
TECHNOLOGY ROADMAP FOR SUSTAINABLE MOBILITY

A long-term perspective

Vienna, November 2025

The background of the lower half of the page is a vibrant red with a complex, abstract pattern. It features a grid of small, glowing red dots that create a sense of depth and movement. Overlaid on this pattern are several white, thin-lined geometric shapes, including circles and a triangle, which appear to be part of a larger, dynamic design. The overall effect is one of high-tech and futuristic aesthetics.

Austrian Association for
Advanced Propulsion Systems

Technology Roadmap for Sustainable Mobility a long-term perspective

Version 2025

Content

Preface.....	3
Introduction	4
Executive Summary.....	8
A Vehicle Innovation, Safety and Sustainability.....	9
B Battery Electric Powertrains	15
C Fuel/Electrolysis Cells and Hydrogen.....	27
D ICE and Hybrid Powertrains	39
E Sustainable Energy Carriers	42
F Innovative Materials and Production	48
List of Acronyms.....	54
List of Roadmap-Tables	56

Preface

The European automotive industry stands at a crucial crossroads, facing an unprecedented set of challenges. Global competition, rising energy and raw material costs, and growing pressure to digitalize and decarbonize the mobility sector. All these challenges call for decisive and coordinated transition. The European Commission's **Industrial Action Plan for the European Automotive Sector** provides a strategic framework to guide this transition, aiming to maintain technological leadership, secure high-quality jobs, and ensure the sector's long-term sustainability. Within this context, the ability to align research and innovation efforts with industrial needs and societal goals is essential to successfully manage the green and digital transition of the European mobility ecosystem.

At the heart of the Automotive Action Plan lies the pillar of **Innovation and Digitalisation**. This pillar highlights the critical role that research, development, and innovation (RDI) must play in enabling the transition to clean, connected, and automated mobility solutions. Leveraging digital technologies and fostering innovation are not only key to achieving environmental objectives, but also to strengthening the competitiveness of Europe's automotive supply chains. In this dynamic environment, the capacity of national ecosystems to collaborate, anticipate technological trends, and accelerate the deployment of breakthrough solutions becomes a strategic asset.

Austria's automotive supply industry significantly contributes to the national economy and includes a notably high proportion of research-intensive companies. To safeguard Austria's competitiveness in the automotive sector and support the successful market introduction of innovative and advanced vehicle technologies, stakeholders founded the Austrian Association for Advanced Propulsion Systems (A3PS) in 2006. Its mission is to strengthen the country's RDI activities in the field of vehicle technologies and to contribute to the successful implementation of the technology policy of my Ministry. Since then A3PS has evolved into an established platform, acting as a trusted intermediary between public and private stakeholders and promoting research and development for clean, sustainable, affordable, and safe mobility. Notably, my Ministry has been a founding partner of A3PS and has become in 2023 a full member of the association.

The A3PS expert groups developed a comprehensive **Technology Roadmap** outlining both short-term developments and medium- to long-term research needs looking toward "2035plus". Two new expert groups **Innovative Materials and Production (IMP)** and **Vehicle Innovation, Safety and Sustainability (VISS)** already contributed to the Roadmap. The expert group evolution reflects the stronger focus on circular economy, production, and materials, key areas that align closely with the expectations of the society at large for climate-neutral, resource-efficient, and safe mobility. Addressing these complex challenges requires close collaboration between industry, science, and public authorities. In this context, the strong partnership between A3PS and my Ministry plays a vital role in defining shared priorities and enabling coordinated RDI efforts.

My colleagues and I look forward to continuing this successful cooperation and jointly advancing Austria's contribution to sustainable mobility through innovation, technological excellence, and long-term vision.

Yours sincerely,

Henriette Spyra

Director General for Innovation and Technology,
Austrian Federal Ministry for Innovation, Mobility and Infrastructure, Vienna

Introduction

The present **Technology Roadmap for Sustainable Mobility** continues the mission of aligning national research, development, and innovation (RDI) efforts with European climate and mobility targets, while reflecting updated priorities of the industrial and scientific A3PS members. It aims to provide an overview on the R&D challenges in the coming years and the necessary R&D activities to strengthen Austria as a competitive industry location. Mission and target of this Roadmap is to illustrate the state of the art of current research fields in transport systems as well as showing the research demand – short-term, medium-term and long-term. It presents a coherent and long-term perspective on technology pathways necessary to achieve climate-neutral mobility, competitiveness of Austria's mobility industry, and alignment with European ambitions under the **Green Deal**¹, the **Clean Industrial Deal**² and the **Sustainable and Smart Mobility Strategy**³.

A3PS, founded in 2006 as an initiative of BMIMI⁴ discussed, phrased and prioritized with members from industry and research institutions, the contents of this roadmap in spring 2025. This roadmap covers all advanced propulsion systems: **battery electric powertrain** technologies, **fuel cell** technologies, **combustion engines** and **hybridized powertrain** technologies, which convert **renewable energy carriers**. The whole life cycle assessment is essential to find the best solution for different transport applications depending on available energy carriers. The chapters **VISS (Vehicle Innovation, Safety, and Sustainability)** and **IMP (Innovative Materials and Production)** frame the chapters focused on advanced propulsion systems and energy carriers.

Since the 2022 Roadmap, there have been significant political, economic, and technological developments. The European Commission has further sharpened its policy tools under the **Green Deal Industrial Plan**⁵ and the **REPowerEU**⁶ strategy, emphasizing the need to accelerate clean technology innovation, critical raw materials independence, and renewable energy deployment. The European automotive sector is challenged by rapid technological changes and increasing competition. To address these changes, the European Commission's **Industrial Action Plan for the European Automotive Sector**⁷ provides a strategic framework. Meanwhile, the BMIMI's ongoing implementation of the **Mobilitätsmasterplan 2030**⁸ and the updated **R&I Mobility Strategy**⁹ continues to guide Austrian contributions to the European and global decarbonization agenda. This roadmap shows contributions to the implementation of the strategies of BMIMI.

This roadmap reflects these priorities and, in addition to the topics of advanced drives and energy sources, also places an emphasis on integrated system approaches, digitalization, and sustainable materials and production in the spirit of the circular economy.

Circular economy must be considered in all technology sectors. This increases the research demand since beside of functional efficiency, safety, security, durability, etc., the 9R* strategies (refuse, rethink, reduce, reuse, repair, refurbish, remanufacture, repurpose recycle, recover) must be considered.

The roadmap illustrates the research demand - it provides neither a forecast which technology will prevail nor specific recommendations for politics. Instead, the roadmap presents the advantages and disadvantages of proposed solutions in a fact-based manner but does not make any evaluation. Technologies with application in the long-term future also require research.

Recent European and Austrian policy developments have reaffirmed the urgent need for:

- **Technology-neutral innovation support** based on full life-cycle assessment (LCA),
- **Integrated system-level solutions** linking propulsion, materials, infrastructure, and digital ecosystems,
- **Industrial transformation** toward resilient, circular, and value-generating supply chains,
- **Climate action** aligned with European targets and Austria's national carbon neutrality goals.

As a "living document", the Technology Roadmap for Sustainable Mobility is regularly checked for topicality and revised if necessary.

The Austrian Roadmap is focused on promising technologies and measures in the following fields:

- Power train technologies
- Overall vehicle technologies (software defined vehicle, safety)
- Energy Carriers & Sustainable Fuels
- Life cycle assessment
- Design, materials and production

All technologies and measures mentioned in the following chapters are of high relevance to the Austrian industry and research institutions. Activities in these areas are currently ongoing or at least planned.

 Text passages regarding commercial vehicles (including heavy duty, buses and off-road) and corresponding measures are marked with a truck icon.

¹ https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_de (retrieved 28 May 2025)

² https://commission.europa.eu/topics/eu-competitiveness/clean-industrial-deal_en (retrieved 11 June 2025)

³ https://transport.ec.europa.eu/transport-themes/eu-mobility-transport-achievements-2019-2024/sustainable-smart-mobility_en (retrieved 28 May 2025)

⁴ Federal Ministry for Innovation, Mobility and Infrastructure <https://www.bmimi.gv.at/en.html>; back in 2006 bmvi – Federal Ministry for Transport, Innovation and Technology

⁵ https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal/green-deal-industrial-plan_en (retrieved 28 May 2025)

⁶ https://commission.europa.eu/topics/energy/repower.eu_en#producing-clean-energy (retrieved 10 June 2025)

⁷ https://transport.ec.europa.eu/document/download/89b3143e-09b6-4ae6-a826-932b90ed0816_en (retrieved 20 June 2025)

⁸ <https://www.bmimi.gv.at/themen/mobilitaet/mobilitaetsmasterplan/mmp2030.html> (retrieved 28 May 2025)

⁹ <https://fti-mobilitaetswende.at/en/> (retrieved 28 May 2025)

In the following chapters, the information is summarized in Roadmap-tables which show each technology in detail, including aims and research demand (specific measures). For each measure, the current TRL¹⁰ (TRL²⁰²⁵) status is given in accordance with the following list:

TRL 1 – Basic principles observed

TRL 2 – Technology concept formulated

TRL 3 – Experimental proof of concept

TRL 4 – Technology validated in lab

TRL 5 – Technology validated in a relevant environment (industrially relevant environment in the case of key enabling technologies)

TRL 6 – Technology demonstrated in a relevant environment (industrially relevant environment in the case of key enabling technologies)

TRL 7 – System prototype demonstration in an operational environment

TRL 8 – System complete and qualified

TRL 9 – Actual system proven in an operational environment (competitive manufacturing in the case of key enabling technologies)

It is important to point out that even if a TRL of 9 is reached for a particular technology or component there is still R&D demand (e.g. for further downsizing, cost reduction, efficiency improvement, safety increase, recyclability or lower resource consumption).

All technology innovations need to consider the 2030 Agenda with its 17 Sustainable Development Goals (SDGs). The 2030 Agenda is a global plan to promote sustainable peace and prosperity and protect our planet.¹¹

Furthermore, the types of (research) projects are specified which are required to bring the technologies onto the market. The “Type of Project Required” in the technology tables provides important orientation in the development of new funding instruments. The projects mentioned are categorized according to the community framework for state aid for research and development and innovation (2006/C 323/01):



‘Fundamental Research’: experimental or theoretical work undertaken primarily to acquire new knowledge of the underlying foundations of phenomena and observable facts, without any direct practical application or use in view.



‘Industrial Research’: the planned research or critical investigation aimed at the acquisition of new knowledge and skills for developing new products, processes or services or for bringing about a significant improvement in existing products, processes or services. It comprises the creation of components of complex systems, which is necessary for industrial research, notably for generic technology validation, to the exclusion of prototypes as covered by ‘Experimental Development’.



‘Experimental Development’: acquiring, combining, shaping and using of existing scientific, technological, business and other relevant knowledge and skills for the purpose of producing plans, arrangements or designs and conceptual definitions for new, altered or improved products, processes or services.



‘Demonstration’: projects with the aim of demonstrating the day-to-day utility of advanced vehicle technologies and/or advanced energy carriers with national and international visibility.

The research topics compiled in the roadmap-tables for each research area are categorized on the one hand according to the period needed (short/medium/long) to tackle the topics and carry research and development activities. On the other hand, actual TRLs are estimated for the state of research and product development. Thus, short term research and development needed paired with actual high TRLs indicate possibly short times-to-market. If there are several short time-to-market research actions identified in a particular research area, one could conclude that research support for such an area could lead to “quick wins” for the stakeholders of Austrian automotive research and industry community.

Nevertheless, research priorities with low TRL and/or long-term perspective should not be ignored, as new approaches and major technological leaps can be expected through basic research.

The Technology Roadmap and previous A3PS roadmaps are available for download online at <https://www.a3ps.at/a3ps-roadmaps>.

¹⁰ TRL (Technology Readiness Levels); Source: Horizon 2020 – Work programme 2014–2015, Annex G: Technology Readiness Levels

¹¹ <https://unric.org/de/17ziele/> (retrieved 29 May 2025)

Circular Economy & Life Cycle Assessment

A circular economy is “a model of production and consumption, which involves sharing, leasing, reusing, repairing, refurbishing and recycling existing materials and products as long as possible”.¹² Circular economy aims to tackle global challenges like climate change, biodiversity loss, waste, and pollution by emphasizing the design-based implementation of the three base principles of the model. The three principles required for the transformation to a circular economy are: eliminating waste and pollution, circulating products and materials, and the regeneration of nature. Circular economy is defined in contradistinction to the traditional linear economy.¹³

Life Cycle Assessment (LCA) is the method to evaluate the environmental impacts (e.g. carbon footprint, material resource and energy consumption, water footprint, pollutant emissions, etc.) during the entire life cycle of a transport system. The life cycle phases include extraction and refining of (critical) raw materials, vehicle manufacturing, distribution, vehicle use, recycling and final disposal (from cradle to grave). It also includes the sourcing of the energy of the transport system. LCA differs from so-called Well-to-Wheel (WtW-) analysis which excludes vehicle manufacturing as well as end of life treatment. Life cycle assessment allows the comparison of different systems offering the same transportation service during the same period.

The current and future design of individual mobility plays a major role in discussions about climate change. One aspect of this is the actual environmental balance of the different drive types over the entire life cycle of a vehicle. A possibility for a comprehensive comparison of vehicle drive types regarding climate-relevant greenhouse gas emissions from production to operation to recycling is possible via an expert-tool for LCA developed by Joanneum Research, ÖAMTC, ADAC and FIA¹⁴ [8], which was published in 2019.

LCA of BEVs involves a large range of influencing factors, such as the electricity supply (incl. intermediate storage of fluctuating renewable electricity) for BEV operation, as well as energy supply for battery manufacturing (share of renewable energy sources), the cell chemistry and related extraction and refining of critical raw materials (e.g. Nickel, Cobalt, Lithium) as well as the production of materials for battery casing (e.g. Aluminum) and the electric motor (e.g. rare earth metals). End-of-life involves the topics “second use of batteries” (e.g. for stationary storage and/or reuse of battery cells) and related allocation of environmental impacts between first and second use, as well as recycling. Battery recycling is an important element to (partly) close “critical” material cycles, however challenges such as (global) used battery co Austrian Roadmap for Sustainable Mobility⁸ Introduction section, diversity of cell chemistries and recycling process efficiencies remain to be solved.

LCA of FCEVs involves a range of influencing factors, such as hydrogen production (incl. use of the co-products oxygen and heat and the system integration, e.g. grid services) for FCEV operation, which can be supplied by various conversion processes and primary energy sources, the system energy efficiency of hydrogen production and use in the fuel cell, the manufacturing of the FCEV propulsion system and related extraction and refining of (critical) raw materials, and the lifetime of the fuel cell in the operation phase.

End-of-life aspects include vehicle and fuel cell recycling as an important element to (partly) closed (critical) material cycles. Additionally, the environmental effects of carbon fibers (CF) for H₂ tank systems, and the end of life of CF like reuse and recycling are essential to be analyzed in consistent LCA to develop a circular economy approach for CF use.

Key factor in LCA of hybrid vehicle architectures is the change in energy demand and efficiency during operation. While research focuses on increasing system efficiency, the impact of the additional weight of the specific components of hybrid vehicles on energy demand also depends on real world driving. LCA of drop-in biofuels and so-called e-fuels based on carbon capture and their utilization involves a wide range of supply chains of different types of biomasses, biomass conversion processes, renewable electricity, hydrogen production, CO₂ sources and separation technologies. LCA-results are therefore highly influenced by the CO₂ source, the degree of process integration and system efficiency, by the allocation of double used fossil CO₂ emissions between emitter and receiver and the long-term availability of fossil-based CO₂ sources.

¹² <https://www.europarl.europa.eu/topics/en/article/20151201ST005603/circular-economy-definition-importance-and-benefits> (retrieved 31 May 2025)

¹³ <https://www.ellenmacarthurfoundation.org/topics/circular-economy-introduction/overview> (retrieved 29 May 2025)

¹⁴ <https://www.oeamtc.at/thema/autokauf/experten-tool-zeigt-erstmal-gesamtumweltbilanz-aller-pkw-antriebsarten-32522717> (retrieved 30 May 2025)

A3PS – Austrian Association for Advanced Propulsion Systems

A3PS is the **strategic platform** of the Austrian technology policy, industry and research institutions and stimulates the development of advanced propulsion systems and energy carriers – to build up common competence and to accelerate market launches.

A3PS addresses all **advanced powertrain technologies** contributing to the improvement of energy efficiency and to the reduction of emissions and supporting the whole innovation cycle (research, development, deployment).

A3PS members congregate in five thematic expert groups. These expert groups elaborated positions, trends, R&D demands and demands concerning the essential legal framework for prospective technologies for this roadmap.

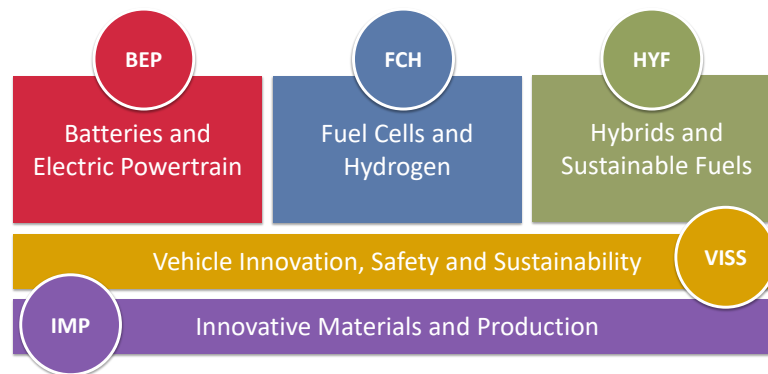


Figure 1: A3PS expert groups

Expert Group BEP – Batteries and Electric Powertrain

Expert group BEP focuses on strong scientific and informative public relations work about energy storage and electric components of **battery electric vehicles**. Thermal consideration is highly essential both for the battery electric propulsion system and for the overall vehicle management. The latter aspects are addressed in Expert Group VISS.

Expert Group FCH – Fuel Cells and Hydrogen

FCH expert group's focus is on **fuel cell technology** for electric vehicles and renewable hydrogen. Regarding **hydrogen**, production from non-fossil sources as well as distribution, storage and hydrogen refueling stations (HRS) are addressed here. Hydrogen combustion can be found in expert group HYF.

Expert Group HYF – Hybrids and Sustainable Fuels

The Expert group HYF concentrates on the identification of research needs in the fields of **sustainable energy carriers** and all kinds of efficient **hybrid** powertrain technologies, including internal combustion engines - fueled with sustainable liquid and gaseous fuels, i.e. incl. "green" H₂ - for vehicles. H₂-production from non-fossil sources as well as distribution, storage and hydrogen refueling stations (HRS) are addressed in expert group FCH.

Expert Group VISS – Vehicle Innovation, Safety and Sustainability

Expert group VISS deals with advanced and future vehicle concepts linking to the other expert groups. The vehicle is increasingly understood as part of a **system of systems**. **Energy efficiency** and **safety** are leveraged by this new view. Major effort, however, must be put on **digitalization**, **automation** and **connectivity** to reach user acceptance and trust in yet new but necessary concepts.

Expert Group IMP – Innovative Materials and Production

Expert Group IMP focuses on design for manufacturing / design for circularity, lightweight materials and hybrid structures. It aims to empower production processes for competitive industries as well as education and human resources in all areas (workers, managers, engineers, scientists) and cost-effective and agile automation.

Executive Summary

To meet European and Austrian climate goals – including net zero greenhouse gas emissions by 2050 and substantial reductions by 2030 – the mobility sector must undergo a comprehensive transition. The 2025 Austrian Technology Roadmap for Sustainable Mobility outlines R&D priorities across six interrelated thematic chapters.

Our road transport system is rapidly transforming in response to climate change and resulting demand for a high sustainability over the full value chain and considering the full life cycle. Advanced propulsion systems are showing steadily increasing market shares, connected and automated vehicles as well as the vision of smart and climate neutral cities demand for new infrastructures and mobility concepts. To define realistic sustainability goals – for all stakeholders in the mobility sector – and to select the most sustainable solution, the environmental impact of technologies and mobility concepts must be assessed and continuously monitored via well-to-wheel or extended via a Life Cycle Assessment Analysis (LCA).

All advanced powertrain technologies discussed in this Technology Roadmap are characterized by a very high “tank/battery”-to-wheel efficiency and through a very high potential for zero local emissions.

A. Vehicle Innovation, Safety and Sustainability

The focus of this chapter is on the vehicle as a system, incorporating software-defined vehicles (SDVs), predictive control systems, digital twins, and non-exhaust particle emission mitigation. Innovations here enable performance optimization, safety, user-centric design, and full lifecycle efficiency. AI integration, thermal management, regenerative braking, and standardized methodologies for LCA and virtual approval are key topics.

B. Battery Electric Powertrains

BEV advancements needed to improve affordability, safety, performance, and sustainability are of high priority. The roadmap covers battery chemistries, high-voltage systems (up to 1500 V), and thermal management. Emphasis is placed on European battery autonomy, circular economy compliance, and critical raw material recovery under new EU regulations.

C. Fuel Cells and Hydrogen

The development of scalable and robust hydrogen systems with a focus on heavy-duty applications and long-range mobility is covered in this chapter. Core priorities include fuel cell system integration, durability, cost reduction, infrastructure development, and synergy with Austria's Hydrogen Strategy. LCA and eco-design are essential components of hydrogen systems' sustainability assessment.

D. ICE and Hybrid Powertrains

Internal combustion engines (ICE) in hybrid systems are still relevant during the transition period and beyond. Research is targeted at optimizing hybrid architectures, improving efficiency and emissions, and integrating renewable fuels. Special emphasis is placed on non-car sectors like heavy-duty and off-road applications, which will rely on ICE well beyond 2035.

E. Sustainable Energy Carriers

Renewable liquid and gaseous fuels, biofuels and RFNBOs are the key to defossilize existing and future powertrains. Integration into a broader energy system, consideration of CO₂ capture, and sector coupling (power-to-X) are essential. The roadmap uses “defossilization” rather than “decarbonization” to reflect a broader systemic view.

F. Innovative Materials and Production

Sustainable production technologies, and advanced materials are essential to reduce resource dependency. Circularity needs to be addressed in the design phase already. Focus areas include lightweight materials, modular vehicle architectures, additive manufacturing, and high-recyclability concepts. The roadmap aligns with the EU Circular Economy Action Plan and the Net-Zero Industry Act.

This roadmap supports policymakers, funding bodies, and R&D stakeholders in aligning investments with systemic needs for defossilization, industrial transformation, and technological sovereignty. It reflects a shared Austrian ambition to lead in clean and competitive mobility technologies and to deliver climate-neutral mobility solutions within a European and global framework.

Besides technology-related challenges in the core areas powertrain and vehicle technology, which are discussed in the respective chapters of this roadmap, other challenges have been identified, that require actions in other disciplines such as politics and regulations. To intensify long-term research and development in all areas addressed within this roadmap, companies and R&D institutions require long-term and stable framework conditions and sufficient time for their activities. Politics should therefore focus on a long-term strategy for funding instruments. To implement sustainable energy and road transport systems, an integrated approach across the disciplines is necessary.

The interlinking and exchange of information between the A3PS member BMIMI, representing Austria in several European and global platforms, and the other A3PS members is very essential for the selection of research and development topics with high impact on the competitiveness of the Austrian automotive sector in the narrow sense and the whole mobility sector from a wider perspective.

A Vehicle Innovation, Safety and Sustainability

Aside from advanced powertrain technologies treated in the following chapters, this chapter focuses on technologies on vehicle level, which considerably influence the vehicle performance, fuel consumption, efficiency and environmental impact. Beside electrification, digitalization rises as new challenge.

Digitalization and digital twinning are key to enable predictive control and bringing components and systems close to their limits, without having to consider production tolerance-based safety margins. Special emphasis will be put on these aspects in this updated version of the roadmap.

ADAS is thought along in this roadmap when directly relevant to the powertrain. Automated vehicles usually are not autonomous but connected and a holistic approach of ADAS always includes both vehicle and infrastructure.

A **Software-Defined Vehicle** (SDV) represents the transition from traditional, hardware-centric automobiles to modern vehicles that are predominantly controlled by software, emphasizing electronic systems over mechanical components. In an SDV software is in the driving force and enables to integrate advanced features such as ADAS and full autonomous driving (AD). Both need a high amount of connectivity of the vehicle both with other road users and the road infrastructure. Also personalized infotainment systems, predictive maintenance and different subscription models are covered by SDVs. Consequently, SDVs also offer to deliver new services and revenue streams to the end consumers. Consumers can get new functionality on demand, such as remote diagnostics, infotainment and also updates over-the-air (OTA). The latter indicates another major difference compared to traditional vehicles. In the hardware-centric approach software was developed with the hardware and also frozen before start of production (SoP) releasing only minor adjustments afterwards. In SDVs software is a living element that can be updated with new features, for instance if demanded by customers or in case of required bug fixes or security updates. This allows for maintenance and innovation throughout the entire lifetime.

Artificial intelligence (AI) in automotive technology is a rapidly growing field that aiming to make vehicles smarter, safer and more efficient. By implementing AI-based systems into SDVs, these vehicles can perform tasks that traditionally required human intervention. These tasks include ADAS/AD, predictive maintenance, traffic flow analysis and personalized user experiences.

This chapter is structured as follows:

1. **Methodology, development tools and measurement**
2. **Advanced auxiliaries, components and systems enabling energy savings**
3. **Advanced vehicle control systems**
4. **Non-exhaust particle emissions**

A.1 Methodology, Development Tools and Measurement

Advanced “Methodologies, Development Tools & Measurement” is the basis for efficiently designing powertrains and systems of the future and control them during operation adaptively (according to their individual and current state). Hence, a digital representation of individual components and systems is needed to predict their behavior, predict maintenance needs and foresee degradation effects.

To retrieve information that is necessary to feed digital twins during operation, new affordable and sometimes higher precision drift-stable sensor technologies are required. These can be augmented with virtual sensors in the control loop and must support the integration of data from heterogeneous sources, such as test systems, real-world vehicle data, physical measurements, and virtual sensor outputs. Ensuring consistency and synchronization across these data domains is a prerequisite for reliable system modeling.

How this information is further processed (with the help of AI methods and machine-learning) in an energy-efficient way is challenging and will not be possible with traditional computing architectures: Edge-Computing, cloud-computing and neuromorphic architectures will be needed as foundation.

On computing level new paradigms have to be considered (edge / cloud / neuromorphic), which enable fast energy saving computation of huge amounts of data that are used for building data-driven models for digital twins. Depending on the development phase, digital twins vary in their level of detail: Early stages require fast and simplified models to enable rapid iterations, while later phases demand higher fidelity and richer detail to capture system behavior more accurately. This dynamic evolution of model granularity must be supported by flexible computational architectures and scalable data handling.

Considering life-cycle aspects, re-use and recycling, this circular economy requires standardized LCA procedures and data that can be implemented in tools providing context-based information to the designers of new systems.

