Batteries Europe

Powering Europe's Green Revolution: Paving the Way to a More Resilient and Sustainable Battery Industry

Research and Innovation Roadmap on Battery Technologies

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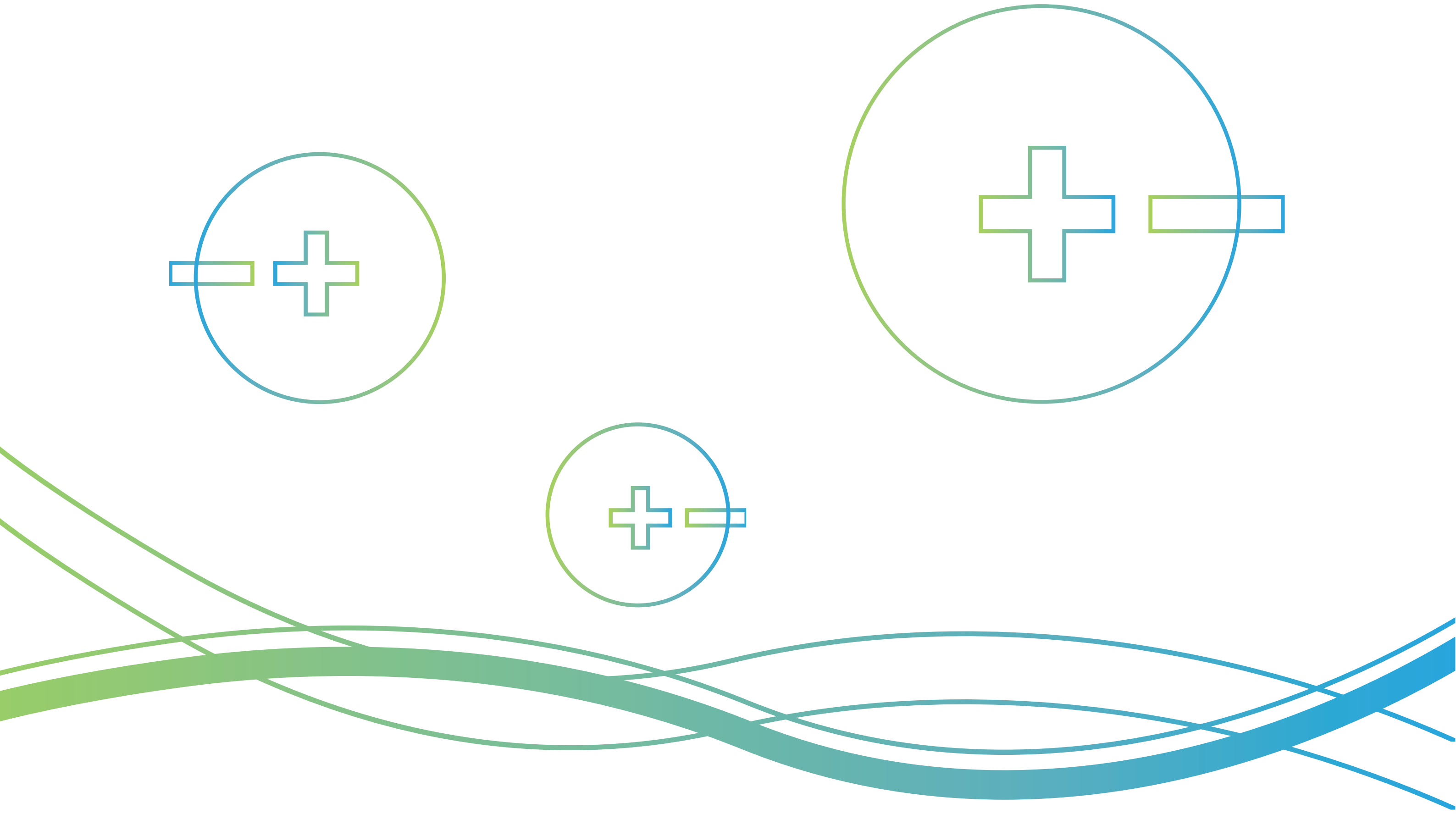

TABLE OF CONTENTS

LIST OF TABLES

Executive Summary

To achieve Europe's ambitious target of reaching zero emissions by 2050, Europe must accelerate the transition from fossil fuel to renewable energy sources while, at the same time, being competitive with global counterparts (China, US). The 2024 Draghi's report , " The future of European competitiveness" highlighted the need to focus on European competitiveness and the requirement to scale-up clean technologies manufacturing, to build domestic capacity in areas of strategic relevance, including batteries. There is little doubt that batteries will be essential for several types of transport including airborne, waterborne, rail, and road, with an increasing number of EVs coming into the global fleet. Furthermore, batteries are increasingly used as a key component for complementing renewable energy sources, such as solar and wind, and will be mandatory for stabilising/levelling the electrical grid. The Draghi's report additionally stresses the importance of European Research and Development (R&D) in battery technology, while highlighting the innovation gaps between Europe and other global leaders. The document calls for a significant increase in funding and infrastructure to support R&D activities including leveraging public funds to de-risk private investments and to attract more institutional investors into the battery sector.

One of the main underlying questions remains, i.e. where will our batteries be manufactured and by whom? If we want to develop a domestic innovative European battery industry we must

- Continue to carry our research, development and innovation (R&D&I) with an end user perspective and strong business mindset.
- Educate the next generation who will be the key to the development of this sector.
- Substantially increase the funding of research and innovation within startups and early-stage companies, through both public and private equity.

In FP9 Horizon Europe calls there is now the opportunity to work with several new affiliate countries outside of the EU in which we can build R&D&I collaboration, alliances and experience globally and develop key research relationships inside a global battery value chain.

Batteries Europe** is the European Technology & Innovation Platform on batteries bringing together all relevant stakeholders in the European batteries research and innovation ecosystem with the vision of **accelerating the growth of a globally competitive and sustainable battery value chain in Europe.

The Batteries Europe R&I Roadmap revision 2025 revisits the areas mentioned in the roadmap of 2023 and points out the changes in focus and timeline due to both research and market developments, which need to be taken into account as the R&D&I community moves forward. It also reiterates the key areas which continue to need investigation.

