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FreeTwinEV

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This updated Strategic Research Agenda, based on the Strategic Research Agenda 1 (delivered in November 2024), has been developed through the collective efforts of the ***FreeTwinEV*** project partners, whose contributions have been invaluable. The Slovak University of Technology (STU) in Bratislava works closely together with the University of Twente, Linz Center of Mechatronics, and ADDSEN, to develop this agenda.

FreeTwinEV is a European Union funded project that received funding from the European Union's Horizon Europe Research and Innovation Program under the Grant Agreement no. 101159989. This funding has been essential in supporting our work in battery management systems, digital twinning, and fostering international cooperation.

We also acknowledge the contributions of the advisory members for their valuable discussions and inputs and 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, aligned with the EU's sustainability objectives. It has been developed through the collective efforts of the FreeTwinEV project partners namely Slovak University of Technology (STU), 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. Besides a strong focus on fostering strong international partnerships for STU the agenda also prioritises creating digital twin models for real-time battery management, improving efficiency and sustainability. In contrast to material- or chemistry-driven battery research, STU's strategic focus lies in system-level electro-thermal modelling, digital twin deployment, and pre-industrial validation across multiple TRL levels. 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
FEI STU	Institute of Automotive Mechatronics at STU
MTF STU	Institute of Applied Informatics, Automation and Mechatronics at STU

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 the 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. Within the FreeTwinEV project, three main teams are involved - 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).

In November 2024 the first Strategic Research Agenda (SRA) was delivered as project deliverable D2.1. The updated Strategic Research Agenda (SRA 2) 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 updated Strategic Research Agenda builds upon the original SRA, while reflecting the rapidly evolving European and global context of battery research and industrial competitiveness. It also aligns with the Draghi Report, which acknowledges Europe's competitive weaknesses in future-oriented industries, including e-mobility, and calls for systemic reforms — stronger innovation coordination, active industrial policy, and investment — to reverse this trend. These conclusions are further reinforced by recent European strategic initiatives for the battery sector, including very recent "A Battery Deal for Europe" and the Considerations for the European Battery Strategic Research and Innovation Agenda, which explicitly highlight the need to strengthen Europe's technological capabilities, accelerate innovation-to-industry pathways, and reduce risks associated with industrial scale-up. The implications from these documents are clear: to close gaps with China and the United States, Europe must more effectively build competitiveness in EV technologies, battery value chains, and associated clean tech sectors. Similarly, the latest BATTERY 2030+ R&I Roadmap[4] emphasizes the importance of advanced modelling, digitalization, data-driven methods, and system-level approaches as key enablers for next-generation battery development. In this context, research activities that accelerate learning, reduce development risks, and support industrial ramp-up become increasingly critical. FreeTwinEV contributes to close this gap by strengthening STU's and its partners capabilities in EV-battery development.

This SRA emerges within the framework of multiple strategic initiatives at STU, including the Horizon Europe supported ***FreeTwinEV*** project (no. 101159989)[5]. ***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

[4] Deliverable-2.2_Roadmap_4th-edition_final_-2025.10.31.pdf

[5] 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

innovative technologies. Within the battery domain, this vision translates into a focus on research areas where universities can provide high added value to industry, such as advanced modelling, diagnostics, system integration, and pre-industrial validation. 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:

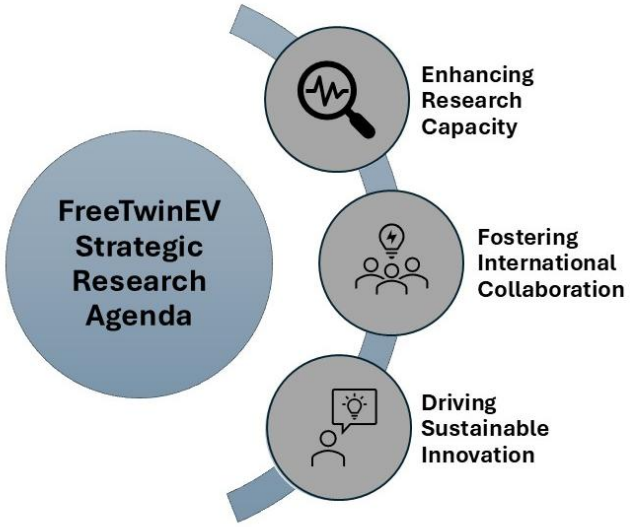


Figure 1: The main pillars of the SRA

- **Enhancing Research Capacity**
  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)[6], Linz Center of Mechatronics (Austria)[7], and ADDSEN (Slovakia)[8] will help STU to align its research goals with global standards and increase its participation in international research projects.

[6] https://www.utwente.nl/en/
[7] https://www.lcm.at/en/
[8] https://addsen.eu/

- **Driving Sustainable Innovation**
  By addressing critical challenges in energy storage and mainly EV applications of batteries, the SRA contributes to the European Green Deal[9] and the transition towards a more sustainable, low-carbon economy.

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 Strategic Research Agenda is rooted not only in long-term institutional ambitions, but also in the rapidly changing European and global context of industrial competitiveness, sustainability, and technological transformation. This is particularly relevant given Slovakia's positions as the world's largest car producer per capita[10], 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 as Europe faces increasing pressure to strengthen its technological sovereignty, reduce dependencies in strategic value chains, and accelerate industrial learning and deployment. With projects like ***FreeTwinEV***, supported by Horizon Europe, STU is well-positioned to contribute to these challenges by focusing on high–added-value research domains, such as battery management systems, electro-thermal modelling, and virtual testing enabled through digital twin technologies.