Overarching above mentioned topics is a system of systems engineering approach, which enables to analyze and optimize complex systems that are composed of several systems. A system of systems approach will lead to more complex systems that are performing better than just the sum of single systems. In early development phases, the reuse of subsystem models from related applications is particularly relevant to accelerate system design. These preliminary models are then successively refined, replaced, or complemented by more detailed and system-specific models as the development progresses. A methodology for system of systems approach is still incomplete and has to be developed.

For this system of systems approach it is necessary that standardized methods are developed that tackle the whole process from

- Data generation: what data is necessary, in which quality, and how it must be acquired and harmonized across sources to retrieve the desired information (AI and machine learning cannot compensate for inadequate, incomplete or wrong data)
- Virtual Approval:
 - design of adequate ODDs (Operating Design Domains) on component, system and system of systems level
 - quantification of uncertainty

Table A-1 provides an overview on development tools, methodologies, measurement and test methods of which some are already implemented. Nevertheless, depending on the applications, there is a high research need to address new challenges with these methods. Therefore, specifying TRL in this overview table makes little sense.

Table A-1: Development Tools, Methodologies, Measurement and Test for Software Defined Vehicles (SDV) of the Future

Development Tools, Methodologies, Measurement and Test	Description, Applications for SDV, Impact, Targets
Digital twin of energy systems	Enabling operation close to limits and prediction
Digital twin (detailed modelling)	Creating an effective digital twin, involving the creation of a comprehensive virtual representation that accurately reflects the physical system, e.g. E-Motor, fuel cell, Battery
Methods for LCA and circular economy in the design phase	In the design phase, Life Cycle Assessment (LCA) and Circular Economy principles can be integrated through various methods, including identifying impact hotspots, testing against changing external factors, comparing similar solutions, and designing for durability, modularity, and ease of disassembly to facilitate reuse and recycling
ADAS sensoric modelling	Development of sensor fusion concepts and virtual sensor models to use in real time but also as development tools
Advanced Software Features	Software-defined vehicles (SDVs) leverage advanced software features to enhance various aspects of driving, including safety, performance, and connectivity. These features often include over-the-air (OTA) updates, advanced driver assistance systems (ADAS), and personalized experiences
Edge and Cloud computing	Shared functionality between onboard and offboard which allows to execute resource demanding functions such as optimisation algorithm, predictive functions using digital twins on a Cloud environment. Energy management on vehicle level, personalized driver preferences and behaviour.
Flexible Data Acquisition	Embedded data clients, data exchange protocols, and cloud services for configurable data acquisition, analyses and storage during vehicle operation - after production. AI-based methods and digital twins for fault analysis, lifetime assessment of components, remote validation of new functions, and collecting load- and usage profiles for next-generation development
System of Systems Engineering	SoSE focuses on managing the complexities of a collection of interacting systems, each with its own purpose and functionality to create a larger system with capabilities greater than the sum of its parts.
Driver behavior and cognition	It is crucial to understand how drivers behave and make decisions on the road to develop effective safety systems. This requires studying human factors such as attention, perception, reaction time, and decision-making.
Human-machine interaction (HMI)	As vehicles become more automated, studying how drivers interact with these systems and ensuring they are intuitive and user-friendly is important.
Data analysis and modeling	Collecting and analyzing data from real-world driving situations can provide valuable insights into the causes of accidents and the effectiveness of safety systems. Developing accurate models of driver behavior and vehicle dynamics is also important for designing effective safety systems.
Electromagnetic Compatibility (EMC) Research	Since electric vehicles (EVs) rely on a complex network of electronic systems and components that generate electromagnetic fields, which can cause interference, EMC research is essential to ensure that EVs meet relevant safety and regulatory standards for electromagnetic compatibility. This involves testing vehicles for electromagnetic interference (EMI) and radio frequency interference (RFI), developing methods to reduce such interference as well as ensuring that the vehicle's electronic systems are designed and constructed to minimize electromagnetic emissions.
EMC Simulation:	Advanced Vehicles in 2025 and beyond will contain more advanced electronic systems with High Performance Computing (HPC), enhanced connectivity for ADAS, automated driving and power electronics. Accordingly, meeting of Electromagnetic Compatibility (EMC), Power Integrity (PI) and Signal Integrity (SI) requirements will be even more challenging. Full EMC simulation of complex automotive electronics is not feasible yet and if for selected cases, this is time consuming, not allowing in depth multiple parameter sensitivity analysis. Therefore, a smart modelling must reveal main EMC effects and concentrates on the design parameters, with influence on EMC, PI, SI.

A.2 Advanced Auxiliaries, Components and Systems enabling Energy-Savings

Energy and Thermal Management: Trustworthiness for range prediction and charging of electrified vehicles have to be increased. Retrieving relevant vehicle information – such as state of charge, and state of health of the battery and information concerning the trip are crucial to plan charging with the power needed to complete the trips in the desired time, while considering time-dependent available power at charging stations. This requires the knowledge of the demand of other drivers, a decent information and control system and also information about the actual state of the distribution grid. Power losses that occur during the charging process shall be transferred to other systems, where these heat losses can be used effectively. Prediction of the behavior and predictive control of components is crucial for increasing energy efficiency on system level. While the predictive control has been demonstrated in several applications, digital twins of components and retrieving information on traffic and road conditions for the upcoming kilometers offer a high potential to increase energy efficiency. Innovative “**Regenerative Braking Systems, particle free braking**” help to enhance efficiency and braking comfort whilst reducing particles if compared with conventional disk braking systems. R&D effort is required in the field of high performance 4-wheel regenerative braking systems for optimal energy recuperation as well as in the field of mechanical energy storage devices.

Thermal management affects both the operating conditions for individual components and auxiliaries and the comfort in the cabin. Cabin heating and cooling under extreme environmental temperatures can significantly reduce a (electric) vehicle's range. In special cases (i.e. city traffic), the energy demand for heating can exceed the demand required for propulsion. Predicting the thermal comfort of passengers in battery electric vehicles is key for reliable range prediction (especially in winter). New solutions for more effective thermal waste energy utilization from (electric) powertrain components, like E-motor and Power Electronics are of particular Interest. This includes, but is not limited to, integrated heat-pump systems, compact system Integration, Improved Insulation and heat storage systems. Unused heat can be stored and effectively used later (e.g. waste heat of powertrain components for interior heating the next day). Chemical heat storage systems (with no insulation and indefinite storage duration) offer high potential for this purpose. Such systems are available at a basic level, but a lot of R&D effort is still required.

For new battery concepts thermal conditioning like Cell-to-Pack design with highly efficient and highly thermal uniformity concepts like dielectric fluid immersion cooling with focus on long-term stability has to be ensured.

For new battery concepts with increased energy density and high charging power to reduce charging time, thermal conditioning such as Cell-to-Pack design with highly efficient and thermally uniform concepts like dielectric fluid immersion cooling must be ensured, with a focus on long-term stability. These considerations need to be integrated into the thermal system layout and system design.

Roadmap-Table A-1: Energy and thermal management

		Short-term until 2030	medium-term 2030-2035	Long-term 2035+
Software Defined Vehicles of the Future	Energy and Thermal Management  efficiency / optimum use of available energy Type of project required 	Access to relevant vehicle information for charging in cooperation with Cooperative, Connected Automated Mobility (CCAM), TRL ²⁰²⁵ 3-7		
		Predictive energy/thermal management of cabin and powertrain components, TRL ²⁰²⁵ 5-8		
		High performance 4-wheel regenerative braking system for optimal energy recuperation, TRL ²⁰²⁵ 5-8		
		Hybrid operation management TRL ²⁰²⁵ 6-9		
		Silent cooling and heat loss recovery during High Power Charging (HPC), TRL ²⁰²⁵ 5-7		
		Operation of components closer to thermal limits, TRL ²⁰²⁵ 4-9		
		Thermal conditioning of new battery concepts, TRL ²⁰²⁵ 4-8		
		Waste-heat recovery (ORC (Organic Racine Cycle), thermo-chemical processes, thermo-electric conversion, etc), TRL ²⁰²⁵ 4-6		
		Energy recuperation / actuators TRL ²⁰²⁵ 7-9		

Conventional **cabin heating and air conditioning systems** use the waste heat from the combustion engine for heating and belt-driven air conditioning compressors for cooling. Since highly efficient powertrains (whether advanced thermodynamic or pure electric) produce less waste heat, heating the cabin requires new innovative and efficient solutions. Therefore, heating and cooling must be treated in an overall context, including infrastructure. Pre-heating and pre-cooling of the cabin at the charging station without affecting the range or use of adiabatic cooling systems and navigation-aided early shutdowns must be considered. Additionally, hybrid or pure electric powertrains require demand-driven air conditioning compressors as the combustion engine is not operated permanently. Furthermore, due to the relatively low capacity of the present battery technologies, Heating, Ventilation and Air Conditioning (HVAC) reduces the total range of the vehicle tremendously. New technologies for efficient

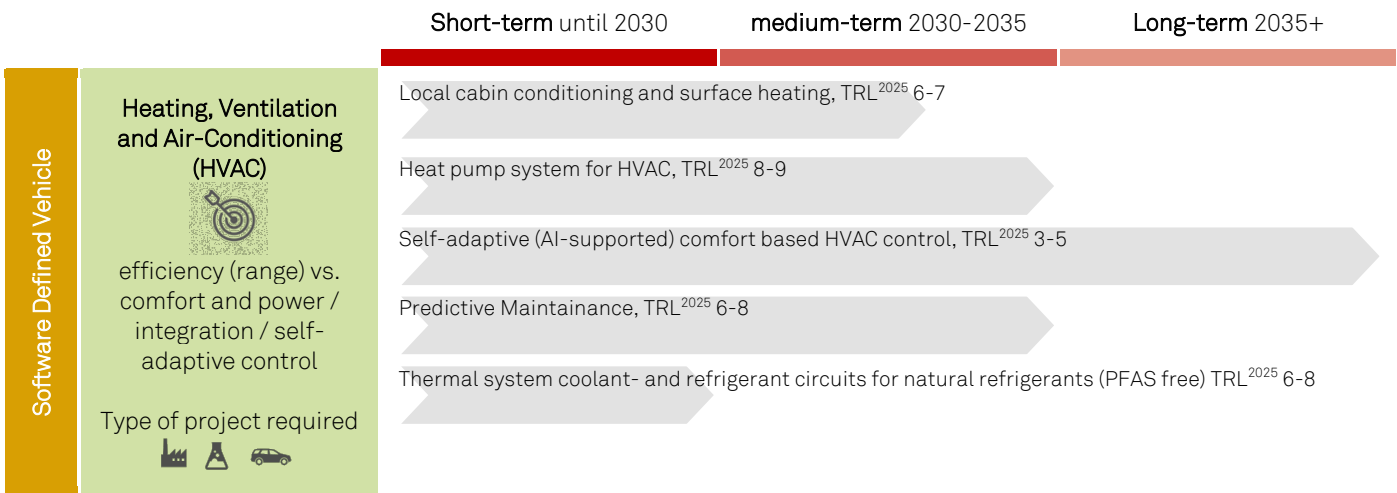
Legend

-  (material) fundamental research
-  industrial research
-  experimental development
-  demonstration

HVAC are latent heat storages, new materials such as zeolite, active thermal materials and heat pump systems.

In thermal systems, the thermal system layout needs to be new designed and components suitable for new refrigerants need to be developed due to regulation (EU) 2024/573¹⁵, which regulates the use of fluorinated greenhouse gases, such as refrigerants. Among other things, the regulation provides for a gradual reduction in the use of HFCs (hydrofluorocarbons), which are to be reduced to 0% by 2050.

Roadmap-Table A-2: Heating, ventilation and air-conditioning (HVAC)



A.3 Advanced Vehicle Control Systems and Software

Advanced control methods for vehicle powertrains (e.g. fuel cell hybrids) that both minimize component degradation and maximize efficiency are crucial. For example, predictive control schemes that consider forecasts on e.g. route, traffic, weather, etc. are necessary. State-of-health monitoring systems (virtual sensors) as well as adequate new sensors to measure the operating conditions (e.g. in batteries or fuel cells) without negatively influencing their operation are required. Future vehicles will continuously provide their operational data (e.g. battery health parameters) to a central unit over the air. This enables new opportunities to evaluate the performance of a whole vehicle fleet in real-time. Adjustments to battery degradation models and associated operation strategies can be fed back to the vehicle fleet. Thus, adaptive control strategies could be implemented on the fleet level, optimizing component lifetimes, emissions and efficiency on the go, without the need for maintenance downtime.

The A3PS members keep track by monitoring the development in the field of advanced vehicle control systems. This is in order to justify innovation in overall vehicle technologies and to increase the chances for the Austrian industry. This also applies to many companies and institutions in the area of vehicle electronics and software.

The technology progress for all kinds of road vehicles in the past decades has significantly improved safety, energy efficiency and emissions as well as the comfort of today’s vehicles. But still, the number of fatalities and injured persons in road traffic is much too high and therefore extended effort is needed to bring these figures down. Increasing number of sensors in vehicles to cope with new challenges, like environmental perception, measurement of components and system states for control functions and the future use of trustworthy digital twins require the efficient use of sensing equipment on board.

Automated driving functions of SAE Levels 3 to 5 will enable the driver to give the driving task to the vehicle to increase safety, comfort as well as efficiency of traffic and transport. However, a prerequisite for this is that the driving functions are objectively verified to an unprecedented extent. Currently, there is no method that allows to perform the associated verification process at a reasonable cost to the industry. In scientific literature, there are approaches available that propose incredible real driving testing distances, but such efforts are not feasible in industrial projects. Therefore, new innovative smart approaches consisting of virtual methods, real-world testing and combination of both must be found that allow a holistic verification of the automated driving functions on complete vehicle level. For the use of such new approaches in industrial vehicle development it is important that these new methods can be performed with the available resources to ensure safe and comfort orientated operation of automated vehicles, whether they are developed for public traffic or for special applications on restricted areas.

Legend

(material) fundamental research

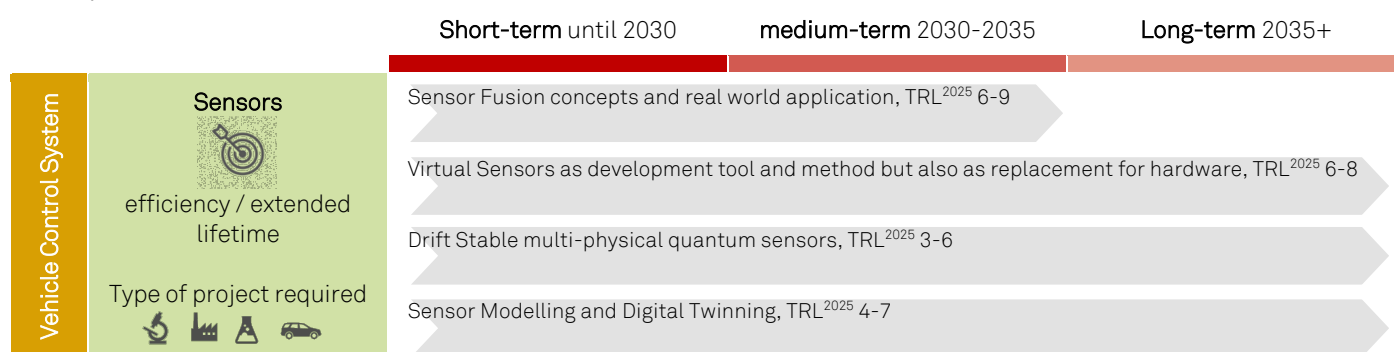
industrial research

experimental development

demonstration

¹⁵ <https://eur-lex.europa.eu/eli/reg/2024/573/oj/eng> (retrieved 13 May 2025)

Roadmap-Table A-3: Sensors



Great R&D efforts are being made in the field of control units (xCU). The term “xCU” encompasses all control units that are relevant for advanced powertrains, including the operating strategy. By merging functions onto an xCU, function allocation and software deployment are no longer fixed to one dedicated control unit. Significant R&D efforts are required for the development of a hardware abstraction layer in combination with a service-oriented architecture for the most flexible, hardware-independent integration of software across different hardware platforms (xCUs).

For xCUs virtual validation will become increasingly important, when over-the-air software updates should become reality. Modular software functions that can be validated in respective (well-designed) ODDs will be essential for virtual validation.

V2X capable on-board units will still have to be validated in real-world traffic.

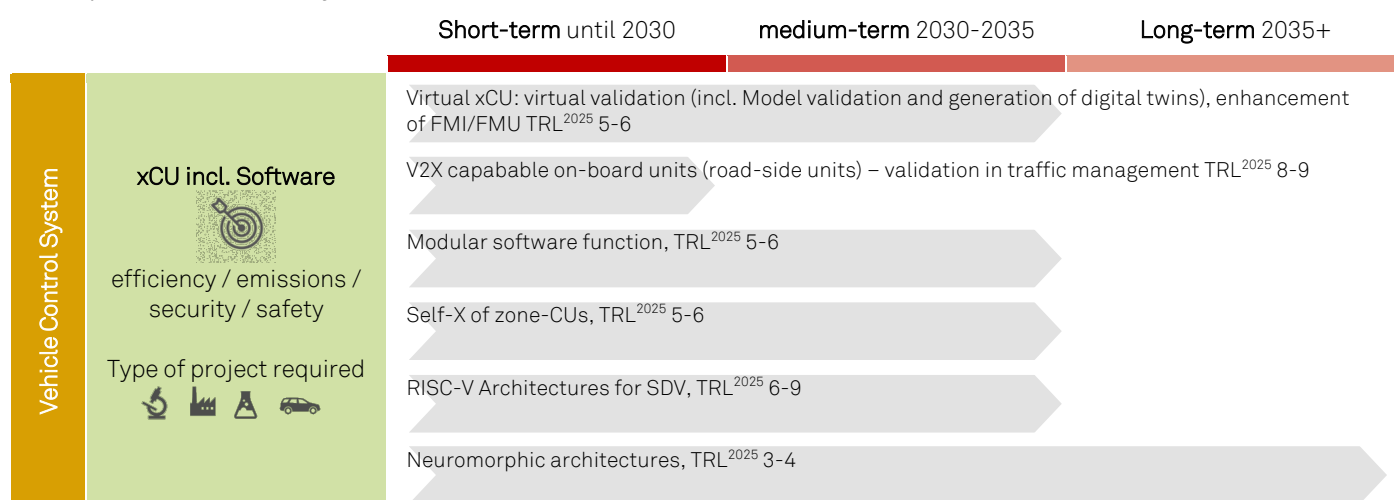
Zone controllers are emerging in the automotive industry as nodes or hubs that solve zone specific tasks, which decreases cabling effort and weight. For these zone controllers to work in a complex system-of-systems self-X capabilities are mandatory (X stands for monitoring, diagnosis and possibly taking over control tasks from other not functional controllers).

RISC-V architectures for SDV: The need for research into RISC-V architectures for software-defined vehicles (SDV) lies in adapting and expanding the architecture for the specific requirements of SDV systems. In particular with regard to safety and real-time capabilities.

SDV systems are particularly susceptible to cyber-attacks due to their networking and software intensity. There is a need for research into the development of robust security mechanisms based on RISC-V hardware, such as hardware-based secure enclaves or isolation techniques.

In SDV systems, real-time requirements for functions such as steering, braking and sensor data management are essential. Research must focus on improving the real-time capabilities of RISC-V architectures, for example by implementing prioritization protocols or hardware-accelerated real-time mechanisms and AI accelerators.

Roadmap-Table A-4: xCU incl. software



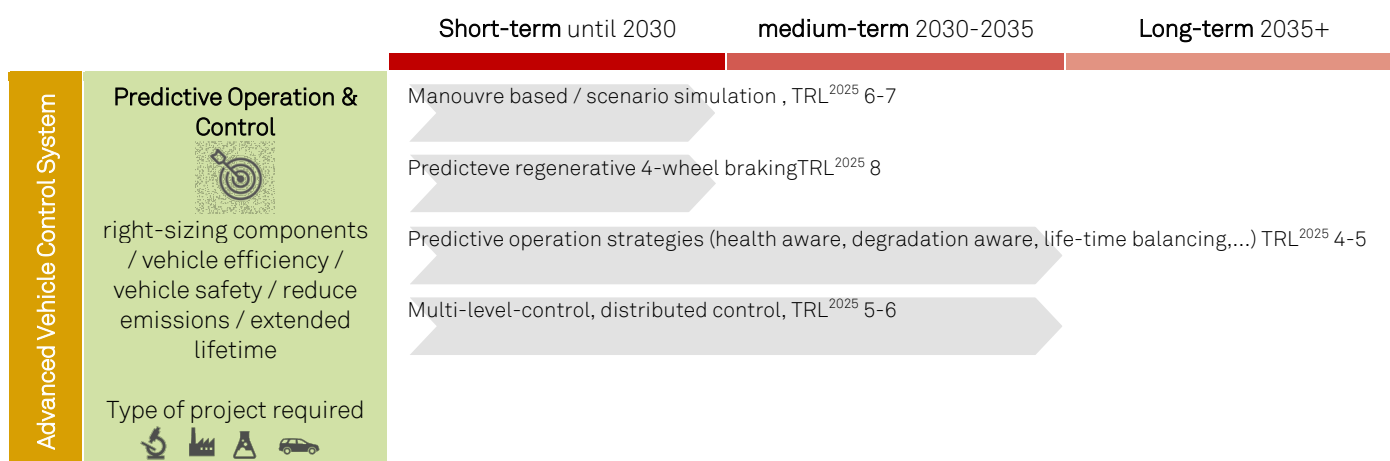
Optimized operation strategies can increase efficiency and reduce pollutant emissions. Predictive operating strategies play an important role, as well as the consideration of a combined controller, for both passenger cars and commercial vehicles. Predictive maintenance is becoming increasingly important when fail-safe operation of relevant drivetrain components is considered but also degradation effects that can affect efficiency of the entire system.

For future control strategies and systems AI technologies need to be considered and developed towards the particular demands of vehicle and vehicle powertrains.

Legend

-  (material) fundamental research
-  industrial research
-  experimental development
-  demonstration

Roadmap-Table A-5 Predictive operation & control



A.4 Non-exhaust particle emissions

Non-exhaust particle emissions refer to the release of small particles into the air from sources other than vehicles' exhaust, such as brake wear, tire wear, road surface abrasion, and construction activities. These particles can have adverse effects on both human health and the environment. Therefore, there is a need for research on non-exhaust particle emissions to better understand their sources, composition, distribution, and potential impacts, and to develop effective mitigation strategies.

One of the main research needs for non-exhaust particle emissions is to improve our understanding of the contribution of different sources to overall particle emissions. This requires the development and application of reliable methods and devices for measuring and quantifying non-exhaust particle emissions, as well as the use of advanced modeling techniques to simulate the dispersion and transformation of particles in the atmosphere.

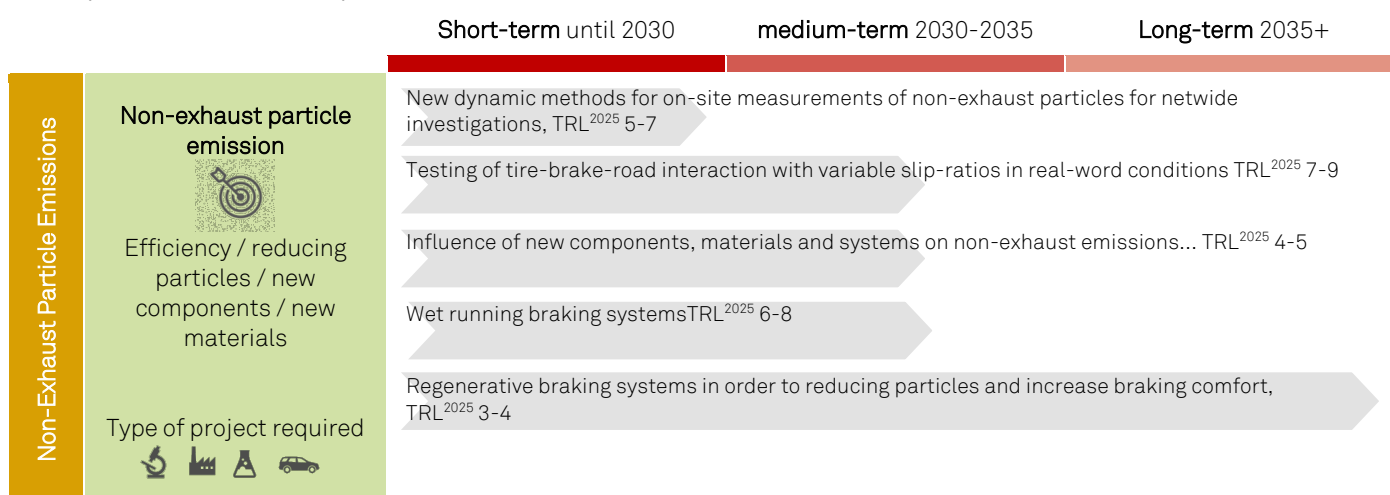
Micro particles caused by brake abrasion are harmful to health and contribute to air pollution. Wet running brake systems could significantly reduce abrasion and capture all micro particles in oil.

Another research need is to investigate the health effects of non-exhaust particle emissions. These particles are typically smaller in size than exhaust particles and can penetrate deeper into the respiratory system, potentially causing respiratory and cardiovascular diseases. Therefore, there is a need for epidemiological studies to assess the health risks associated with exposure to non-exhaust particles.

Furthermore, research is needed to identify effective mitigation strategies for reducing non-exhaust particle emissions. This may include the vehicle operating strategy from complete vehicle level down to system behavior, the development of new materials for tires and brake pads that generate fewer and less toxic particles or even capture those, the implementation of measures to reduce road surface abrasion, and the use of dust suppression technologies at construction sites.

- Particle Emissions: Checking the suitability of available measurement methods and subsequent development of new measurement methods (test bench and dynamic "real-world" methods) and tools.
- Development of suitable test bench infrastructure as well as on-site measurement procedures for netwide investigations.
- Development of technical solutions and operating strategies to reduce particle emissions, especially in real operation.
- Research on zero-emission concepts for the fundamental new components and systems that offer the same range of functions and the same functional safety.

Roadmap-Table A-6: Non-exhaust particle emission



B Battery Electric Powertrains

Compared to thermodynamic powertrain technologies, electric powertrain technologies are characterized by a very high “tank/battery”-to-wheel efficiency and the potential for zero local emissions. Electric powertrain technologies enable an incredible performance regarding drivability and - in combination with Advanced Driver Assistance Systems (ADAS) - personal safety. In addition, such systems will substantially support defossilization efforts to reach the climate targets. These advantages justify and request high R&D effort. Although the basic technical principles have already matured and an increasing number of systems are already on the market, they must be made more affordable, efficient, durable, sustainable and safe. These goals can only be achieved by performing R&D activities on the materials, component, and system-levels of the electric powertrain. Within the next few years BEV powertrains must be compatible with new regulations on critical raw materials, minimum levels of recycled content, and circularity rates. Therefore, apart from existing powertrain designs and basic principles, diverse approaches focused on design-for-disassembly (linked design with less integration) are needed. Aspects regarding materials and production are covered in more detail in the **F Innovative Materials and Production** of this roadmap.