Research and Innovation areas across the entire battery value chain are addressed in each of the six segments covered by the dedicated Working Groups (WG), with the support of the transversal Task Forces (TF). **The experts performed a review of the state-of-the-art technologies, identified the main strategic research areas in each domain and concluded with key recommendations for the battery community.** The timeframes have been shifted in accordance with the current research and innovation needs, considering short term (2029), medium (2035) and long term (2040+).

1. New and Emerging Technologies. The chapter contains an update on suggested strategic research necessary on a broad **series of promising battery technologies** that are expected to predominantly influence the progress of integrating renewable energy sources and the exploration of cost-effective and sustainable solutions able to exceed Li-ion battery limitations. Included are the next-generation of flow batteries, metal air batteries, durable metal-sulfur batteries, and aqueous batteries which have the advantage of greater safety and sustainability. Furthermore, this document includes the concepts to develop "Zero Li excess" (or anode-less) batteries. This concept is extended to Zero Na excess batteries for Sodium-based batteries. Additionally, multivalent non-aqueous battery systems (Ca, Mg, Al, Zn, etc) are considered, while Na has been removed from this list with the substantial advancement of Na-ion batteries. Hybrid supercapacitor batteries are also mentioned.
There are also other advancements, not specifically based on a particular chemistry, which can make an enormous difference in battery technology. These research areas are transversal and require collaboration of stakeholders from several sectors. The development of a European battery hub to develop and collect multimodal/multiscale correlative characterisation, along with the accelerated materials discovery and multiscale modelling, could lead to breakthrough for novel battery chemistries. Furthermore, the development of biometrics as smart functionalities for batteries can support our knowledge of the processes within a battery and may be harnessed to facilitate repair to damaged battery cells on materials level. Finally, new methods of manufacturing future battery cells, along with designing battery cells specific for given applications may be a game changer in the future to improve sustainability, circularity and safety while simultaneously reducing costs upon upscaling.

2. Raw Materials and Recycling section highlights the continued importance of research into **logistics, collection, sorting, and discharging/deactivation**, as well as the role that AI, robotics and industry 4.0 could play in these developments. The **adaptability and tolerance of the existing recycling processes to new technologies** in addition to its formerly suggested R&D&I areas, now focuses on the development of direct recycling, e.g. for Na-ion batteries. It also points out new needs for PFAS handling during recycling and simplified methods for qualitative analysis of recycled materials flows. The chapter clearly points out the absolute need to develop **recycling processes for Lithium Iron Phosphate (LFP) batteries** whose use is becoming mainstream for stationary energy grid storage. **New recycling processes for Li metal batteries and other emerging chemistries** are considered research areas for the longer term. However, it is noted that the recycling process should be given considerable thought to the early-stage development of these new chemistries. The remainder of this chapter deals with raw materials supply with a midterm focus suggested for R&D&I on the **integration of secondary raw materials**, and a more urgent shorter term for t**he Na-ion and other new**

chemistries battery supply chain, in addition to the key essential area of **sustainable sourcing and processing of raw materials**. In addition, three transversal R&D&I challenges have been reiterated: **Generative AI for new predictive models, Objective sustainability assessment methodologies and Physics-based and AI models with automated data collection.**

3. Advanced Materials section highlights the need for further R&D&I of the same technologies as expressed in the Roadmap 2023 with the following exceptions and additions. In the area of R&D&I efforts around **Li-ion batteries** ((gen. 3) with liquid state electrolytes) from mobility we see the exclusion of LFP development, however LMFP continues to be included. In addition, it calls for a focus on ceramic-coated separators, thinner current collectors and, in the midterm, research on laminated current collectors which will reduce the weight of the battery overall. **Lithium based solid-state batteries** (SSB, gen. 4) require research to achieve higher energy and power densities, faster charging capabilities, improved cyclability, and enhanced safety. However, there is a need to strengthen the European industry to match and exceed Asian governments set to invest more than $800 million dollars into SSB R&D &I in 2024. Meanwhile, **Na-ion batteries** offer the greatest potential for materials advancement, IP generation, technology development and supply chain independence for Europe. Therefore, R&D&I should be a top priority in this area. **Long-lasting batteries** for stationary storage consider both utility level storage over 100 MWs and commercial high-power storage under 100 MW, both which will need considerable different battery chemistries to achieve the optimal cost-effective sustainable solutions.

4. Cell Design and Manufacturing. As the battery market evolves, innovative cell and battery design, coupled with advanced manufacturing processes, is essential for driving sustainability, performance, and competitiveness in Europe. This section outlines the strategic research areas necessary to achieve large-scale, efficient, and environmentally friendly production of current and future battery technologies. Strategic research areas, such as **Sustainable innovative cell and battery design**, and **Sustainable production processes of cells and batteries** focus on making batteries with optimized potential for second-life applications and recycling, leveraging abundant, cost-effective materials, such as sodium, to reduce environmental impact and ensure resource availability. Additionally, innovative processes, intelligent automation to minimize scrap and promote recycling, and increased utilization of recycled or up-cycled materials are crucial for lowering production costs, enhancing manufacturing efficiency, and reducing carbon footprints. **Flexible production technologies** are also identified as relevant to develop adaptable manufacturing systems. These systems can support the transition of emerging technologies into large-scale production and respond to evolving supply chains and market demands. Digital twins play a significant role here, enabling real-time optimization of machinery and process configurations. Finally, **Processes and product scaling and industrialisation** are identified as crucial for advancing industrialization techniques to support European competitiveness. The integrated approach described in WG4 ensures the alignment of sustainability, safety, and digitization, creating a robust and future-proof battery value chain.

5. Application and Integration: Mobile. Widespread electrification of the mobility sector depends on addressing key challenges across various transport modes, including road, airborne, waterborne, rail, and off-road applications. Transversal challenges such as **fast charging, battery refurbishing**, and **advanced diagnostics** are the core for ensuring practicality, sustainability, and longevity across all sectors. Fast charging focuses on improving battery design to enable quicker energy replenishment while minimizing degradation. Battery refurbishing, supported by advanced diagnostics and smart sensors, enhances reuse, recycling, and overall sustainability. Specific needs for transport modes, such as **lightweight, high-performance batteries** for aviation and **robust systems for maritime and off-road applications**, highlight the importance of tailoring solutions while addressing overarching challenges like safety, system integration, and thermal management.

