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FreeTwinEV

D2.1 Strategic Research Agenda 1			
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Table of contents

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We also acknowledge the contributions of various research teams across STU, whose expertise in material science, automotive engineering, and digital technologies has been critical in shaping this agenda. Their work in developing cutting-edge battery technology and digital simulation models serves as the backbone of our research initiatives.

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Executive Summary

The ***FreeTwinEV*** *Strategic Research Agenda (SRA)* is a comprehensive roadmap for advancing battery technology and digital twin innovations, aligning with the EU's sustainability objectives. Developed by the Slovak University of Technology (STU) in collaboration with international partners such as the University of Twente (NL), Linz Center of Mechatronics (AT) and ADDSEN(SK), this agenda is funded under the Horizon Europe initiative and focuses on positioning Slovakia as a leader in sustainable battery systems and Electric Vehicle (EV) technology.

Key priorities in this SRA include:

1. **Enhancing Research Capacity**: Strengthening STU's research infrastructure with a focus on digital twin technology for battery management, digital simulation, and innovative automotive solutions.
2. **Fostering International Collaboration**: Establishing partnerships with European institutions like the University of Twente and Linz Center of Mechatronics to align STU's research efforts with global standards.
3. **Driving Sustainable Innovation**: Targeting energy efficiency, sustainable design and EV safety improvements to support the European Green Deal and decarbonization goals.

The SRA leverages Slovakia's strong automotive industry and supports the EU's climate neutrality goals by developing technologies that promote battery safety, lifespan, and sustainability. The agenda also prioritises creating digital twin models for real-time battery management, improving efficiency and sustainability. Key performance indicators (KPIs) will track progress in areas like research output, international partnerships, and advancements in battery safety.

Over a three-year timeline, STU aims to solidify its position as a relevant institution in sustainable technology through collaborative research, funding from Horizon Europe and Slovak government programs, and active industry partnerships. Through periodic reviews and stakeholder feedback, the SRA will adapt to emerging needs and technologies, ensuring sustained impact and alignment with EU and global sustainability objectives.

List of Abbreviations

AI	Artificial Intelligence
EBA	European Battery Alliance
EIS	Electrochemical Impedance Spectroscopy
ERDF	European Regional Development Fund
EU	European Union
EV	Electric Vehicle
GITT	Galvanostatic Intermittent Titration Technique
KPI	Key Performance Indicator
NMR	Nuclear Magnetic Resonance
RRF	Recovery and Resilience Facility
SRA	Strategic Research Agenda
STU	Slovak University of Technology in Bratislava

1 Partners of the project

The ***FreeTwinEV*** consortium is composed of four partners, as shown below.

Slovak University of Technology in Bratislava (STU)

Universiteit Twente (UTWENTE)

Linz Center of Mechatronics GmbH (LCM)

ADDSEN SRO (ADDSEN)

2 Introduction

The Slovak University of Technology (STU) in Bratislava is premier technical university in Slovakia, with a distinguished legacy of over 80 years[1]. Originally rooted in the tradition of the Mining Academy in Banská Štiavnica, STU has developed into a key institution for higher technical education and research in Slovakia. Known for its innovation and contributions to science and engineering, STU has become a significant force in shaping the future of the region, particularly in fields like digital engineering, battery technology, and sustainability. 3 main teams are involved in the FreeTwinEV project - the Institute of Automotive Mechatronics (FEI STU), Institute of Electronics and Photonics (FEI STU) and the Institute of Applied Informatics, Automation and Mechatronics (MTF STU).

The Strategic Research Agenda (SRA) aims to solidify STU's role as a research leader in Central and Eastern Europe, especially in emerging sectors such as advanced battery technology, digital twinning, and sustainable engineering solutions. The agenda aligns with both regional and European priorities, including Slovakia's Research and Innovation Smart Specialization Strategy[2] and the European Union (EU) goals for sustainability and decarbonization[3]. The agenda seeks to enhance research capabilities, foster international collaboration, and leverage on Slovakia's position as a leading car producer per capita in the world, to expand its R&D possibilities and experience.

[1] https://www.stuba.sk/english/university/about-us/profile-and-rankings.html?page_id=8198
[2] https://mirri.gov.sk/wp-content/uploads/2018/10/Research-and-innovation-strategy-for-smart-specialisation-of-the-Slovak-Republic-2021-2027.pdf
[3] https://climate.ec.europa.eu/eu-action/climate-strategies-targets/2050-long-term-strategy_en

This SRA emerges within the framework of multiple strategic initiatives at STU, including the Horizon Europe supported ***FreeTwinEV*** project (no. 101159989)[4]. ***FreeTwinEV*** focuses on advancing digital twin technology for battery management systems, aiming to foster a sustainable and safe Electric Vehicle (EV) industry. With Slovakia's automotive sector at its core, this SRA is positioned to leverage the country's industrial strengths while addressing critical global challenges such as climate change, energy efficiency, and technological innovation.

STU envisions becoming a globally recognized research institution, excelling in technology-driven solutions that address the grand challenges of our time. The mission of STU is to deliver high-quality education and research that contributes to societal progress, economic development, and the creation of sustainable and innovative technologies. This research agenda will support STU in achieving its vision of being a leading research hub, particularly in fields like advanced materials, smart energy solutions, and EV technologies.

The *FreeTwinEV* Strategic Research Agenda focuses on three main pillars:

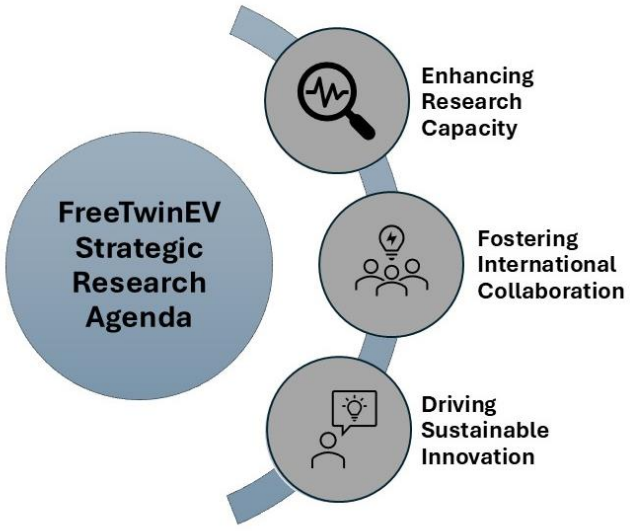


Figure 1: The main pillars of the SRA

- **Enhancing Research Capacity**

[4] https://ec.europa.eu/info/funding-tenders/opportunities/portal/screen/opportunities/projects-details/43108390/101159989/HORIZON?order=DESC&pageNumber=1&pageSize=10&sortBy=title&keywords=FreeTwinEV&isExactMatch=true

Through initiatives like ***FreeTwinEV***, STU aims to strengthen its research infrastructure, focusing on cutting-edge automotive and digital technologies such as digital twin for battery systems and advanced automotive solutions.