To meet the requirements of EU regulations, large investment in disruptive research and optimization steps must take place. These investments must focus on new technologies (software, hardware), development methodology (simulation), production technologies, and modular and scalable designs for electric powertrain systems. These concepts must also be circular. Furthermore, the application of less expensive, more abundant, and sustainably sourced materials must be explored, ensuring strategic European autonomy from existing material supply chains.

To achieve a net carbon-free society by 2050, the market penetration of battery electric vehicles must be increased significantly. This can be ensured by reducing the cost of BEVs. However, an indispensable precondition for positive environmental effects of battery electric vehicles is the availability of almost 100 % renewable electric energy.

Both battery electric and fuel cell vehicles are considered as the best solutions with respect to the local emissions^{16,17}, and in this chapter, new technologies for next generations of battery electric vehicles are considered. Conversely, fuel cell electric vehicles are addressed in **C Fuel/Electrolysis Cells and Hydrogen**. Industry and research institutions typically treat fuel cell powertrains differently than battery electric vehicle technologies, although fuel cell vehicles are, technically speaking, hybrid electric powertrains. Plug-in Hybrid Electric Vehicles (PHEV) can lower local CO₂ emissions even more than hybrid electric vehicles due to the larger battery capacity of PHEVs. Hybrid electric vehicles are considered in **D ICE and Hybrid Powertrains** and. However, the electric components discussed in the Battery Electric Powertrains chapter are also relevant for hybrid electric vehicles.

Currently, Europe's electricity is 60 % green and 40 % fossil. As Europe has the world's largest meshed electricity grid, a similar **electricity mix** is available for every consumer in Europe, regardless of the country. As the available electric power will be used in the grid first, EVs recharged from the grid will automatically use energy from fossil sources, unless the charging is done by non-grid connected private PV generation. Therefore, the switch from fossil fuel vehicles to BEVs will only significantly reduce CO₂ emissions from transport if the European grid is virtually 100 % CO₂ neutral and the regulating power plants for stabilizing the European grid release significantly less than e.g. 660 g CO₂ eq/kWh¹⁸. The goal of an entirely green power grid can only be achieved if electricity demand grows at a slower rate than the increase in the electric energy generation from low CO₂ power plants. This means that saving electricity and not increasing the grid load must be the priority. During this transition, a well-balanced mixture of hybrid and full electric vehicles is needed to minimize the well-to-wheel CO₂ emissions from transport. Research and development in the short-, mid- and long-term is key to achieve these minimum emissions in the powertrain types presented in the overall roadmap and to be prepared for a long-term fossil free transport system.

The measures that must be adopted to ensure renewable electricity are not part of this technology roadmap. The transition towards 100 % renewable electricity in Austria is part of the “Erneuerbaren-Ausbau-Gesetz”¹⁹. This law covers the feed-in of **electricity generation** from Austria into the European grid and requires Austria to use only green power plants for electricity generation by 2030.

To realize the full potential of BEVs, sufficient charging infrastructure must be available, and the use of renewable electricity is assumed, both of which require a highly committed technology policy. Furthermore, due to high power demand, PHEVs and BEVs require high voltages in the range of 1000 V for both power and adequate charging times.

 In the field of heavy commercial vehicles and buses, depot-bonded battery electric vehicles are the relevant powertrain concepts. Since the distances covered by depot-bonded vehicles are calculable in both course and length, such applications are particularly suitable for pure battery-electric operations. The use of battery-electric, depot-bonded vehicles in urban scenarios with intensive stop- and-go traffic will lower pollutants and emissions due to the recovery of braking energy. Battery electric heavy-duty vehicles are already on the market, and full electric battery powered trucks and buses for distances over 400 km are already available in a first generation. In these applications, high voltages are mandatory to achieve the expected charging performance.

¹⁶ICCT (2021). White Paper: -A Global Comparison of the Life-Cycle Greenhouse Gas Emissions of Combustion Engine and Electric Passenger Cars; <https://theicct.org/publication/a-global-comparison-of-the-life-cycle-greenhouse-gas-emissions-of-combustion-engine-and-electric-passenger-cars/> (retrieved 8 March 2025)

¹⁷JRC Technical Report (2014). JRC Well-to-Wheels Analysis of Future Automotive Fuels and Powertrains in the European Context, https://publications.jrc.ec.europa.eu/repository/bitstream/JRC85327/ttw_report_v4a_online.pdf (retrieved 15 April 2025)

¹⁸BEV with 20 kWh/100 km => 13,25 kg CO₂ eq and ICE with 5,0 l Diesel/100 km => 13,25 kg CO₂ eq but without considering the additional CO₂ footprint for the battery production

¹⁹https://www.bmimi.gv.at/themen/klima_umwelt/energiewende/waermestrategie/ewg.html (retrieved 15 April 2025)

The focus will be on voltage levels in the range of 1000V to 1250 V²⁰, whereas in the long-term, the voltage levels might go up to even 1500 V²¹. The availability of semiconductors and power modules, which can cope with these high voltages and the dynamic loads in driving vehicles are indispensable for this technology and could be developed based on today's industrial applications.

B.1 Energy Storages

Battery technologies are the key drivers for the success of electric vehicles. Li-ion batteries (LIBs) have permeated the market and will remain in focus for the next few years. In 2023, global EV battery demand reached 750 GWh, representing a 40% relative increase from 2022²². Although the market is dominated by China (415 GWh in 2023, representing a 55 % share of the global market), Europe is fast-growing, and demand has already reached 185 GWh in 2023 (approximately 25% of the global market). In the short-term, research is focused on the stacking and vehicle integration of existing LIB chemistries. For the mid- and long-term vehicle generations, continuous R&D effort is needed to achieve the required utilization of generation 3 systems (LIBs with advanced cathodes and anodes and a liquid electrolyte) and to push the technological development of generation 4 systems (solid electrolytes with/without the Li-metal anode)²³, thereby promoting their adoption in future BEVs. On a broad perspective, battery R&D is mandatory to achieve the goals that are set for performance, efficiency, safety, cost, recyclability and circularity. Energy contents and power-to-energy-ratios must be improved, and new levels of geometrical and structural integration must be achieved while reducing costs, increasing efficiency, durability (cycle stability), and safety. Furthermore, the European Commission has set levels for minimum contents of lithium, cobalt and nickel in new batteries, which must be recovered from battery manufacturing waste or post-consumer waste²⁴.

To meet expected and future demand, the energy density of the cell must be increased, and this factor drives the current research on battery technologies. For mobility applications, both high-capacity and high-voltage systems employing liquid electrolytes (generation 3) are considered for design-for-performance systems. The high-capacity systems will employ both layered and olivine phosphate cathodes and combined them with graphite or composite anodes. The high-voltage systems are expected to use both layered cathodes with high Ni-contents and spinel-based cathodes. Since the Chinese OEM BYD integrated LFP cells into the battery pack structure, allowing for a higher energy density at the pack level, LFP cells have re-gained interest in the battery market²⁵. This re-emergence is also facilitated by LFP's higher safety compared to Ni-containing chemistries. Since LFP is a cobalt-free chemistry, it is classified under design-for-cost systems. Other cobalt-free cathode chemistries such as lithium manganese iron phosphate (LMFP) and layered, high lithium manganese (HLM) chemistries are also design-for-cost and must be further developed. In systems containing solid electrolytes with/without the Li-metal anode (generation 4), advances are expected via developing polymer, inorganic and composite electrolytes that exhibit high ionic conductivities and that are compatible with the metallic Li anode. The energy density targets will be pushed further by moving from layered and olivine cathodes (generation 4b) to cobalt-free, layered, HLM and spinel cathodes. In terms of new chemistries, specific targets have already been established for the following systems: Li-sulfur with liquid electrolytes, Li-sulfur with solid electrolytes, Mg-metal systems, and metal-ion aqueous systems. Although Na-ion chemistries may not achieve the specific energy and volumetric energy density targets set for Li-ion chemistries, they should still be considered for mobility applications due to their lower costs and performance similar to LFP chemistries, as shown recently by CATL²⁶. This chemistry also appears to be very promising for battery swapping applications, where driving range is no longer considered a limiting factor. Key R&D objectives include improving efficiency and durability and enabling circular design through CRM-free and PFAS-free materials.

Regarding safety, several approaches are used to achieve the set targets. While safety can be addressed on the system level, targeted advances must also be made on the cell level to improve the EUCAR hazard ratings for automotive applications from 4 to 3 at cell level. This necessitates research and development at the materials level, including improvements in electrolyte formulations with additives for H₂O and HF-scavenging, functionalized separators, protectively coated cathodes, higher operating voltage anodes, and sensors that trigger the initiation of self-healing mechanisms and/or controlled cell discharge and/or shut-down before thermal runaway events occur.

Key activities in R&D for all electric energy storage technologies for vehicles are concentrated in the areas of:

1. Optimization of materials and cells:

- Advanced Li ion – 3rd generation, with design-to-cost and design-to-performance chemistries.
- Solid state Li ion – 4th generation, incorporating the use of metallic Li as the anode.
- Integration of real and virtual sensors to improve safety and assessment for second-life applications.
- Increased contents of recycled materials to be in line with the EU battery regulation (EU) 2023/1542²⁴.
- Design for recycling, refurbishment and reuse, following the EU's shift to a circular economy.
- Compatibility with the battery passport.

2. Optimization of battery cells and pack integration

- Design of advanced battery packs based on new cell formats (e.g. 4680.)

²⁰<https://www.charin.global/technology/mcs/> (retrieved 15 April 2025)

²¹<https://www.sae.org/news/2020/05/chademo-3.0-to-harmonize-global-ev-quick-charging-standards>, <https://en.wikipedia.org/wiki/ChaoJi> (retrieved April 15, 2025)

²²<https://www.iea.org/reports/global-ev-outlook-2024/trends-in-electric-vehicle-batteries> (retrieved May 15, 2025)

²³Strategic Research and Innovation Agenda – BATT4EU (retrieved May 15, 2025)

²⁴REGULATION (EU) 2023/1542 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 12 July 2023 concerning batteries and waste batteries, amending Directive 2008/98/EC and Regulation (EU) 2019/1020 and repealing Directive 2006/66/EC

²⁵The future of electric vehicles & battery chemistry | McKinsey (retrieved May 15, 2025)

²⁶CATL presents three new battery breakthroughs at 'Super Tech Day' - electrive.com (retrieved May 15, 2025)

- Battery pack safety / “no propagation pack” based on midterm upcoming up Li-ion cell technologies.
 - Pack engineering for improved recyclability.
 - Assembly and joining process technologies.
3. New methods and materials to improve performance and cost (needed for 1. and 2.)
- New integrated modelling and simulation methods.
 - New statistical testing methods.
 - Research in advanced materials.
 - Process equipment development.

The R&D topics listed under “3. New methods and materials” need to be part of both R&D programs dealing with “1. Optimization of materials and cells” and “2. Optimization of battery cells and pack integration”. Li ion batteries are already on the market, but production, but environmentally friendly, solvent-free production technologies, the elimination of CRM, recyclability and scalability, as well as cost and affordability, remain important research topics.

Advanced mechanical and chemical **modelling methods and simulation** tools will allow conclusions to be drawn from battery cell level to systems level and therefore save time considerably during the development process. The main difficulty lies in the proof of scalability for chemical simulation methods. As parameter variation results in complex and time-consuming tests, **new statistical testing methods** are required to reduce the effort for battery testing. Additionally, expert knowledge is rare in this field: rising it could be a great opportunity for Austrian industry and R&D institutions. Experts predict a high potential for **material research** including interplay of different materials on cell as well as on pack or system level to improve basic characteristics of future batteries and help to achieve the performance, efficiency, weight, and cost goals.

B.1.1 Battery Technologies

Advanced Li-ion (3rd generation), solid state batteries (4th generation) as well as long-term new battery technologies require disproportionately high R&D efforts to achieve the large benefits possible. Although significant progress has been achieved in recent years, further research on the materials and cell levels are essential to improve cyclability and high-voltage stability. In addition, safety must be addressed, and EUCAR hazard levels, which are currently at 4, must decrease to 3 in the medium and long-term. On the one hand, the large-scale production of generation 3 cells and packs is already commercialized, but specific cell production steps can be made more environmentally sustainable. On the other hand, resources must now be invested to develop cell designs and environmentally sustainable techniques to enable the large-scale manufacturing of generation 4 cells. To promote uptake of advanced cell technologies, cell costs at pack level, which are estimated at 150 €/kWh, must decrease to 50-75 €/kWh by 2030, with further reductions to < 50 €/kWh beyond 2030.

The following steps are necessary to further improve advanced Li ion battery technologies (3rd generation). The KPIs listed are in-line with the Strategic Research and Innovation Agenda (SRIA)²³ of the Batteries European Partnership Association (BEPA):

- Advanced Li-ion batteries with enhanced safety behavior, achieving an EUCAR hazard level of 2.
- Improved cyclability and operational lifetime of cells, aiming to achieve 2000+ cycles for design-for-performance chemistries and 6000+ cycles for design-for-cost chemistries.
- Achieving competitive energy targets approaching > 350 Whkg⁻¹ for design-for-performance chemistries and > 250 Whkg⁻¹ for design-for-cost chemistries.
- Improved sustainability and recyclability to achieve the minimum amounts of recycled contents of 26% for cobalt, 12% for lithium and 15% for nickel²⁴.
- Design for recycling to increase the recovery targets to 80% for Li and 95% for cobalt, nickel and copper²⁴, aiming to eventually achieve 100 % recovery in the long term.
- Fostering of research and further development of methods/processes, materials, components, etc. to support the necessary massive reduction in manufacturing costs and the associated industry-location preservation "Made in Austria".

The following steps are necessary to push solid state battery technology (4th generation), following KPIs which are in-line with the Strategic Research and Innovation Agenda of BEPA²³:

- Increases in Li-ion conductivity at room temperature from current values of 10⁻⁴ Scm⁻¹ to → 10⁻³ Scm⁻¹ for polymer and composite electrolytes.
- Increases in Li-ion conductivity at room temperature from current values of 10⁻³ Scm⁻¹ to → 10⁻² Scm⁻¹ for inorganic (oxides and sulfides) electrolytes
- Incorporation of inert ceramic separators with polymer, oxide, sulfide and composite electrolytes to enable the use of Li-metal anodes for generation 4b and generation 4c architectures.
- Improved cyclability and safety.
- Enabling higher thermal and electrochemical stability while targeting higher energy/power densities, especially including fast charging capabilities.
- Large scale Li metal/electrode production for generation 4b (4-6 years) preparation for industrial scale-up of manufacturing
- For limited-excess (anode-less) cells, development of current collectors or substrates favoring highly efficient (>99.7% coulombic efficiency) Li-metal plating and stripping.

- For zero-excess (anode-less) cells, development of current collectors or substrates favoring highly efficient (>99.95% coulombic efficiency) Li-metal plating and stripping

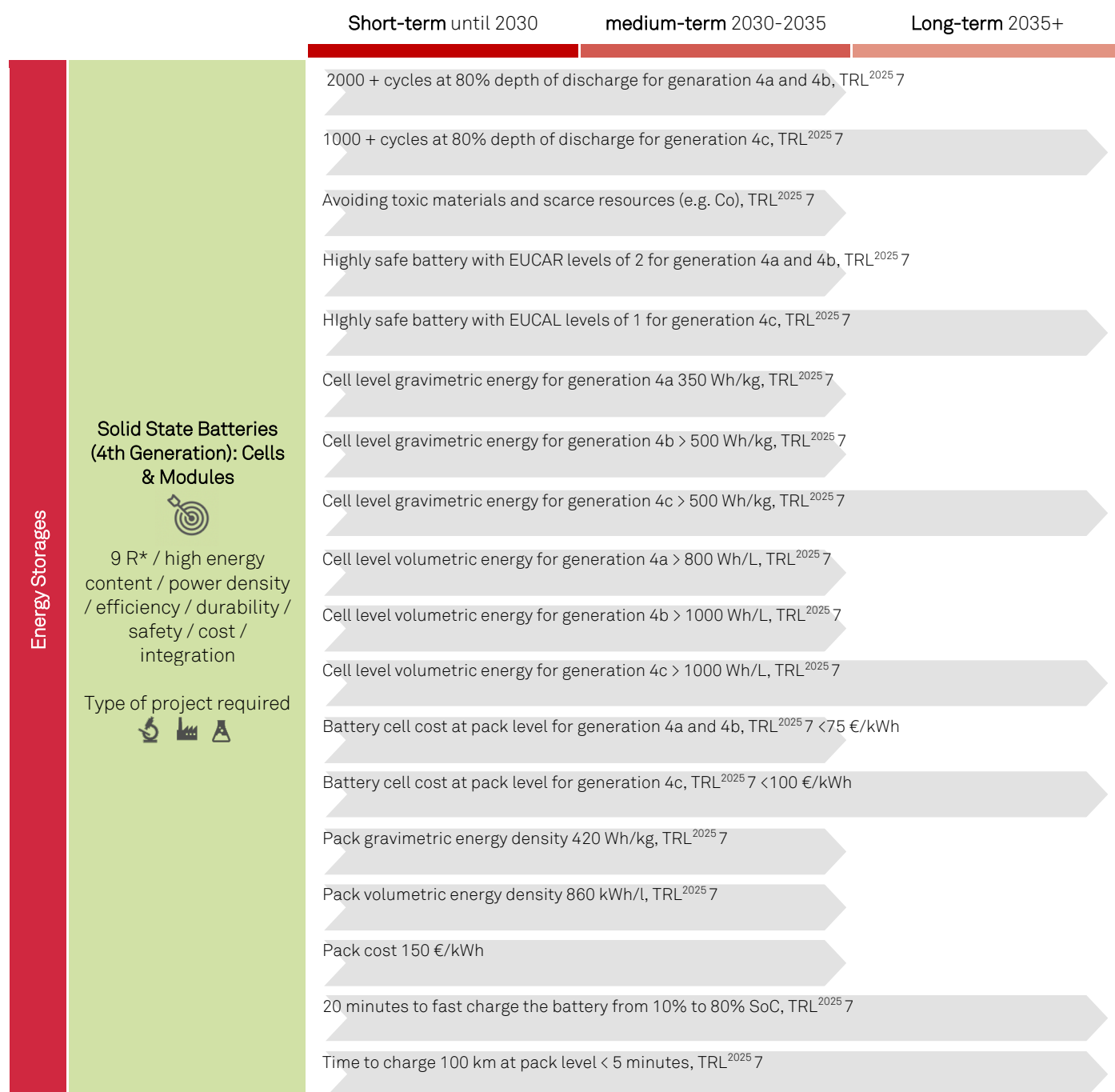
In addition, new cell technologies must be developed to meet future projected battery demands, as well as to enable a diversity in choice of cell chemistries to reduce the strain on existing Li-ion supply chain. These concepts focus on batteries with metal anodes such as single-valent Li-S with both liquid and solid-state electrolytes, multi-valent systems such as Mg-metal systems, and metal-ion aqueous systems such as Zn-ion. The goals are to perform research at the material and cell levels to achieve the following KPI's as established by BEPA²³:

- Increasing the nominal specific capacities on the cell level (> 1300 mAhg⁻¹ for Li-S with liquid electrolytes, >1500 mAhg⁻¹ for Li-S with solid electrolytes, > 800 mAhg⁻¹ for Mg-S)
- Increasing the nominal rates for charge and discharge (0.1 C for Li-S and Mg-S, and 5-10 C for metal-ion aqueous). These are the rates at which the nominal capacity can be expected.
- Increasing the maximum charge rates (3 C for Li-S, 2 C for Mg-S, >100 C for metal-ion aqueous)
- Increasing the gravimetric energy (> 400 Whkg⁻¹ for Li-S with liquid electrolyte and Mg-S, 600 Whkg⁻¹ for Li-S with solid state electrolytes and 40-150 Whkg⁻¹ for metal-ion aqueous).
- Achieving a cycle life of 400+ cycles for the Li-S and Mg-S systems and 1000 + for metal-ion aqueous systems.

Roadmap-Table B-1: Advanced Li-Ion batteries (3rd generation): cells & modules



Roadmap-Table B-2: Solid state batteries (4th Generation): cells & modules



Legend

-  (material) fundamental research
-  industrial research
-  experimental development
-  demonstration

Roadmap-Table B-3: New battery technologies

		Short-term until 2030	medium-term 2030-2035	Long-term 2035+
Energy Storage	New Battery Technologies	Nominal specific capacity >1300 mAhg ⁻¹ for Li-S with liquid electrolyte > 1500 mAhg ⁻¹ for Li-S with solid electrolyte, > 800 mAhg ⁻¹ for Mg-S, TRL ²⁰²⁵ 5		
		Gravimetric energy of >400 Wh/kg for Li-S with liquid electrolyte and Mg-S systems, >600 Wh/kg for Li-S with solid state electrolyte, and up to 150 Wh/kg for metal-ion aqueous chemistries, TRL ²⁰²⁵ 5		
	higher energy content / power-to-energy ratio / efficiency / durability / safety / cost / integration / independency of CRM	Maximum charge rates of 3 C for Li-S, 2 C for Mg-S, >100 C for metal-ion aqueous, TRL ²⁰²⁵ 5		
	Type of project required	Cycle life of 400+ for Li-S and Mg-S and 1000+ for metal-ion aqueous systems, TRL ²⁰²⁵ 5		
	 			

B.1.2 Optimization of cell and battery integration/packaging in the overall vehicle structure

Additional approaches to increase the total energy available to a vehicle (more useable energy for higher vehicle mileage) are the optimization of the battery cell and pack integration. Current optimization efforts are labelled as Cell-to-Pack (C2P) whereas future concepts are called Cell-to-Chassis or Cell-to-Vehicle (C2C / C2V). The C2P approach (which is now entering the mass market) already optimizes the battery pack itself as a component. The cell modules are formed to larger cell arrays / cell clusters to create a better space utilization of the given battery packaging space inside the vehicle. The cell cluster housings/structures are omitted/reduced while still maintaining the electrical and structural functionalities and performance. This approach allows weight savings with better space utilization, which leads to a higher volumetric/gravimetric energy density on pack level.

The C2C concept is a future concept (>2025), which re-evaluates the integration of the battery pack into the vehicle's underbody. The battery pack is no longer a standalone component but will be integrated into the chassis. The concept behind this development is to consider the battery and chassis as one component, thereby reducing weight, e.g. by removing redundant structures, less needed packaging space and better Z-stack behavior. This will not only increase the total energy available to the vehicle but also lower the cost of the vehicle by reducing the amount of parts required.

For systems containing cylindrical cells, trends are moving towards larger cells, e.g. 4680 formats. This volume of 4680 cells is more than 5 times larger than that of 2170 cells, translating in increased energy. Since the ratio of active material compared to inactive parts is larger, 4680 cells also exhibit higher volumetric energy densities. The significant increase in cell size and volume demands major adaptations in mechanical pack design including safety and cooling. These activities go hand in hand with the ultimate goal of no-propagation packs, which are battery systems where a cell in thermal runaway does not trigger further runaways. A redesign in packaging, venting channels and safety vents, flame distance and barriers are required with the support of simulation and testing for optimization and verification.

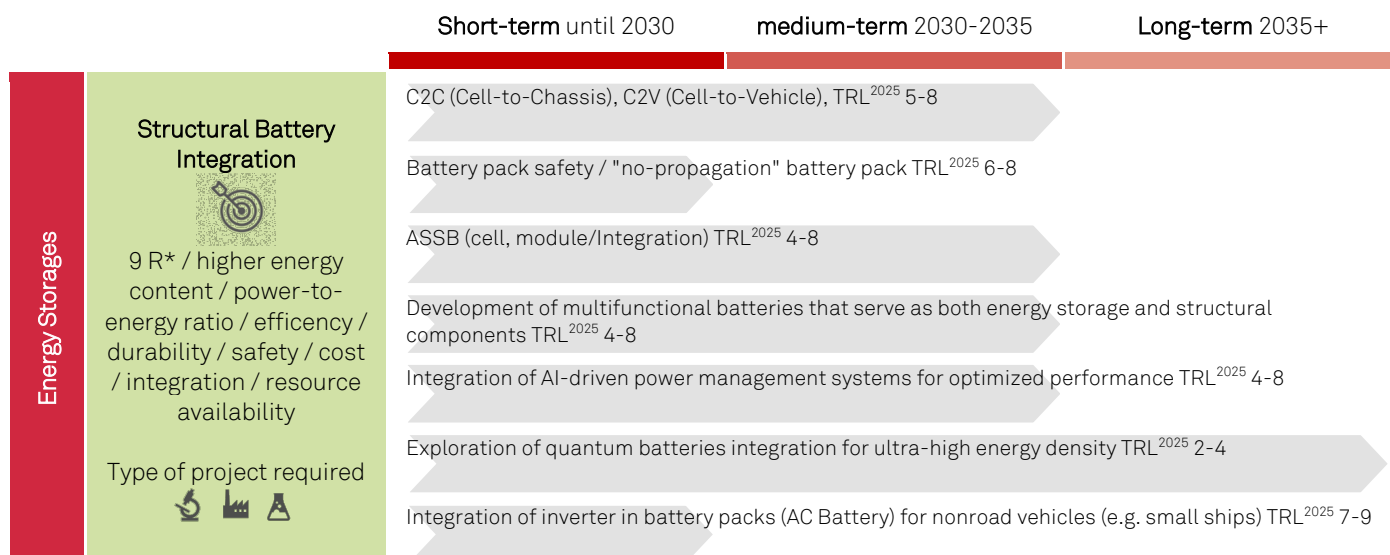
It must be mentioned that the adoption of highly integrated C2C and C2V solutions can significantly change the development trajectory. For example, new validation strategies and regulations must be developed to enable these technologies. In addition, the decision to build a battery electric vehicle using C2C and C2V approaches must be taken much earlier in the design process, which will affect the component supply and value chain.

For the successful integration of the batteries and electric high voltage (HV) circuits into the vehicle, safety elements play a vital role – namely to achieve the requested automotive safety integration level (ASIL) standard in the emergency shut down. Controlled and safe dissipation of the high energy stored in the battery as well as safe discharge of the residual energy in the electric HV circuits needs to be addressed. R&D is needed to achieve the performance levels for those elements regarding short circuit currents (up to more than 30 kA) and circuit inductances (up to > 100 nH) for the steadily increasing battery energies (> 100 kWh) and voltages up to 1250 V (with potential to 1500 V in the long-term). New solutions are needed for high performance cars and electric trucks.

Legend

-  (material) fundamental research
-  industrial research
-  experimental development
-  demonstration

Roadmap-Table B-4: Structural battery integration



 Battery swapping systems offer a time-efficient and therefore end customer-friendly charging approach for rapid energy replenishment without long charging times and allows for a flexible and scalable energy supply solution. The suitability of battery swapping depends on the vehicle type and use case. Battery swapping technologies seem unlikely to reach a major breakthrough in passenger cars, as conventional charging solutions are expected to be sufficient. In contrast, especially (but not exclusively) for commercial vehicle applications such as trucks, buses, non-road mobile machinery and other heavy-duty machines, battery swapping presents a promising alternative.