6. Application and Integration: Stationary. Stationary energy storage systems are critical for enhancing renewable energy utilization and grid reliability. Key research areas focus on **front-of-the-meter (FTM)** and **behind-the-meter (BTM)** applications, as well as **medium-to-long duration storage,** with transversal challenges connecting these domains. For FTM systems, advanced digital energy management algorithms are essential to optimize battery operation, including multi-use concepts like revenue stacking and predicting battery reliability and safety in aging systems. **Vehicle-to-Grid (V2G)** and **Vehicle-to-Home (V2H)** services are gaining more interest when integrated in BTM systems, with the goal of maximizing grid impact and enhancing the value of stationary battery installations. Medium-to-long duration storage emphasizes the need for upscaling technologies based on low-cost and sustainable materials, ensuring broad applicability and economic feasibility. Transversal challenges include advancing **safety, reliability, and extended lifetime** of battery systems, improving **bidirectional charging efficiency**, and incorporating **design for second life** into battery development. This includes design for disassembly to streamline recycling and enables sustainability from the start.

Many of the research priorities will be addressed by the BATT4EU Partnership under Horizon Europe, but others will need to be addressed on a national or regional level, perhaps as part of the IPCEIs. In addition, not all the segments of the entire value chain are covered by the Partnership; therefore, some research concepts need to be further promoted in other programs. BATT4EU works together with partnerships covering research on different areas including raw materials (EIT Raw Materials) and transport applications, namely: 2Zero (road transport), ZEWT (waterborne), Clean Aviation and Europe's Rail.

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Prepared by WG1 - New and emerging battery technologies. Main contributors:

Kristina Edström, Daria Giovannacci, Ivana Hasa, Montserrat Casas Cabanas, Edoardo G. Macchi, Nagore Ortiz Vitoriano, Julia Amici, Katharina Ahlbrecht, Holger Altheus (FhG IWS), Gwinevere Giffin, David McNulty, Daniela Fenske (FhG IFAM), Sébastien Martinet (CEA-LITEN), Maria Rosa Palacín, Sandrine Lyonnard, Robert Dominko, Samson Lai, Ivano Castelli, Iker Boyano, Lucas Moreno, Elixabete Ayerbe-

Prepared by WG2 - Raw materials and recycling. Main contributors:

Marja Wilkman (VTT), Victor Trapp (ISC - Fraunhofer) and acknowledging previous roadmap edition contributors On transversal topics Antonio Martins (University of Porto, Teresa Mata (INEGI), and acknowledging the chairs of the TF Sustainability and Digitalization and previous roadmap edition contributors

Prepared by WG3 - Advanced materials. Main contributors:

Daniel Gloesener (Syensqo), Silvia Bodoardo (Polito), Marcel Meeus (EMIRI), Mihails Kusnezoff (IKTS- Fraunhofer), Giffin Guinevere (ISC Fraunhofer), Marina Urbina (CEA Liten), Daniela Pohl (FBE), FBE and acknowledging previous roadmap edition contributors. On transversal topics Anwar Ahniyaz (RISE), Silvia Bodoardo (Polito) and acknowledging previous roadmap edition contributors

Prepared by WG4 - Cell design and manufacturing. Main contributors:

Arno Kwade (TU Braunschweig), Arnold Gillner (Fraunhofer ILT) ,Carl Telford (Battery innovation) ,David McNulty (Uni. of Limerick), Daniela Fontana (Comau), António Martins (Uni. of Porto), Elixabete Ayerbe (CIDETEC Energy Storage), Jean-Paul de Mussy (Pole Mecatech), Fernando Machado (Battery Cluster Portugal), Filippos Farmakis (INEM Technologies) Maica Morant-Miñana (CIC energiGUNE) Nicolas von Drachenfels (TU Braunschweig), Sebastian Risse (Helmholtz-Zentrum Berlin), Tazdin Amietszajew (Coventry Uni.), Teresa Mata (INEGI), Timo Danner (DLR) ,Yvan Reynier (CEA).

Prepared by WG5 - Cell design and manufacturing. Main contributors:

Arno Kwade (TU Braunschweig), Arnold Gillner (Fraunhofer ILT) ,Carl Telford (Battery innovation) ,David McNulty (Uni. of Limerick), Daniela Fontana (Comau), António Martins (Uni. of Porto), Elixabete Ayerbe (CIDETEC Energy Storage), Jean-Paul de Mussy (Pole Mecatech), Fernando Machado (Battery Cluster Portugal), Filippos Farmakis (INEM Technologies) Maica Morant-Miñana (CIC energiGUNE) Nicolas von Drachenfels (TU Braunschweig), Sebastian Risse (Helmholtz-Zentrum Berlin), Tazdin Amietszajew (Coventry Uni.), Teresa Mata (INEGI), Timo Danner (DLR) ,Yvan Reynier (CEA).

Prepared by WG6 – Application and integration: Stationary. Main contributors:

Anders Christian Solberg Jensen (Forretningsleder hos Teknologisk Institut), David McNulty (Bernal Institute - University of Limerick), Edoardo Gino Macchi (Fondazione Bruno Kessler - FBK.), Fast Lars (Ri.SE), Franco di Persio (CIRCE-Centro Tecnologico), Fride Vullum-Bruer (SINTEF), Iosu Cendoya (Cidetec), Javier Olarte (CIC - EnergiGUNE), Jeroen Büscher (VITO/EnergyVille), Lluis Trilla (IREC Catalonia Istitute), (TF Hybridisation)

Task Force Digitalisation

Aleksandra Naumann (Technische Universität Braunschweig), António Martins (Faculty of Engineering - University of Porto), Christoph Grzeschik (VDI/VDE-IT), Elixabete Ayerbe (CIDETEC Energy Storage), Francesco Guaraldi (Flash Battery), Gunther Bohn (Technical University of Applied Sciences Würzburg-Schweinfurt), Lluis Trilla (IREC), Maher Chebbo (Univers), Sebastian Risse (Helmholtz-Zentrum Berlin), Simon Stier (Fraunhofer Institute for Silicate Research ISC), Teresa Mata (INEGI – Institute of Science and Innovation in Mechanical and Industrial Engineering)