[9] https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en
[10] https://www.globsec.org/what-we-do/publications/slovakia-automotive-industry-perspective

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.

A central reference framework in this context is 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 with the European Green Deal and Horizon Europe programs and contribute to corresponding Sustainable Development Goals24 (SDG)[11]. In this way, the FreeTwinEV SRA is positioned as a complementary and implementation-oriented contribution to the broader European battery research and innovation ecosystem.

3.1 Key stakeholders and funding bodies

The successful implementation of this Strategic Research Agenda relies on a broad ecosystem of stakeholders, spanning public authorities, industry, research institutions, education providers, and society, whose coordinated engagement enables sustainable research development and long-term impact.

3.1.1 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.
  - *European Regional Development Fund (ERDF)* promotes regional development through innovation and sustainability

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

projects, including battery research and digitalization initiatives in Slovakia.

- *Slovak Research and Development Agency* (SRDA)- grant provider, 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 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.

- <u>*European Union–level research and innovation frameworks*</u>:
  At the European level, research and innovation activities relevant to this Strategic Research Agenda are supported through Horizon Europe - large-scale, multiannual funding frameworks focused on sustainability, industrial competitiveness, and the green and digital transition. These frameworks place strong emphasis on energy storage, electromobility, digitalisation, and the resilience of strategic value chains. In the battery domain, European initiatives aim to strengthen technological sovereignty by supporting coordinated research, pre-industrial validation, and industrial scale-up across the

battery value chain, including recycling and sustainable energy storage solutions.
Within this context, collaborative European mechanisms have been established to reduce Europe's dependence on non-European battery suppliers and to support the development of an integrated European battery ecosystem, spanning research, manufacturing, and end-of-life management. These mechanisms provide an important reference framework for research agendas focused on battery innovation, circularity, and system integration..

- *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)

3.1.2 Industry

- *Automotive Sector*: As Slovakia is one of the leading car producers[10], 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 increasingly engaged in innovations related to electrification, battery technologies, and electric vehicles (EVs).
As a recent example of Industry-Academy collaboration, Kia Slovakia launched an educational and research-oriented initiative within which it provided 12 new EV4 electric vehicles to Slovak universities and secondary vocational schools. The objective of this initiative is to support practical technical education and applied research in electromobility, which is increasingly critical for the future of transport. The vehicles serve as experimental platforms for research in diagnostics, autonomous driving, high-voltage systems, and battery systems. The initiative involves three major technical universities in Slovakia — the University of Žilina, the Technical University of Košice, and the Slovak University of Technology in Bratislava — and additionally includes four secondary vocational schools located in Kysucké Nové Mesto, Žilina, Prešov, and Trebišov.

- EV-System suppliers: In Slovakia, several companies are active in the electric vehicle (EV) system supply, services, and diagnostics. Here are some notable ones:

  ZSE Drive - A leading provider of charging solutions, ZSE offers a network of charging stations and related services.

  GreenWay - This company focuses on electric mobility and provides comprehensive charging solutions across Central and Eastern Europe, including Slovakia.

  Slovenská Elektrizačná Prenosová Sústava (SEPS) - While primarily focused on electricity transmission, they play a role in integrating EVs into the grid.

  E.ON - This global energy company also operates in Slovakia, offering EV charging solutions and services.

  In addition to the just listed, predominant companies, there is a vast number of other local automotive industry suppliers which provide OEMs with components and systems for EVs, including battery technology and management systems.

- 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 *ACC* (Automotive Cells Company) - France/Germany/Italy, *Saft* (TotalEnergies) – France, Varta – Germany, ***InoBat Auto* – Slovakia**, *Verkor* – France, *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.

  - **Latest development of battery manufacturers situation:**

  Europe's battery manufacturing sector is under significant pressure (see changes in Battery Cell production in Europe from 2024 to 2025 in Figure 2). Several high-profile initiatives have faced serious challenges, and others continue to operate under constrained market and financial conditions. Recent developments highlight the difficulty of scaling battery cell manufacturing in Europe without sustained industrial experience, stable market conditions, and long-term policy support. Notable examples are Northvolt, which has already gone bankrupt, Britishvolt was liquidated, and companies such as ACC, Saft, Verkor, and InoBat Auto face serious financial strain and uncertain long-term viability without external support or improved market conditions. Only a few players like Varta appear relatively stable, while others (InoBat, Basquevolt) remain niche, early-stage, or unclear in outlook. Overall, the most successful battery factories in Europe today are those backed by Chinese (CATL) or Korean (LG) companies rather than purely European initiatives.