Battery swapping will ensure continuous operation, minimize downtime and is particularly advantageous in regions or industries where charging infrastructure is limited or unavailable. Even in areas with existing charging infrastructure, battery swapping offers significant benefits by reducing the need for high-power charging during operational pauses. Instead of requiring fast charging with high electrical loads (potentially leading to accelerated battery-ageing), swapped/replaced batteries can be charged more gradually and with lower power while the machine or vehicle is in operation. This may optimize grid usage, reduce peak demand and help prevent strain on the power supplying infrastructure. However, the technology is still in its early stages, and many aspects have to be further researched and fully industrialized, especially for heavy-duty vehicles. Holistic approaches including scalable swapping mechanisms and components on machines and swapping facilities as well as potentially needed efficient battery logistics are still in development, requiring further technological advancements and industry collaboration to enable widespread adoption. The development, production and implementation of battery swapping, and associated charging systems, create significant potential for added value in Austria, fostering industrial development and potential job creation in a new and still unoccupied industrial pillar. Therefore, in the near future, battery swapping might make a valuable contribution to the off-highway, heavy-duty and logistics sectors. However, vehicle architectures must be modified to enable the use and implementation of standardized battery packs and ancillary systems. Standardization of battery packs could support the implementation of battery swapping but doesn't seem likely in near future.

In the logistics realm, particular attention must be paid to so called "Intermodal Transportation", meaning the transportation of goods on different modes of transport such as rail, road, ship etc. For example, cargo containers equipped with batteries can be charged during the journey on train and then serve as an electrical range extender when transferred to truck platforms. Integrating batteries in standardized container platforms in order to aid electric propulsion also brings the advantage of reducing the burden on the grid as they can be charged at low power either when stationed on the logistics terminal or via the railroad grid. Furthermore, the availability of electric energy on a cargo container allows safe, uninterrupted cooling of good (if required) and or continuous monitoring of other potentially relevant parameters such as geographical location, temperature, humidity, acceleration. This application hence goes beyond the task of vehicle propulsion alone.

Legend

-  (material) fundamental research
-  industrial research
-  experimental development
-  demonstration

Roadmap-Table B-5: Structural battery integration

		Short-term until 2030	medium-term 2030-2035	Long-term 2035+
Energy Storages	Battery Swapping Systems  standardization / efficiency / intergation Type of project required   	Conceptual design of novel multi-modal logistics applications involving battery swapping, TRL ²⁰²⁵ 4-6		
		Energy self-sufficient cooling cargo containers with IoT for battery swapping and propulsion TRL ²⁰²⁵ 4-6		
		Vehicle integration and testing of rail/road/naval/off-highway interchangeable battery solutions TRL ²⁰²⁵ 5-8		
		Packaging and thermal management of swappable battery modules TRL ²⁰²⁵ 5-8		
		Implement V2G (Vehicle-to-Grid) technology to support grid stability TRL ²⁰²⁵ 5-8		

B.2 Electric Components & Electric Drive Units (EDU)

New regulations on circularity and supply chain security, as well as improvement on system costs, safety (torque accuracy, cyber security), package, power density and efficiency can be achieved by **further developments of the electric motor and inverter**. Therefore, advanced electric motor and inverter design concepts must be developed to include and implement:

- Magnet-free electric motors with power densities comparable to permanent-magnet synchronous motors (PMSMs).
- New winding types
- Advanced magnet materials with zero use of Heavy Rare Earth Elements (HREEs)
- Advanced cooling fluids to run the E-Motor and bring the correct torque to the wheel
- 9R strategies within the circular economy context, with emphasis on finding a balance between highly integrated designs (saving weight and cost) and ease of disassembly to promote 9R circularity concepts at end-of-life.

Furthermore, highly integrated electric motors with adequate (high) revolution speeds will be able to provide the required performance targets at lower weight and with less space requirements if the high temperatures can be handled accordingly. While increasing the rotational speed of an electric motor is an effective means to achieve greater power densities (and specific power for that matter), rotor dynamics and bearing torque loss (i.e. frictional losses) start to play a critical role. In this context, the following aspects require extensive R&D work:

- Low-loss resilient bearing systems for high-speed electric motors
- High-strength materials to accommodate centripetal forces and rotor stresses
- Novel motor cooling systems allowing the rejection of eddy current induced heat losses
- Novel condition monitoring systems

Roadmap-Table B-6: Electric motor

		Short-term until 2030	medium-term 2030-2035	Long-term 2035+
Electric Components	E-Motor  9R* / efficiency / cost / safety / reliability / high volume production / thermal stability Type of project required   	Speeds >> 20.000 rpm (e.g. bearing, seal, magnet fixation, retention sleeves), TRL ²⁰²⁵ 5-6		
		Heavy rare earth element (HREE) free and/or non-permanent-magnet concepts, TRL ²⁰²⁵ 4-5		
		Advanced motor topologies (e.g. in-wheel motors, disc shape motors), TRL ²⁰²⁵ 3		
		Cooling concepts (e.g. direct slot cooling, embedding, direct active part cooling), TRL ²⁰²⁵ 5		
		HF-switching and insulation systems, TRL ²⁰²⁵ 4-5		
		Modular concepts and platforms for diverse E-motor technologies for cost reduction, TRL ²⁰²⁵ 3-4		
		Interconnected development tools and software for fast and high-precision motor design, TRL ²⁰²⁵ 4-6		
		creation of adequate end-user use cases (inclusive 9R* strategy) for fundamental cost reduction in R&D, TRL ²⁰²⁵ 4-5		

Roadmap-Table B-7: Inverter, power electronics

		Short-term until 2030	medium-term 2030-2035	Long-term 2035+
Electric Components	Inverter, Power Electronics  9 R* / efficiency / cost / safety / reliability / durability Type of project required   	Increase packaging density by e.g. functional integration and reduce costs while considering 9 R strategies, TRL ²⁰²⁵ 5-7		
		Utilization of wide-bandgap semiconductors (cost efficient, high temp. operation, lifetime, minimized parasitic losses, safety circuit) in advanced EDUs TRL ²⁰²⁵ 5-7		
		Increase performance of passive electronic components (e.g. capacitors, inductors, resistors, TRL ²⁰²⁵ 6-9		
		Application of power electronics for measurement and test systems with mixed operation of simulation models and real test beds, TRL ²⁰²⁵ 5-8		
		Multi function components development, multi level inverter topologies with higher battery current, TRL ²⁰²⁵ 5		
		Methods to detect faulty situation (e.g. bridge short circuit), improve safety of Inverter and complete EDU, improve electro magnetic compatibility TRL ²⁰²⁵ 3		
		Improved cooling structures for DC/DC converter and inverters to improve performance and efficiency, - TRL ²⁰²⁵ 3-6		
		LV-battery-free concepts using DC/DC converter with enhanced reliability and lifetime, TRL ²⁰²⁵ 3-4		

Multi function components development in Roadmap-Table B-7 include inverter+OBC combination, Xin1 power electronics, multi use in terms of functionality & packaging.

Roadmap-Table B-8: Electric drive unit (EDU)

		Short-term until 2030	medium-term 2030-2035	Long-term 2035+
Electric Components	Electric Drive Unit (EDU)  9 R* / efficiency / cost / safety / reliability / EMC / security Type of project required   	Increase packaging density by e.g. functional integration and reduce costs while considering 9 R strategies, also for subsystems E-Motor and Inverter, TRL ²⁰²⁵ 5-7		
		Dismantling/disassembling design for 9R, business cases for alternative use of subcomponents or single components, use cases for recycled materials and / or components for after end of life, TRL ²⁰²⁵ 3		
		Creation of use cases based on end of life and extended life vehicle data, data management for cycle load definition and regulation work on data protection and utilization TRL ²⁰²⁵ 3		
		Virtual testing and validation methods of complete Electric Drive Units, TRL ²⁰²⁵ 5		
		Transmission (e.g. reduction gear, 2-speed, NVH) for efficient EDU architecture, also for high speed and Light and Heavy Duty Vehicle to improve system efficiency, TRL ²⁰²⁵ 5-6		
		Methods to detect faulty situation (e.g. bridge short circuit), improve safety of EDU and subsystems, improve electro magnetic compatibility and NVH, TRL ²⁰²⁵ 3		
		New testing and validation methods w/ and w/o HW (incl. complete EDU) to reduce costs, high accuracy and accelerate development speed, TRL ²⁰²⁵ 5		

The right cooling is not only significant for the E-Motor and Inverter but also for the whole electric drive unit (EDU). Therefore, extensive research must be performed, taking into consideration 3 in 1 or even 5 in 1 architecture. In fact, the cooling strategy of the whole BEV depends on this with significant impact on costs, efficiency and durability. Research needs are evident in heat exchange technologies, novel multi-material composites, fluids, as well as Computational Fluid Dynamics (CFD) simulations to predict and thereby control temperature distribution. Exact knowledge of the temperature pattern over cycle load and peak are important for design and durability.

To transmit torque from the E-Motor to the wheels with a cost efficient, quiet, and compact transmission and high integration into the E-Motor, an in-depth engineering effort is needed. In particular, the 3 in 1 architecture requires overall optimized design of the E-Motor, inverter and transmission unit, as each subsystem affects the other. Considering the indefinite amount of use cases and cycle loads simulation tools are required to define the optimal drive-system fitting to the vehicle requirements.

Control strategies for EDUs are mostly related to known industrial applications, but there is room for further innovation. New control strategies are not only necessary to gain the potential benefit of new MOSFET and IGBT power modules but also for new functions implemented on the inverter. All software and system innovation must be tested on specific test benches and demonstrator vehicles. To reduce the design phase time, simulation tools must be innovated and engineered accordingly. This is compounded by the fact that there is an almost infinite number of use cases and cycle loads for EDUs. Therefore, the cost intensive testing of electrified powertrains can only be tackled by using verified simulation tools, which are not available yet.

Legend

-  (material) fundamental research
-  industrial research
-  experimental development
-  demonstration

The term “**Power Electronics**” summarizes the inverter / converter, DC-DC converter and on-board charging unit. New materials, “self-learning” inverters and high-volume production will reduce costs and create added value. Extensive research on manufacturing, simulation and testing must be performed on SiC and GaN power modules, which may have higher efficiencies and lower costs. High frequency switching equally demands research on motor simulation methods for including parasitic losses and insulation stability. Safety circuit minimized parasitic loss topologies, EMC (Electro-Magnetic Compatibility) and passive power electronics components (fuses, resistors, capacitors, inductors), which can cope with the high energy density, automotive safety and cost requirements, need further development. Advanced cooling, joining and EDU packaging (motor, inverter and gearbox) technologies to harvest the full potential of wide band gap semiconductors also need further investigation.

High Power Systems with up to 1250 V voltage level²⁷ for passenger cars and especially for commercial vehicles (with a potential voltage level of up to 1500 V²⁸) open the window for ultra-fast charging up to the MW range. This is enabled via wide bandgap power modules. Research is necessary on the motor level and the electric circuit level (insulation, EMC, passive components) to deal with these high voltages in the EDU package. Further, **cost reductions are necessary in the manufacturing and production of all electric powertrain components**, as lower costs will increase the market uptake of BEVs, which will help the CO₂ targets to be met. Therefore, innovation, applied research and development in the field of production technologies are required. End-of-life materials must also be re-introduced into the manufacturing loop. This not only means that diverse design guidelines must be used but procedures and protocols need to be established to identify if end-of-life materials should be rehabilitated and directed toward second-life applications or if they should be used as raw materials for the manufacturing of new components.

Regarding “**Motor Control and Diagnostic Software**” further aims are fast parameterization, enhanced modularization and increased safety features. Therefore, significant R&D effort is necessary for advanced, model-based control such as self-learning adaptive algorithms.

Roadmap-Table B-9: Motion-, drive- or powertrain-control and software for E-motors

		Short-term until 2030	medium-term 2030-2035	Long-term 2035+
Electric Components	Motion-, Drive- or Powertrain-Control, Software  efficiency / safety / driveability / reliability Type of project required  	Advanced control strategy algorithms for inverter applications encompass novel E-Motor architectures, TRL ²⁰²⁵ 5		
		Control strategies for EDU using no inherent but alternative vehicle sensors for accurate torque setting and cost reduction TRL ²⁰²⁵ 3		
		self-learning adaptive algorithms and next generations of model-based control, TRL ²⁰²⁵ 4-5		

B.3 Vehicle Control Unit – Hardware and Software

The trend towards connected systems and the fast technical progress of driver assistance functions will lead to an extending high data exchange between today's independently developed and operating control units (e.g. propulsion, braking, steering, charging, etc.). A more cross-domain thinking, centralized and integrated approach will be essentially required, starting in the first step with an integration of established powertrain domain functions in one control unit (e.g. motion controller) and in the long-term towards an extensive function aggregation in a powerful central vehicle computer.

Today, a vehicle is in its best condition when it leaves the factory. However, vehicle software can be continuously optimized to improve performance within the limits of the hardware. This means that, in future, the vehicle can even improve after leaving the factory, for example via updates to the vehicle features and upgrades and improvements. Software solutions will therefore become the key feature that vehicle manufacturers and fleet operators use in the future to set themselves apart. This paradigm shift is made possible in the first place by the separation of hardware and software.

To enable these future steps, large R&D efforts are required in areas such as:

- Hardware with increased processing power and storage capacity for the introduction of new features, which use machine learning and deep learning methods e.g. for higher levels of ADAS.
- Flexible software integration platform, enabling a cost optimized cross-domain integration of functions developed in different environments/domains.
- Multi-ASIL (Automotive System Integration Level) capability on one hardware, integration, and execution of applications with different safety requirements (ASIL classification).
- Secure data and loop analysis consisting of the data preparation in the vehicle, analysis of transmitted data on a cloud server as well as the re-programming of resulting adjustments of parameter or the exchange of complete software packages.

Legend

-  (material) fundamental research
-  industrial research
-  experimental development
-  demonstration

²⁷<https://www.charin.global/technology/mcs/> (retrieved 15 April 2025)

²⁸ <https://www.sae.org/news/2020/05/chademo-3.0-to-harmonize-global-ev-quick-charging-standards> (retrieved 15 April 2025),

<https://en.wikipedia.org/wiki/ChaoJi> (retrieved 15 April 2025)

- Use of AI methods such as machine learning, deep learning, as well digital twins for predictive component diagnosis and maintenance.

More details to the roadmap are presented in **A Vehicle Innovation, Safety and Sustainability**.

B.4 Charging Technologies

Although the focus of this technology roadmap is clearly the vehicle, charging must also be addressed on the vehicle level, as the vehicle must fulfill specific and necessary requirements, especially for fast charging. Therefore, the development and vehicle integration of **efficient charging technologies** is critical to the success of battery electric vehicles. Conductive charging systems (with plugs) are available with different global standards (interfaces) and have already been partially introduced to the market. Inductive charging is seen as a medium to long-term charging technology for improved end customer comfort. Since the efficiency of such systems is still too low and the effects of magnetic fields on the human body and the environment are still not fully clear, further investigation and R&D effort is needed. Alternatives for an improved end-customer friendly charging functionality can be realized with automated conductive charging systems, which have been demonstrated as first concepts with major R&D demand for industrialization and integration in a series development vehicle.

Finally, **battery swapping systems**, already addressed in B.1.1 Battery Technologies., could also be a friendly charging approach for end-customers. However, such systems require a high level of standardization, which affects OEMs in their freedom of design and business case, including warranty issues. This concept also stands in opposition to highly integrated C2C and C2V architectures, which are proposed as strategies to increase the energy available to the vehicle, reduce vehicle part costs, and lower vehicle weight (see B.1.2 Optimization of cell and battery integration/packaging in the overall vehicle structure). Therefore, battery swapping is not expected to be adopted for personal BEVs applications, but may be more suitable for heavy-duty, depot-bonded BEVs. Battery swapping would require a high number of additional batteries to guarantee their constant availability to the end user. This is seen as a financial, logistic, and infrastructure challenge, and safety risks associated with the storage of large amounts of battery packs must be assessed. Cost and image are serious hurdles as long as warranty jurisdiction is not legally clarified in the EU. However, there are some advantages to battery swapping. First, the production of battery and charging systems has a high potential to create added value in Austria. Second, during their down time at storage facilities, battery swapping systems would allow the testing and evaluation of cells for performance loss and degradation that may affect the safety of the battery pack.

(Ultra) Fast charging (charging with high power over a longer time period) is a functional improvement to shorten the charging time. However, fast charging requires sophisticated knowledge in switching mode, reliable and affordable power modules and durable insulation technologies. Thermal management and its implementation in the overall vehicle operating strategy is key to use the potential of fast charging. This means in detail the pre-conditioning of the battery in order to prevent overheating or to prepare for upcoming high-power charging demands under cold weather situations in order to prevent and overcome reduction of the battery's durability and a loss of efficiency of the charging process itself. Besides, fast charging presents major challenges to satisfy the high-power demand while keeping the stability of the grid. One approach to overcome grid restraints is to use buffering batteries in the charging stations – first solutions are already available on the market. However, fast charging technologies and their widespread availability may help to meet users' range anxiety and might be a solution to limit the battery weight in commercial (regional) vehicles. Therefore, an improved charging infrastructure is crucial. For commercial vehicle applications the charging powers are expected to increase to the MW (Megawatt) range, which still have the need to improve the efficiencies beyond 95 %.

Next to the availability of charging infrastructure the authentication and payment procedure itself is still a big global issue to be solved. Therefore, standardized procedures and protocols need to be developed and implemented. ISO 15118-20:2022²⁹ is the standard for Vehicle-to-Grid (V2G) communication interface. PnC (Plug and Charge) still faces challenges despite an existing standardization³⁰.

B.4.1 Smart Charging / Bidirectional Charging:

The bidirectional charging (BDC) standard ISO15118 enables the integration of electric vehicles into the power grid. EV's with charging flexibility via smart charging and bidirectional energy flow solutions (V2G, V2H, V2B, etc.) can reduce investments in the electric grid, prevent grid overloading, system instability and voltage drop issues.

Today, there are some prototype implementations for a sustainable market launch of smart charging and V2G services. However, a high R&D effort is still required. The main development areas and challenges are:

- Cost-efficient bi-directional charging components are needed to maximize the efficiency of the whole energy system.
- Interoperable end-to-end smart charging and V2X services across EVs, service providers and energy networks, in order to be widely deployed and accepted in the market.
- Efficient smart energy management (grid) functions and flexibility services, using accurate forecasts via real-time data from EVs and EV users.
- Intelligent optimization algorithms with lower computational complexity to determine a reliable short-term forecast based on reliable real data such as vehicle location, battery capacity, EV user's acceptance. The

²⁹<https://www.iso.org/standard/77845.html> (retrieved 15 April 2025)

³⁰<https://www.auto-motor-und-sport.de/tech-zukunft/mobilitaetsservices/plug-and-charge-einfach-laden-probleme/>, retrieved 15 April 2025)

execution time of the algorithms is crucial as the problem must be solved within appropriate time constraints for a big number of EVs

- Enabling the communication with fleets of moving EVs and real-time interaction with users.
- Develop more reliable models for battery degradation and cost implications due to frequent charging and discharging cycles required by bidirectional V2G implementation, (electro-thermal and aging modelling).

The following charging functionalities shall be enabled to utilize the potential contributions of a high number of vehicle batteries for load distribution, peak buffering and in the long run for supporting the grid stability. They are all designated as vehicle to “X” (V2X) functions, which are already known and an upcoming technology approach, which must be considered for different charging functionalities.

- V2L: vehicle to load can provide an electrical interface from the vehicle to any standard electrical device.
- V2V: vehicle to vehicle could transfer energy from one vehicle to another.
- V2H: vehicle to home as an important functionality to be used as back-up power supply or buffer battery in combination with advanced intelligent (smart home) electric systems.
- V2G: vehicle to grid finally could be a big infrastructure topic / business to support net stability and/or support grid power management (e.g. peak shaving).
- V2H and V2G concept and solution development needs the involvement of grid companies and could be a topic for preliminary, exploratory studies to define detailed Research and Development needs.

Roadmap-Table B-10: Charging technologies

		Short-term until 2030	medium-term 2030-2035	Long-term 2035+
Charging Technologies	Charging Technologies	High-Performance battery cooling during High Power Charging (HPC), TRL ²⁰²⁵ 6-8		
	 efficiency / user friendliness / safety	Optimize components for requirements of High Power Charging systems (e.g. cooling), TRL ²⁰²⁵ 6-8		
	Type of project required	Implementation of V2X functionality, TRL ²⁰²⁵ 4-6		
	 			

Legend

-  (material) fundamental research
-  industrial research
-  experimental development
-  demonstration

C Fuel/Electrolysis Cells and Hydrogen

This chapter's focus is on R&D requirements of fuel cell technology for electric vehicles and hydrogen production via electrolysis, hydrogen distribution, storage and hydrogen refueling stations (HRS). H₂ combustion can be found in **DICE and Hybrid Powertrains**. Fuels, including those produced with hydrogen or syngas produced via electrolysis, are addressed in **E Sustainable Energy Carriers**.

Fuel cells are electrochemical energy converters that directly transform the chemically bound energy of a fuel - most often hydrogen - into electricity with high efficiency, free of pollutants, greenhouse gases, and noise. They are inherently resource-efficient, and the by-product heat can be used for heating, further increasing overall system efficiency. As such, fuel cells represent a key technology for the energy- and resource-efficient electrification of transport. Long-term R&D have led to significant progress, positioning fuel cells as a viable solution for mobility. Two main fuel cell technologies are currently used or nearing market readiness in transport: Polymer Electrolyte Membrane Fuel Cells (PEMFCs) and Solid Oxide Fuel Cells (SOFCs). PEMFCs operate at low temperatures (up to 90 °C) using a proton-conducting polymer membrane, making them well suited for fuel cell vehicles (FCVs) and range extenders (REXs). In contrast, SOFCs work at high temperatures (600–1000 °C) with ceramic electrolytes and are mainly suitable as auxiliary power units (APUs) or range extenders (REXs) for mobile applications.

Emerging fuel cell technologies such as High-Temperature PEM (HT-PEM) and Anion Exchange Membrane (AEM) fuel cells are gaining attention in research. HT-PEM offers advantages in thermal integration and system simplification, while AEM fuel cells promise high efficiency and lower costs due to reduced platinum-group metal (PGM) use. These fuel cell types show strong synergy with their respective electrolysis counterparts (PEMEL, AEMEL, SOEL), further integrating them into hydrogen ecosystems.

Technological advancements have significantly improved PEMFCs: costs have dropped by over 90%, catalyst loading reduced by 80%, and both durability and power density have quadrupled. These improvements have enabled vehicle developments and underscore the potential of fuel cells for defossilizing and electrifying transport simultaneously. FCVs typically combine fuel cells with batteries in hybrid powertrains, creating synergies with the development of BEVs and HEVs. Applications like fuel cell forklifts, buses, and to a lesser extent, passenger cars, have demonstrated market proximity, with reduced dependency on subsidies. Current development efforts also target FC powertrains for light- and heavy-duty vehicles. Table C-1 provides an overview of the technology readiness level (TRL) and most important challenges for different vehicle types. The specified TRL apply globally, while the list of challenges is not exhaustive and only includes topics where the authors of this roadmap see potential of Austrian research participation.

Table C-1: TRL and research need of various mobility applications

Application	TRL	Research Need
Passenger cars	6-8	- Scaling and cost reduction - Improvement of cold-start capability, efficiency, and durability - Vehicle integration and improvement of thermal management
Light commercial vehicles (≤ 3.5 t, logistics & delivery vans)	6-7	- Cost-effective, compact FC systems suitable for urban and regional logistics - Optimization for frequent stop-and-go and partial load operation - Fast refueling for high fleet turnover - Robustness in daily high-utilization operation
Trucks (heavy-duty vehicles)	5-7	- Long-life high-performance fuel cell stacks - Fast refueling and high-capacity on-board storage concepts - Continuous operation & thermal management
Buses (public transit)	7-8	- Reduction of operational costs - Robustness in urban stop-and-go traffic - Integration into fleet and refueling infrastructure
Maritime (ships, ferries)	3-5	- Marine-grade fuel cell systems - Development of safety and certification standards - Integration of H₂ storage or alternative energy carriers (e.g., LOHC, ammonia)
Rail (trains)	6-7	- High durability under continuous load - Hydrogen logistics for remote or rural lines - Integration into existing rail systems
Aviation (air mobility, e.g. passenger aircraft, drones)	2-4	- Ultra-lightweight, high-performance fuel cell systems - Hydrogen storage suitable for flight conditions - Certification and redundancy concepts
Non-road mobile machinery (e.g. construction machinery)	3-6	- Compact and rugged fuel cell systems for mobile machinery - Operation in dusty, high-vibration and inclined environments - Mobile hydrogen refueling: fast refueling to ensure high equipment availability - Hybrid FC-battery systems for peak power demands - Durability under intermittent duty cycles

Application	TRL	Research Need
		- Alternative high-capacity on-board storage concepts - Certification and homologation aspects, standardization and modularity across machine types
Special vehicles (e.g. tractor, material handling, sport vehicles, racing vehicles, agricultural machinery) and mobile power supply (mobile gen sets)	4-7	- Modular, compact fuel cell systems for varied duty cycles - Cold-start and low-temp operation (e.g., for snow vehicles) - Fast refueling for high-utilization fleets (e.g., forklifts) - Noise reduction and emission-free operation for indoor or sensitive environments - Economic viability in low-volume markets through platform standardization
Auxiliary Power Unit (APU)	4-7	- Reduction of costs - Improving efficiency and durability - Integration concepts for cars, trucks, special vehicles, aircraft, maritime applications, ...

Continued research and demonstration are required in sectors such as heavy-duty transport, industrial and off-road vehicles, trains, shipping, and aviation. Existing knowledge from FC passenger cars and buses can be transferred to these applications, with cost reduction and efficiency gains expected through upscaling, modular platforms, and integrated manufacturing. Key areas for further progress include improving stack and hydrogen storage technologies, adapting existing systems to LDVs and HDVs, establishing quality control in component production, and customizing fuel cell technologies and storage systems for rail and maritime use, as well as next-generation aviation systems.

Hydrogen-based transport also relies on advances in R&D, production scale, and the cost and availability of hydrogen fuel. Therefore, supporting the broad rollout of FCVs in Europe is as essential as advancing innovation, particularly in hard-to-electrify sectors. Austrian industry, academia, and research institutions have been active in fuel cell development and validation for decades. With the global hydrogen economy ramping up, A3PS members anticipate increased international competition and call for stronger instruments to bolster Austria's position in research and industry.

The objective is to develop and implement **holistic production and scaling concepts** for these key components of the hydrogen economy. The focus is on the **automation, standardization, and modularization** of manufacturing processes to enable cost-effective mass production. In particular, innovative production methods - such as digital manufacturing technologies, additive manufacturing processes, and flexible assembly systems - are to be explored and integrated into existing industrial environments. For hydrogen storage and refueling systems, both the production of high-pressure storage units and system integration must be optimized regarding **safety, reliability, and cost-efficiency**. Furthermore, the establishment of **scalable manufacturing platforms** is targeted to allow demand-oriented production of electrolyzers and refueling systems. Special emphasis is placed on **reducing production times, lowering manufacturing costs, and ensuring high quality standards** in order to sustainably strengthen the competitiveness of the Austrian industry in the international hydrogen market. This is addressed in **F Innovative Materials and Production**.