Task Force Social Sciences and Humanities

Viera Pechancová (Tomas Bata University in Zlín), Jens Peters (University of Alcalá), Evelina Castellana (LOMARTOV S.L.), Yamina Guidoum (LOMARTOV S.L.), Francesco Ghezzi (Sant'Anna School of Advanced Studies), Jozsef Kadar (Arava Institute), Paola Mazzucchelli (CIRCE- Centro Tecnológico), Spyridon Pantelis (EERA), Zane Datava (NTNU), Adam Cooper (UCL Department for Science, Technology, Engineering and Public Policy), Gabriela Benveniste (Fundació Institut de Recerca en Energia de Catalunya IREC)

Task Force Safety

Lars Fast (RISE), Emilie Bekaert (CIC EnergiGUNE), Elixabete Ayerbe (CIDETEC), Anwar Ahniyaz (RISE), Franco Di Persio (CIRCE), Mihails Kusnezoff (Fraunhofer), Antonio Martins (University of Porto)

Task Force Sustainability

Antonio A. Martins (University of Porto), Teresa Mata (INEGI), Nicolas Drachenfels (TU-Braunschweig), Arnold Gillner (Ilt – Fraunhofer), Taz Amietszajew (Coventry)

Task Force Education and Skills

Antonio A. Martins (University of Porto), Teresa Mata (INEGI), Nicolas Drachenfels (TU-Braunschweig), Arnold Gillner (Ilt – Fraunhofer), Taz Amietszajew (Coventry)

Edited by the Secretariat of Batteries Europe

Contributor	Role	Affiliation
Alessandro Romanello	Coordinator	EIT Innoenergy
Roberto Scipioni	Technical Leader	SINTEF Energi AS
Edel Sheridan	Technical Advisor	SINTEF Energi AS
Montserrat Casas Cabanas	WG1 Technical Support	CIC energiGUNE
Eliana Quartarone	WG2 Technical Support	University of Pavia/INSTM
Francis Kinyanjui	WG3 Technical Support	SINTEF AS
Christoph Grzeschik	WG4 Technical Support	VDI/VDE-IT
Margherita Moreno	WG5 Technical Support	ENEA
Annalisa Aurora	WG6 Technical Support	ENEA
Dimitra Maleka	TF Education Technical Support	EIT Innoenergy
Estibaliz Crespo	Member	CIC energiGUNE
Penelope Nabet	Member	EIT Innoenergy
Piercarlo Mustarelli	Member	University of Milano-Bicocca/INSTM
Gabriele Gaffuri	Administrative Support	Zabala Innovation
Lucia Sardone	Administrative Support	CLERENS
Adeola Adeoti	Administrative Support	CLERENS

List of acronyms

AI	Artificial Intelligence	**DoD**	Depth of Discharge
ALBATTS	Alliance for Batteries, Technology, Training and Skills	**DPP**	Digital Product Passport
AORFB	All-Organic Based Redox Flow Batteries	**DSO**	Distribution Systems Operator
ASSB	All Solid-State Battery	**DSS**	Decision Support System
B2C	Business to Consumer	**EBA**	European Battery Alliance
BAT	Best Available Technique	**EC**	European Commission
BattINFO	Battery InterFace Ontology	**EMC**	Electromagnetic Compatibility
BEPA	Batteries European Partnership Association	**EMS**	Energy Management System
BESS	Battery Energy Storage Systems	**EoL**	End of Life
BEV	Battery Electric Vehicle	**EQF**	European Qualifications Framework
BIG-MAP	Battery Interface Genome – Materials Acceleration Platform	**ESS**	Energy Storage Systems
BIP	Business Investment Platform	**EU**	European Union
BMS	Battery Management System	**EUBatIn**	European Battery Innovation IPCEI Innovation IPCEI
BREFs	BAT Reference Documents	**EV**	Electric Vehicle
BTM	Behind-The-Meter	**e-VTOL**	Electric-Vehicle Take-Off and Landing
BVCO	Battery Value Chain Ontology	**LFP**	Lithium Iron Phosphate
C&I	Commercial and Industry	**LIB**	Lithium Ion Battery
C2C	Chassis-to-Chassis	**$LiPF_6$**	Lithium hexafluorophosphate
C2V	Cell-to-Vehicle	**LMB**	Lithium Metal Battery
CAN	Control Area Network	**LMFB**	Lithium Manganese Iron Phosphate
CAPEX	CAPital EXpenditure	**LMO**	Lithium Manganese Oxide
CF	Carbon Footprint	**LNMO**	Lithium Nickel Manganese Oxide
CCD	Critical Current Density	**LTMO**	Layered Transition Metal Oxide
CO_2	Carbon Dioxide	**LTO**	Lithium-Titanate Oxide
CRM	Critical Raw Material	**MAB**	Metal Air Batteries
Cu-HCF	Copper Hexacyanoferrate	**MAP**	Material Acceleration Platform
CVET	Continuing Vocational Education and Training	**ML**	Machine Learning
DBP	Digital Battery Passport	**Mn-HFC**	Manganese Hexacyanoferrate
DoD	Depth of Discharge	**MOOC**	Massive Open Online Course
DPP	Digital Product Passport	**MTTF**	Mean Time To Failure