- **Fostering International Collaboration**
  Establishing long-term partnerships with institutions such as the University of Twente (The Netherlands)[5], Linz Center of Mechatronics (Austria)[6], and ADDSEN (Slovakia)[7] will help STU to align its research goals with global standards and increase its participation in international research projects.

- **Driving Sustainable Innovation**
  By addressing critical challenges in energy storage and mainly EV applications of batteries, the SRA contributes to the European Green Deal[8] and the transition towards a more sustainable, low-carbon economy.

[5] https://www.utwente.nl/en/
[6] https://www.lcm.at/en/
[7] https://addsen.eu/
[8] https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en

3 Overall Context

STU plays a pivotal role in advancing Slovakia's technical and scientific capabilities, particularly in areas such as digital twinning, battery technology, and sustainable engineering solutions. The motivation behind STU's SRA stems from the growing global emphasis on sustainability, technological innovation, and the transition to a low-carbon economy. This is particularly relevant given Slovakia's positions as the world's largest car producer per capita[9], which aligns the country with the global shift toward EVs and sustainable mobility.

The need for innovation in energy storage, digitalization, and advanced manufacturing processes has become critical. With projects like ***FreeTwinEV***, supported by Horizon Europe, STU is well-positioned to become a centre of excellence in developing strategic research goals like advanced battery management systems through digital twinning technology.

Motivated by EU initiatives, this SRA seeks to align STU's (and those of the partners within the ***FreeTwinEV*** Project) research efforts with broader European objectives of achieving climate neutrality, increasing energy efficiency, and advancing technological innovations in key sectors such as transportation, energy storage, and digitalization.

An outstanding role in this context plays the Strategic Research and Innovation Agenda of the Batteries European Partnership (BATT4EU). Both ***FreeTwinEV*** and BATT4EU focus on the European Union's objectives for sustainability, climate neutrality, and innovation in the battery industry. They explicitly align their agendas

[9] https://www.globsec.org/what-we-do/publications/slovakia-automotive-industry-perspective

with the European Green Deal and Horizon Europe programs and contribute to corresponding Sustainable Development Goals24 (SDG)[10].

Key stakeholders and funding bodies relevant for STU's Strategic Research Agenda include:

3.1 Government Bodies

- *Slovak Government*: A critical supporter of research and innovation, providing funding and aligning national strategies with EU priorities. In Slovakia, funding for battery research is available through national programs and strategic initiatives. These are:
  - *National Research and Innovation Programs* by the Slovak Ministry of Economy and Ministry of Education.
  - *Recovery and Resilience Facility (RRF)* as part of the EU's *NextGenerationEU* recovery package, the RRF funds projects that align with green and digital priorities.
  - *European Regional Development Fund (ERDF)* promotes regional development through innovation and sustainability projects, including battery research and digitalization initiatives in Slovakia.
  - *Slovak Research and Development Agency* (SRDA)- grant provider, providing funding for research and development in Slovakia. SRDA offers financial resources for projects across various scientific and technological fields, including for electric vehicles and digital twin technologies. By future securing of SRDA funding, the ***FreeTwinEV*** project can advance its research objectives in the post project follow-up research activities. Funding is provided in different schemes including international consortia under specific conditions.
  - *Slovak Innovation and Energy Agency (SIEA)* provides funding and technical support for projects related to energy efficiency and innovation. SIEA funds projects in renewable energy and

[10] https://sdgs.un.org/goals

energy storage, and offers subsidies, consultations, and support services for companies and research institutions in Slovakia working on battery and energy-related technologies.
    - *Public-Private Partnerships (PPP)*: International automotive and technology companies with a presence in Slovakia, such as Volkswagen and PSA Group, often collaborate with local research institutions and universities. These partnerships focus on advancing battery research for electric vehicles and other sustainable technologies, providing additional resources and industrial insights.
    - *Smart Specialisation Strategy (RIS3 SK)* supports the development of innovative sectors, including battery technology and energy storage.

- *European Union and Horizon Europe:* Horizon Europe is the EU's largest research funding program, open to Slovakia, which provides substantial funding for sustainable technology and mobility projects. Battery research projects that focus on next-generation battery technologies, enhanced energy storage solutions, and digital twin applications for battery management systems are well-aligned with Horizon Europe's themes. Through the *European Battery Alliance (EBA)*, Slovakia is eligible for funding under the *Important Projects of Common European Interest (IPCEI)* initiative. IPCEI funding supports the creation of a European battery value chain to reduce reliance on non-European battery suppliers. This funding targets both research and industrial scale-up of battery technologies, making it suitable for projects focused on battery innovation, recycling, and sustainable energy storage solutions.

- *National funding agencies* within the European Union: To intensify the research activities also nationally funded projects will be pursued. In the partner countries Austria and the Netherlands, various national and EU funding programs support battery research, focusing on sustainable energy, electric mobility, and innovation in energy storage. In Austria and the Netherlands, the following agencies support projects that promote climate protection and energy

transition, battery research, particularly in energy storage for renewable energy systems and electric mobility

- Climate and Energy Fund (Klima- und Energiefonds, AT)
- Austrian Research Promotion Agency (FFG, AT)
- Austrian Science Fund (FWF, AT)
- Austrian Federal Ministry for Climate Action, Environment, Energy, Mobility, Innovation, and Technology (BMK, AT)
- International Partnerships and IPCEI (AT)
- Topsector Energy (TKI Energie, NL)
- Netherlands Enterprise Agency (RVO, NL)
- Dutch Research Council (NWO, NL)
- MOOI (Mission-driven Research, Development, and Innovation) Subsidy (AT)
- Green Growth Fund (Groene Groei, NL)

3.2 Industry

- *Automotive Sector*: As Slovakia is one of the leading car producers[9], automotive companies are crucial stakeholders. Companies like Volkswagen, PSA Peugeot Citroën, Kia Motors, Volvo, Porsche and Jaguar Land Rover, which have established manufacturing bases in Slovakia, are keen on innovations in battery technology and EVs.

- The electrification of *Mobile Machinery Producers* in Europe is progressing fast as manufacturers are confronted with stricter environmental regulations and rising demand for sustainable solutions. Especially this holds true in urban and indoor areas where mobile machinery is frequently used. Key aspects of the status are the increased regulatory pressure, a general shift to battery-electric power and also the rise of hydrogen and hybrid drive solutions. Overall, European mobile machinery suppliers are making substantial progress toward electrification, though the pace varies by segment and application. Prominent companies working on battery-electric mobile machinery are *Volvo Construction Equipment* (Volvo CE) – Sweden, *JCB* - United Kingdom, *Liebherr Group* – Germany, *Wacker Neuson* – Germany, *Manitou Group* – France, *CNH Industrial* (New Holland and CASE) - Italy/Netherlands, *Kärcher Municipal* – Germany, *Avant Tecno* – Finland, *Hitachi Construction Machinery Europe* (HCME) - Netherlands/Japan, *Doosan Bobcat* - South Korea with European Operations.