The strategy for fuel cell system development in transport will continue to pursue cost reduction, performance enhancement, and extended lifetime. These goals will benefit all transport applications and must be pursued in parallel with sustainability principles such as eco-design, recyclability, and reduced environmental impact throughout the component lifecycle.

C.1 Fuel Cell Vehicle Concepts

To fully unlock the potential of fuel cell propulsion as an environmentally friendly solution across all transport modes, vehicle costs must become comparable to those of conventional vehicles. This requires significant reductions in the cost of core powertrain components - fuel cell stacks, Balance of Plant (BoP), and on-board hydrogen storage - through technological innovation, automation, and production scale-up. Embedding modularity in component and system design enables cross-sector application without re-engineering, supporting mass production even at low initial deployment volumes.

High upfront investment in large-scale manufacturing remains a key barrier to market entry. In passenger vehicles, focus is on PEM fuel cells, which operate at lower power levels for range extenders and auxiliary units, scaling up to 100 kW or more for fuel cell-dominant propulsion. Range extenders are battery-electric vehicles with a fuel cell as a charger, while dominant systems rely fully on the fuel cell for propulsion, with small batteries or supercapacitors to manage dynamic loads. In the heavy-duty sector, early commercial deployment of fuel cells is underway, particularly in city buses. Hydrogen storage is shifting toward 700 bar systems for cars and long-haul trucks due to energy density needs, while 350 bar is preferred for buses and trains with lower range demands. Liquid hydrogen is increasingly seen as a viable option for heavy-duty vehicles, offering high energy density, simplified infrastructure, and lower operational costs.

R&D is focusing on cost-effective, scalable, and modular fuel cell systems suitable to different transport needs. Modular designs with multiple independently operated stacks enhance efficiency, reliability, and allow dynamic operational adaptation. Intelligent system control is key to maximizing efficiency and lifetime. Predictive management uses data such as route, traffic, and weather forecasts to guide operations, while real-time adaptive control accounts for component health to reduce degradation and optimize performance. This includes on-the-fly thermal and energy management to prevent premature aging, especially in heavy-duty use.

Accurate degradation prediction is vital for these strategies. Future vehicles will wirelessly transmit operating data for centralized, model-based analysis and adaptive maintenance planning. On-board diagnostics with virtual sensors and physics-based aging models will estimate remaining service life under changing loads in real time.

While several vehicle types are already in series production, ongoing research is needed to further reduce costs, increase efficiency, and improve sustainability. Current developments include non-precious metal catalysts, function-integrated manufacturing, recyclable materials, and lifecycle monitoring. These advances are essential to making fuel cell vehicles fully competitive and enabling their use beyond automotive applications in rail, maritime, and aviation sectors.

The main research needs for fuel cell vehicles across vehicle segments are summarized in Roadmap-Table C-1.

Roadmap-Table C-1: Fuel cell technology across vehicle segments

		Short-term until 2030	medium-term 2030-2035	Long-term 2035+
Fuel Cell Technology Across Vehicle Segments	Fuel Cell Technology Development and Deployment Across Vehicle Segments  NVH optimization / increase consumer acceptance / cost / efficiency / reliability / recyclability Type of project required 	Develop and validate scalable, cost-effective FC system designs and manufacturing processes to achieve < 300 €/kW by 2030 and < 100 €/kW long-term, TRL ²⁰²⁵ 4–6		
		Develop application-specific methodologies for optimal and ideally modular fuel cell and battery sizing to maximize efficiency and lifetime in diverse duty cycles, TRL ²⁰²⁵ 5–6		
		Advance FC technology tailored for non-road mobile machinery by improving durability, efficiency, and integration under harsh operating conditions, TRL ²⁰²⁵ 4–6		
		Demonstrate reliable and scalable FC solutions in real-world on-road (trucks, buses) and non-road mobile machinery applications, TRL ²⁰²⁵ 6–8		
		Conduct large-scale demonstration of vehicle fleets and hydrogen infrastructure, TRL ²⁰²⁵ 6–8		
		Enhance reliability and safety of FCVs across all operating modes, including driving, refuelling, and parking conditions, TRL ²⁰²⁵ 5–7		
		Develop efficient and integrated thermal management systems for FCVs to optimize performance, durability, and efficiency, TRL ²⁰²⁵ 4–6		
		Develop advanced operation strategies, lifetime monitoring, and on-board diagnostics, TRL ²⁰²⁵ 5–7		
		Develop systems for on-board recovery and utilization of waste energy to enhance efficiency, TRL ²⁰²⁵ 3–5		
		Develop cost-effective, safe, and high-density on-board gaseous hydrogen storage solutions, TRL ²⁰²⁵ 5–7		
		Explore and develop alternative hydrogen storage systems (e.g. adsorption, liquid) to improve energy density, efficiency, and cost-effectiveness, TRL ²⁰²⁵ 3–6		

C.1.1 Polymer Electrolyte Membrane Fuel Cells

PEM fuel cell technology has progressed to the point where it can be deployed in small series vehicles - regarding operational reliability and cost - for passenger cars and, to some extent, in trucks and heavy-duty applications. The current focus is on significantly reducing costs through economies of scale, technological innovation, and production automation. This includes lowering material costs - especially by reducing or substituting precious metals - and improving design and manufacturing at the stack and system levels (e.g., cathode subassemblies). Alongside improvements for light-duty vehicles (LDVs), synergies are expected for heavy-duty vehicles (HDVs) and other sectors such as rail, maritime, and aviation, where performance demands are comparable.

A key research priority is developing next-generation fuel cells by replacing precious metal catalysts, adopting new manufacturing methods, and implementing adaptive operating strategies to reduce degradation. Low-TRL activities are driving progress in power density, energy efficiency, durability, safety, and recyclability. At the same time, digital and virtual methods for condition monitoring and system control are being explored, including simulation-based design, virtual sensors, and advanced diagnostics.

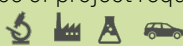
Simplifying system architectures and standardizing interfaces and components aim to cut production costs and support integration. Along with innovative, function-integrated manufacturing, sustainability is gaining importance - through eco-friendly materials, better recycling concepts, and emission reduction. The overarching goal is to extend Europe's and Austria's leadership in fuel cell technology beyond the automotive sector into broader mobility areas such as maritime and aviation.

The main research needs for PEM fuel cells are summarized in Roadmap-Table C-2. Synergies between PEM Fuel Cells and PEM Electrolysis in Roadmap-Table C-8 are considered.

Legend

-  (material) fundamental research
-  industrial research
-  experimental development
-  demonstration

Roadmap-Table C-2: PEM fuel cells

		Short-term until 2030	medium-term 2030-2035	Long-term 2035+
PEM Fuel Cell Systems	PEM Fuel Cells (synergies with PEMEL)  Power density / efficiency / endurance / lifetime, cost reduction / operation stability & dynamics / recyclability & environmental impact Type of project required 	Catalysts: Catalyst development for reduced PGM content, enhanced stability and deeper understanding of degradation mechanisms under real-world and dynamic operating conditions, TRL ²⁰²⁵ 3-5		
		Membranes: Development of next-generation PFAS-free membranes with enhanced conductivity, durability, and transport properties, TRL ²⁰²⁵ 3-7		
		Electrodes and MEA: Optimization of MEA structures and manufacturing techniques for improved performance and reproducibility), TRL ²⁰²⁵ 4-7		
		Electrodes and MEA: Improved coating techniques for reproducible MEA manufacturing, TRL ²⁰²⁵ 3-6		
		Stack design: Advanced stack design for durability, lightweight, and uniform current/thermal distribution; TRL ²⁰²⁵ 5-8		
		Water management: Enhanced water and thermal management strategies for simplified and robust operation, TRL ²⁰²⁵ 4-7		
		Thermal management: enhanced integration concepts and alternative cooling concepts, TRL ²⁰²⁵ 4-7		
		System Integration and Design: System-level optimization of BoP, energy efficiency, TRL ²⁰²⁵ 4-8		
		System Integration and Design: Improved operations strategies and condition monitoring, TRL ²⁰²⁵ 4-6		
		Manufacturing: Scalable, automated manufacturing and cross-application standardization of fuel cell components, TRL ²⁰²⁵ 5-8		
		Degradation: Degradation modelling, accelerated testing, and predictive diagnostics, TRL ²⁰²⁵ 2-7		
		Sustainability & Resource Efficiency: Eco-design and sustainable production using recyclable, non-critical materials, TRL ²⁰²⁵ 3-6		

Roadmap-Table C-3: Solid oxide fuel cells

		Short-term until 2030	medium-term 2030-2035	Long-term 2035+
SOFC for FCV	Solid Oxide Fuel Cells (SOFCs) (synergies with SOEL) for APU and REX  efficiency / endurance / life-time / cost reduction / operation stability / recyclability & environmental impact Type of project required 	Cell components for Solid Oxide Fuel Cells (SOFC): Increased power density and durability of novel electrodes, electrolyte, and current collectors without or with low content of critical raw materials, internal hydrocarbon reforming catalysts TRL ²⁰²⁵ 2-6		
		Protonic Ceramic Fuel Cells (PCFCs): Novel components (electrodes, electrolytes, current collectors) with high durability and without or with low content of critical raw materials, internal hydrocarbon reforming catalysts TRL ²⁰²⁵ 2-5		
		Metal supported solid oxide and protonic ceramic fuel cells: Novel components (electrodes, electrolytes) with increased power density and durability without or with low content of critical raw materials, improved start-up behaviour TRL ²⁰²⁵ 3-8		
		Operation: Reduction of operation temperature for SOFCs and PCFCs, high pressure operation TRL ²⁰²⁵ 2-5,		
		Degradation mechanisms and mitigation: Cell components, cell, stack; accelerated stress testing, degradation modelling TRL ²⁰²⁵ 2-5		
		Stack design: Lightweight, optimized current distribution, gas and thermal management, reduction of CAPEX/OPEX TRL ²⁰²⁵ 4-8		
		Stack design: Interconnects and coatings with improved Cr-retention capability, TRL ²⁰²⁵ 4-6		
		Monitoring and diagnostic tools: Improved tools for cells and stacks including degradation and failure modes, TRL ²⁰²⁵ 4-6		
		System integration: Improving efficiency, durability and costs of BoP components TRL ²⁰²⁵ 4-7		
		Sustainability and resource efficiency: Novel production technologies for improved recyclability of cells and stacks, including critical raw materials utilization TRL ²⁰²⁵ 3-6		

C.1.1 Solid Oxide Fuel Cells

To reduce the use of the EU-defined “critical raw materials”, more R&D is required in the field of lightweight SOFC stack components– for instance through recycling, reducing or avoiding the use of cobalt and rare earth elements. This is of special importance, since electrolysis is an important route to produce green hydrogen. R&D activities are required for the development of new low-cost materials with high durability as well as on the improvement of the BoP components of SOFC systems.

For automotive applications (including APU and REX concepts), increasing the dynamics and reducing the time of the start-up phase is important. This also needs to be investigated and solved through R&D activities. As for PEM, there are synergies between SOFCs in Roadmap-Table C-3 and SOEL in Roadmap-Table C-9.

C.1.2 Anion Exchange Membrane Fuel Cells

To reduce the costs of established fuel cell technologies such as PEMFCs, research is increasingly focusing on Anion Exchange Membrane Fuel Cells (AEMFCs) and cost-effective hydrocarbon-based polymers. Thanks to their less corrosive alkaline environment, AEMFCs potentially allow the use of non-precious metal catalysts like nickel (anode) and silver (cathode), offering significant cost-saving potential. AEMFCs are generally considered promising in terms of energy and resource efficiency. However, their development has so far been hindered by high degradation rates and the lack of durable membrane materials. Current research is therefore focused on new AEM materials with improved conductivity, chemical stability, and mechanical strength. At the same time, robust electrode structures and PGM-free or low-PGM catalysts are being developed - using approaches such as nano-structuring or targeted doping. Advanced manufacturing processes for membrane-electrode assemblies and hybrid concepts combining AEMFCs with other fuel cell types or batteries are also being explored. Austria has strong expertise in nickel-based and PGM-free catalyst development and is well positioned to play a key role in advancing this technology. In the medium term, AEMFCs are seen as a promising alternative for cost-sensitive applications such as light-duty vehicles, decentralized energy supply, and mobile auxiliary systems.

Roadmap-Table C-4: Anion exchange membrane fuel cells for FCV

		Short-term until 2030	medium-term 2030-2035	Long-term 2035+
AEMFC for FCV	AEM Fuel Cells  efficiency / endurance / lifetime / cost reduction Type of project required   	Catalysts: Low PGM and ideally PGM-free content catalysts, identification and optimisation of alternative catalysts with high activity and stability, TRL ²⁰²⁵ 2-4		
		Membranes: Development of durable, highly conductive anion exchange membranes (PFAS free membranes) with improved alkali resistance, TRL ²⁰²⁵ 3-4		
		Electrodes and MEA: Optimisation of electrode microstructure and MEA manufacturing methods for maximum performance and durability, TRL ²⁰²⁵ 3-5		
		Electrodes and MEA: Engineering of electrode microstructure for effective gas/water transport and optimized catalyst-ionomer interface in the electrodes, TRL ²⁰²⁵ 3-4		
		Water management: Concepts for membrane humidification and improved water management between cathode and anode, TRL ²⁰²⁵ 3-5		
		Water and CO ₂ management: Strategies for carbonate mitigation (e.g., CO ₂ -free air or carbonate-tolerant designs), TRL ²⁰²⁵ 2-4		
		Stack design: Stack-level water management strategies for uniform ion conduction, TRL ²⁰²⁵ 3-5		
		Stack design: Improved voltage uniformity and cell balancing, TRL ²⁰²⁵ 3-5		
		System Integration and Design: BoP components compatible with alkaline environments, TRL ²⁰²⁵ 3-5		
		System Integration and Design: Development of robust operating strategies and balance-of-plant (BoP) components, TRL ²⁰²⁵ 4-5		
		Degradation: Understanding and minimising ageing processes under realistic operating conditions, TRL ²⁰²⁵ 3-4		
		Degradation: In situ and operando diagnostics to monitor degradation, TRL ²⁰²⁵ 2-4		
		Manufacturing: Scale-up of membrane and MEA production, TRL ²⁰²⁵ 3-5		

C.1.3 On-board Hydrogen Storage

Gaseous on-board hydrogen storage systems are a critical enabler for fuel cell vehicles, particularly at 700 bar pressure levels, which are currently the industry standard. However, to support mass market adoption and meet future cost, efficiency, and sustainability targets, significant R&D efforts are still required. Key

Legend

-  (material) fundamental research
-  industrial research
-  experimental development
-  demonstration

technology trends focus on increasing storage density at reduced pressure levels, lowering system costs, and minimizing the carbon footprint—especially by addressing the environmental impact of carbon fiber used in high-pressure tanks.

Research is advancing in multiple directions, including the development of novel liner materials and reinforcement strategies for cost-effective, lightweight, and fast-refueling tank systems. Additionally, there is growing interest in alternative storage technologies such as cryo-compressed hydrogen (CcHS), liquid hydrogen (LH₂), and liquid organic hydrogen carriers (LOHC), which offer potential for higher volumetric efficiency. Innovations in system integration, safety-by-design approaches, and smart monitoring technologies are also crucial to ensure reliable and scalable deployment.

To accelerate progress, an R&D roadmap must prioritize the validation of new materials, manufacturing processes, and integrated safety systems, alongside supporting market introduction programs to stimulate industrial scale-up and technology maturity.

The main research needs for On-Board Hydrogen Storage are visualized in 3 Roadmap-Tables: Roadmap-Table C-5 includes gaseous hydrogen on-board storage, Roadmap-Table C-6 is about liquid hydrogen on-board storage and alternative hydrogen storage-systems are shown in Roadmap-Table C-7. The further Development of new hydrogen tank technologies to reduce carbon footprint and costs (vehicle fuel system, < 300 EUR/kg H₂ stored) is an important research goal

Roadmap-Table C-5: Gaseous hydrogen On-board hydrogen storage

		Short-term until 2030	medium-term 2030-2035	Long-term 2035+
On-Board Hydrogen Storage	GH₂-storage systems  cost / lifetime / safety / optimization of production / weight reduction / packaging Type of project required 	Type IV Tanks (700 bar, passenger cars): Cost reduction, improved manufacturability and automation of composite winding and curing processes, TRL ²⁰²⁵ 7–8		
		Type I and II Tanks (e.g. for forklifts, NRMM): Design optimization, cost reduction, lightweighting, material optimization, TRL ²⁰²⁵ 5–7		
		350 and 700 bar HDV tanks: Improved thermal management under high refueling loads, pressure cycling durability, TRL ²⁰²⁵ 6–7		
		New sensor technologies for production and lifetime monitoring of components (e.g. fiber, liner): Embedded sensing, NDT methods, TRL ²⁰²⁵ 3–5		
		System-level diagnostics and model-based lifetime prediction: Predictive maintenance, failure mode detection, data fusion, TRL ²⁰²⁵ 3–5		
		Joining technology (tubes, fittings, end caps): Leak-tight and low-cost joining under thermal/pressure cycling, TRL ²⁰²⁵ 4–6		
		Fiber technology (e.g. impregnation, winding strategies): Cost reduction, energy efficiency, carbon footprint reduction (LCA-based), TRL ²⁰²⁵ 4–6		
		Liner production (thermoplastics, barrier layers): Enhanced gas barrier properties, recyclability, weldability, TRL ²⁰²⁵ 4–5		
		Replaceable systems (modular exchange units): Design for maintenance, serviceability, circularity, TRL ²⁰²⁵ 4–5		
		Conformable or shaped tanks: Development of novel materials, structural integrity validation, crash resistance and integrated mounting concepts, TRL ²⁰²⁵ 3–5		
		Tank integration for marine/rail applications: Packaging in constrained environments, shock/load resistance, fire safety validation, TRL ²⁰²⁵ 3–6		
		Development of fast-refueling systems (trucks, buses, NRMM): High throughput protocols, system durability, pre-cooling & heat management, TRL ²⁰²⁵ 4–6		
		Fast-refueling protocols: Real-time heat prediction, embedded sensors, harmonization with refueling infrastructure, TRL ²⁰²⁵ 5–7		
		Multi-chamber storage systems (e.g. OTV, segmentable): Concepts for modularity, passive safety, pressure control and system-level integration, TRL ²⁰²⁵ 3–5		
		2 nd life of storage tanks: Qualification for reuse, non-destructive testing (NDT), tracking and certification systems, TRL ²⁰²⁵ 2–4		
		Legislation, regulations, codes and standards (RCS): Harmonized technical standards for safety, interfaces, refueling protocols and BoP integration, TRL ²⁰²⁵ 5–7		

Liquid hydrogen (LH₂) on-board storage offers significant advantages in terms of volumetric energy density, making it particularly attractive for long-range and heavy-duty applications such as trucks, aviation, and rail. LH₂ enables light and compact storage solutions, but poses specific technological challenges related to cryogenic temperatures (–253 °C), insulation, boil-off management, and system safety.

Current R&D focuses on developing advanced cryogenic tank materials and insulation systems to reduce weight and thermal losses, while ensuring fast and safe refueling. Further efforts are needed to improve system durability under thermal cycling, integrate high-efficiency vapor handling, and develop scalable manufacturing techniques. Safety, standardization, and system integration with fuel cells are also key priorities.

Roadmap-Table C-6: LH₂-storage systems

		Short-term until 2030	medium-term 2030-2035	Long-term 2035+
On-Board Hydrogen Storage	LH₂-storage systems  cost / lifetime / safety / optimization of production / weight reduction / packaging Type of project required    	Cryogenic Tank Design & Insulation: Development of lightweight, low-boil-off cryotanks using advanced composite materials and MLI insulation, including shape-optimized, conformable designs for better vehicle integration, TRL ²⁰²⁵ 3–6		
		Boil-Off Management & Refueling: Development of low-loss refueling protocols, connectors and integrated boil-off gas recovery systems for improved efficiency and safety, TRL ²⁰²⁵ 3–5		
		Material Compatibility & Cryogenic Durability: Testing and qualification of materials (metals, polymers, adhesives, foams) under 20 K conditions including fatigue, embrittlement and microcrack formation, TRL ²⁰²⁵ 3–5		
		System Integration into Vehicles: Design and integration of tank components (venting, valves, sensors) and structural layout for crash, vibration and acceleration loads, TRL ²⁰²⁵ 3–5		
		Safety, Standards & Certification: Development of LH ₂ -specific safety protocols and certification frameworks (ISO, SAE, IMO, etc.), including refueling infrastructure, TRL ²⁰²⁵ 2–6		
		Monitoring, Sensing & Diagnostics: Development of 20 K-compatible level and pressure sensors, real-time tank health diagnostics, and predictive safety systems, TRL ²⁰²⁵ 3–5		
		Thermal Integration & System Architecture: Linkage of LH ₂ systems with vehicle thermal management and exploration of cryogenic cooling for superconducting or highly efficient electric components, TRL ²⁰²⁵ 2–6		
		Freeform Tank Designs: Development of novel, conformable hydrogen tank geometries for improved packaging and volume utilization, TRL ²⁰²⁵ 3–5		
		Pressurization and liquid hydrogen fluid circulation by cryogenic pump and further alternative concepts, TRL ²⁰²⁵ 2–3		

Alternative hydrogen storage systems - such as solid-state storage, cryo-compressed hydrogen (CCH₂), and liquid organic hydrogen carriers (LOHC) - offer promising pathways to overcome the limitations of conventional high-pressure and liquid storage in mobile applications. These technologies aim to improve storage density, safety, and system integration while reducing overall cost and environmental impact.

Current research focuses on developing lightweight, compact storage materials and systems that enable efficient hydrogen release and refueling under practical conditions. Solid storage materials (e.g., metal hydrides, porous materials) and LOHCs offer lower-pressure operation and inherent safety benefits, though challenges remain in reaction kinetics, temperature management, and energy efficiency.

To bring these alternatives closer to market readiness R&D should prioritize material development, thermal integration, refueling strategies, and full system validation in real-world mobile environments. These technologies have strong potential for niche or future use cases in aviation, rail, and off-road transport where specific storage requirements must be met.

Legend

-  (material) fundamental research
-  industrial research
-  experimental development
-  demonstration

Roadmap-Table C-7: Alternative hydrogen storage systems for mobile application

		Short-term until 2030	medium-term 2030-2035	Long-term 2035+
On-Board Hydrogen Storage	Alternative Storage Systems  cost / lifetime / safety / weight reduction Type of project required 	Solid-State Storage (Metal Hydrides): Development of lightweight, reversible hydrides with high storage density and low operating temperature, TRL ²⁰²⁵ 3–5		
		Solid-State Storage (Metal Hydrides): Integration into mobile systems including thermal management and safety aspects, TRL ²⁰²⁵ 4–5		
		Adsorption (e.g. MOFs, Activated Carbon): Development of high-capacity adsorbents for moderate temperature and pressure conditions, TRL ²⁰²⁵ 3–4		
		Adsorption (e.g. MOFs, Activated Carbon): Ensuring material stability and efficient cycle performance under real operating conditions, TRL ²⁰²⁵ 3–4		
		LOHC (Liquid Organic Hydrogen Carriers): Compact and efficient onboard dehydrogenation units using advanced catalysts, TRL ²⁰²⁵ 3–4		
		LOHC: Safety and system concepts for mobile use, including closed-loop handling of the carrier medium, TRL ²⁰²⁵ 4–5		
		Cryo-compressed Hydrogen (C ₂ H ₂): Tank designs with high storage density and robust insulation for combined pressure and cryogenic conditions, TRL ²⁰²⁵ 4–6		
		Cryo-compressed Hydrogen: Efficient heat and pressure management during refueling and operation, TRL ²⁰²⁵ 4–5		
		Ammonia Cracker On-Board: Development of compact, high-conversion efficiency crackers with fast start-up behavior, TRL ²⁰²⁵ 3–4		
		Ammonia Cracker On-Board: Hydrogen purification and integration with fuel cell systems, TRL ²⁰²⁵ 3–5		
		Standards, Safety & Regulation (Cross-cutting): Development and harmonization of safety standards, certification procedures, and refueling/interface regulations, TRL ²⁰²⁵ 4–6		

C.2 Hydrogen Production via Electrolysis

C.2.1 Hydrogen Generation

The rapid expansion of renewable energy requires storage and smart grid solutions to manage variability. Hydrogen plays a key role as an energy carrier, bridging spatial and temporal gaps, and supporting decarbonization across industry, transport, energy, and buildings. If sustainably produced, hydrogen is emission-free and can accelerate the transition to climate neutrality. As a complement to batteries and pump storage, it also enables seasonal storage and can repurpose existing gas infrastructure.

Electrolysis, particularly water electrolysis powered by renewables, is currently the most promising pathway for producing green hydrogen. Alkaline electrolysis (AEL) has long been used in industry, while newer technologies—such as PEMEL, AEMEL, SOEL, and PCEL—are under development to improve efficiency, flexibility, and integration with renewable power. However, electrolysis is still cost-intensive due to high capital expenditures and electricity dependency. Key R&D objectives include reducing CAPEX/OPEX, increasing current density, improving efficiency and durability, and enabling circular design through CRM-free and PFAS-free materials.

Research focuses on novel catalysts (e.g., low-/non-PGM, bioinspired), advanced membranes and electrodes, improved manufacturing, and optimized stack and system designs. Each electrolysis type has specific challenges and innovation needs: AEL targets compact stacks and high current density without noble metals; PEMEL aims to reduce gas crossover and catalyst costs; SOEL³¹ focuses on pressurized stacks and advanced materials; AEMEL works on membrane performance and KOH reduction; and PCEL seeks scale-up with robust cell designs.

Future efforts also include real-time diagnostics, flexible system operation, and integration with renewables, including offshore and off-grid systems. Electrolysis technologies must demonstrate value in applications like hydrogen-based fuels, ammonia, methanol, steel production, and synthetic chemicals (Power-to-X). Additionally, using by-product oxygen and waste heat from electrolysis could further improve system efficiency and sustainability. Scaling electrolysis to 50–200 MW and integrating it into industrial systems is a critical step toward competitiveness and climate targets.