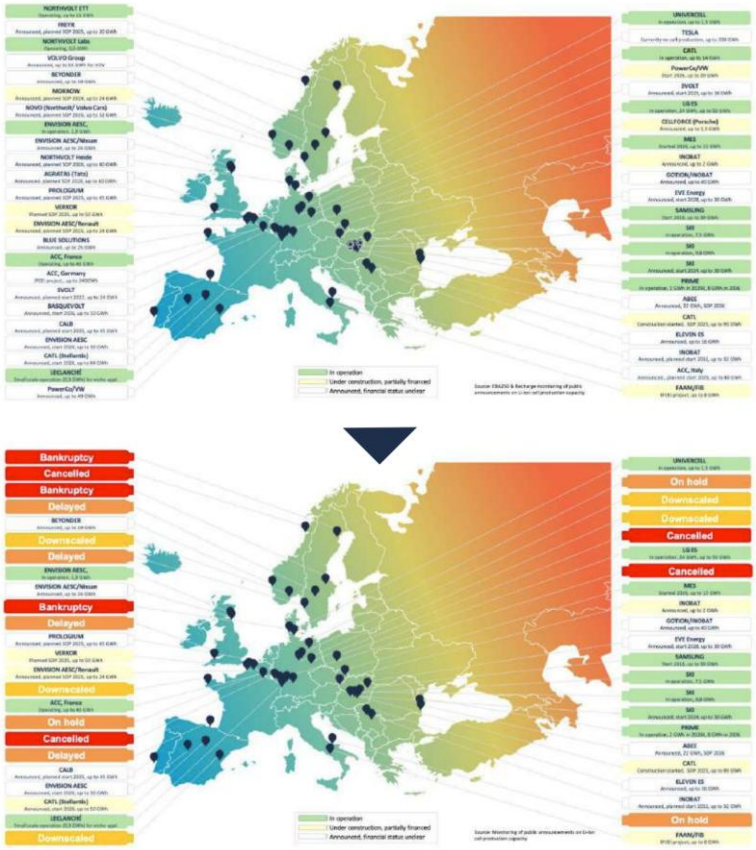


Figure 2: Overview of Changes in Announced Battery Cell Production Capacity (2024 vs. 2025). https://batterydeal.eu/wp-content/uploads/2025/10/A-Battery-Deal-for-Europe-document-1.pdf

3.1.3 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

Conclusion:
Across Europe, research institutions are not retreating from batteries but broadening and strengthening their focus. Many have expanded from a narrow Li-ion or materials perspective toward the full battery value chain, including manufacturing, systems, recycling, lifecycle analysis, and digitalisation, while others reinforce industrialisation and applied R&D. At the same time, several institutes are diversifying technologically, emphasizing post-Li chemistries, solid-state batteries, AI-driven discovery, and links to hydrogen or e-mobility, with only a few (e.g. INRIA) keeping batteries as a secondary application area.

3.1.4 Education, 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. Their activities help shape public awareness, societal acceptance, and long-term policy priorities related to clean mobility, energy storage, and low-carbon technologies.

- General Public:
  Citizens will benefit from advancements in sustainable technologies, improved mobility solutions, and the overall economic development generated by high-tech innovation. In the long term, research activities in battery systems, electrification, and digital technologies contribute to improved air quality, energy efficiency, and quality of life, particularly in urban environments.

- Education Institutions:
  Educational institutions play a crucial role in the long-term development of competencies and human capital required for battery research, electromobility, and related digital technologies. In addition to higher education, primary and especially secondary schools are highly relevant stakeholders, as they represent the stage at which future researchers, engineers, and developers begin to form their technical interests and skills.
  STU actively engages with secondary schools through outreach activities such as on-site visits, technical seminars, lectures, competitions, and hands-on demonstrations promoting engineering, energy technologies, and sustainable mobility.
  A concrete example of this engagement is STU's involvement in the Greenpower initiative, which supports student teams working on electric vehicle projects and provides early exposure to electromobility concepts, teamwork, and applied engineering.
  Further outreach activities are being developed, including competitions focused on hydrogen-powered model vehicles and emerging collaborations with secondary schools linked to international student engineering challenges, such as Shell Eco-marathon.
  Through these activities, STU contributes to building a sustainable education-to-research pipeline, supporting the long-term availability of skilled professionals for battery research, innovation, and the broader energy transition.

3.2 EU Objectives

The EU has set ambitious objectives that directly align with the SRA. These objectives are shaped by recent policy evaluations, emerging geopolitical pressures, and evolving industrial realities within the European battery and automotive sectors. Key initiatives that form the backbone of STU's strategic focus include recent developments within the European battery and clean mobility policy landscape.

On 24 May 2024, at the 8th High-Level Meeting of the European Battery Alliance, the European Commission and key stakeholders **reviewed the implementation of the 2018 Battery Action Plan and discussed the need to shape a renewed strategic approach in response to geopolitical shifts**, including increased competition from

China and the United States, changes in global EV demand, and growing concerns related to critical raw materials and supply-chain resilience. While the title "**Strategic Action Plan on Batteries**" remains formally unchanged, several new policy frameworks and instruments have significantly shifted the focus and implementation mechanisms of EU battery-related strategies.

In particular, the European Defence Fund (EDF) heavily promotes dual-use technologies (civilian & military) and advanced battery systems as crucial for European security, integrating them into strategies like the Defence Readiness Roadmap 2030 and the EUDIS (EU Defence Innovation Scheme) to boost innovation, reduce reliance on external suppliers, and foster "dual-use by design," with specific funding for energy storage (like the NOMAD project) and innovation in critical defence tech through initiatives like the EIC Accelerator and the STEP Scale-up Scheme, aiming for greater tech autonomy. The EU sees dual-use tech (AI, quantum, sensors, etc.) as central to future defence, shifting from separate civil/military tech to integrated "omni-use" thinking. Within this context, **energy storage** is recognised as a **strategically important capability**, supporting both civilian resilience and military mobility, logistics, and energy independence.