MTTR	Mean Time To Repair	**FTM**	Front-of-The-Meter
NCA	Lithium Nickel Cobalt Aluminium Oxide	**GHG**	Green House Gasses
NECPs	National Energy and Climate Plans	**GLAD**	Global LCA Access Database
NMC	Lithium Nickel Manganese Cobalt Oxide	**HCV**	Heavy Commercial Vehicle
NO_x	Nitrogen Oxides	**HER**	Hybrid Electric Regional
NRMM	Non-Road Mobile Machinery	**HESS**	Hybrid Energy Storage Systems
OPEX	Operational Expenditure	**HLM**	High Lithium, Manganese
P/E	Power/Energy	**HPA**	Hydrogen-Powered Aircraft
PBA	Prussian Blue Analogues	**HW**	Hardware
PCR	Product Category Rules	**ICE**	Internal Combustion Engine
PEFCR	Product Environmental Footprint Category Rules	**IoT**	Internet of Things
PFAS	Per- And Polyfluorinated Substances	**IPCEI**	Important Projects of European Common Interest
PFAS	Pumped Hydroelectric Energy Storage	**IVET**	Initial Vocational Education and Training
PINN	Physics-Informed Neural Network	**IWG**	International Working Group
PM	Particulate Matter	**JRC**	Joint Research Centre
PV	Photovoltaic	**KPI**	Key Performance Indicator
PVGIS	Photovoltaic Geographical Information System	**LBA**	Local Balancing Area
PWA	Prussian White Analogues	**LCA**	Life Cycle Assessment
QRL	Quality, Reliability and Life	**LCC**	Life Cycle Costing
R&D	Research & Development	**LCI**	Life Cycle Inventory
R&I	Research & Innovation		Long Duration Energy Storage
REACH	Registration, Evaluation, Authorisation and Restriction of Chemicals	**ROM**	Reduced Order Model
REE	Rare Earth Element	**SbD**	Safe By Design
RES	Renewable Energy Storage	**SE**	Solid Electrolyte
RFB	Redox Flow Battery	**SEI**	Solid Electrolyte Interphase
RFID	Radio-Frequency Identification	**SET**	Strategic Energy Technology
ROI	Return On Investment	**SIB**	Sodium Ion Battery
FAIR	Findability, Accessibility, Interoperability, Reusability	**SMR**	Short and Medium Range
FCE	First Cycle Coulombic Efficiency	**SoX**	State-of-X where X = Charge (C), Health (H), Power (P), Temperature (T)

SRA	Strategic Research Area		
SRIA	Strategic Research and Innovation Agenda		
SSbD	Safe and Sustainable by Design		
SW	Software		
TRL	Technology Readiness Levels		
V2X	Vehicle-to-Everything		
VRFB	Vanadium Redox Flow Battery		
VRFB	Waste electrical and electronic equipment		
WG	Working Group		
ZEWT	Zero-Emission Waterborne Transport		

1. Vision

The vision of Batteries Europe is to support and accelerate the growth of a globally competitive and sustainable battery industry in Europe, as part of the journey toward the goal of becoming the first climate-neutral continent by 2050.

The European Battery R&I community consists of a rapidly growing number of individuals, organisations and industry companies whose primary collective vision is to have an active, vibrant, sustainable and competitive battery value chain in Europe, from materials production to battery cell and system production, to integration in mobility and stationary storage in addition to active recycling and reintroduction of battery materials to the value chain again. Our reasons behind this drive for a battery value chain is twofold, firstly we see batteries as a good sustainable alternative to provide low emission transport and stationary storage and secondly, we see the potential to provide high value jobs and a competitive industry value chain for generations to come. We as a community work toward this and view research and innovation throughout all parts of the value chain, as one of the cornerstones that the industry will rely on in the future to ensure sustainability and competitive advantage.

1.1 The European policies on batteries and related technologies

As per this vision, Batteries Europe aims to support and enhance the competitiveness of the European battery value-chain, in particular by aligning Research and Innovation priorities with European policy objectives. As acknowledged in the Draghi report, this effort to reinforce the connection between Research and Innovation, policy, and industry is central in ensuring that Europe can remain relevant in battery technology globally. This Roadmap therefore includes a short section on policy.

Reminder on the political and institutional context

This year was marked by the European elections in June and the renewal of the European leadership over the following months. Ursula von der Leyen remains at the head of the European Commission with a political agenda prioritising industrial policy but also implementation of the Green Deal policies adopted in the past five years. In addition, she will drive the work on the next European Multiannual Financial Framework (2027-2034) including the Framework Programme for Research and Innovation which should also reflect this reinforced industrial focus.

Key priorities for the Batteries Europe community

Batteries Europe, based on its objectives and network, is well-equipped to support this agenda and steer the battery Research and Innovation ecosystem towards an impactful contribution. Here is an overview of the relevant policies and pieces of legislation - new or upcoming - for Batteries Europe.

1. Political priority on European competitiveness ignited by the Draghi report

Mario Draghi presented his report addressing Europe's future competitiveness in September. This extensive work was commissioned by Commission President Ursula von der Leyen with the aim to support her new political priorities. It highlights the need for Europe to develop the conditions for industry to thrive in the long-term by closing the innovation gap with the United States and China, matching our climate-neutrality target with a "sustainable competitiveness" plan, and tackling dependencies on imports for critical technologies like batteries.

For the battery value-chain specifically, the report points the central role of public support for Research and Innovation in strengthening Europe's position in battery development globally. To address the innovation gap with competitors, it recommends improving the link between Research and Innovation policy and industrial priorities, notably through a greater focus on manufacturing processes. Looking at the next Framework Programme, it puts forward a new approach, with the creation of a dedicated Competitiveness Joint Undertaking to lead on the industrialisation of the next generation of battery technologies.

2. Implementation of Key Regulations for the battery value-chain

The Green Deal which was at the heart of the past mandate (2019-2024) led to the adoption of a number of relevant targets and measures for the battery industry. This includes targets bolstering market demand for batteries in transport and stationary storage enshrined in the CO_2 Emission Performance Standards Regulation for cars and trucks, in the Renewable Energy Directive, or in the revised Electricity Market Design. More importantly, this includes three key Regulations which will have to be implemented in the next years by the battery industry.

- **Battery Regulation**

The Battery Regulation is a new, comprehensive framework aimed at reinforcing the sustainability and competitiveness of the European battery value-chain. It covers the whole lifecycle of batteries from production to recycling. It set out new obligations for economic operators placing batteries on the European market with requirements notably on carbon footprint, recycled content, durability, and replaceability.

- **Net-Zero Industry Act**

The Net-Zero Industry Act stems from Europe's industrial ambition. It aims to develop domestic production capacity for a list of net-zero technologies by fostering a more favourable environment for manufacturing projects. The provisions of this Regulation include facilitated and accelerated permitting for industrial facilities as well as the creation of a Strategic Project label to help channel funding to projects.