Legend

-  (material) fundamental research
-  industrial research
-  experimental development
-  demonstration

³¹ Sitte, W.; Merkle R., (Eds.), High Temperature Electrolysis - From Fundamental to Applications, IOP-Publishing 2023

Roadmap-Table C-8: PEM electrolyzers

		Short-term until 2030	medium-term 2030-2035	Long-term 2035+
Hydrogen Generation	PEMELs  efficiency / endurance / up-scale / life-time / cost reduction / reliability Type of project required 	Catalysts: Development of PGM-free or ultra-low PGM catalysts with high stability under acidic and high-voltage conditions, TRL ²⁰²⁵ 4–6		
		Membranes and Ionomers: Development of PFAS-free, high-conductivity proton exchange membranes with improved mechanical and chemical stability under varying pressure and temperature, TRL ²⁰²⁵ 3–6		
		Electrodes and MEA: Optimization of electrode microstructure and scalable, high-throughput MEA fabrication methods, TRL ²⁰²⁵ 3–7		
		Stack Design: Development of low-cost, durable bipolar plates, sealing systems and design strategies for uniform current and fluid distribution in multi-MW stacks, TRL ²⁰²⁵ 4–7		
		Stack Design: Validate multi-MW stack durability under dynamic load, TRL ²⁰²⁵ 6–7		
		System Integration and Balance of Plant (BoP): Optimization of BoP components and control strategies for efficient, simplified operation and pressure regulation, TRL ²⁰²⁵ 5–7		
		High-Pressure Operation: Improve sealing materials and stack design for safe and efficient operation under high-pressure differentials, TRL ²⁰²⁵ 3–5		
		Degradation & Durability: Mitigation of degradation effects under dynamic load profiles (e.g. PV/wind coupling), TRL ²⁰²⁵ 5–6		
		Manufacturing: Scale-up of automated production and standardization of stack and MEA components for mass production, TRL ²⁰²⁵ 4–6		
		Sustainability & Circularity: Development of recyclable components, catalyst recovery methods and eco-design strategies including LCA, TRL ²⁰²⁵ 3–5		

Roadmap-Table C-9: Solid oxide electrolyzers

		Short-term until 2030	medium-term 2030-2035	Long-term 2035+
Hydrogen Generation	Solid Oxide Electrolyzers (SOELs) for Hydrogen and Syngas Production  efficiency / endurance / lifetime / cost reduction / operation stability / recyclability & environmental impact Type of project required 	Cell components for electrolysis of steam for production of hydrogen (SOEL): Increased power density and durability of novel electrodes, electrolyte, current collectors without or with low content of critical raw materials TRL ²⁰²⁵ 2–5		
		Cell components for co-electrolysis of steam and carbon dioxide (co-SOEL) for production of syngas (PtX): Increased power density and durability of novel electrodes, electrolytes, current collectors with or without or with low content of critical raw materials TRL ²⁰²⁵ 2–5		
		Protonic Ceramic Electrolyzers (PCELs): Novel components (electrodes, electrolytes, current collectors) with high durability and without or with low content of critical raw materials TRL ²⁰²⁵ 2–5		
		Metal supported solid oxide and protonic ceramic electrolysis cells: Novel components (electrodes, electrolytes) with high durability and without or with low content of CRM TRL ²⁰²⁵ 2–6		
		Operation: Reduction of operation temperature for SOELs and PCELs, high-pressure operation TRL ²⁰²⁵ 2–4,		
		Degradation mechanisms and mitigation: Cell components, cell, stack (including interconnects and seals); accelerated stress testing, degradation modelling TRL ²⁰²⁵ 2–4		
		Stack design: Lightweight construction, optimized current distribution, gas and thermal management, modelling, reduction of CAPEX/OPEX TRL ²⁰²⁵ 4–7		
		Stack design: Interconnects and coatings with improved Cr-retention capability, TRL ²⁰²⁵ 4–6		
		Stack design: Reversible SOELs and PCELs TRL ²⁰²⁵ 4–7		
		Monitoring and diagnostic tools: Improved tools for cells and stacks including degradation and failure modes, TRL ²⁰²⁵ 3–5		
		System integration: Improving efficiency, durability and costs of BoP components TRL ²⁰²⁵ 4–7		
		System integration: Integration with industrial processes (PtX) TRL ²⁰²⁵ 4–7		
		Sustainability and resource efficiency: Novel production technologies for improved recyclability of cells and stacks including critical raw materials utilization, TRL ²⁰²⁵ 3–6		

Research on other forms or alternative hydrogen production methods beyond PEM, AEM, and Solid Oxide electrolysis focuses on unlocking additional pathways for renewable hydrogen. Key areas include photoelectrochemical water splitting, thermochemical cycles, pyrolysis, and biological routes (e.g. algae, bacteria). These technologies hold long-term potential for sustainable, decentralized, and low-cost hydrogen generation.

Roadmap-Table C-10: Other forms of hydrogen generation

		Short-term until 2030	medium-term 2030-2035	Long-term 2035+
Hydrogen Generation	Other forms of Hydrogen Generation	Photoelectrochemical (PEC) Water Splitting: Development of integrated, durable photoelectrode systems with efficient solar-to-hydrogen conversion (>10%), TRL ²⁰²⁵ 2–4		
		Thermochemical Water Splitting: Design of high-temperature thermochemical cycles with long-term stable redox materials and reactor integration, TRL ²⁰²⁵ 3–5		
	Efficiency / costs	Methane Pyrolysis: Development of efficient, CO ₂ -free pyrolysis reactors with scalable carbon separation and valorisation, TRL ²⁰²⁵ 4–6		
	Type of project required   	Biological H ₂ Production (e.g. algae, bacteria, biophotolysis): Optimization of bio-H ₂ -producing organisms and photobioreactor systems for scalable, low-impact production, TRL ²⁰²⁵ 2–4		

C.2.2 Hydrogen Storage and Distribution

Hydrogen storage and distribution form a critical link between production and end-use, ensuring that hydrogen can be reliably delivered from renewable generation sites to hydrogen refueling stations (HRS) and consumers. As outlined in the EU Hydrogen Strategy, hydrogen must become an integral part of a connected energy system—serving as both a daily and seasonal energy buffer to enhance supply security. To achieve this, a diverse set of storage technologies (e.g. compressed gas, liquid hydrogen, LOHC) and transport solutions (pipelines, trucks, ships) must be developed. Building a flexible, EU-wide infrastructure will be key to connecting renewable-rich regions with demand centers and hydrogen refueling stations across all transport modes.

Roadmap-Table C-11: Hydrogen storage and distribution

		Short-term until 2030	medium-term 2030-2035	Long-term 2035+
Hydrogen Storage and Distribution	Hydrogen Storage and Distribution	Hydrogen Quality & Compatibility: Ensuring hydrogen quality compliance across the entire supply chain, including production of various sources, transport, storage, and dispensing, TRL ²⁰²⁵ 5–7		
		Energy System Integration: Optimization of energy system linkage between the electricity and gas grid for flexible hydrogen production, storage, and dispatch, TRL ²⁰²⁵ 4–6		
	Cost / efficiency / safety	Liquid Hydrogen: Development of LH ₂ logistics and distribution chain, including boil-off management, insulation, pumping, and safe transfer systems, TRL ²⁰²⁵ 4–6		
	Type of project required	Develop and optimize hydrogen delivery systems (e.g. tube trailers, liquid hydrogen trucks, LOHC transport) for cost-efficient, flexible and scalable refueling station supply, TRL ²⁰²⁵ 5–7		
	   	Advance pipeline-based hydrogen distribution, including materials for H ₂ compatibility, pressure management and integration with existing gas grids, TRL ²⁰²⁵ 4–6		
		Compression Technologies: Development of advanced hydrogen compression systems, including electrochemical and thermal processes to reduce energy demand and maintenance, TRL ²⁰²⁵ 4–6		

C.2.3 Hydrogen Refuelling Stations

Hydrogen refueling stations (HRS) are a key enabler for the large-scale rollout of hydrogen mobility, especially in the heavy-duty sector, where fast refueling and high daily throughput are essential. While Europe leads globally in station deployment and manufacturing expertise, most existing HRS are designed for light-duty vehicles and are not yet suitable for trucks, buses, or trains. The revision of the EU's Alternative Fuels Infrastructure Regulation (AFIR) mandates hydrogen refueling every 150 km along the TEN-T network, highlighting the urgency of developing high-capacity, reliable, and standardized HRS infrastructure. Key challenges remain in reducing CAPEX and OPEX, improving station availability and reliability, accelerating permitting processes, and developing interoperable heavy-duty refueling protocols and components. Research is needed to increase system flexibility, enable integration with locally produced renewable hydrogen, and improve components such as heavy-duty nozzles, chillers, and multi-purpose refueling systems. The development of high-throughput HRS capable of delivering over 1,000 kg/day—including for maritime, rail, and fleet applications—is essential, as is the standardization and industrialization of HDV-compatible systems.

Reducing the physical footprint of stations, managing boil-off (especially with LH₂), and exploring mobile and on-demand refueling concepts will also support the effective and scalable deployment of hydrogen infrastructure across Europe.

Legend

-  (material) fundamental research
-  industrial research
-  experimental development
-  demonstration

Roadmap-Table C-12: Hydrogen refuelling stations (HRS)

		Short-term until 2030	medium-term 2030-2035	Long-term 2035+
Hydrogen Refuelling Stations	 HRS Cost / safety / reliability Type of project required 	Heavy-duty refueling components: Development of nozzles, hoses, chillers, compressors and dispensers for >200 kg fills in <20 min, TRL ²⁰²⁵ 4–6		
		Boil-off and cooling management: Advanced thermal systems for compressed and liquid hydrogen, TRL ²⁰²⁵ 4–5		
		Flexible HRS operation: Enable low inlet pressure and variable flow rates for integration with on-site renewable hydrogen, TRL ²⁰²⁵ 4–6		
		Standardisation of HDV protocols and interfaces: Communication interface, harmonised components and fuelling procedures across heavy-duty applications, TRL ²⁰²⁵ 5–7		
		Reduce CAPEX/OPEX: Through modular system design and integration of innovative components, TRL ²⁰²⁵ 5–7		
		Compact station layout: Development of low-footprint HRS designs to ease permitting and urban integration, TRL ²⁰²⁵ 4–6		
		High-throughput infrastructure: Supply chain integration for >1,000 kg/day refueling stations (HDV, trains, ships), TRL ²⁰²⁵ 5–7		
		Mobile/on-demand refueling concepts: Trailer-based or modular HRS for flexible deployment, TRL ²⁰²⁵ 3–5		

C.3 Cross-Cutting R&D topics

Robust testing, simulation, and validation are essential cross-cutting enablers for the reliable and accelerated development of hydrogen technologies, fuel cells, and electrolysis systems. Key R&D priorities include long-term durability testing under real-world conditions, as well as accelerated stress testing to assess ageing and failure mechanisms. Advanced validation platforms such as hardware-in-the-loop (HiL), model-based development, and XiL (X-in-the-loop) approaches are increasingly important for system optimization and virtual integration. The development of high-pressure test beds, including refueling scenarios for 700 bar systems, is critical for both component and full-system validation. Accurate gas analytics - both off-line and integrated on-board - are required to monitor hydrogen purity and detect critical impurities across the supply chain. Improved CFD tools tailored to multi-physics and multi-phase processes (e.g. water and gas flow in MEAs or electrolyzer stacks) will enhance predictive capabilities. In parallel, new generations of measurement and diagnostic equipment, including end-of-line testing tools, mechanical stress test benches, and modular validation systems, are needed to support safe, fast, and standardized testing procedures for industrial-scale deployment. **Austria plays a leading role in this domain**, with a high degree of value creation in measurement and testing technology, certification services, and specialized instrumentation - providing a strong industrial and scientific foundation for future innovation in hydrogen system validation.

Legend

-  (material) fundamental research
-  industrial research
-  experimental development
-  demonstration

Roadmap-Table C-13: Test and validation

		Short-term until 2030	medium-term 2030-2035	Long-term 2035+
Test & Validation	Test & Validation  Efficiency / cost Type of project required    	Long-term durability testing under real-world operating conditions for understanding degradation and lifetime in actual use cases (e.g. mobility, industry), TRL ²⁰²⁵ 4–6		
		Accelerated stress testing methods for components and systems (stacks, MEAs, BoP) to simulate long-term degradation and failure modes in shortened timeframes, TRL ²⁰²⁵ 4–6		
		Hardware-in-the-loop (HiL) and XiL (X-in-the-loop) simulation platforms for system development of FC and electrolyzer systems in combination with real hardware, TRL ²⁰²⁵ 4–6		
		High-pressure test beds including dynamic refueling scenarios (e.g. 350/700 bar) for testing storage tanks, valves, nozzles and refueling protocols under realistic conditions, TRL ²⁰²⁵ 5–7		
		Virtual validation and model-based development tools supporting faster iteration and safer system integration in early design stages, TRL ²⁰²⁵ 4–6		
		Improved CFD simulation tools for multiphysics and multiphase phenomena in cells and stacks, TRL ²⁰²⁵ 3–5		
		Development of next-generation gas analytics for hydrogen purity (on-board and off-line) enabling early detection of contaminants affecting FC, TRL ²⁰²⁵ 4–6		
		Mechanical stress and vibration testing of storage systems and components, TRL ²⁰²⁵ 4–6		
		End-of-line testing systems for industrial production of fuel cell and electrolyzer stacks to verify quality and safety at scale, TRL ²⁰²⁵ 5–7		
		Testing and certification infrastructure for system validation and regulatory compliance including safety, lifetime, efficiency, and H ₂ compatibility standards, TRL ²⁰²⁵ 5–7		
		Application of comprehensive AI Methods, TRL ²⁰²⁵ 3–6		

Legend

	(material) fundamental research
	industrial research
	experimental development
	demonstration

D ICE and Hybrid Powertrains

Considering the fact of an existing fleet of vehicles dominantly powered by Internal Combustion Engines (ICE) until well beyond 2030, significant fuel consumption and fossil CO₂ reductions without disadvantages for the users can be achieved via two approaches: (i) fuel consumption reduction by optimizing ICE's with or without an electric powertrain (hybrid vehicles), and (ii) CO₂ neutral gaseous and liquid fuels. Despite major efforts to electrify the transport sector, ICE powertrains are still a reasonable solution, since some mobility sectors, such as marine, cannot be reasonably electrified even in the medium and long term.

Hybrid powertrains allow the combination of the advantages of pure electric propulsion, e.g. highly efficient torque generation with E-motors as well as recuperation and storage of brake energy, with that of ICE driven vehicles, i.e. conversion of high energy-density chemical energy into kinetic energy in a robust device of highest power density which is insensitive against fuel impurities. Obviously, such energy converters have to fulfill all – also future – emission standards and are, thus, fully environmentally compatible. Such powertrain systems can be used throughout the entire transition phase from fossil dominated to purely sustainably generated energy carriers. Hybrids range from micro-hybrid systems with dominant torque generation by the ICE to powertrains where torque is completely generated by one or more E-motors and the ICE – coupled to a generator – provides the average driving power only. In a strong Hybrid (i.e. vehicle propulsion dominantly/completely provided by E-motors) the design of the combustion engine can be optimized towards best efficiency as a Dedicated Hybrid Engine enabling significant efficiency and, hence, CO₂ emission improvements.

Hybrid, battery-electric and fuel-cell-electric powertrains are sharing many components such as E-motors, power electronics, energy buffers (batteries etc.) and subsystems such as e-axes. Hence, all R&D needs and objectives related to these component and subsystems are elaborated in full detail in **B Battery Electric Powertrains**.

D.1 Sustainable Combustion Engine

Internal combustion engines will remain a widely spread power unit in conventional and in hybrid powertrains also beyond 2035 (as the average lifetime of road vehicles is about 13 years in the EU and even longer for other means of transportation). The fastest way to reduce CO₂ emissions of vehicles is the reduction of fossil fuel consumption by both, increasing the efficiency of the propulsion system and by using CO₂-neutral hydrogen or other gaseous and liquid energy carriers such as ammonia and methanol generated from renewable primary energy sources. There is still a lot of potential for improvement if an ICE is operated in a hybrid powertrain. If combined with electric powertrain components that allow sufficient pure-electric driving, it promotes real-world electric driving without range anxiety. Fuel consumption can be further reduced by 20% or more due to special operating conditions focusing the ICE's efficiency sweet spot, with additional variability, mechatronic subsystems and the application of new materials e.g. for further friction reduction. This means, a **peak efficiency of 50% and more remains as a target for ICEs**. Further, even if CO₂ neutrality is achieved via defossilized energy carriers, the combustion processes have to be developed towards “zero-impact exhaust emissions” (no particles, NO_x and other toxic emissions).

Further, since the ICE will be operated in the future with CO₂-neutral energy carriers such as synthetic fuels as well as H₂ and in a substantially different way (peak shaving, load point shifting, start/stop etc.) in **hybrids** (compared to a pure ICE powertrain), **Dedicated Hybrid (combustion) Engines (DHE's) as “fuel converters”**, a further reduction of emissions and fuel consumption can be realized. Such fuel converter applications open the doors for R&D and new products in (i) waste heat recovery, (ii) electrical energy storage, and (iii) ICE development when the ICE is operated at only a single load point supplying power to the electric drivetrain and electric energy storage via a generator.³²

(i) A waste heat recovery system will achieve optimum efficiency in converting exhaust gas energy from the ICE into electricity when the combustion has a known exhaust gas temperature and energy content. Reliable, cost-effective and highly efficient technical solutions must be found. Such waste heat recovery systems could be used then also for other applications in e.g. industrial production.

(ii) Relatively smaller electric storage capacities are needed in such serial and electrical powerful hybrids to provide high power during braking and acceleration. Electric storage systems capable of C-rates of 10 to 20 for a few hundred thousand cycles with a depth of discharge of 80 % are needed but not yet fully developed and require public funding to provide optimal solutions. Such storage systems can also be used in fuel cell powertrains where they are needed to recuperate the brake energy and to shave off power peaks for the fuel cell.

(iii) An ICE operated as a fuel converter in a single load point at peak efficiency and minimum emissions has a different requirement profile than “classic” hybrid vehicles. The power output of the combustion engine is much lower than that of “classic” hybrids and much lower than the power of the electric drivetrain. The ICE, together with the waste heat recovery system and the generator, forms the fuel converter and its power is set to a value to obtain a specific permanent cruising speed on a highway without depleting the electric storage system. Keeping the NVH of the ICE system below the passenger's recognition level is essential to always allow ICE operation in the efficiency sweet spot. It could be replaced in the future by a fuel cell able to be operated on liquid fossil or synthetic green fuels.

³²G. Brasseur, „Hochwirkungsgrad Hybridantrieb für nachhaltige Elektromobilität“, open access doi:10.1553/0x003b46cd, Austrian Academy of Sciences, Feb. 5, 2020, pp. 1-36.

In the field of commercial vehicles, the R&D focus is on engines operated with hydrogen and synthetic climate-neutral fuels.

The main development routes are:

- Fuel/gas preparation, ignition and combustion systems for hydrogen and climate-neutral energy carriers for different engine processes (port-/direct-injection)
- Exhaust gas after treatment considering all types of climate-neutral energy carriers - focus on DeNO_x, PF (Particle Filter) - incl. emissions caused by lubrication oil
- Structural optimization (new materials, advanced joining technologies, high-strength, functional materials) incl. resistance against new gaseous and liquid fuels
- Advanced hybrid systems with extended real-world-driving pure electric range above 100 km
- Modular ICE powertrain with eDriveline Systems (eTransfer Case, electrified axle drive front and rear)
- Minimization of friction losses (new materials and surface structures)
- Thermal management (heat storage, reduction of heat losses, waste heat recovery)
- Transmission optimization (high reduction gears, alternative lubricants for friction reduction, clutch & actuators, axle drive incl. differential, hybrid materials, joinings, thermal management)
- Development tools and methodologies for component and system level application (simulation & control platform/development, digital twins for development and optimal operation)
- Development of new lubricants on the one hand tailored to alternative fuels on the other hand completely synthetic, more sustainable, biodegradable

The mandatory CO₂ reduction targets for on-road trucks and buses will require outstanding efforts in the coming years to be able to utilize zero-emission technologies that have so far made an insufficient appearance. In particular, it is essential, in the context of research funding, to assign the same priority as batteries and fuel cells to the internal combustion engine, powered by zero-emission fuels (H₂, NH₃, methanol, etc.) produced from renewable energy for usage in on-road trucks and buses, non-road mobile machinery, special vehicles, and maritime applications. Especially in energy-intensive and decentralized applications, pure electrification is rather unrealistic with the current state of technology. This is precisely where the combustion engine with defossilized fuels offers a good opportunity for decarbonization. The energy carriers ammonia and methanol will be accorded an equally high priority as hydrogen in the long term. Either as direct fuels for use in internal combustion engines or, in the case of ammonia, also for the operation of a fuel cell by splitting ammonia into hydrogen (and nitrogen) in the vehicle (ammonia cracker). Particularly in the marine and off-road sectors, ammonia and methanol offer the advantage over hydrogen that they can be stored much more easily in liquid form.

Roadmap-Table D-1: ICE technologies

		Short-term until 2030	medium-term 2030-2035	Long-term 2035+
Sustainable Combustion Engines	ICE Technologies  zero emissions and significant efficiency improvement (η>50 %) for passenger cars, trucks, busses and non-road applications Type of project required 	Low-pressure port/direct injection H ₂ -engine (H ₂ -injector, tank/gas pressure of PFI/DI, ignition system, combustion stability, avoidance of backfiring/anomalies, safety of H ₂ -engines), TRL ²⁰²⁵ 6-8		
		High-pressure direct injection of H ₂ -engine (tank/gas pressure, H ₂ -DI-injector, combustion stability/anomalies, safety of H ₂ -DI-engines), TRL ²⁰²⁵ 5-7		
		Highly efficient compressors, turbines and turbochargers incl. E-blowers mech./electr. compound turbines, TRL ²⁰²⁵ 5-9		
		Combustion and aftertreatment systems for H ₂ and climate-neutral/fossil-free energy carriers (e-gas, e-fuel, advanced biofuels, NH ₃ , alcohols), TRL ²⁰²⁵ 6-9		
		ICE with special operation strategies (incl. Single point operation and range extender operation), TRL ²⁰²⁵ 5-6		
		ICE related sensors and controllers for highly efficient operation (incl. comb. real and virtual sensors, AI-based control systems, etc.), TRL ²⁰²⁵ 3-8		
		Lubricants adapted to alternative fuels, resistant plain bearings against alternative fuels, increased water ingress, TRL ²⁰²⁵ 5-9		
		Ammonia and methanol ICE solutions for on-road truck and large-size non-road mobile machinery and marine applications, TRL ²⁰²⁵ 4-6		

D.2 Transmission

The transmission for an ICE powertrain is common but with increasing electrification, there is need for further innovation. A **dedicated hybrid transmission** fulfils the function of an actuator to operate the ICE and electric motor in parallel and/or serially. Efficiency can be improved by up to 15 % by optimizing the inter-action between transmission and the overall powertrain. By integrating the electric motor into the transmission new transmission concepts/configurations can be designed and optimized where the electric motor for instance may take over the synchronization function. Advanced simulation methods and tools are required to support the efficient development of new transmission concepts and combined ICE/electric motor operation with regards to NVH, friction and durability challenges.

Due to their higher power, **truck transmissions need to deal with much higher torques** in both directions at higher numbers of transmission steps compared with passenger cars, making the integration of an electric motor more complex. The R&D effort is particularly high, since durability and reliability expectations require more extensive testing than in passenger car applications. Austria's added value in this area mainly lies in the development of complete transmission systems (transmission, electric motor, inverter, clutch) with associated actuators and operating strategy.

Clutches will still play an important role in hybrid resp. full electric vehicles. This is for functions like

- clutches for multi speed transmissions (improve efficiency), limited slip differential and torque vectoring to achieve requested vehicle dynamics
- especially for BEV with their high weight (battery), torque limiting clutches (between wheel and E-motor) to prevent mechanical shocks from varying road and load conditions and allow the use of light weight mechanical parts. Therefore, friction materials have to be developed to fit the upcoming new environmentally friendly, lowest viscosity (below brake fluid) lubricant generations (e.g. glycol based) often with specified electric properties.

Roadmap-Table D-2: Transmission and components

		Short-term until 2030	medium-term 2030-2035	Long-term 2035+
Transmission	Transmission & Components  efficiency / weight reduction / durability / advanced functionality / noise reduction Type of project required    	Control strategy including advanced model-based control and functional safety, TRL ²⁰²⁵ 3-5		
		optimization of friction / thermal management – integration in thermal management in powertrain (fast warm-up / cooling), TRL ²⁰²⁵ 6-8		
		high component and function integration for hybrid transmissions, TRL ²⁰²⁵ 5-9		
		Lubricants and coolants for transmissions, multipurpose fluids, TRL ²⁰²⁵ 4-7		
		New transmission concepts (aiming at improved costs, quality, assurance, reliability, durability, new bearing materials, ...), TRL ²⁰²⁵ 3-7		
		Enhanced electrified transmission for non-road mobile machinery and special purpose vehicles, e.g. electric power split, to support any power source (battery, fuel cell, ICE), TRL ²⁰²⁵ 4-9		

Roadmap-Table D-3: Clutch and actuators

		Short-term until 2030	medium-term 2030-2035	Long-term 2035+
Transmission	Clutch, Actuators  efficiency / durability / heat resistance / control strategy / safety and security Type of project required  	Efficient and durable clutch systems (friction materials, fluid material, function integration), TRL ²⁰²⁵ 3-7		
		Actuator with higher efficiency, durability and functional safety (cyber security), TRL ²⁰²⁵ 3-6		
		functional software for higher accuracy and predictive maintenance, TRL ²⁰²⁵ 4-6		

Legend

-  (material) fundamental research
-  industrial research
-  experimental development
-  demonstration

E Sustainable Energy Carriers

Further to suitable propulsion technologies, renewable energy carriers play a significant role for sustainable mobility since battery electric vehicles as well as hybrids with ICE and fuel cell electric vehicles need energy carriers, which dominantly originate from a fossil feedstock to this day. On the way to a sustainable mobility, these energy carriers need to become defossilized. In this roadmap the term “defossilization” is preferred over the more common term “decarbonization” since synthetic gaseous or liquid fuels except of hydrogen (H_2) and ammonia (NH_3), or solid energy carriers such as metals (for stationary applications), contain at least one carbon atom. This carbon is completely climate neutral as long as it is obtained from biomass or other sources where the carbon is kept in a closed cycle (e.g. CO_2 capturing out of the air).

This Roadmap will not go into detail about renewable electricity production and storage. This topic is covered in other publications³³. The focus of this roadmap is on liquid and gaseous fuels based on biogenous feedstock and/or renewable electricity.

These chemical energy carriers are converted on board of vehicles (but also in other non-road machines such as ships, airplanes or stationary power generators) in thermal and mechanical energy or directly to electric energy in fuel cells. The energy converters considered here are:

- Fuel Cells (FC), where hydrogen (high purity according to ISO 14687-2) but also methanol, ethanol, ammonia and other liquid fuels can be used as an energy carrier.
- Spark Ignition (SI) engines, in which all types of flammable gases (hydrogen, bio-methane, etc.) or liquid fuels (alcohols, ether, etc.), can form an ignitable mixture, are suitable for use. In contrast to a fuel cell, the purity of the fuel is not that important.

