information for charging in cooperation with Cooperative, Connected Automated Mobility (CCAM)
  - Use case definition for personalized route planning and charging strategy
- Predictive energy/thermal management of cabin and powertrain components (human behavior) complemented by using environmental data (traffic, weather, etc.)
- Optimal Cooling Concept with SiC inverters
- Silent cooling and heat loss recovery during High Power Charging (HPC)
- Usage pattern identification from vehicle-fleet-data to derive vehicle and component requirements and optimize system layouts.
- Methodologies for update and optimization of operating strategies based on vehicle-fleet-data
- Energy management on subsystem and system of system’s level
- Cloud-based digital twin
  - Over-the-air update strategies for battery degradation models
  - Adaptive operation strategies

B.5.5 Requested National Funding Instruments for “Battery Electric Vehicles”

- Low TRL research
- Co-operative industrial research and experimental development
- Flagship projects
- High TRL research (close to serial production) with focus on vehicle test fleet operations to drive market introduction of innovative and sustainable vehicles

B.5.6 Estimated National R&D Project Volume for “Battery Electric Vehicle”

Starting in 2023, an annual[12] volume of 80 M€ is estimated for R&D projects on BEV. The list below is an assessment of project types needed to cover all topics from basic to applied research, demonstration and R&D infrastructure:

- 12 M€ for low TRL research: 8 projects of 1 M€ each
- 20 M€ for applied & cooperative research: 11 projects of x 2 M€ each
- 28 M€ for flagship projects or a cluster of flagship projects: 2 projects of 10-20 M€ each
- 20 M€ for F&E infrastructure (e.g. testing, pilot production, technology laboratory) excl. COMET, CD-Lab, public infrastructure)

This **total R&D project volume of 80 M€** should be supported with a **funding volume of about 40 M€** considering an average funding rate of about 50 %.

Suggested allocation of projects/funding volume defined above to the research areas in this chapter:

1. Energy Storages: 3/10
2. Electric Components: 3/10
3. Charging Technologies: 1/10
4. Thermal Management and Energy Management 3/10

[12] for projects granted within one year – project/funding volume for the whole project duration