- **Critical Raw Materials Act**

  The Critical Raw Materials Act fosters the resilience of Europe's raw materials supply through diversification and the expansion of domestic production capacity. It tackles extraction, processing, and recycling of raw materials used in critical technologies for the green and digital transitions. It provisions mirrors that of the Net-Zero Industry Act on permitting and Strategic Project label.

3. Expected initiatives in the new mandate

Ursula von der Leyen and the newly appointed Commissioners have announced many relevant initiatives for the battery Research and Innovation community. Here is a non-exhaustive list of upcoming initiatives that Batteries Europe should monitor.

- **Clean Industrial Deal**
  - Industrial Decarbonisation Acceleration Act
  - Action Plan on Affordable Energy
  - Industrial Action Plan for the automotive sector
  - Circular Economy Act

- Roadmap towards ending Russian energy imports
- Revision of the CO_2 Emission Performance Standards Regulation for cars and vans
- Sustainable Transport Investment Plan
- Electrification Action Plan
- Advanced Materials Act
- Chemicals Industry Package (with a possible revision of the REACH Regulation)

The European policy landscape for the battery industry has significantly changed in the recent years will be further enriched in the next years. Batteries Europe will continue to follow and analyse these new measures, inform its network, and ensure alignment between policy and Research and Innovation priorities in the field of batteries.

1.2 The European battery research ecosystem

The European battery research community has enlarged greatly and become more organised and focused over the last decade. The European Battery Alliance and the two IPCEI's on batteries have made significant efforts to support the European industry in the battery value chain, however more extensive support and investment, both public and private, is required on both a national level and European level to establish the roots of this industry in Europe, which can yield significant gains for the European economy and high value jobs in the future.
Batteries Europe ETIP has ensured a place for all stakeholders across the sector to have a fo-

rum to express their interests and document them, through the many roadmaps, position papers and workshops over recent years. The platform also supports the collection of technical key performance indicators across the entire battery value chain and the SET Plan reporting. In addition, the international activities of the platform has provided insight into what is happening beyond European borders, thus equipping the European Commission with essential knowledge.

The Battery European Partnership Association BEPA has been working closely with Batteries Europe ETIP and Battery 2030+. The Strategic Research and Innovation Agenda (SRIA) takes into consideration the Batteries Europe ETIP Roadmap and updates, and Battery 2030+ roadmap. BEPA are working together with the European Commission in the form of BATT4EU to prioritise topics and budgets which are then transposed into the Horizon Europe calls and projects. BEPA also supports the creation of clusters of EU projects and the monitoring of project outcomes.

One of the most successful yearly events on the European battery calendar is the Battery Innovation Days, which is a collaboration between BEPA, Batteries Europe, Battery 2030+, and the two IPCEIs. This is an arena that truly takes all members across the battery value chain from industry to research together to present and highlight recent research, discuss collaboration and develop alliances for future innovations.

1.3 Scope and Objectives of the Technology Roadmap Update

The Batteries Europe Technology Roadmap update is designed with the objective to update stakeholders (including Member States, policymakers, industry & start-ups, the research community, the general public and associations) with an overview of specific topics which will provide a basis for developing strategic planning for research and innovation. The scope covers the entire battery value chain, in addition to addressing specific topics including education and skills and social science and humanities.

1.4 Methodology

Batteries Europe has 6 Working Groups (WGs) and 6 transversal Task Forces (TFs) each focused on a particular part of the value chain or specific cross cutting area related to battery technology development respectively, as detailed on the Batteries Europe website. The working groups and task forces consist of individual experts from industry and academia. These experts have contributed to the development of both the earlier roadmaps of Batteries Europe and to this Roadmap update.
Each group of experts met in 3-4 telco-meetings during autumn and winter of 2024 to con-

sider what additional updates could be added. They worked with members of the secretariat to complete these updates. Each of the Working Groups had members of the Task Forces included in their groups who contribute to the transversal topics. In addition, the Task Forces working on Education and Skills, and working on Social, Science and Humanities have contributed a separate section as the considerations cannot be taken into account in the technical input from the Working groups. This resulting document also takes in to account the EUs policy which will or does currently influence the battery value chain.

1.5 Education and Skills to address the industry needs

Battery value chain activities are expanding in Europe and are crucial to achieving the EU's climate and energy goals. However, competitive and trade conditions are forcing a reorientation of investments connected with the discontinuation of formerly announced battery factories, posing risks to the development of a European battery ecosystem. Despite this, the need for skills remains critical. Sustained R&D funding is essential to ensure a future pipeline of young battery experts, focus on regional and attractive hotspots of scaled battery manufacturing, and foster partnerships across the EU and globally to access knowledge and complementary resources.