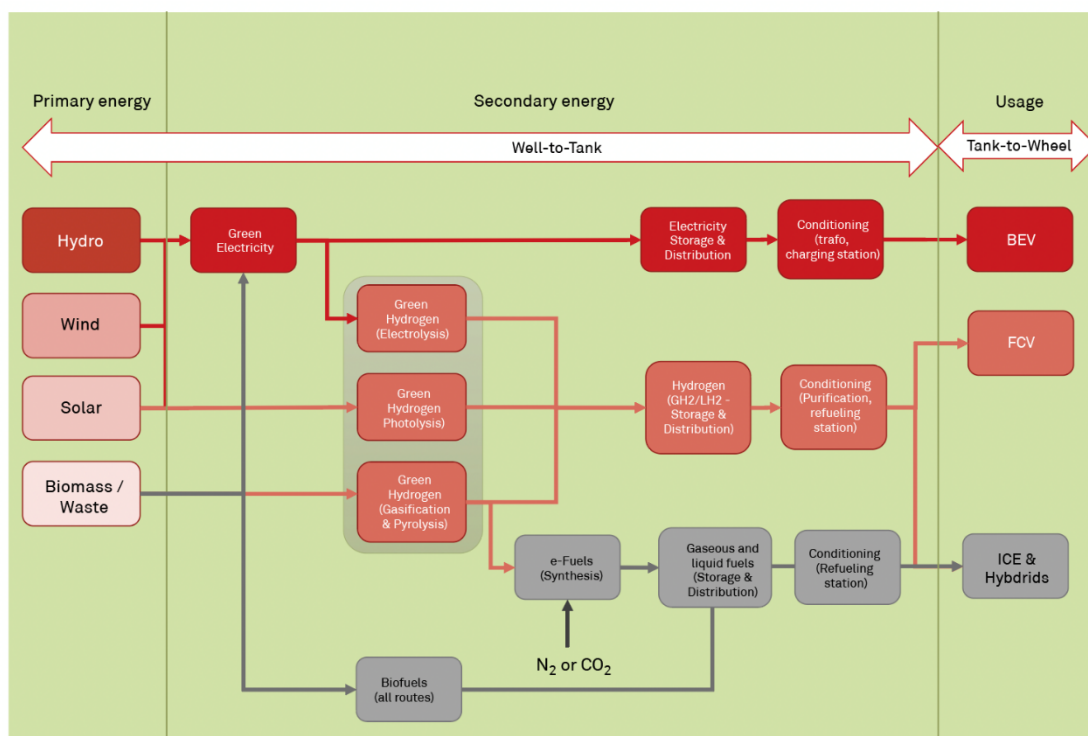


Figure E-1: Scheme: Renewable energy carriers for transportation

- Compression ignition (CI) engines, which are characterized by a generally higher efficiency than spark ignition engines. Above all, self-ignitable fuels such as FAME, HVO, OME, DME are primarily used as energy carriers. Alcohols with additives (e.g. ethanol with an ignition improver) can also be used in modified CI-engines. In dual-fuel diesel engines, any type of liquid (alcohols, ammonia) or gaseous (hydrogen, bio-methane) fuel, ignited with a diesel pilot jet, can be converted into mechanical energy. Also In this case, the purity of the fuel is not relevant.

For the future variety of alternative liquid and gaseous fuels, it is difficult to make a general statement about the combustion and emission behavior. Rather, it is crucial how well the tuning and adaptation of the engine control to the respective fuel takes place. There is still a considerable need for research in this area regarding:

- Chemical and physical properties of future synthetic bio- and e-fuels and, thus, their combustion behavior – particularly emission species.

³³ e.g. <https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=COM:2011:0885:FIN:EN:PDF> (retrieved 13 April 2025)

<https://energie.gv.at/energiewende/wie-schreitet-der-ausbau-von-erneuerbaren-energien-in-oesterreich-voran> (retrieved 13 April 2025)

<https://energieforschung.at/wp-content/uploads/sites/11/2020/12/Technologie-Roadmap.pdf> (retrieved 13 April 2025)

- Use in combustion engines with advanced combustion processes (e.g. ultra-lean combustion, pre-chamber ignition, homogenous charge compression ignition etc.) and special operation conditions (e.g. single point operation or operation at constant engine speed).

Renewable electricity is important both as an unconditional requirement for e-mobility and to produce renewable hydrogen via electrolysis. Additionally, fuels produced from biogenous feedstock play an important role for defossilization of the transport sector.

Direct use of renewable electricity in battery electric vehicles results in the highest efficiency but electricity is not always produced where or when needed and therefore must be stored and transported. Besides, a share of vehicles with internal combustion engines will prevail until 2050, and probably beyond, and there is a need to supply an existing fleet with sustainable fuels. Compared to batteries, energy carriers such as hydrogen, e-fuels and advanced solid materials like metals have much higher energy densities. Hence, instead of converting them back to electricity when needed and then charge a BEV, it is more efficient and rational to use these energy carriers directly in the vehicle for combustion or in fuel cells.

The use of sustainable fuels (including renewable hydrogen) in internal combustion engines allows a significant reduction of GHG emissions (down to CO₂ neutral mobility, or even negative emissions in case of carbon capture and storage) for the existing vehicle fleet. Of all options to reduce GHG emissions from road transport in the near future, the use of renewable energy has the largest potential.

The importance of hydrogen is also covered in the recently published hydrogen strategy “Wasserstoffstrategie für Österreich”³⁴, which concludes that in areas of mobility that are difficult to electrify, climate-neutral hydrogen is indispensable as a gaseous energy carrier and chemical raw material and represents the most effective path to decarbonization.

In the long-term, optimized combustion engines will still be needed and applied in powertrains for particular applications such as heavy duty or long-distance on/off-road transportation, non-road mobile machineries, trains, ships and airplanes as well as in stationary applications. Therefore R&D must aim for increased efficiency and zero-impact emissions. Each improvement shall directly contribute to short- and medium-term reductions of GHG and local pollutant emissions. Depending on the GHG emissions from the production pathway, hydrogen and sustainable fuels can be at least as environmentally friendly from well-to-wheel as systems with all-electric powertrains. Additionally, they offer the advantage that they can be used in the existing infrastructure.

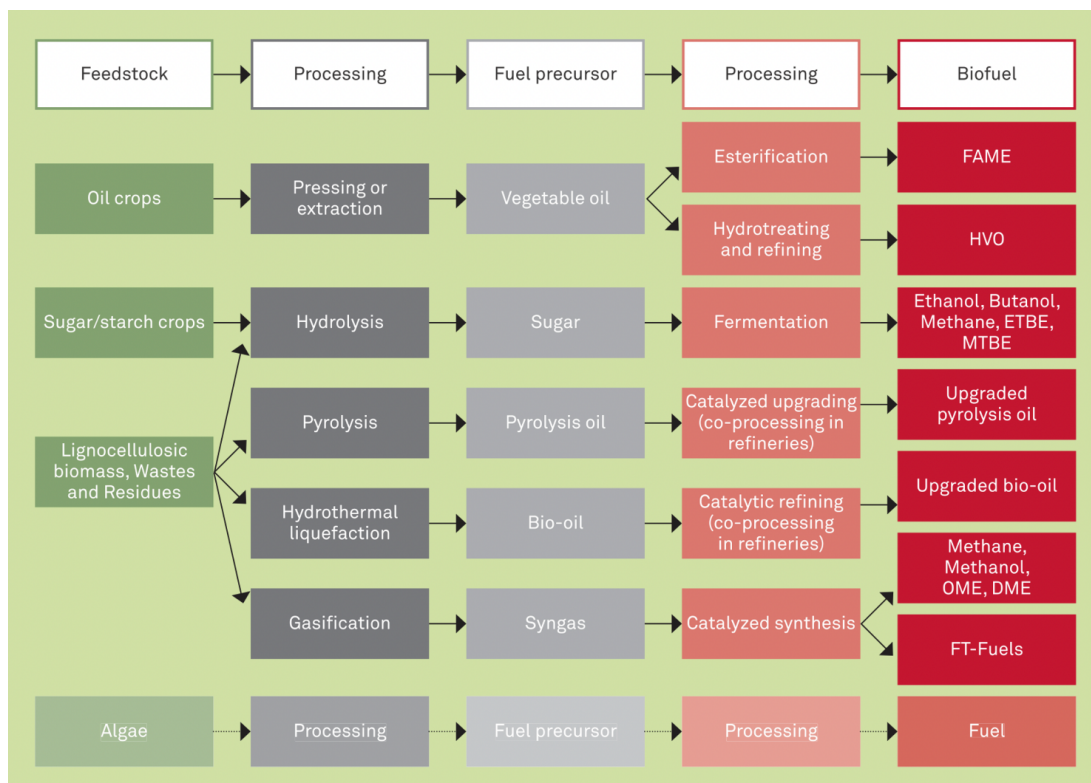


Figure E-2: Main production pathways of biofuels

³⁴ <https://www.bmwet.gv.at/Themen/Energie/erneuerbare-energie/Wasserstoff.html#wasserstoffstrategie-des-bundes-0-1> (retrieved 30 May 2025)

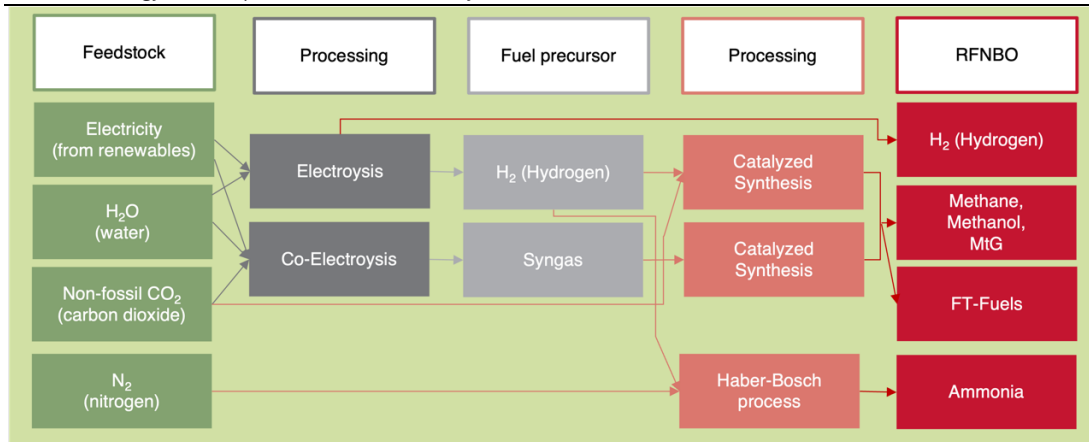


Figure E-3 Main production pathways of hydrogen via electrolysis and Renewable Fuels of Non-Biological Origin (RFNBO)

There is a range of renewable fuels that can contribute to defossilisation of the transport sector. The considered fuels are either based on biomass only or combine hydrogen from renewable electricity with a carbon source through a PtX technology. Focus of this chapter is on renewable fuels that can directly replace fossil fuels in road transport (and thus can be used by common internal combustion engines and existing infrastructure with little to no adjustments). They can be used either as a substitute or as a blending component.

Many production pathways exist for biofuels and for e-fuels. Figure E-2 provides an overview of the production pathways for biofuels considered in this chapter, and Figure E-3 provides a schematic representation of the production of e-fuels.

The main driver for the implementation of renewable fuels is the European Renewable Energy Directive 2023/2413/EC³⁵, which obligates fuel suppliers to ensure a share of renewable energy within the final consumption of energy in the transport sector of at least 29 % by 2030.

Internal combustion engines especially as part of hybrid powertrains will remain an important power unit at least in the period covered by this roadmap and further on applications such as long-distance and heavy-duty vehicles, mobile machineries, trains, ships and airplanes. However, increasingly stringent requirements for GHG and local pollutant emissions will apply to these engines. Furthermore, the requirements for fuels are changing due to the consequent and continually ongoing optimization of the ICE (in particular the optimization of the combustion process).

Sustainable fuels have great potential to reduce GHG emissions and local pollutant emissions in the existing vehicle fleet. Even with increasing electrification of road transport (mainly cars), sustainable fuels will remain important for several sectors, such as heavy-duty trucking, aviation and shipping that are hard to defossilize by other means. Production technologies utilizing oil crops or sugar and starch crops (1st generation or conventional biofuels) are already commercialized. Those based on lignocellulosic biomass, wastes and residues (2nd generation or advanced biofuels), algal biomass (3rd generation), or on CO₂ and hydrogen (e-Fuels) still require further research and development.

E-Fuels (PtL, PtG) are synthetic fuels, which combine CO₂ as carbon source with renewable hydrogen. CO₂ can be sourced from exhaust gases of industrial processes (integrated energy), from biomass installations, or directly from the air. E-Fuels can be used as an excellent surplus electricity (from variable renewable sources such as wind and solar) storage and have the potential to be fully CO₂ neutral. E-Fuels also enable easy seasonal energy storage.

E.1 Hydrogen and syngas production via electrolysis

Hydrogen production via electrolysis and syngas production via co-electrolysis as well as storage and distribution are addressed in **C Fuel/Electrolysis Cells and Hydrogen** while this chapter covers Biofuels and RFNBOs including fuels with renewable hydrogen from electrolysis as a feedstock.

E.2 Renewable Fuels of Non-Biological Origin (RFNBOs)

Examples of PtL processes included the production of hydrocarbons via the Fischer-Tropsch (FT) process and the production of methanol, and the resulting fuels, e.g. MtG (Methanol-to-Gasoline), can be used as full substitutes or blends. PtG (methane) can be produced via the Sabatier process, can be stored in the existing natural gas grid, and can be used for industrial applications or in gas engine vehicles.

Renewable fuels of non-biological origin (RFNBOs) face several challenges, such as tendentially higher production costs, largely driven by energy-intensive processes like electrolysis, that at the moment hinder their widespread adoption. Additionally, ensuring a consistent renewable energy supply for production poses reliability issues. Advancements in technology and supportive policies are crucial for overcoming these barriers.

The production of RFNBOs requires a well-established hydrogen supply and CO₂ supply (except for ammonia), which can be obtained from various sources such as combustion gases, industrial processes (e.g. off gases), biogenic CO₂, and CO₂ captured

³⁵ <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32023L2413> (retrieved March 10, 2025)

directly from the air. Carbon capture and utilization (CCU) is considered an important CO₂ mitigation strategy to support and complement carbon capture and storage (CCS) objectives for the abatement and sequestration of CO₂.³⁶

To address the challenges of renewable fuels of non-biological origin (RFNBOs), increased research and financial support are essential. Research should focus on improving electrolysis efficiency, developing cost-effective catalysts, and enhancing energy storage solutions to ensure stable production. Financial investments are crucial to scale up infrastructure, fund pilot projects, and reduce production costs through innovation. Strong policy incentives and public-private partnerships can further accelerate advancements and market integration.

Even though industrial E-fuel plants should be located primarily in regions with availability of cheap renewable electricity as well as a source of non-fossil CO₂, it is sensible to develop and improve the necessary technology in Austria or with Austrian participation, e.g. in demonstration units. Roadmap-Table E-1 shows research needs considering E-Fuels.

Roadmap-Table E-1: Renewable fuels of non-biological origin (RFNBO)

		Short-term until 2030	medium-term 2030-2035	Long-term 2035+
RFNBOs	E- Fuels (PtL, PtG)	Energy efficient, low cost and ageing resistant catalysts, TRL ²⁰²⁵ 5-7		
		Demonstration of small to medium scale PtL/PtG gas units, integration in AD plants, or other CO ₂ sources, TRL ²⁰²⁵ 8		
	Pilot plants or demonstration units / industrialization	Technologies to separate CO ₂ from the atmosphere, TRL ²⁰²⁵ 3-5		
	Type of project required	Commercial E-Fuels Facilities, TRL ²⁰²⁵ 5-8		
		Carbon Capture and Storage/Utilization, TRL ²⁰²⁵ 4-6		

E.3 Biofuels

Biofuels are produced through contemporary processes from biomass, rather than by the very slow geological processes involved in the formation of fossil fuels, such as oil.

Advanced biofuels, also known as 2nd generation biofuels, are fuels that can be manufactured from various types of non-food biomass. Conventional biofuels, also known as 1st generation biofuels, are made from sugar-starch feedstocks and edible oil feedstocks, which are generally converted into bioethanol and biodiesel, respectively. Advanced biofuels are made from different feedstocks and therefore may require different technology to extract useful energy carriers from them.

Alcohols can be used as blending components in gasoline. **Ethanol** is the most widely used alcohol. Methanol and butanol are other options, but less common. Ethanol can be produced from sugar or starch crops (1st generation) or from lignocellulosic biomass or other wastes and residues (2nd generation). Ethanol is currently distributed as blend with fossil fuel at 5 % to 10 % volume. For higher blends (E85), vehicle modifications are required. Even low blends of 10 % to 20 % reduce PM and CO₂ exhaust emissions significantly. Ethanol can be further processed into **ETBE** and then blended with fossil fuel.

Methanol can be used in various blends with gasoline³⁷, or further processed into **MTBE**. Generally, methanol combustion shows low emissions of CO, hydrocarbons, nitrogen oxides and particles, but its toxicity may lead to application challenges.

FAME (Fatty Acid Methyl Ester), a renewable diesel fuel is currently distributed as blend with fossil fuel to around 7 %. FAME can be produced from vegetable oil or used cooking oil and animal fat as raw materials.

HVO (Hydrogenated Vegetable Oil)/**HEFA** (Hydroprocessed Esters and Fatty Acids) is a renewable Diesel fuel from hydrogenated vegetable oil or used cooking oil and animal fat as raw material. HVO can be mixed with fossil fuel and is free of sulfur and aromatics. Furthermore, the use of HVO significantly reduces PM, CO and HC compared to fossil fuel. HVO improves the NO_x-PM trade-off in engine applications.

The Fischer-Tropsch (FT) process is a well-established method for producing high-quality synthetic fuels from carbon-containing materials. This process involves three key stages: gasification of the feedstock to generate raw gas, treatment of the gas to obtain synthesis gas (syngas), and catalytic synthesis to produce liquid fuels. While the FT process is primarily optimized for Diesel production, it can also yield gasoline and jet fuel (kerosene). FT fuels are sulfur- and aromatic-free, resulting in significantly reduced local pollutant emissions such as particulate matter (PM), carbon monoxide (CO), and hydrocarbons (HC). Additionally, FT fuels improve the NO_x-PM trade-off compared to conventional fossil fuels. Thanks to their exceptional purity and performance characteristics, FT fuels can be used either as a full substitute (manufacturer approval for EN 15940³⁸ fuels needed) or as a blending component in existing fuel infrastructure.

Fischer-Tropsch-Fuels from biomass use biomass as carbon containing material and have the potential to be fully CO₂ neutral. Fischer-Tropsch Fuels (FT-Fuels) from biomass count as biofuels. In case of utilization of Hydrogen from electrolysis, they could be called „E-Fuels“ as well and research topics in

Legend

-  (material) fundamental research
-  industrial research
-  experimental development
-  demonstration

³⁶ <https://publications.jrc.ec.europa.eu/repository/handle/JRC135099> (retrieved 13 April 2025)

³⁷ https://iea-amf.org/content/fuel_information/methanol (retrieved 14 April 2025)

³⁸ ONORM EN15940 specifies requirements and test methods for paraffinic diesel fuel

Roadmap-Table E-1 are valid for FT-Fuels, too, but FT-Fuels from biomass are not RFNBOs per definition because of the biological feedstock. Roadmap-Table E-2 provides an overview of research topics considering FT-Fuels using biomass as a feedstock.

Bio-Methane can be produced from various sources of biomass via two different pathways (fermentation or gasification). In any case, after upgrading, the resulting product is methane of a quality like that of natural gas. Bio-Methane can be blended at any ratio with or fully substitute natural gas.

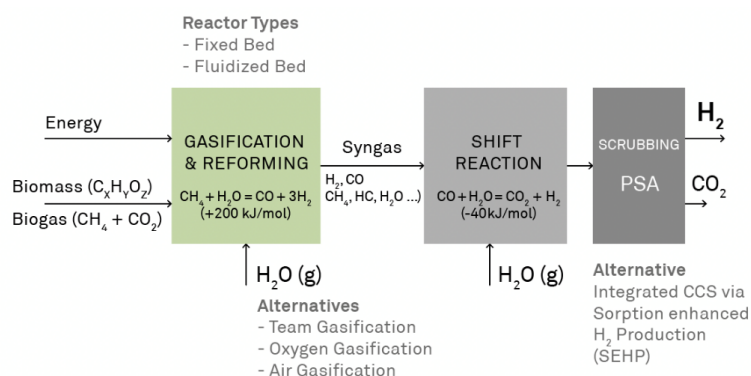


Figure E-4: Scheme H_2 production process via thermal gasification of biomass

Hydrogen from Biomass: Hydrogen production from biomass faces challenges such as low conversion efficiency, high costs, and the need for improved gas cleaning technologies to remove impurities (especially S contents). Research efforts are crucial to enhance thermochemical and biochemical processes, develop efficient catalysts, and optimize reactor designs. Advancing biomass pretreatment methods and improving carbon capture integration are also key priorities. Increased investment in innovative technologies can help improve efficiency, scalability, and environmental sustainability in hydrogen production from biomass.

For the conversion of biomass to (green) hydrogen the following paths are of interest to the industry:

- 1) Thermal gasification,
- 2) Production of biogas (methane fermentation) and steam reforming,
- 3) Biological H_2 production via bacteria,
- 4) Electrochemically assisted production.

Thermal gasification & reforming process, characterized through an endothermic process, Gasification using steam, oxygen within the biomass supports the endothermic process, water gas shift reaction to increase H_2 output is seen with very high potential. Algae-based biofuels, which are also referred to as 3rd generation fuels, comprise a wide range of fuels which can be produced through a variety of conversion technologies.

In contrast to the state-of-the-art blending of biofuels into the finished refinery product, co-processing technologies already implement the biomass feedstock (e.g. pyrolysis oil or bio-crude from hydrothermal liquefaction) in the fuel production process in the refinery. The resulting fuels are of the same quality as conventional refinery fuels and can be used as blends or full substitutes. Roadmap-Table E-3 provides an overview of research topics considering co-processed fuels.

Roadmap-Table E-2: Fischer-Tropsch fuels (FT-Fuels) from biomass



Legend

- (material) fundamental research
- industrial research
- experimental development
- demonstration

		Short-term until 2030	medium-term 2030-2035	Long-term 2035+
Biofuels	Co-processed fuels  commercial facilities / addition to refinery (demo plant available) / biogenic content in fossil fuels	Hydrotreating & upgrading of FT-waxes, pyrolysis oil, or other biocrudes (products from HTL or APR), TRL ²⁰²⁵ 9		
	Type of project required			

Legend



(material) fundamental research



industrial research



experimental development



demonstration

F Innovative Materials and Production

Vehicles of the future must be designed and produced based on the latest research results in material and production science to keep Europe at the forefront as the automotive continent. The very wide research area has to be structured, e.g. into the following five subtopics F.1 to F.5. Economic success and prosperity in our society can only stay at the actual high level, when the challenges of high productivity and sustainability will be managed in the future with low-cost solutions.

The target of “climate neutral vehicles” can only be achieved by the highest possible weight reduction based on lightweight materials, topology optimization and powerful joining processes. The demanding requirements regarding CO₂/GHG emissions and safety make integrative vehicle concepts the major driver of innovations as a result of value and function analysis, material selection and the choice of the best-fitting joining technologies.

The use of fiber-reinforced plastics as well as new types of aluminum or magnesium alloys, and hybrid lightweight construction represent the most promising solutions. But innovative materials are more than “only” lightweight, since with the target to transform to a circular economy they must offer recyclability, reuse and refurbishment.

Lightweight construction will be essential for the further development of electromobility in order to compensate the fact, that new electric cars are 10 to 30 percent heavier than conventionally driven vehicles due to the additional battery weight.

So far, actual designs and modular building block systems are still based on conventional series, as higher quantities result in lower costs. Therefore, cost-effective solutions and modular concepts with high batch sizes are essential for the total transformation to lightweight and smart constructions.

The holistic approach considering both materials and production is the key for the success of the next vehicle generations. Producibility, low carbon footprint and independence from critical raw materials are the dominant decision criteria. The competences material selection, process optimization, supply network design and last but not least data analysis must be strengthened.

As a result of the above-mentioned requirements the following five subtopics are covered in the A3PS roadmap:

1. Design for Manufacturing / Circularity
2. Advanced Materials / Lightweight Hybrid Structures
3. Production Processes for Competitive Industries
4. Cost-effective and Agile Automation (AI-Integration, Robotics, Sensors)
5. Human-Centered Production

F.1 Design for Manufacturing / Circularity

Design for Manufacturing is not only driven by performance requirements but mainly considers the need for a high level of circularity, existing European supply chains and possibly future European alternatives (e.g. Magnesium from Dolomite and/or sea water) for structural applications.

Even for engine design, lightweight construction and materials will play the major role. High-strength materials and in the long-run, materials with special thermal properties (low thermal conductivity and capacity), will be introduced. For EDU (Electric Drive Unit), comprised of E-Motor, inverter, transmission and cooling System lightweight design and materials and joining technologies are covered mainly by functional integration.

Improved materials and processes will make it possible to develop highly efficient, durable and acoustically optimized EDUs, – e.g. reduction of gear sets and/or coupling elements to reduce drag losses. Design in E-Motor winding, insulation, stack manufacturing and magnet insertion technologies are important and need still research to guarantee more power density and thermal stability. An important aspect of using new materials is the consideration of the entire product life cycle, including recycling. In order to gain international acceptance as an Innovation leader in this area, Austria must keep a close collaboration with industry and university research institutes in the field of basic material research.

Minimizing friction has very relevant potential to reduce CO₂. Therefore, further effort in basic materials research, design, simulation and intensive testing (validation) is required.

Meaningful Life Cycle Assessment (LCA) of vehicles must cover the entire life cycle including material origin, second life, and recycling for a circular economy approach. These aspects need to be quantified and considered in simulation and optimization of the product in parallel to efficiency, weight reduction and performance. This holistic view shall equally cover the carbon footprint of production processes and will promote regional solutions and competitiveness, rather than delegating material consumption and emissions to other global regions.

For a circular economy approach, recyclability is not enough, additionally reuse, refurbishment, remanufacture and repair must be addressed. Design for circular economy aims to support the recovery of materials for further use. Eco-design methodologies addressing secondary and bio-based materials are principally available, but the higher variation of material properties compared to the virgin material has to be considered.

The authors of this roadmap recommend a Digital Product Passport for Materials, Production and Parts. As a quick win, such a passport could decrease the effort for compliance and supply chain transparency, standardized location for all product data such as material, sustainability, repair information, recycling information, etc. and eliminate manually maintained databases, simplification of recycling and processing parameters.

The digital product passport and the need to provide documents for the technical cycle in particular, are drivers for an increased focus on modularization and the use of kit systems in powertrain and vehicle chassis technology. The past has shown that

modularization can significantly strengthen competitiveness and at the same time is a key element for the individualization of products. The necessary know-how in the areas of mass production processes (e.g. die casting, joining techniques) and automation in the assembling and demounting of parts must be specifically expanded within research projects.