• *Battery Manufacturers and Suppliers*: These companies are stakeholders for STU's research in advanced energy storage technologies, providing practical industry applications and partnership opportunities. Examples for EV Battery Producers in Europe are *Northvolt* – Sweden, *ACC* (Automotive Cells Company) - France/Germany/Italy, *Saft* (TotalEnergies) – France, Varta – Germany, ***InoBat Auto* – Slovakia**, *Verkor* – France, *Britishvolt* - United Kingdom, *Basquevolt* - Spain

Relevant Battery Testing System Manufacturers in Europe *are Keysight Technologies* – Germany, *AVL* – Austria, *Digatron* – Germany, *Voltabox* – Germany, *FEV Group* – Germany, *Arbin Instruments* - United Kingdom/Germany, *Greenlight Innovation* – Germany, Bitrode - United Kingdom, *Siemens* – Germany.

3.3 Academic and Research Institutions

- International Academic Partners: Collaboration with institutions such as the University of Twente (The Netherlands) and Linz Center of Mechatronics (Austria) is essential for fostering research excellence and knowledge transfer.

- Slovak Research Community: Local research bodies and universities are integral for advancing Slovakia's position in global research through interdisciplinary collaboration.

- To establish STU amongst the leading research institutions in Europe it is crucial to intensify connections to the leading Institutions in this branch. Some of the most prominent institutes in Europe leading the way in EV battery research are *Fraunhofer Institutes* – Germany, Helmholtz Institute Ulm (HIU) – Germany, *Centre for Solar Energy and Hydrogen Research Baden-Württemberg* (ZSW) – Germany, *CEA-Liten* (French Alternative Energies and Atomic Energy Commission) – France, *The Faraday Institution* - United Kingdom, *IMEC* (Interuniversity Microelectronics Centre) – Belgium, *National Institute*

for Research in Digital Science and Technology (INRIA) – France, *The Netherlands Organisation for Applied Scientific Research* (TNO) – Netherlands, *AIT Austrian Institute of Technology* – Austria, *SINTEF* – Norway, *Politecnico di Milano – Department of Energy* – Italy, *Forschungszentrum Jülich* – Germany, *University of Warwick* - Warwick Manufacturing Group (WMG) - United Kingdom, *Chalmers University of Technology* – Sweden, and *IK4-CIDETEC* – Spain

3.4 Society and Environment

- Environmental Advocacy Groups: As sustainability is a key driver of this SRA, groups promoting environmental health and sustainability are indirect but significant stakeholders.

- General Public: Citizens will benefit from advancements in sustainable technologies, improved mobility solutions, and the overall economic development generated by high-tech innovation.

3.5 EU Objectives

The EU has set ambitious objectives that directly align with the SRA. Key initiatives that form the backbone of STU's strategic focus include:

3.5.1 The European Green Deal

The EU aims to be climate-neutral by 2050[11], and research in sustainable energy storage and EVs is vital to achieving this goal. The European Green Deal outlines the need for sustainable battery production and innovation in key technologies to reduce carbon emissions, promote circular economies, and enhance energy efficiency. STU's work in battery technologies and digital twinning will contribute directly to these goals.

[11] https://climate.ec.europa.eu/eu-action/climate-strategies-targets/2050-long-term-strategy_en

3.5.2 Horizon Europe

As the EU's largest funding framework for research and innovation, Horizon Europe provides key opportunities for STU to secure funding for large-scale collaborative projects in sustainable technologies, such as ***FreeTwinEV***. STU's research aligns with Horizon Europe's emphasis on digital and green transitions, ensuring its research output is in step with the latest EU priorities.

3.5.3 The Strategic Action Plan on Batteries

As Europe seeks to build a competitive battery value chain, initiatives like the European Battery Alliance (EBA)[12] have been pivotal in reducing dependency on non-European battery producers. STU's focus on battery management systems and innovation in energy storage fits well within the EU's broader strategy of achieving battery independence and supporting sustainable mobility.

3.6 European Landscape

The European landscape is shaped by the rapid rise in demand for EVs and the integration of renewable energy sources, both of which rely heavily on advancements in battery technology. The European automotive industry is transitioning from traditional combustion engines to electric-powered vehicles, creating significant demand for research in battery management systems and digital technologies.[13]

In addition to the automotive sector, energy storage solutions are a crucial component of Europe's strategy to increase the penetration of renewable energy. This has driven a surge in demand for innovation in sustainable, high-capacity battery systems that can ensure grid stability and energy efficiency. The REPowerEU Plan[14] and EU's battery regulation initiatives[15] promote the development of batteries that are efficient, safe, and sustainable, further emphasizing the importance of research initiatives like those underway at STU.

The European battery value chain is also undergoing significant transformation, with multiple gigafactories being established across the continent to meet rising demand. However, challenges remain, including the need to reduce reliance on

[12] https://www.eba250.com/

[13] https://www.idos-research.de/uploads/media/DP_29.2014.pdf, https://link.springer.com/article/10.1007/s10663-022-09554-9

[14] https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal/repowereu-affordable-secure-and-sustainable-energy-europe_en

[15] https://environment.ec.europa.eu/topics/waste-and-recycling/batteries_en

foreign raw materials, improve battery affordability, and develop flexible manufacturing systems. These issues provide ample research opportunities for STU in fields such as circular economy, battery sustainability, and next-generation battery chemistries.