In response to these policy shifts, STU's research strategy prioritises methods that reduce development risks, shorten industrial learning cycles, and support system-level optimisation, particularly through digital twins, virtual testing, and data-driven battery diagnostics.

3.2.1 The European Green Deal

The EU aims to be climate-neutral by 2050[12], 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.

The battery topic is now embedded in the broader EU Battery Strategy / EU Green Deal industrial policy, focusing on sovereignty, de-risking from China, and industrial competitiveness (https://www.sciencespo.fr/psia/chair-sustainable-development/2025/05/26/eu-battery-strategy/).

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

In December 2025 the European Commission unveiled a plan to drop the EU's effective ban on new combustion-engine cars from 2035 after pressure from the region's auto sector, marking the bloc's biggest retreat from its green policies in recent years. This would allow continued sales of non-electric vehicles.

For the FreeTwinEV project, this shift has only **minor relevance**, because it represents only a limited adjustment in the overall policy direction:

- a slight shift in the role of internal combustion engine (ICE) vehicles, as the EU still maintains a 90 % CO_2 emission reduction target for new cars by 2035, which will result in a continued strong demand for EVs in the future,
- therefore, the European Commission is not reducing its overall support for electric mobility,
- the draft automotive action plan (2025) includes measures to boost EV demand, increase European content in batteries, and give financial support to battery production & recycling,
- this approach ties the battery strategy more closely to the short-term industrial resilience and competitiveness of European car manufacturers, particularly in response to recent turbulence in the European battery sector (e.g. Northvolt, Britishvolt, ACC) (https://www.reuters.com/business/autos-transportation/eu-propose-push-boost-ev-demand-require-more-local-batteries-2025-02-28/)

A strong impact is seen from the **Critical Raw Materials Act (2023)** which

- targets by 2030, at least 10 % mining, 40 % processing, 25 % recycling of critical raw materials – including battery metals – inside the EU https://www.reuters.com/world/europe/eu-announces-list-47-strategic-metals-projects-2025-03-25/?utm_source=chatgpt.com ,
- lists of strategic raw materials projects (mining, processing, recycling) in and outside the EU strongly reshape how the Action Plan's "secure raw materials" pillar is implemented.

Overall: the strategic direction (build an EU battery ecosystem) is unchanged, but implementation has shifted from "grow fast and catch up" to **"grow sustainably, secure raw materials, and rescue competitiveness"**.

3.2.2 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.

3.2.3 The Strategic Action Plan on Batteries

As Europe seeks to build a competitive battery value chain, initiatives like the European Battery Alliance (EBA)[13] 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.

3.3 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.[14]

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[15] and EU's battery regulation initiatives[16] 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

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

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

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

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

foreign raw materials, improve battery affordability, and develop flexible manufacturing systems. Within this evolving landscape, STU positions itself primarily at the interface between research and pre-industrial application, addressing gaps between cell-level understanding and system-level deployment. These issues provide ample research opportunities for STU in fields such as circular economy, battery sustainability, and next-generation battery chemistries.

3.4 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. Since publishing the SRA 1 the focus of these trends has shifted from breakthrough chemistries toward scalability, cost, safety, regulation, and system integration, under strong pressure from Asian incumbents and tighter market conditions. 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. OEMs currently focusing on manufacturability, cost, and interface stability rather than pure energy-density claims.
- **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. In the last year Lithium–sulfur has lost momentum for near-term EVs and is increasingly seen as niche, mainly for aviation, defense, or long-range specialty applications, due to unresolved cycle-life and scalability issues.
- **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. The industry converged on partial silicon integration (5–15%), now entering series production.

- **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. Economics remain challenging because second-life EV batteries are progressing slower than expected because of logistics and standardization issues.
- **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.

  In the past Sodium-ion transitioned from “emerging” to early commercialization, mainly for stationary storage and entry-level EVs. Energy density improvements are modest, confirming sodium-ion as a complement, not a lithium replacement.
- **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

STU's activities in battery research and innovation are embedded within a broad European ecosystem that spans research and innovation frameworks, industrial stakeholders, policy instruments, and education initiatives. Figure 3 provides an overview of this ecosystem and illustrates how existing partnerships of STU are positioned across different TRL levels and domains, highlighting the interconnections between research, business, policy, and education that jointly support the development and deployment of battery technologies. Some of the notable partnerships and organizations are described below.