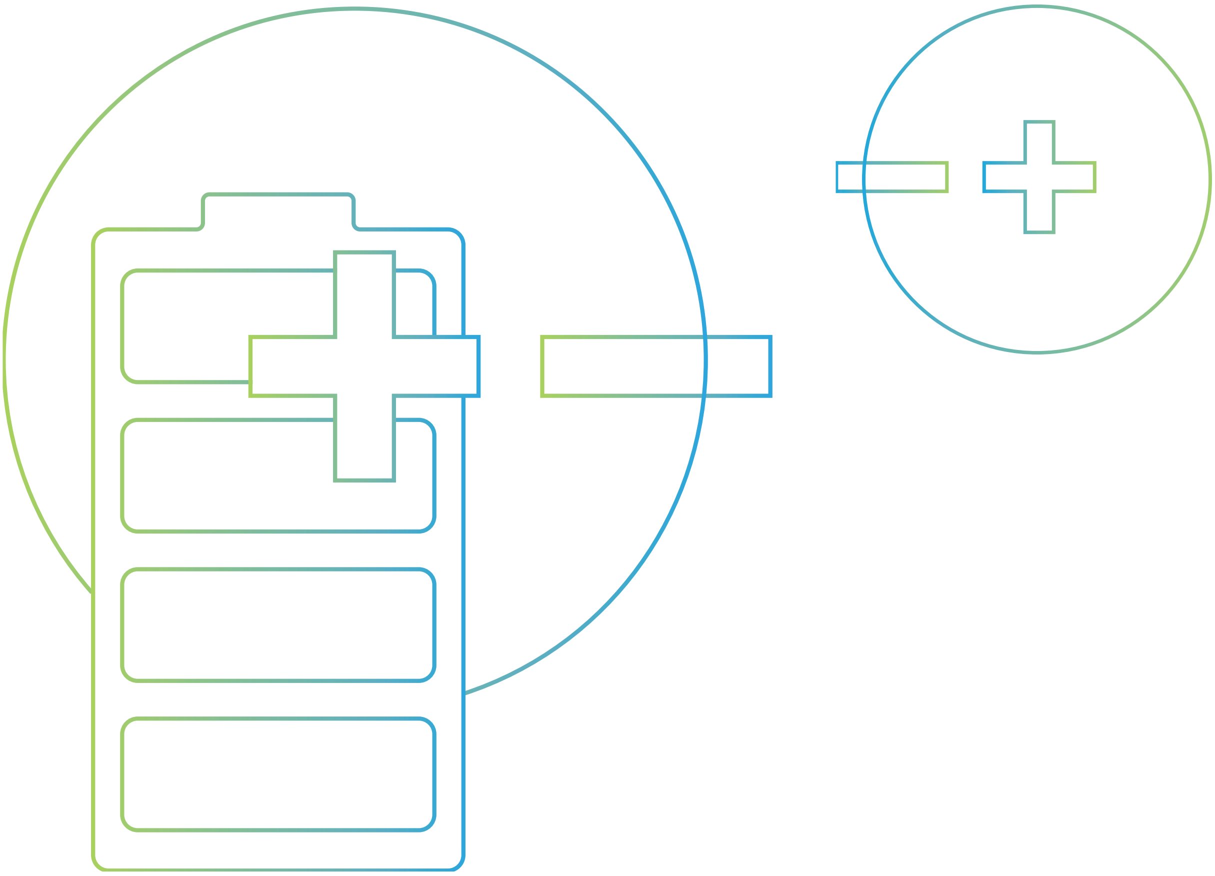
Employment in EV and battery storage is expected to increase between 1.5 - 3.5 times by 2030 compared to 2023, with ~ 1.5 million workers needing re/upskilling by 2030. Hence, building a skilled workforce and strengthening research capabilities within the growing European battery industry represents an even more critical challenge. Both white- and blue-collar jobs require technical and cross-disciplinary skills, making educational programmes and training initiatives fundamental, not only for scaling Europe's battery cell production sector, but also for establishing a competitive battery ecosystem in Europe. This challenge is transversal to all WGs of Batteries Europe.

The battery sector is multidisciplinary, and education/training is required on raw materials, next-generation batteries, materials science, recycling, as well as on cell and battery pack production and safety – supporting applications from automotive and stationary energy storage - without excluding further actual current and future needs. To address these diverse needs, a wide-reaching strategy is needed to bridge gaps: skills, attractiveness, geographical (to ensure workforce availability across regions), and timing; in order to accelerate the preparedness and to match industry growth.

In response to these challenges, Europe must rapidly develop a well-coordinated education and training ecosystem, including the establishment of standardised curricula, vocational programs for technical training, high quality standards, and flexible learning opportunities to match varying industry needs. The important concept of Train-the trainers is yet to be developed to the level required and must be accelerated as part of this strategy, to ensure high-quality, and skilled instructors who can teach current and future generations of professionals.

Significant work has already been completed to assess and map existing educational activities. Leading initiatives and projects such as Battery2030 plus1, ETIP Batteries Europe2, Fraunhofer and EIT Raw Materials3, ALBATTS4, Automotive Skills Alliance5, and InnoEnergy Skills Institute (former EBA Academy)6 have already done significant work in outlining European needs, emerging job roles, essential skills, and educational objectives. While these projects have laid the groundwork, an intensified focus on re-skilling and upskilling at all levels is needed urgently, from vocational training to advanced academic research.

In order to enforce the broad implementation and roll-out of education, re- and up-skilling measures the short-, medium- and long-term actions should consequently build on each other from academic, professional/ vocational to the public/ user level as summarised in the roadmap and table below (more details can be found in the Position Paper of the Task Force on Education & Skills).



Short-term needs and actions (<2027)

Academic level

- **Prioritise university funding** as a constant base (pipeline) of **young** talents and skilled experts in Europe and to develop **standardised programmes and grants** for early-stage researchers, focusing on battery-related subjects from pre-university levels to Master's and doctoral studies.
- **Promote cross-institution mobility and interdisciplinary programmes** for early-stage researchers and students to support EU-wide mobility, allowing for knowledge exchange and collaboration through joint programs between universities and industry that utilise **pilot lines and other R&D infrastructure.**
- Fast-track the **rollout of specialised courses** across academic institutions, ensuring coverage of skills needed from materials sourcing and production to recycling and safety, with a particular focus on emerging roles and gaps in the industry.

Professional/vocational level

- Continuously **assess emerging industry needs** and expand accordingly **targeted training programmes and re-skilling initiatives** through cross-industry knowledge transfer.
- **Boost hands-on and vocational training** by developing learning labs, training simulation tools, digital/modular learning, and vocational programmes focused on practical skills, process scaling, digitalisation and automation.
- Shift perceptions of battery production to **attract local talent** through partnerships and showcasing industry opportunities.
- **Strengthen trainer preparation** by implementing Train-the-Trainer programs with practical and pedagogical training, also to scale re-/upskilling momentum and throughput, and develop and implement certification schemes to ensure the quality and reliability of trainers specific training.

Public/user level

- **Fund initiatives to raise public awareness** on battery safety, environmental impact, and recycling, especially in communities close to production facilities and gigafactories.
- **Prioritise public education** and develop **EU-wide information platforms and community outreach programmes** to enhance understanding and acceptance of battery technologies' contributions to the energy transition and circular economy. Accelerate the development and implementation of regulatory aspects, including the creation of a regulatory/evaluation organisation.