3.7 Relevant Trends in Battery Technology and for *FreeTwinEV*

The latest **trends in battery development** are driven by the need for higher energy density, faster charging times, enhanced safety, and improved sustainability. These trends are crucial for advancing electric vehicles (EVs), consumer electronics, and renewable energy storage. General key trends are:

- **Solid-State Batteries:** Solid-state batteries use a solid electrolyte instead of a liquid one, enabling higher energy density, improved safety, and longer lifespan. This technology is a major focus for EVs due to its potential to provide greater range and faster charging.
- **Lithium-Sulfur (Li-S) Batteries** replace the conventional cathode materials with sulfur, offering a much higher theoretical energy density. Although lithium-sulfur batteries face issues with cycle life and degradation, research is addressing these through electrolyte and separator advancements. They are particularly promising for aviation and heavy-duty applications where weight reduction is crucial.
- **Silicon Anodes in Lithium-Ion Batteries** replacing or supplementing graphite with silicon in lithium-ion battery anodes can significantly increase energy capacity, as silicon can store up to 10 times more lithium ions than graphite. Companies like Sila Nanotechnologies and Tesla are researching silicon anodes to extend battery range. Although silicon expands and contracts during charging cycles, advanced binders and nanostructured silicon are helping to address this issue.
- **Fast Charging Technologies** are essential for EV adoption, with a focus on reducing charging times to 10-15 minutes without compromising battery life or safety. Researchers are exploring advanced electrolyte formulations, thermal management, and battery structures to enable ultra-fast charging. StoreDot and Enovix are developing lithium-ion batteries capable of charging within minutes by optimizing ion flow and battery chemistry.
- **Cobalt-Free and Low-Cobalt Cathodes** reducing or eliminating cobalt, which is costly and ethically challenging to source, is a major focus in battery cathode development. Nickel-rich cathodes, manganese-based cathodes, and lithium iron phosphate (LFP) chemistries are being developed as alternatives. Tesla and CATL are leading efforts to integrate cobalt-free and low-cobalt options into their battery production.

- **Battery Recycling and Second-Life Applications** are crucial for sustainability, allowing for the recovery of valuable materials like lithium, cobalt, and nickel. Advanced recycling processes, such as direct recycling and hydrometallurgical methods, are making battery recycling more efficient and economically viable. Companies like Redwood Materials and Li-Cycle are leading in the commercialization of battery recycling.
- **Sodium-Ion Batteries** are emerging as an alternative to lithium-ion for applications that require lower cost and do not need high energy density, such as grid storage. Companies like CATL and Faradion are advancing sodium-ion battery technology, which uses sodium instead of lithium, allowing for potentially lower costs and easier sourcing. However, these batteries typically have lower energy densities than lithium-ion.
- **Battery Management Systems (BMS) and Digital Twin Technology** are enhancing battery performance, safety, and lifespan by allowing real-time monitoring and predictive maintenance. Integrating AI and machine learning in BMS allows for precise monitoring of battery health, improving safety and enabling better performance optimization. Digital twin technology, which creates a virtual replica of the battery, is used for predictive maintenance and simulation testing.
- **Hybrid and Dual-Chemistry Battery Systems** combine different chemistries (e.g., lithium-ion with supercapacitors or lithium-sulfur) to optimize performance for specific use cases. By combining chemistries, these systems offer tailored energy density, power output, and cycle life. Hybrid systems are particularly useful in applications requiring both high power and energy storage, such as EVs and grid storage.
- **Enhanced Safety Features** has become a priority in battery development, especially to mitigate risks of thermal runaway and battery fires. Research is focused on new electrolytes (e.g., non-flammable electrolytes), separators, and battery designs that minimize overheating risks. Solid-state batteries inherently offer greater safety, and liquid electrolyte systems are being improved with additives that reduce flammability.
- **High-Voltage and High-Energy-Density Cathodes** such as nickel-rich cathodes (NMC 811), are being developed to increase the energy density of lithium-ion batteries. These cathodes support higher capacities and longer ranges for EVs, though they require more advanced battery management due to higher degradation rates and thermal sensitivity. The development of stable electrolytes that work with high-voltage cathodes is a parallel area of research.

- **Green and Sustainable Battery Production** Sustainable manufacturing processes that reduce carbon footprint and use recycled materials are gaining traction. Companies are incorporating renewable energy in production, using eco-friendly materials, and developing closed-loop systems that allow for material recovery and reuse. Initiatives by companies like Northvolt focus on producing "green batteries" with lower environmental impact.

For ***FreeTwinEV*** in particular, the following trends are relevant:

- **Novel Approaches for a Sustainable Battery Design**: New Design approaches driven by battery multi-physics simulation models and system models, suitable for further usage in digital twins allow holistic design approaches addressing a better battery integration, better recyclability and repairability etc.

- **Battery Management Systems (BMS) and Digital Twin Technology** for enhancing the accuracy of the physics-based system models. The battery internal states estimation based on real and virtual sensing using modelling and digital twinning is of increasing importance for a long lifetime at a high performance of batteries. Here new estimation methods for internal states of the batteries in a system, based on advanced single-cell methods and their scaling to the system level are arising and will be addressed within ***FreeTwinEV***.

- **Intelligent Distributed Thermal Management** to enable perfect temperature conditions in a wide range of operation is another key for a long battery life at high performance data. ***FreeTwinEV*** will address this key problem by a decentralized, highly flexible cooling system.

4 Partnerships in the Consortium

4.1 Existing Partnerships of STU

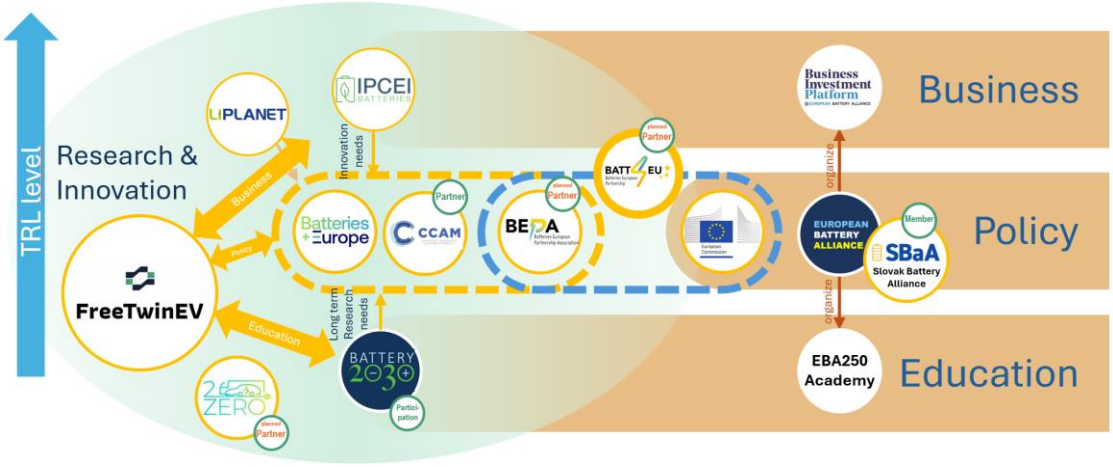


Figure 2: Overview of the entire European battery R&I ecosystem, developed by VDI-VDE-IT, complemented by LCM

Slovak Battery Alliance is a national independent interest association of legal entities and acts as an industrial cluster. It is a powerful platform for collaboration between the public and private sectors, innovators, academia and financial institutions to participate in the battery value chain in Europe.

STU is a member of this organization and several researchers (some included in the ***FreeTwinEV*** project) are part of SbaA's expert committees. As a member of European Battery Alliance, SBaA gives STU indirect connection also to this organization and its information or policies.