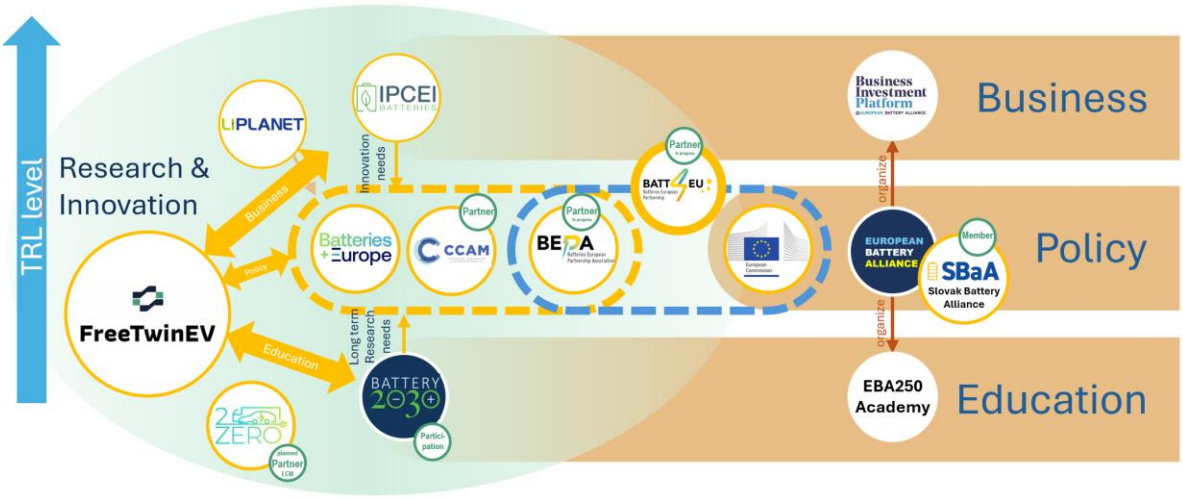


Figure 3: Overview of the entire European battery R&I ecosystem, developed by VDI-VDE-IT, complemented by LCM

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.

Following the selection procedure as described in D2.3, BEPA was chosen as the primary platform for STU to join, mainly due to its extensive and diverse network and the close alignment of its focus with FreeTwinEV objectives. The application process, as described below, is set out in the Rector's Directive *"Rules for the Entry of the Slovak University of Technology in Bratislava into Other Legal Entities."*[17]. STU is **currently in the first phase** of the procedure:

- ***Review at the Faculty Level*** *– the proposal must first be discussed and approved within the faculty.*
- ***Submission of the Proposal to CEPSIT STU*** *– after the faculty-level review, the Deans submit the proposal with all required elements to CEPSIT STU (Centre of European Projects, Cooperation with Practice, Innovations and Technology Transfer STU).*
- ***Review and Assessment*** *– CEPSIT STU checks the completeness of the proposal and forwards it to the Legal and Economic Departments of the Rectorate for legal and financial assessment.*
- ***Completion and Preparation of Documents*** *– once all comments are addressed, the documents are prepared for discussion at the university level.*

[17] Rules for the Entry of the Slovak University of Technology in Bratislava into Other Legal Entities

- ***Approval Process*** *– the proposal must be approved by the STU Leadership, followed by the Rector's Collegium, the relevant STU governing bodies, and the STU Administrative Board.*
- ***Implementation*** *– after all approvals are obtained, the faculty or STU unit completes all necessary steps to establish or enter the legal entity.*

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. FreeTwinEV partner Linz Center of Mechatronics (LCM) is planning to become a partner with the 2ZERO in future.

4.3 Events relevant to FreeTwinEV

Battery technologies are gaining importance across Europe. This is reflected in the density of events that span nearly all European industrialized countries. In the fourth quarter of 2025 alone, industry players and trade audiences can visit around half a dozen high-profile events. The partners in the FreeTwinEV will attend the most relevant events such as the Automotive Battery Tech in Munich in March 2026, the Battery Innovation Days 2026 in Stockholm or the Battery Show Europe 2026 in Stuttgart Germany in order to widen its network and present the results of the project. The picture in **Error! Reference source not found.** provides an overview of planned trade fairs, conferences, and similar events on battery topics in Europe for 2025/2026.

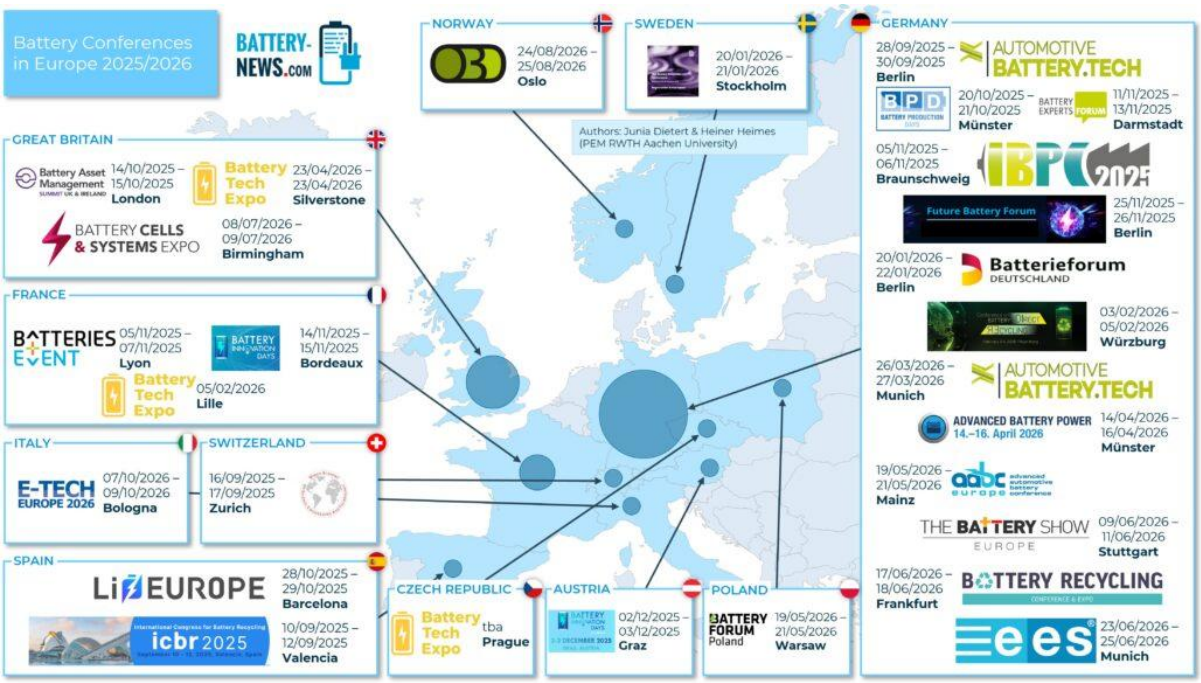


Figure 4: Relevant Events for FreeTwinEV in 2025/2026

5 Research Priorities

When planning our research priorities for this project and future projects, 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[18]. 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.