Roadmap-Table F-1: Design for manufacturing / design for circularity

		Short-term until 2030	medium-term 2030-2035	Long-term 2035+
Design	Design for Manufacturing / Circularity  costs / technical guidelines / regulations / durability/ independency Type of project required   	New methods for circular design to ensure automated disassembling/dismantling and re-assembling on component and part-level TRL ²⁰²⁵ 3		
		Research for optimized design of E-Motor windings, insulation, stack manufacturing and magnet insertion to guarantee more power density and thermal stability, TRL ²⁰²⁵ 5		
		Creation of real load data (mechanical, thermal, electric, magnetic, acoustic) for component material design which cover the life span of the product, TRL ²⁰²⁵ 3-5		
		critical raw materials act ³⁹ conformity of supply networks , TRL ²⁰²⁵ 2-6		
		Design for production of power electronics and semiconductors TRL ²⁰²⁵ 3-5		
		Digital Product Passport for Materials/Production/Systems/Parts, TRL ²⁰²⁵ 4		
		Consideration of modular design principles for manufacturing, TRL ²⁰²⁵ 5-6		

F.2 Advanced Materials / Lightweight Hybrid Structures

In order to become independent of raw material chains outside Europe (availability and price of raw materials) and thus reduce or avoid vulnerability to geopolitical upheavals, it is necessary to keep the materials currently and in the future available in Europe in a cycle and to develop new materials from them.

Furthermore, securing the supply of critical raw materials in parallel to material reduction, substitution, reuse, and recycling needs to become a core part of the value chain to foster a more circular economy.

Materials in the right quality are always crucial for product costs. Especially for E-Motors the content of heavy rare earth magnets for PMSMs and copper have an important contribution to the unit costs. Europe depends currently strong on material markets outside of the territory which implies a strain on supply security for a long-term running series project production (up to 10 years). The strain is not only on the long-term availability but also on the stable price of these materials. Political or economic interferences can lead to catastrophic business case or even complete market failure of the entity. In the past materials were chosen based on the available source (price) and appropriate material properties. With the introduction of new circularity and sustainability regulations, based mostly on the Critical Raw Materials Act and the Green Deal, the material approach has changed significant. CO₂ footprint and 9R are important for the new designs which foster alternative material picks, recycling and reuse of materials as well as research in material properties for second used components.

Lightweighting using innovative and sustainable high-performance materials is a key technology and a cross-cutting issue, which itself requires more attention in research and development instead of being only enabler of other topics like low-emission mobility. In today's world, lightweight construction must be sustainable, smart and affordable in order to be able to support the European goals of the former green deal and actual clean Industrial deal or national aims as e.g. from the Mobilitätsmasterplan 2030⁴⁰. For the focus area of A3PS, this means on the one hand, the lightweight vehicle design to minimize energy consumption through reduced vehicle weight and thus extending the range of the vehicles. On the other hand, lightweight construction is of particular relevance for future, new propulsion systems and their components. The basic idea of high-performance materials in lightweighting, to use constructions and materials with better mechanical properties at a lighter weight is still valid. Now, however, these materials should be produced as independently as possible of critical raw materials (to be independent of global market fluctuations and thereby strengthen the sovereignty of the EU) and still deliver good mechanical properties, be energy-efficient to manufacture and recyclable. Thus, further topics are still the improvement of high-strength materials and new lightweighting alloys, such as Aluminum, Magnesium, Titan etc. for engines, transmissions, electric components and of course the whole chassis. In addition, new alloying/material concepts like the "one-alloy/material-fits-all" approach is one of the most promising technological options that make subsequent recycling more efficient and save resources during production. In this way, the issues of recycling and circular economy, which are no longer negligible nowadays, are considered by means of modern materials in the powertrain. In addition to this material approach, the consistent pursuit of functional integration to drastically reduce the number of components and expand the tasks of structural components, for example, is a promising approach. Additive manufacturing is a key technology that enables the production of these complex, function-integrated

Legend

-  (material) fundamental research
-  industrial research
-  experimental development
-  demonstration

³⁹https://single-market-economy.ec.europa.eu/sectors/raw-materials/areas-specific-interest/critical-raw-materials/critical-raw-materials-act_en

⁴⁰ <https://www.bmimi.gv.at/themen/mobilitaet/mobilitaetsmasterplan/mmp2030.html> (retrieved 28 May 2025)

components. To further increase the sustainability of lightweight construction, it is necessary to design the function-integrated components and constructions in such a way that they are suitable for repair/reuse/recycling (including even automated dismantling) and thus enable a longer service life and circular economy. With all these new materials and components in the powertrain, it must be considered that the joining techniques also meet the new requirements and must therefore also be adapted and optimized in additional research projects. However, all these approaches are only promising if the energy content (or the CO₂ footprint) in the material and the resulting lightweight construction are also considered and reduced. An additional focus should be laid on an overall cost-benefit view, including economic and ecological factors.

Bio-based materials, such as bioplastics, are increasingly being used in the automotive industry to reduce dependence on petroleum and improve sustainability. They are used in interior components, but also in body parts and even some engine components.

Materials Acceleration Platforms based on AI tools, existing materials can be developed more quickly under new conditions and for new applications, while at the same time standardized data sets are available for further processing, leading to better cooperation between different players along the value chain. Thus, costs and development time can be saved.

Sustainable and secondary materials suitable for repair/reuse/recycling/circular economy (including steel, aluminum, magnesium, titan, thermo-plastics and composites) keep (raw) materials in the European ecosystem and reduce dependence of global material flows which are susceptible for geopolitical warp.

Roadmap-Table F-2: Advanced materials /lightweight hybrid structures

		Short-term until 2030	medium-term 2030-2035	Long-term 2035+
Materials	Advanced Materials / Lightweight Hybrid Structures  9R* / cost / durability / reliability / independancy / standardization / weight reduction / energy efficiency Type of project required    	Simulation-supported life cycle assessments for technology scouting and decision-making processes, TRL ²⁰²⁵ 5-6		
		Sustainable and secondary materials suitable for 9R*(including steel, aluminium, magnesium, titan, thermo-plastics and composites), TRL ²⁰²⁵ 3-5		
		Alternative materials to replace HRE or RE magnet materials, use of magnet materials with downgrade properties (recycling), alternative insulation materials for windings TRL ²⁰²⁵ 3-5		
		Lubricant material coating, new materials (e.g. plastics) surface structuring (nano structures,...) TRL ²⁰²⁵ 5-6		
		New materials for wider use of plain bearings (save weight, improve energy efficiency, ...) TRL ²⁰²⁵ 2-4		
		Development and exploitation of new bio-based materials, TRL ²⁰²⁵ 2-3		
		Evaluation of interaction between alternative fuels and oils. TRL ²⁰²⁵ 4-6		
		Coatings and sealing materials for rotating or current conductive components in EDUs to increase EMC, durability and reduce NVH enabling lifet-ime expansion, TRL ²⁰²⁵ 4-6		
		Materials Acceleration Plattformen based on AI tools TRL ²⁰²⁵ 3		
		Standardized Hybrid Structures and joining interfaces (Construction Catalog based on latest technologies and research), TRL ²⁰²⁵ 4-6		
		High performance lightweight materials incl. *one-alloy/material fits all" approach, TRL ²⁰²⁵ 5		

F.3 Production Processes for Competitive Industries

Production technologies and furthermore industrial operations are the backbone of the financial success of the European Automotive sector. Over hundreds of years Europe is master in manufacturing of components for transmissions, internal combustion engines, axles, tank systems and even complete vehicles. Europe has a strong innovative machine tool industry which works hand in hand with the automotive industry to generate new production processes and tools. The product costs not only depend on the engineering efforts and chosen materials, but also on the production process to manufacture and assemble the product. But set up of industrial operations is cost intensive and with the current labor prices Europe is losing ground in manufacturing competitiveness. Innovative technology processes are therefore fundamental to support a price reduction and secure the existing production in Europe.

The seamless introduction of networked development backbones is necessary to remain successful in the global market. A particular challenge is the seamless integration of information from field tests into development and production processes. The closed loop of engineering data to manufacturing during development process as well as while lifecycle change management is mandatory but steady raising required relevant data types are to reflect – Geometry and parts list of the past have not been sufficient for a long time. Equally important is to efficiently incorporate the production requirements to the product from

Legend

-  (material) fundamental research
-  industrial research
-  experimental development
-  demonstration

manufacturing into development to ensure efficient manufacturability in general but especially for new technologies.

For sustainable, efficient and, above all, competitive vehicle construction in Europe - in general and especially in electromobility - it is becoming increasingly important to take a holistic view of materials and production together. It is becoming apparent that, in addition to ever higher demands on material properties, sustainable and energy-efficient, resource-saving producibility and further processability of these materials are becoming increasingly important. This is despite the new material composition due to the higher degree of recycling, the circular economy and possible future European alternatives (e.g. Magnesium from Dolomite and/or sea water).

The manufacturing industry is confronted with small and zero series (prototyping) for new vehicle concepts and their innovative components (e.g. smart components, smart materials). At the same time, it is important to create individualized products with "high volume" processes (mass customization).

Function oriented process control of parts can help to achieve zero defect manufacturing. The trustworthy simulation of parts and their production processes are key to predict their behavior in operation and help to predictively maintain tools in the process.

Especially for production and logistics we are well advised to develop an automated closed loop for gathering data from engineering and the manufacturing processes, processing those to the relevant information and provide the relevant decision bases easy understandable to our employee, or to an AI for knowledge-based decision making with automated execution of measures in a closed loop.

Additive manufacturing has great potential, especially in lightweight construction, energy efficiency (creating complex flow channels, cooling in the parts) and functional integration. To enable this, the materials must be further optimized for this purpose, the processes (e.g. energy parameters) must be optimized and must be even faster, cheaper and with higher throughput, for which great efforts must be made in research. For individual manufacturing and small series, it must be ensured that the "additive processes" used for the first test components also allow conclusions to be drawn about the later large-series solution.

Likewise, the optimization of the "classic" technologies with a high degree of maturity (pressure die casting, metal forming, machining, joining, etc.) should not be forgotten. When optimizing well known processes in conjunction with further material optimization, energy intensive steps (e.g. heat treatments) can be skipped. An important task to do so is the digitalization and the data collection of our (traditional) processes in our brownfield factories.

A central focus of this roadmap is the evaluation and targeted utilization of existing production lines and manufacturing technologies within the Austrian automotive industry. The objective is to systematically assess and leverage their transfer potential for the production of fuel cells and electrolyzers. This will enable rapid, flexible, and cost-efficient manufacturing and scaling-up of these key technologies in the hydrogen economy.

Particular emphasis is placed on identifying and utilizing **synergistic effects** between the manufacturing of fuel cells and electrolyzers. In this context, the following actions are intended:

- Existing production capacities within the automotive industry shall be tapped through adaptive conversion or expansion for component and system manufacturing of fuel cells and electrolyzers.
- Standardized manufacturing processes and automation technologies, as established in automotive production (e.g., stamping, welding, coating, and assembly technologies), shall be examined for their transferability and potential to increase efficiency.
- The **transfer potential between fuel cell and electrolyser production** shall be actively promoted in both directions, in order to achieve higher utilization rates and economies of scale through the shared use of facilities, machinery, and expertise.
- Flexible production concepts (e.g., modular manufacturing) shall be developed to enable rapid adaptation to market developments and varying production volumes.

Furthermore, cooperative models between automotive companies, technology providers, and research institutions will be established to shorten innovation cycles and facilitate efficient technology transfer.

An integral part of this roadmap is the consideration of **quality management**, **process reliability**, and **cost optimization** in order to create internationally competitive production solutions for fuel cell and electrolyser technologies **"Made in Austria"**.

Legend

-  (material) fundamental research
-  industrial research
-  experimental development
-  demonstration

Roadmap-Table F-3: Production technologies

		Short-term until 2030	medium-term 2030-2035	Long-term 2035+
Production	Production Processes for Competitive Industries  cost / 9R* / quality / availability / reliability Type of project required 	Metal Additive Manufacturing, incl. high-deposition rates (outputs greater than 10-15kg/h) for big parts, and for variation of cast components, TRL ²⁰²⁵ 4		
		Industrialization of multi-material AM processes, TRL ²⁰²⁵ 3-4		
		Novel casting and forming processes (e.g. vacuum-assisted casting, semi-solid-casting, cryoforming, electroforming) for optimized material utilization (e.g. uniform thinning) or for improved mechanical properties, TRL ²⁰²⁵ 4-5		
		Manufacturing of smart products (intelligent components, smart materials) with integrated sensor functionality in parts, components and materials, TRL ²⁰²⁵ 2-4		
		Pilot line of large-scale production and recycling of fuel cells, TRL ²⁰²⁵ 4-6		
		Industrialization of advanced(hybrid) joining technologies and equipment, TRL ²⁰²⁵ 5-6		
		High grade of production automatization to improve production speed combined with flexibility, TRL ²⁰²⁵ 5		
		Process optimization for efficient manufacturing (e.g. for hybrid materials) through e.g. elimination of intermediate steps (for reduction of energy consumption, CO ₂ -output, costs, ...) TRL ²⁰²⁵ 3-4		
		EDU manufacturing (E-Motor stacks, active components, gears) and assembling (windings, power electronics, insulation, complete EDU) processes, new end of line testing methods, TRL ²⁰²⁵ 5		
		Development of magnesium production technologies (especially for other Mg alloys than AZ31), TRL ²⁰²⁵ 3-4		
		Assembling of high-volume products considering disassembling and recyclability, TRL ²⁰²⁵ 5		
		Processes for economic driven recycling, TRL ²⁰²⁵ 2-4		
		R&D in for new machines, like test benches, quality lines, EoL and measurement technologies, end-of-line testing, TRL ²⁰²⁵ 4-6		
		Empowering of industries with data analysis and edge computing devices, TRL ²⁰²⁵ 4-5		
		Increase of agility and sustainability using modular production units, TRL ²⁰²⁵ 5-6		

F.4 Cost-Effective and Agile Automation, Robotics, Sensors

Automation is definitely the order of the day. Coupled with the latest methods and the easy access to AI-based optimization algorithms, the high staff costs in Europe and the increased operational reliability and availability of sensor systems, automation must be pushed forward in the best possible way. An important advantage of automation is the flexibility that it offers and, at a level above this, agility. The current uncertainty regarding future powertrain technologies and volumes in Europe can thus be effectively tackled. If it is also possible to increase the standardization of plant components and therefore their reusability, even shorter amortization periods can be obtained. Automation technology also creates more jobs, as long as European manufacturers are selected. Predictive maintenance and operational reliability will guarantee long operating periods and resource efficiency. Automated quality inspection and the increased use of quality control systems make it possible to further raise the well-known high level of quality in Europe and to utilize additional sustainability benefits by minimizing scrap.

Robots are technically mature – but the total costs of industrialization (integration, programming, sensors, IT connection, operational safety, etc.) are often many times higher than the robot itself. An important goal is therefore to reduce overall costs and entry barriers.

Legend

-  (material) fundamental research
-  industrial research
-  experimental development
-  demonstration

Roadmap-Table F-4: Cost-effective and agile automation, robotic, sensors

		Short-term until 2030	medium-term 2030-2035	Long-term 2035+
Automation	Cost-Effective and Agile Automation, Robotic, Sensors  9R* / costs / durability / reliability / modularization Type of project required   	Development of valid simulation models and algorithms for production processes, "virtual product development", TRL ²⁰²⁵ 4		
		Development and application of digital twins considering 9R*, TRL ²⁰²⁵ 3-5		
		Combination of process data, big data mining, and material data as input for numerical simulations, Co-simulation of materials and manufacturing processes and modelling as well as generative and self-learning production planning tools, TRL ²⁰²⁵ 3-4		
		Retrofittable, cost-effective, modular automation kits for existing production lines, TRL ²⁰²⁵ 5-6		
		High performance automation systems (using AI and other emerging digital technologies) with condition monitoring functions, TRL ²⁰²⁵ 4		
		Development of a holistic approach ("decision guide") (robotics, sensors, automation, TRL ²⁰²⁵ 2-4		
		Real-time automated quality control in the manufacturing process, TRL ²⁰²⁵ 4-6		
		Use of physical AI for collaborative, humanoid robots capable of adapting to their physical environment, TRL ²⁰²⁵ 2-4		

F.5 Human-Centered Production

The recent years have shown that the originally intended concepts of Industry 4.0, involving the organization of production with cyber-physical systems and the highest possible degree of autonomy, do not have the desired effect. In particular, the investment and the ongoing costs of updating hardware and software were clearly being underestimated. With Industry 5.0, it was therefore decided to take an adapted path by focusing more on human-orientation, resilience and sustainability.

In particular, the consideration of human needs is seen as central to the recovery of industrial competitiveness in Europe. Collaborative robotics and agile production systems are topics that, coupled with the use of AI, are receiving more and more attention. New working methods and exoskeletons are being tested and applied to ensure that people's health is kept as long as possible and physical and mental stress is reduced to a minimum. Providing people with the best possible support in the digitalized world is the central objective of this thematic block.

Roadmap-Table F-5: Human-centered production

		Short-term until 2030	medium-term 2030-2035	Long-term 2035+
Human-Centered Production	Human-Centred Production  safety / qualification / trust / health Type of project required 	Improving domain knowledge in production and material science on all levels (workers, managers, engineers, scientists, ...)		
		Implementation of standardized collaborative robot cells		
		Research in safety and exoskeletons		
		Empowering people for co-design and co-production with trustful data spaces		
		Quality and precision thinking as key competence for sustainability		

Legend

-  (material) fundamental research
-  industrial research
-  experimental development
-  demonstration

List of Acronyms

AC	Alternating Current
AD	Autonomous Driving
AD plant	Anaerobic Digestion plant
ADAS	Advanced Driver Assistance Systems
AEL	Alkaline Electrolysis
AEM	Anion Exchange Membrane
AEMEL	Anion Exchange Membrane Electrolysis
AEMFC	Anion Exchange Membrane Fuel Cells
AI	Artificial Intelligence / Alcohol Interlock
APR	Aqueous Phase Reforming
APU	Auxiliary Power Unit
ASIL	Automotive Safety Integration Level
BEV	Battery Electric Vehicle
BMIMI	Federal Ministry Republic of Austria for Innovation, Mobility and Infrastructure
BoP	Balance of Plant
C2C	Cell-to-Chassis
C2P	Cell-to-Pack
C2V	Cell-to-Vehicle
CAPEX	Capital Expenditures
CcH ₂	Cryo-Compressed Hydrogen
CcHS	Cryo-compressed Hydrogen System
CCS/CCU/CCSU	Carbon Capture and Storage, Utilization
CFD	Computational Fluid Dynamics
CI	Compression Ignition
CO	Carbon monoxide
CO ₂	Carbon dioxide
CO ₂ eq	CO ₂ equivalent: unit of measurement that is used to standardize the climate effects of various greenhouse gases
CRM	Critical Raw Materials
CU	Control Unit
DC	Direct Current
DeNO _x	Denitrification (Elimination of NO _x)
DHE	Dedicated Hybrid (Combustion) Engine
DI	Direct Injection
DME	Dimethyl Ether
EC	European Commission
EDU	Electric Drive Unit
EMC	Electro-Magnetic Compatibility
EoL	End-of-Line/End-of-Life
EUCAR	European Council for Automotive R&D
FAME	Fatty Acid Methyl Ester
FC	Fuel Cell
FCV	Fuel Cell Vehicle
FMI	Functional Mock-up Interface
FMU	Functional Mock-up Unit
FT	Fischer-Tropsch
GHG	Greenhouse Gas
H ₂	Hydrogen
HC	Hydrocarbon
HDV	Heavy Duty Vehicle
HEFA	Hydro processed Esters and Fatty Acids
HEV	Hybrid Electric Vehicle
HiL	Hardware in the Loop
HPC	High Power Charging / High Performance Computing
HRE(E)	Heavy Rare Earth (Element)
HRS	Hydrogen Refuelling Station
HTL	Hydrothermal Liquification
HV	High Voltage
HVAC	Heating, Ventilation and Air Conditioning
HVO	Hydrogenated or Hydrotreated Vegetable Oils
ICE	Internal Combustion Engine
IEA	International Energy Agency
IGBT	Insulated-Gate Bipolar Transistor
ISO	International Organization for Standardization
JRC	Joint Research Centre
KPI	Key Performance Indicators
LCA	Life Cycle Assessment
LDV	Light Duty Vehicle

LFP	Lithium Ferro phosphate
LH ₂	Liquid Hydrogen
Li	Lithium
LOHC	Liquid Organic Hydrogen Carriers
LTO	Lithium Titanate Oxide
LV	Low Voltage
MEA	Membrane Electrode Assembly
Mg	Magnesium
MOSFET	Metal Oxide Semiconductor Field-Effect Transistors
MtG	Methanol-to-Gasoline
MW	Megawatt
N ₂	Nitrogen
Na	Sodium
NMC	Nickel Manganese Cobalt
NO _x	Mono-nitrogen oxides (NO and NO ₂)
NVH	Noise, Vibration and Harshness
ODD	Operating Design Domains
OEM	Original Equipment Manufacturer
OME	Oxymethylene Ether
OPEX	Operational Expenditures
ORC	Organic Rankine Cycle
OTA	Over-The-Air
PCEL	Proton Conducting Ceramic Electrolysis
PCFC	Protonic Ceramic Fuel Cell
PEM	Polymer Electrolyte Membrane
PEMEL	Polymer Electrolyte Membrane Electrolysis
PEMFC	Polymer Electrolyte Membrane Fuel Cell
PF	Particle Filter
PFAS	Per- and polyfluoroalkyl substances
PFI	Port Fueled Injected
PGM	Platinum Group Metals
PHEV	Plug-in Hybrid Electric Vehicle
PI	Power Integrity
PM	Particulate Matter
PMSM	Permanent-Magnet Synchronous Motor
PnC	Plug-and-Charge
PtX (PtL, PtG)	Power-to-X (X= Liquid or Gas)
R&D	Research and Development
RCS	Regulations, Codes and Standards
RE	Rare Earth
RES	Renewable Energy Sources
REX	Range Extender
SAE	Society of Automotive Engineers
SDV	Software Defined Vehicle
SI	Spark Ignition / Signal Integrity
SoSE	System of Systems Engineering
SOEL	Solid Oxide Electrolysis
SOFC	Solid Oxide Fuel Cell
TEN-T	Trans-European Transport Network
TRL	Technology Readiness Level
V2B	Vehicle-to-Building
V2G	Vehicle-to-Grid
V2H	Vehicle-to-Home
V2L	Vehicle-to-Load
V2V	Vehicle-to-Vehicle
V2X	Communication from vehicle to X (e.g. Vehicle, Infrastructure, ...)
WtW	Well-to-Wheel
xCU	Any Control Unit
xiL	Model, software or hardware in the Loop

List of Roadmap-Tables

Roadmap-Table A-1: Energy and thermal management	11
Roadmap-Table A-2: Heating, ventilation and air-conditioning (HVAC)	12
Roadmap-Table A-3: Sensors	13
Roadmap-Table A-4: xCU incl. software	13
Roadmap-Table A-5 Predictive operation & control	14
Roadmap-Table A-6: Non-exhaust particle emission	14
Roadmap-Table B-1: Advanced Li-Ion batteries (3rd generation): cells & modules	18
Roadmap-Table B-2: Solid state batteries (4th Generation): cells & modules	19
Roadmap-Table B-3: New battery technologies.....	20
Roadmap-Table B-4: Structural battery integration.....	21
Roadmap-Table B-5: Structural battery integration.....	22
Roadmap-Table B-6: Electric motor	22
Roadmap-Table B-7: Inverter, power electronics	23
Roadmap-Table B-8: Electric drive unit (EDU).....	23
Roadmap-Table B-9: Motion-, drive- or powertrain-control and software for E-motors	24
Roadmap-Table B-10: Charging technologies	26
Roadmap-Table C-1: Fuel cell technology across vehicle segments.....	29
Roadmap-Table C-2: PEM fuel cells.....	30
Roadmap-Table C-3: Solid oxide fuel cells.....	30
Roadmap-Table C-4: Anion exchange membrane fuel cells for FCV	31
Roadmap-Table C-5: Gaseous hydrogen On-board hydrogen storage.....	32
Roadmap-Table C-6: LH ₂ -storage systems.....	33
Roadmap-Table C-7: Alternative hydrogen storage systems for mobile application.....	34
Roadmap-Table C-8: PEM electrolyzers	35
Roadmap-Table C-9: Solid oxide electrolyzers	35
Roadmap-Table C-10: Other forms of hydrogen generation	36
Roadmap-Table C-11: Hydrogen storage and distribution.....	36
Roadmap-Table C-12: Hydrogen refuelling stations (HRS).....	37
Roadmap-Table C-13: Test and validation.....	38
Roadmap-Table D-1: ICE technologies	40
Roadmap-Table D-2: Transmission and components.....	41
Roadmap-Table D-3: Clutch and actuators	41
Roadmap-Table E-1: Renewable fuels of non-biological origin (RFNBO)	45
Roadmap-Table E-2: Fischer-Tropsch fuels (FT-Fuels) from biomass.....	46
Roadmap-Table E-3 Co-processed fuels	47
Roadmap-Table F-1: Design for manufacturing / design for circularity	49
Roadmap-Table F-2: Advanced materials /lightweight hybrid structures.....	50
Roadmap-Table F-3: Production technologies	52
Roadmap-Table F-4: Cost-effective and agile automation, robotic, sensors	53
Roadmap-Table F-5: Human-centered production	53

Imprint

A3PS – Austrian Association for Advanced Propulsion Systems

A3PS is the **strategic partnership** between the Austrian technology policy, industry and Research institutions.

A3PS stimulates the development of advanced propulsion systems and energy carriers – to build up common competence and to accelerate market launches.

A3PS addresses **all advanced drivetrain technologies** with contributions to the improvement of energy efficiency and reduction of emissions supporting the whole innovation cycle (research, development, deployment).

Media owner and editor

A3PS – Austrian Association for Advanced Propulsion Systems

Österreichische Plattform zur Förderung von innovativen Antriebssystemen und -technologien für mobile Anwendungen sowie deren Energieträger.

Webgasse 9/2/3, 1060 Wien

Phone: +43-(0)1-890-4906

e-mail: office@a3ps.at

web: www.a3ps.at

November 2025 Edition

Editors:

Dr. Astrid Wolfbeisser (A3PS)

Prof. h.c. Dr. Peter Prenninger, Chairman of A3PS Executive Board (AVL)

Prof. Dr. Bernhard Brandstätter, Member of the A3PS Executive Board (Virtual Vehicle Research)

Dr. Damian Cupid, Expert Group Leader “Battery and Electric Powertrain” (AIT)

Ass.Prof. Dr. Alexander Trattner, Expert Group Leader “Fuel Cells and Hydrogen” (HyCentA)

Univ.Prof. Dr. Franz Haas, Expert Group Leader “Innovative Materials and Production” (TU Graz IFT)

Dr. Christian Chimani, Vice Chairman of the A3PS Executive Board (AIT)

Dr. Michael Nöst, MBA, Member of the A3PS Executive Board (IESTA)

Dr. Günter Offner, Expert Group Leader “Hybrids and Sustainable Fuels” (AVL)

Dr. Barbara Unterauer, Expert Group Leader “Vehicle Innovation, Safety and Sustainability” (Magna)

Mag. Anton Werkgartner, Member of the A3PS Executive Board (Magna)

Figures: A3PS and Members of A3PS

A3PS – Austrian Association for Advanced Propulsion Systems

Webgasse 9/2/3, 1060 Wien

www.a3ps.at

© A3PS, 2025