The CCAM (Connected Cooperative Automated Mobility) Partnership is a private public partnership, which aligns all stakeholders' R&I efforts to accelerate the implementation of innovative CCAM technologies and services in Europe. It aims to exploit the full systemic benefits of new mobility solutions enabled by CCAM: increased safety, reduced environmental impacts, and inclusiveness. The Partnership is developing and implementing a shared, coherent and long-term R&I agenda by bringing together the complex cross-sectoral value chain actors with

the joint vision: "European leadership in safe and sustainable road transport through automation".

STU is already a partner of this initiative, through its Faculty of Informatics and Information Technologies and their joint collaboration with Faculty of Mechanical Engineering, as a part of their research of autonomous and connected vehicle technologies, roofed under "Automotive Innovation Lab (AIL)".

4.2 Planned Future Partnerships

The Batteries European Partnership Association (BEPA) is the international non-profit making association (AISBL) representing the private side of the BATT4EU Partnership. It gathers the European battery community willing to contribute to the ambitious upcoming Research & Innovation Batteries Partnership under Horizon Europe. U Twente is a member of BEPA and is involved in defining the KPIs for various European calls including advising the European Commission and can provide valuable support to other partners of ***FreeTwinEV*** when joining this partnership.

BATT4EU is a Co-programmed Partnership established under Horizon Europe – the Framework Program for Research and Innovation of the European Union- that aims to achieve a competitive and sustainable European industrial value-chain for e-mobility and stationary applications. It is a contractual public-private Partnership gathering – on the public side – the European Commission; and – on the private side – BEPA, which regroups all the battery stakeholders from the European Research community. U Twente is also a member of BATT4EU and is involved in strategic meetings within the same.

The 2ZERO Partnership sets an ambitious research program to accelerate the development of zero tailpipe emission road transport in Europe via a system approach. It will develop a common vision and deliver a multi-stakeholders

roadmap for a climate-neutral and clean road transport system. This will improve air quality, the mobility safety of people and of goods, hence ensure future European leadership in innovation, production and services. By paving the way to a climate-neutral road transport system, the Partnership will make a key contribution to the success of the European Green Deal.

5 Research Priorities

When planning our research priorities for this project and future project, we based it on our experience and domain knowledge in batteries and battery systems, but also followed the trends and challenges identified by Strategic Research & Innovation Agenda of BATT4EU[16]. The most relevant part of the document for our research consortium and STU research teams is the priorities for application of batteries in the mobility segment. On the figure below, we can see the plans and priorities of 4 identified strategic actions defined for European battery research community, more specifically, those focused on mobility applications.

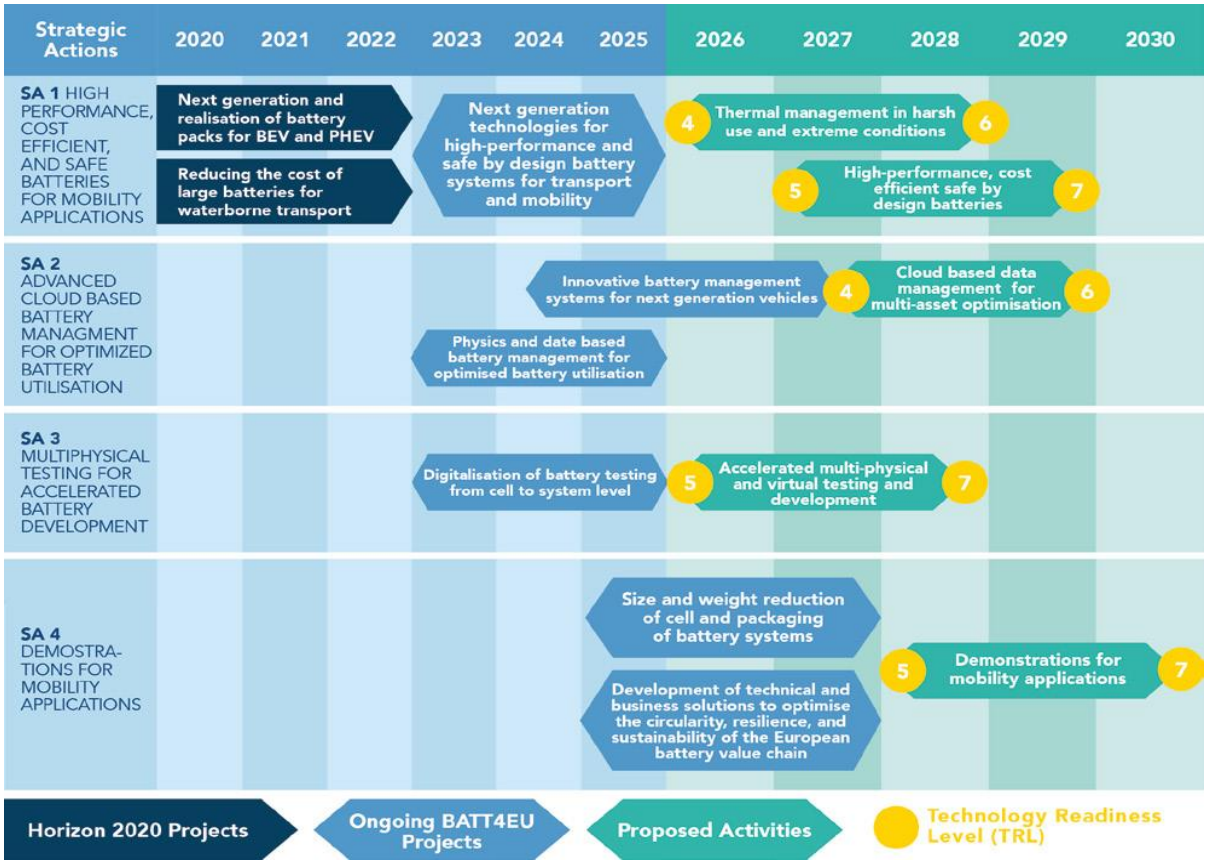


Figure 3: Strategic actions defined for European battery research community

[16] https://bepassociation.eu/our-work/sria/

The SRA of STU identifies several critical themes aligned with European priorities and STU's strengths in battery research and sustainable technologies. These themes include:

- **Advanced Battery Technologies**
  Focusing on safety, efficiency, and lifespan improvements in lithium-ion and post-lithium batteries, including solid-state batteries and next-generation chemistries.

- **Automotive and Stationary Battery Applications**
  Innovating in battery system design, including safety and thermal management systems, in both automotive and stationary applications.

- **Digital Twinning for Battery Management**
  Developing and exploring digital twin technology for enhanced prediction, monitoring, and management of battery states to optimize safety, performance, and lifecycle.