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

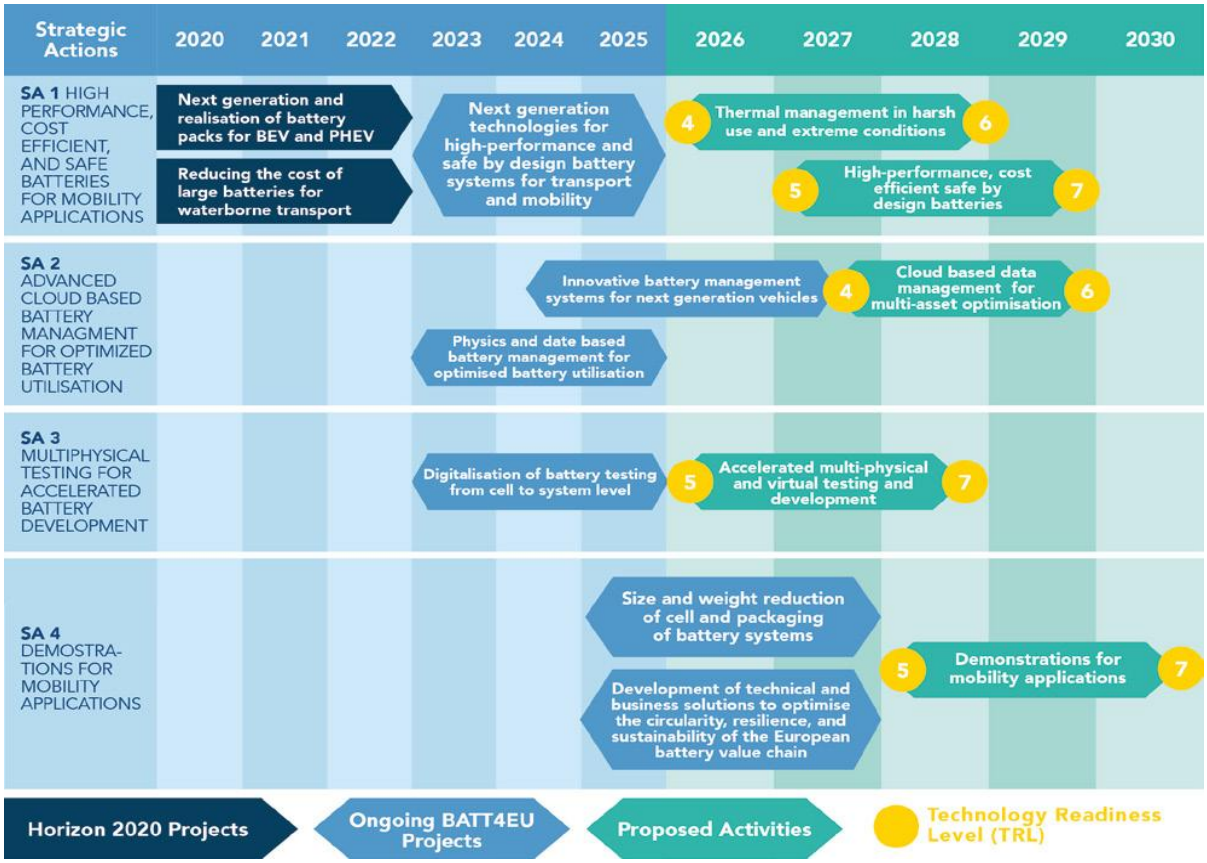


Figure 5: Strategic actions (SA) defined for European battery research community

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. While the time-horizon of the different topics is indicated by the textbox's background colour, dashed lines surrounding a textbox indicates focus topics within FreeTwinEV while boxes without a dashed frame contain topics that are generally focused by STU.

