R&D Challenges: Battery Electric Vehicle 2023+

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.

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 in order 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 in order to bring advanced products onto the market safely, cost efficient and sustainably.

Requirements on Technology Development and Research Demand

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 supplier industry: the safe integration of new battery cell technologies, the early detection and avoidance of critical errors in the battery system and drive train, 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).

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

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 to enable fast charging capability to reach charging times in comparison to combustion engines pump stop in the area 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.

Electric Components

(High) Voltage Level BEV System

High-voltage systems with voltage levels towards 1200 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).

Electric 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) and efficiency requirements. An important aspect is the possible **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 such as compact in-wheel motors and axial flux machines. The development of directly cooled (high-speed) machines with a particularly high power-to-volume ratio is crucial.

Due to the outstanding vehicle and consumer requirements to affordability, convenience, traction and safety, a large number of machine designs for different types are possible, which needs remarkably high R&D requirements. The R&D efforts include the optimization of the E-Motor (compactness, power and torque density) and the system level (E-Motor - converter - control and communication), addressing the unsolved problems of optimal system design. Equally, also the manufacturing and assembling excellence and the necessary functional safety and system (cyber) security.

There are **special tasks also in the field of transmission** (NVH, lubrication, bearings, shaft sealing, actuation (with several gear ratios), loss minimization, torque vectoring, park lock, etc.) and direct liquid cooling of the rotor and stator using a single cooling circuit, which must be solved. 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 rather new semiconductor materials** such as silicon carbide (SiC) and 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**. 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 in order 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.

Vehicle Control Unit – Hardware and Software

Almost all vehicle manufacturers are planning to change their E/E vehicle architecture from a decentralized function-oriented to a zone architecture. The detailed design of the E/E architecture itself is very OEM-specific with partly diverse requirements.

This transformation requires new scalable and high-performance HW platforms that rely on µ-controllers as well as on µ-processor technologies with the ability for a scalable partitioning from software functions to hardware resources.

Software functions are no longer tied to a specific hardware (VCU) and software domain but are flexibly distributed across different software integration or hardware platforms, depending on the E/E architecture selected. The implementation according to standards (e.g. AUTOSAR, COVESA, etc.) and the use of harmonized interfaces and exchange formats (containers) for sw function, are essential for a flexible cross-domain integration.

In the area of connectivity (V2G), the future focus will be on the implementation of cross vehicle-cloud functions. The seen trend is to implement demanding optimization algorithm on a backend server (off-board) used for predicted functions, thermal system control, component health management. This reasons a continuous data exchange with requirements regarding safety, reliability, and real time as well as service-oriented communication between vehicle and cloud ("open vehicle API"). The development of open standards and technologies that accelerate the full potential of connected vehicle systems are in focus of future research and innovations.

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 (typically 100 kW and more) is transferred via a suitable interface using direct voltage (DC). 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.

Thermal Management and Energy Management

Batteries, power electronics and electric motors for **electric vehicles require complex thermal management in order to survive cold and heat** (e.g. during fast charging) without thermal damage (service life, early shutdown...). There is an increasing demand from OEMs for fast charging possibilities, which result in a high demand for new ideas for efficient cooling using innovative heat exchangers, as well as a need for new manufacturing processes. In addition, new "safety regulations" must be met, which place increased demands on the components and therefore require new component solutions. Any waste heat generated can be used via suitable technical processes (e.g. heat pumps). Heat storage concepts have to be developed (especially using new chemical latent heat storage devices that can hold heat without loss for any length of time). 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 and control engineering issues**. It is essential to include all components of the whole vehicle system that are relevant from an energy perspective (in addition to the energy storage and drive system, in particular the areas of air conditioning, cooling and conditioning and operating strategies). This also means that control units and software functions for previously independent subsystems either have to be combined to form a central control unit or have to be increasingly networked with one another.

The consideration of predictive data in the control of thermal components is important for further efficiency improvements, to overcome the latency times of thermal systems by preparing for events in advance.

In addition to the development of intelligent energy, heating and cooling concepts, modular thermal architectures have to be developed, which meet different requirements (e.g. country-specific requirements), performance requirements (e.g. power levels of e-machines or fast charging) and different comfort requirements. This requires modular architectures at the system and component level.

The implementation of modular systems, which quickly helps to define the most efficient system architecture at the beginning of a development phase, can be supported by means of scalable simulation models and further by scalable, seamless testing environment for the individual components, especially if not all components are available at the beginning of the development.

There is a high need for research and development in the methodical development of scalable thermal models for all relevant components and an electrified powertrain (electric machine, inverter, battery and cables).

As the number of battery electric vehicles in real-world operation increases rapidly, the availability of in-vehicle/fleet data also increases. An important research topic in this context is the development of concepts and algorithms, which enable an update of battery performance and degradation models, which are typically used for remaining useful life (RUL) prediction, based on fleet data. Specifically, ageing prediction models that are typically parameterized with laboratory data from accelerated ageing tests can thus be improved significantly and a cloud-based digital twin of the battery can be created. Depending on the vehicle use, environmental conditions, topography, driver, etc. the operating (energy and thermal management) and charging strategies can thus be optimized (even for individual vehicles) in order to mitigate degradation (or predict/prevent early failure) and extend battery lifetime.

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 as a result 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.

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

Life Cycle Assessment and Circular Economy

Life Cycle Assessment (LCA) of BEVs, 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
- energy supply for battery manufacturing (share of renewable energy sources)
- cell chemistry and related extraction and refining of critical raw materials (e.g. Nickel, Cobalt, Lithium)
- production of materials for battery casing (e.g. Aluminum)
- Electric motor (e.g. rare earth metals).

But also end-of-life treatment of EV batteries influences their life cycle performance. Especially in Europe, battery recycling is an important element to (partly) close “critical” material cycles. However challenges such as (global) used-battery collection, the diversity of cell chemistries as well as metallurgical material recovery rates remain to be solved. 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. The method of LCA is currently developed to include KPIs (key performance indicators) for circularity.

Research Requirements

The research requirements listed below are expected to be most relevant within a short-term perspective (2023-2025).

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).

1. Energy Storages

(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

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 also 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

2. Electric Components

Electric 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[7] 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

Vehicle-, Motion-, Drive- or Powertrain-Control, Software & Hardware

- New software and hardware functions & services to enhance safety, security, cyber security, range, comfort and drive ability with continuous and active software maintenance over live time (continuously maintained vehicle)
- Enlarged use of AI methodology and digital twins for predictive and model-based control functions and component maintenance
- Real time health monitoring methods and data management of components and EDUs for reuse applications
- New testing and validation methodologies und systems (e.g. continuous testing, SIL)
- Development of open standards and technologies (vehicle API, vehicle services) to expose and enabling the access to vehicle data (vehicle individual and fleet).
- Software integration platforms efficient for flexible deployment of software functions on different control units.
- Motion/Drive-Controller hardware capable for future demanded applications and extended use of AI methods

[7] IIoT: Industrial Internet of Things

Inverter, Power Electronics

- Advanced materials (e.g. printed circuit boards, housings, capacitors) and advanced manufacturing technologies
  - Material and component design for reusability and recyclability
  - Jointing 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)

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

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)
- 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

Estimated National R&D Project Volume for "Battery Electric Vehicle"

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

- 8 M€ for low TRL research: 8 projects à 1 M€
- 22 M€ for applied & cooperative research: 11 projects à x 2 M€
- 30 M€ for flagship projects or a cluster of flagship projects: 2 projects à 10-20 M€
- 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: 2/10
4. Thermal Management and Energy Management 2/10