- **Thermal management and advanced cooling systems**
  Focusing on efficient cooling strategy and thermal monitoring, improved lifespan and safety, including improvements for second life of cells and reduction of battery pack maintenance requirements.

- **Fast charging optimisation**
  Development of methods for fast charging of batteries with a minimal impact on the SOH and service life of the battery will be a topic.

- **Size & weight reduction and integration of cells into battery systems**
  Multi-functionality of materials and components, where applicable and depending on the end-user applications, technologies like Cell-to-Chassis (C2C), Cell-to-Vehicle (C2V), Cell-to-Airframe (C2A).

- **Battery systems fire and crash safety**
  Pack design including flame retardant materials to prevent thermal runaway, inflammation, and toxic gas release during crash and handling and recovery of crashed batteries

- **Multiphysics testing for accelerated validation and verification**

Employing virtual multi-physical modelling methods to simulate physical processes of the system during design and development, to optimize and inform design aspects, shortening the development cycle and improving quality.

- **Sustainable Materials and Recycling**
  Researching sustainable materials for energy storage, recycling batteries, and efficient utilization of raw materials, including molten salt processes and supercapacitor development. Additionally, design concepts addressing optimal recycle-capability is in the focus.

- **Contributions to the European Battery Ecosystem**
  One of the key topics of ***FreeTwinEV*** is the development of powerful simulation methods for fast and optimal battery development, based on and further development of a valid and up-to-date Information base and offering these methods to a wider European Battery R&I Community (Batt4EU Partnership).

These and more topics are visualized in the diagram on the figure below.

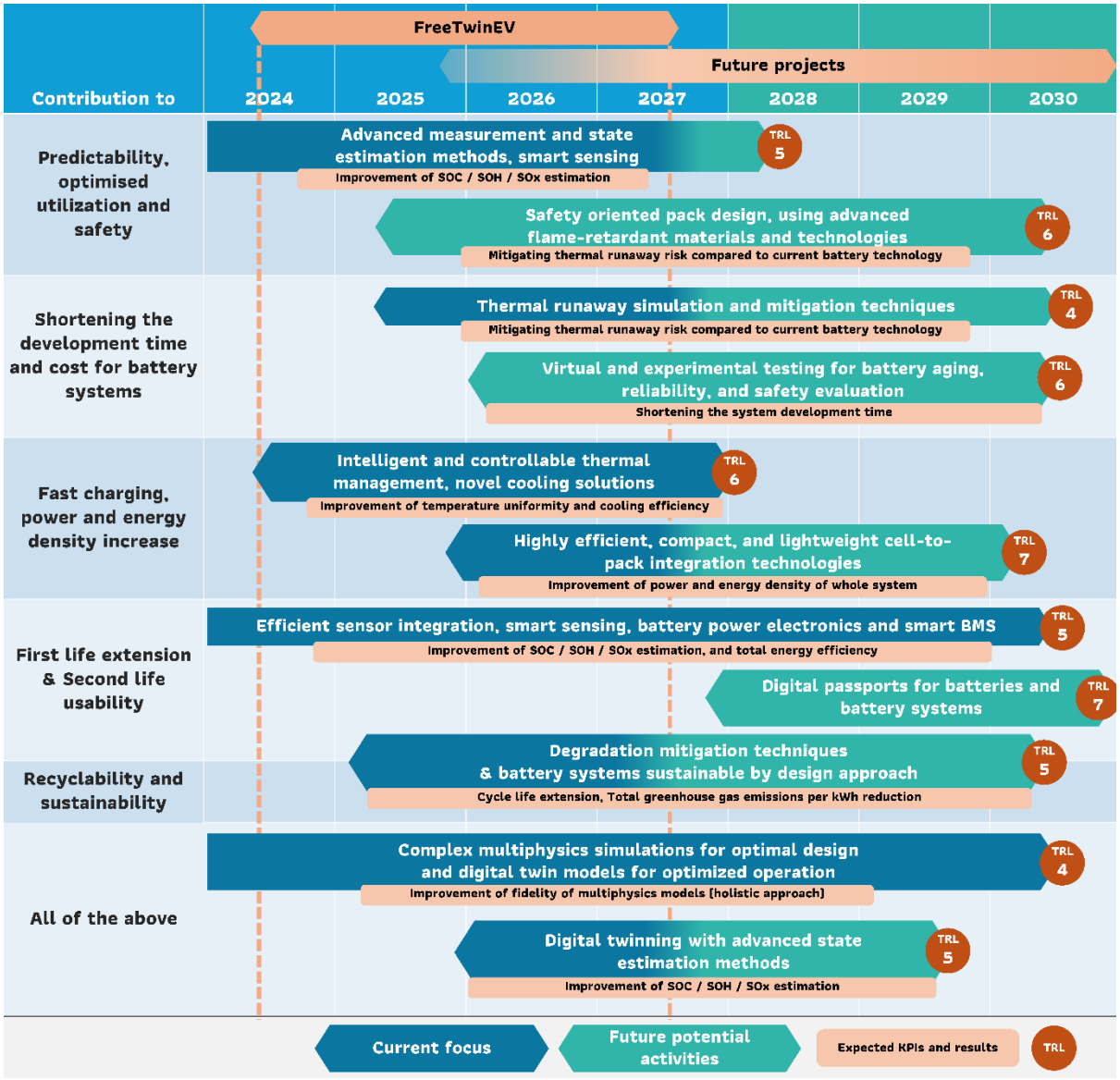


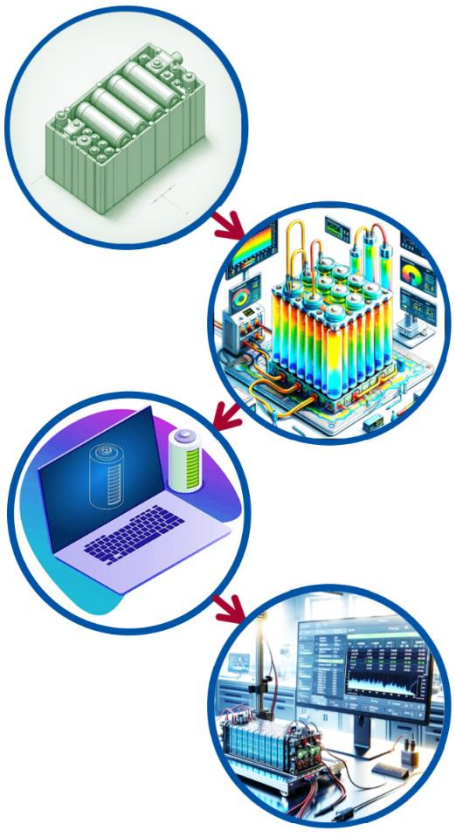
*Figure 4: Ongoing research topics of STU and **FreeTwinEV** and future topics*

The identified themes are driven by the growing demand for energy storage solutions for mobile and stationary applications and the need for sustainable technological advancement. Europe's commitment to achieving carbon neutrality by 2050 and reducing dependency on non-European battery producers necessitate the above addressed research topics and advancements in battery technologies, digital management systems, advanced design and sustainable materials. STU's strategic focus on digital twinning for battery management, safety improvement, advanced monitoring methods and sustainable battery system design directly responds to these needs, aligning with EU objectives and leveraging Slovakia's strengths in the automotive industry.