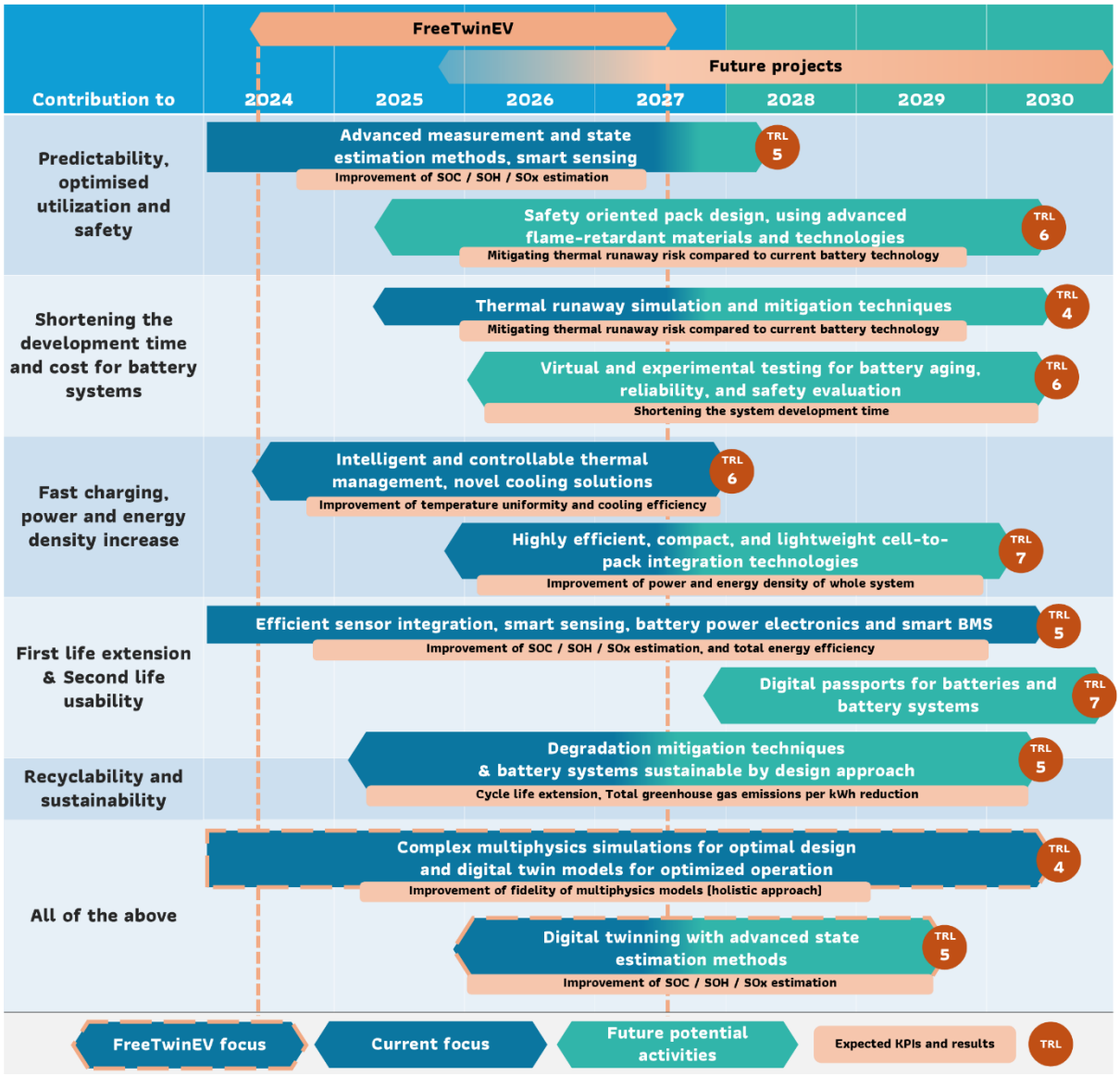
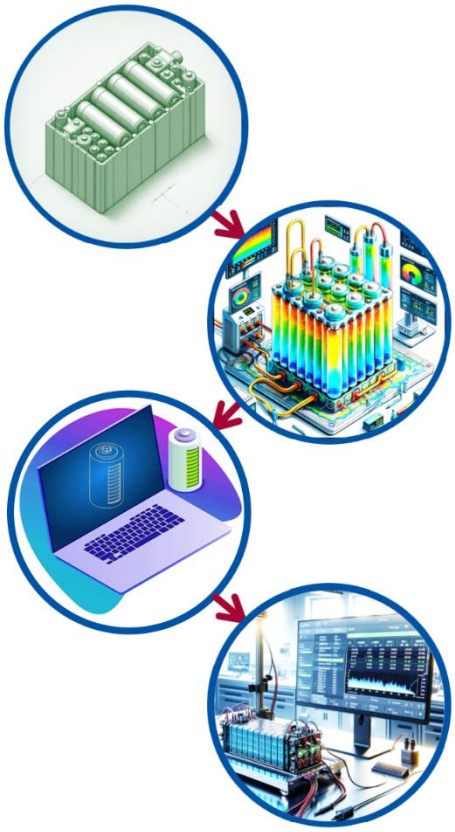


*Figure 6: Ongoing research topics of STU and **FreeTwinEV** and future topics*

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. Among the listed priorities, FreeTwinEV and STU place primary emphasis on digital twin–enabled battery system modelling, electro-thermal coupling, and accelerated validation, while materials- and chemistry-oriented topics are addressed mainly through collaboration. 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 (FEI 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 (FEI 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 (MTF 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 (SjF 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 (FCHPT 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.
- *Slovak Battery Ecosystem Organisations (SEVA and Slovak Battery Alliance)*: National coordination and networking organisations supporting the development of the battery ecosystem in Slovakia by connecting industry, research institutions, academia, and public authorities. These organisations focus on strengthening collaboration across the battery value chain, promoting knowledge exchange, supporting strategic initiatives in energy storage and electromobility, and representing Slovak stakeholders within broader European battery-related platforms and partnerships.
- Czech Battery Cluster: A national innovation platform bringing together industry, research institutions, and academia to support the development, manufacturing, and deployment of advanced battery technologies. The cluster focuses on strengthening the battery value chain in the Czech Republic, fostering collaboration, knowledge transfer, pilot production, and the international competitiveness of battery-related R&D and industrial activities.