Long-term strategic cooperation of STU in the research field of battery research among the project partners of ***FreeTwinEV***, and potential future partners will allow participation in international projects, increasing attractiveness for excellent PhD. students, increase the reputation of the coordinator, and create new job positions for national and international researchers. This will lead to a better involvement in strong consortia within the Horizon Europe funding scheme.

The following research questions can be posed to elaborate the relevant topics:

- How can digital twin technology improve the safety and lifespan of battery management systems for automotive applications?
- What new materials and processes can enhance the sustainability and efficiency of next-generation batteries?
- How can the recycling and second-life applications of lithium-ion and post-lithium batteries be optimized for circular economy models?
- What role can advanced simulation and multiphysics analysis play in improving the design and performance of battery systems in harsh operating conditions?



STU's SRA promotes interdisciplinary collaboration across fields such as material science, automotive engineering, digital simulation, and environmental science. For example, the integration of digital twinning with battery research combines expertise in data analytics, Artificial Intelligence (AI), and battery physics, offering insights into real-time battery monitoring and predictive maintenance. Similarly, the collaboration between material scientists, mechatronic and electrotechnical engineers in developing sustainable battery systems is crucial for achieving STU's sustainability goals.

5.1 Methodology and Approach

STU employs a combination of experimental research, multi-physics simulations, and advanced diagnostics (e.g., Electrochemical Impedance Spectroscopy (EIS), Galvanostatic Intermittent Titration Technique (GITT), and acoustics) to study battery performance and degradation. The integration of AI models in battery management and neural networks for state estimation is central to the research approach. This approach is crucial for aligning the SRA with the strategic objectives of STU, including strengthening research capabilities and expanding research excellence. The Linz Center of Mechatronics (LCM) will contribute with modern methods of efficient modelling and digital twinning of cells, batteries, and thermal management capabilities. Additionally, LCM will bring in its optimization tool SyMSpace to enable an optimized battery system for maximizing the innovation potential and also in the future help in satisfying needs of industrial partners during collaborations.

Data from laboratory experiments, real-world battery systems, and simulations will be gathered to enhance digital twin models. This includes thermal data, battery cycle life, and safety metrics, supporting the development of predictive models.

The agenda emphasizes the development of digital twin technology for real-time monitoring and control of battery systems. This involves creating sophisticated models that simulate the behaviour of batteries under various conditions, thus improving reliability and efficiency.

The research adheres to ethical guidelines concerning data privacy, especially in the context of digital twin technologies and data sharing. It also focuses on sustainability, ensuring that all innovations contribute positively to environmental goals.

5.2 Implementation Plan and Expected Outcome

The ***FreeTwinEV*** project, as a backbone of this agenda, is structured over a three-year period (36 months), from 2024 to 2027, with specific milestones for developing digital twins, advancing battery modelling, thermal management and system design. The project's timeline will ensure that the development of the SRA is methodical, with key milestones for approval, stakeholder engagement, and periodic updates based on evolving research needs. STU will involve the following Institutes and advanced laboratories for the described project contributions:

- *Institute of Automotive Mechatronics FEEIT STU:* Focused on battery systems within the field of electromobility, leveraging its previous experience from other areas. Key research areas include the design, modelling, and

simulation of electrical, thermal, multiphysics, and CFD processes in battery cells, modules, and entire systems. Additional efforts are directed toward Battery Management Systems (BMS) and their integration, software and algorithms for state estimation (SOC, SOH, etc.). Most recent focus is on the use of reduced complex models to improve these estimations, through digital twinning.

- *Institute of Electronics and Photonics FEEIT STU*: Focused on research and development of a new battery and supercapacitor technologies and systems, and sensing approaches for monitoring and precise state estimation (SOC, SOH, SOx, etc.). Their work is also focused on development of innovative approaches for battery regeneration and charging, as well as development of mathematical models, algorithms, and AI for system control. Additionally, the work include research in the field of estimation, prediction and mitigation of safety risks and thermal runaway in battery systems. Future efforts aim to optimize materials for higher energy density and adapt sensing and control methods to new technologies, such as silicon-graphite anode batteries, solid-state batteries, and large-scale battery-supercapacitor systems, to enable real-world applications.
- *Institute of Applied Informatics, Automation, and Mechatronics FMST STU*: Focused on applying numerical methods and simulations to study advanced technological processes like welding, forming, heat treatment, and casting. Key areas include temperature, fluid dynamics, structural integrity, and coupled field analyses. Special emphasis is on electric and induction heating, high-energy heat sources, nucleation processes, and rapid solidification of metallic melts. The integration of mechatronics and hybrid processes, combining techniques like machining or welding with ultrasound and lasers, is also explored to enhance product quality and efficiency.

Other relevant identified institutes for future collaborations:

- *Institute of Process Engineering FME STU*: Focused on the acquisition and mechanical processing of active materials for energy storage from a material and process point of view. The main operations are extraction of raw materials from molten salts, grinding of raw materials, agglomeration, modification of mechanical and surface properties of powdered energy carriers for their use in the battery industry, and recycling of electrode material.
- *Central Laboratories FCHFT STU*: Focused on early-stage development in advanced measurement techniques, particularly solid-state NMR

spectroscopy. This technology, widely utilized in battery research, is supported by the institute's efforts to enhance NMR spectrometer capabilities for solid-state applications.

Further investment is planned for expanding digital infrastructure and upgrading experimental facilities.

Collaborations with international partners are central to the agenda. Industry partnerships with automotive manufacturers will ensure that research outputs are aligned with current and future market needs, translating them into relevant research topics, and ensuring that the research outcomes of STU and its partners are aligned with market demand. In this regard, additional roundtable discussions and workshops will facilitate engagement with industry leaders and corresponding authorities, while membership in European platforms like AVERE[17] will help increase STU's visibility and networking opportunities within the European research community. Potential risks include delays in funding, technological challenges in scaling digital twin solutions, and market shifts in battery demand. These will be managed through regular project reviews, flexible planning, and stakeholder engagement.