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[19] 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

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

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*: With a potential to contribute to battery lifetime extension of up to ~20% under selected operating conditions, 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 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.

First Industry roundtable "Academia meets Industry" took place in STUBA on 18th of September 2025. Event attracted relevant stakeholders from Slovakia, Austria, Czech Republic and the Netherlands. Detailed information about the event is summarized in the deliverable D2.3 First report on collaborations submitted at the end of September 2025.

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 6, 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. Three research papers are currently under review, submitted by STU, one in the *Journal of Energy Storage* (*Journal of Energy Storage |*

ScienceDirect.com by Elsevier), one in the journal Energies (Energies - Open access Journal by MDPI), and another one in *Batteries & Supercaps (Batteries & Supercaps - Chemistry Europe - Wiley Online Library)*. And one that has been already published by STU, in the Journal of Mechanical Engineering (Design and Manufacturing of a High-Performance Battery Module for an Electric Racing Vehicle)

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

As mentioned before, 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 FreeTwinEV project and other project 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) are being explored.

In this context, STU has recently taken a further strategic step by successfully submitting the CEBATEX (Central European Battery Excellence Hub) project in November 2025. CEBATEX is conceived as a complementary and follow-up initiative to FreeTwinEV, focusing on strengthening institutional research excellence, governance capacity, and long-term international cooperation in the battery domain. The consortium brings together Slovak University of Technology in Bratislava (STU) and Brno University of Technology (BUT) as widening institutions, supported by advanced European partners including TU Wien (Austria), the University of Twente (Netherlands), and the Linz Center of Mechatronics (Austria). The project further integrates key ecosystem and industry actors such as ADDSEN (Slovakia), EVC Group (Czech Republic), BatteryCheck (Slovakia), the Slovak Electric Vehicle Association (SEVA), and the Czech Battery Cluster (CBC), ensuring

strong links between academic excellence, industry needs, and regional innovation ecosystems.

The submission of CEBATEX demonstrates the continuity of the strategic direction defined by the SRA and confirms STU's commitment to sustained capacity building and international positioning beyond the lifetime of a single project.

To ensure long-term impact, the FreeTwinEV project and this agenda focus on building robust industry partnerships and fostering a pipeline of skilled researchers in battery technologies. STU builds to sustain its research activities beyond the initial project period through strong partnerships. The SRA acts as 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

This updated **FreeTwinEV** Strategic Research Agenda consolidates the role of STU and its partners as strategically relevant players within the evolving European battery and electromobility ecosystem. It reflects both the progress achieved since the first SRA and the rapidly changing external context shaped by intensified global competition, industrial turbulence in the European battery sector, and slightly shifting policy priorities at EU level. The agenda positions the Slovak University of

Technology in Bratislava (STU) and its partners in a high–value segment of the battery value chain, focusing on system-level innovation and digitalisation.

The SRA confirms that advanced modelling, digital twin–enabled battery management, electro-thermal system understanding, and virtual validation are critical enablers for improving battery safety, lifetime, performance, and sustainability across multiple application domains. These capabilities directly address key European challenges: reducing development risks, shortening innovation cycles, supporting industrial competitiveness, and enabling more resilient and sustainable battery systems under real-world operating conditions.

By aligning closely with European initiatives such as BEPA, BATT4EU, BATTERY 2030+, the European Green Deal, and emerging industrial policies focused on resilience and technological sovereignty, the agenda ensures strategic coherence with EU priorities while remaining grounded in realistic industrial needs. The strong emphasis on international cooperation, interdisciplinary research, and close interaction with industry reinforces STU's ambition to act as a credible research and innovation partner at European level, particularly within Central and Eastern Europe.

Importantly, the SRA demonstrates continuity beyond the FreeTwinEV project. Initiatives such as the submission of CEBATEX illustrate how FreeTwinEV serves as a foundation for sustained capacity building, governance improvement, and long-term integration into the European battery research landscape. In this sense, the agenda functions not only as a roadmap for research topics, but also as an institutional development strategy supporting excellence, visibility, and impact.

Outlook

Looking forward, the Strategic Research Agenda will remain a living document that evolves alongside technological progress, policy developments, and industrial realities. For the remaining project duration, the focus will increasingly shift toward translating digital twin methodologies, and system-level models into robust tools for industrial application, pre-industrial validation, and regulatory-relevant evidence generation.

Future activities will prioritise:

- **Deepening system-level battery research**, particularly through multi-physics digital twins, advanced state estimation, and data-driven lifecycle optimisation.

- **Strengthening European and international partnerships**, including deeper engagement in platforms such as BEPA and other Horizon Europe partnerships.
- **Enhancing industry integration**, ensuring that research outputs address concrete challenges related to safety, fast charging, thermal management, lifetime extension, and sustainability under real operating conditions.
- **Building long-term institutional capacity**, through follow-up projects, researcher development and exchange, and improved research management structures.

In a European battery landscape increasingly characterised by consolidation, risk awareness, and pressure for rapid industrial relevance, the FreeTwinEV Strategic Research Agenda provides a realistic and forward-looking pathway. By focusing on areas where academic research can deliver the highest added value, and by embedding this work in strong European cooperation, STU and its partners are well positioned to contribute meaningfully to Europe's battery innovation capacity, industrial competitiveness, and climate objectives in the years ahead