The expected outcomes of the EU-funded ***FreeTwinEV*** project focus on enhancing research and development in sustainable e-mobility and battery technology. These include:

- *Enhanced Research Excellence and Capacity*: The project aims to establish Slovak University of Technology (STU) as a key research center for battery management and electric vehicle (EV) systems in Central and Eastern Europe.
- *Strengthening Research Infrastructure and Management*: ***FreeTwinEV*** will upgrade STU's project management office, improving administrative capabilities to handle large-scale, EU-funded projects. This includes training at least six staff members in research management, creating an administration handbook, and setting up collaboration agreements with industry partners.
- *Environmental Impact through Innovation in Battery Lifecycle Management*: By extending battery life up to 20%, the project estimates a high potential for CO2 reduction across Europe. Improvements in battery temperature control and lifecycle management are expected to optimize battery durability and

[17] https://www.avere.org/

reduce environmental impact, contributing significantly to EU Green Deal goals.

- *Promotion of Knowledge and Skill Transfer*: Through joint research papers, training programs, and exchange activities, ***FreeTwinEV*** plans to foster international collaborations, including with the University of Twente and Linz Center of Mechatronics. The project anticipates training at least 15 researchers and students, producing joint research outputs, and increasing participation in high-impact scientific communities.
- *Economic and Technological Advancements*: This project is expected to benefit Slovakia's automotive sector by advancing battery research and providing industry-ready graduates. Collaborations with local industries aim to enhance innovation, with impacts extending to job creation and industrial transformation towards higher value-added production in the automotive sector.

These outcomes align with the EU's goals for research excellence, environmental sustainability, and technological innovation, positioning ***FreeTwinEV*** as a driver of both local and international progress in e-mobility and sustainable energy storage.

5.3 Round Tables

The round table events aim in fostering collaboration and developing content for partnership agreements between local businesses and Research & Technology Organizations (RTOs). This concept is designed to align with a summer school program, bringing together academic experts, industry partners, and RTOs in a collaborative, interactive setting.

5.4 Impact Assessment and Key Performance Indicators (KPIs)

The success of the ***FreeTwinEV*** and this SRA will be measured through its contribution to sustainable energy storage solutions, improvements in battery safety, and advancements in digital twin technology for battery management systems.

The following Key Performance Indicators (KPIs) will track the progress of professional training programs, the effectiveness of new research collaborations, and the overall impact of the SRA on STU's research output:

- Number of research publications in high-impact journals
- Increase in the lifespan and safety of battery systems through digital twin applications

- Partnerships with at least three international research institutions and two industry leaders

Expected outcomes, results and KPIs, specifically provided in Figure 4, include new digital twin models for battery management, improvement of model fidelity for multiphysics simulations and advanced state estimation methods. Key deliverables will be prototypes of digital twin-supported battery systems and comprehensive reports on the impact on battery sustainability. Research findings will be shared through conferences, peer-reviewed journals, and workshops with industry stakeholders. Public engagement activities will also be conducted to raise awareness about the environmental benefits of advanced battery technologies. Participation in these formats will facilitate the sharing of findings from STU's research projects, as well as opportunities to influence European research priorities. This strategy will ensure that the outcomes of the SRA and the associated training programs are effectively communicated to both industry stakeholders and the broader research community.

5.5 Funding and Sustainability

Key funding sources include Horizon Europe grants, Slovak government research programs, and private sector contributions from automotive and battery manufacturing partners. To emphasize the importance of securing funding for international research projects, particularly under Horizon Europe, the training will focus on equipping STU's researchers with the skills needed to prepare competitive proposals. Additionally, to ensure the sustainability of networking efforts, opportunities to co-fund membership fees for European platforms through national resources such as the Recovery and Resilience Facility (RRF) and European Regional Development Fund (ERDF) need to be explored.

The budget will be allocated across core research activities, infrastructure upgrades, and collaborative projects. A portion will be reserved for the dissemination of findings and public outreach.

To ensure long-term impact, the project and this agenda focuses on building robust industry partnerships and fostering a pipeline of skilled researchers in battery technologies. STU aims to sustain its research activities beyond the initial project period through strong partnerships. The SRA will provide a roadmap for continuous engagement with stakeholders, ensuring that research efforts remain appropriate and well-funded. Additionally, the emphasis on life cycle extension,

better predictability and second-life battery applications ensures alignment with circular economy principles.

5.6 Review and Adaptation Process

The SRA will undergo regular reviews to incorporate new scientific findings, technological advances, and shifts in industry needs. This will ensure that the agenda remains relevant and impactful. The agenda will be updated based on feedback from industry stakeholders and research trends, allowing it to adapt to emerging opportunities and challenges. This ensures that the SRA remains a living document that evolves alongside the university's research capabilities.

STU will establish feedback mechanisms involving both internal and external stakeholders, allowing for iterative improvements in research focus and implementation strategies. The feedback loops will ensure that the SRA is responsive to stakeholder needs, enabling STU to align its research priorities with the demands of the market and policy environment. An evaluation framework will be developed to assess the success of research outputs against defined KPIs and objectives.

6 Conclusion and Outlook

The ***FreeTwinEV*** Strategic Research Agenda (SRA) marks a pivotal step forward in advancing battery technologies and their digital twin applications, aligning closely with European sustainability and innovation goals. By leveraging Slovakia's strong automotive industry and fostering international collaborations, this agenda positions the Slovak University of Technology (STU) as a central player in the development of next-generation energy solutions. Key expected achievements include strengthening research infrastructure, enhancing international partnerships, and promoting sustainable innovations in battery systems.

The research priorities, ranging from advanced battery materials to digital twin technologies, reflect a holistic approach to addressing critical challenges such as energy efficiency, battery safety, and circular economy integration. The SRA's emphasis on digital twin technology for battery development and management offers aims to enhance battery performance, safety, and lifespan, contributing to the European Green Deal's decarbonization objectives and paves the way to a strong international partnership with industry, European authorities and academia.

Outlook

Looking ahead, the ***FreeTwinEV*** initiative is poised to make significant contributions to both regional and European advancements in sustainable mobility. The focus for the next three years emphasizes continuous adaptation through stakeholder feedback, ensuring responsiveness to evolving technological trends and market needs. Future efforts will focus on:

- *Expanding International Collaborations*: Strengthening partnerships with leading European research institutions and industry stakeholders.
- *Innovative Research Initiatives*: Exploring emerging areas such as solid-state batteries, digital battery passports and second-life usage, and AI-driven battery management systems.
- *Industry Integration*: Translating research outputs into practical applications, enhancing Slovakia's competitiveness in the global EV market.
- *Sustainability and Impact*: Aligning with circular economy principles and EU climate goals, thereby contributing to a greener, more sustainable future.

The SRA's dynamic and adaptive framework will ensure that STU remains at the forefront of battery research, fostering innovation, economic growth, and environmental stewardship for years to come.