Mid- and long-term needs and actions (2027 - 2030+)

Academic level

- **Scale up and continuously strengthen battery-focused educational programs**; deepen **academia-industry partnerships** offering practical experiences that evolve with workforce demands and changing industry standards.
- **Standardise and expand curricula** by developing EU-wide interdisciplinary programmes covering the **entire battery value chain**, encouraging collaborative academic and industry-driven projects; initiate regular updates to incorporate sustainable design, circularity, and other industry-relevant trends.
- **Emphasise early development of transversal skills**, preparing students to adapt to the battery industry's dynamic challenges with flexible, interactive learning options such as long-life learning courses, MOOCs, and VR simulations.
- **Boost mobility and internships** by continuously securing **funding** to support student and researcher mobility across EU R&D centres, infrastructures, and battery facilities for hands-on training.
- **Establish innovation hubs** connecting industry and academia to tackle real-world battery industry challenges through collaborative research and internships.

Professional/vocational level

- Further align education with industry needs and establish a collaborative EU education-industry model, continuously adapting vocational and professional programmes based on updated Battery Sector Data Platform insights on job market trends and skills demand.
- **Promote professional and trainer mobility** and encourage cross-institution knowledge exchange and trainer certification, with **EU-wide curriculum standards** covering the entire battery value chain and aligned with European Qualification Framework levels.
- **Develop and expand standardised CVET programmes** and continue developing and integrating **physical and virtual learning labs across Europe** into academic and industrial sites (e.g., FBF); establish and support academies to provide hands-on, industry-aligned training and EU-recognised certifications, e.g. using micro-credentials.
- **Invest in continuous 'Train-the-Trainer and Train-the-Teachers' initiatives** and implement structured training, regular feedback systems, and specialized course structures (e.g., MOOCs, VR, simulations) to keep trainers current with industry advancements and enhance their teaching methods.

Public/user level

- **Raise continuous awareness of battery industry careers** by developing **engaging, early-stage programmes** for public audiences to increase understanding of industry opportunities, with a focus on reaching young people to foster long-term interest.
- Offer and expand **digital and onsite resources,** and provide accessible, **multilingual** resources on the role and impact of batteries, safety, and regulatory insights, ensuring these are regularly updated to reflect new industry developments.
- Foster broad **public acceptance and awareness** and promote the **benefits of the**

battery sector to policymakers and public/end-users to build sustained support and understanding.
- Implement **initiatives for public education** on **safe battery use and handling practices,** contributing to a continuously well-informed user base.
- Collaborate with stakeholders to address and **eliminate regulatory barriers.**

1.6 Social Science and Humanities

Batteries are becoming increasingly vital in harmonising the energy needs of daily life—whether in homes, businesses, or for travellers—with the growing reliance on renewable and low-carbon energy systems. Understanding people's attitudes towards batteries is critical if we are to build out a low carbon economy rapidly and fairly. The Social Sciences and Humanities (SSH) are essential in exploring the societal and human dimensions of battery technology development. By analysing the interaction between technology and society, SSH research sheds light on the broader impacts of battery innovations on communities, policies, and societal well-being. This interdisciplinary perspective moves beyond technical performance to address public acceptance, equitable access to energy storage, and the alignment of technologies with societal needs. In turn, this approach encourages technologists to design solutions that are both responsive to public interests and better positioned for successful implementation.

In the context of battery technologies, SSH addresses key issues such as social risks, ethical considerations, policy development, stakeholder engagement and societal readiness. It explores questions of sustainability, fairness across the battery value chain, desired futures and the implications for labour, local economies, and resource management. SSH research also informs strategies to align technological advancements with public interest, tackling concerns about environmental impact, labour conditions and distributional justice across the battery value chain, and the role of batteries in achieving a just and inclusive society living within planetary boundaries.

For this purpose, SSH combines quantitative and qualitative methods from various disciplines and engages actively with affected stakeholders to understand their future visions and expectations and their present concerns, decision processes and options to act. This helps to identify discrepancies between individual or collective expectations, reality and exogeneous limitations (e.g., planetary boundaries) and thus to tailor more goal-oriented policy measures towards a truly sustainable battery value chain beyond the currently prevailing techno-centric perspective.

1.6.1 Social Sciences and Humanities Strategic Research Area

The Social Sciences and Humanities (SSH) research area emphasizes understanding the complex socio-cultural, economic, and ethical dimensions of technology deployment and consumption. It addresses needs such as identifying the motivations, barriers, and behavioural factors influencing stakeholder and consumer decisions regarding battery technology. Using methods like citizen science, open data initiatives or living labs, SSH research involves local stakeholders to understand user behaviours, assess community impacts, and support the creation of innovative, sustainable business models. Furthermore, it aims at advancing methods such as Social Life Cycle Assessment (S-LCA) beyond their current scope, providing more granular insights into social and environmental sustainability, quality of life, and capturing aspects of global and local justice, ethics, human needs and wellbeing. Through scenario development and vision assessments, SSH research aids in shaping futures by guiding technology design towards alignment with community expectations and broader sustainability goals. In a nutshell, SSH goes beyond the currently prevailing technology focus and tackles the question of what a ‘good’ battery is and how it can contribute to improving the quality of life globally. Table 5 lists the key methods and envisioned outcomes clustered into four categories.

Category	Approach	Outcome
Stakeholder considerations	**Engage with stakeholder** across the battery value chain, back casting approaches. Assess the effects of battery production on **local communities** (e.g., jobs, gentrification, inclusion, housing prices) and wealth distribution all along the battery value chain.	Understanding of **concerns, drivers, and expectations** of decisions of different stakeholder groups, understand the role of batteries within the narratives and scenarios. Understanding the **impacts** of battery deployment (e.g., gigafactories, mines) on local communities facilitates recommend of best practices to tackle aspects of justice, equality and participation, ultimately creating acceptance and increased benefit.
Policy & practice	Assess how **engineering design** can improve well-being, develop scenarios and suggest design improvement. Transitioning to **batteries-as-a-service** to promote a circular economy through innovative **business models**, public perception research, and prosumer engagement. Extending the lifespan of batteries through second and third-life applications.	Identifying specific **design requirements** for **better batteries.** Sustainability by design recommendations, going beyond current techno-centric approaches. Understanding **user behaviour** (use profiles, purchase drivers) to inform sustainable, service-based business models and **prosumer** initiatives in the battery ecosystem. Finding **barriers** to behaviour change and technology adoption.
Future visions	Develop **future scenarios** that address sustainability challenges and identify **gaps** between expected and desired futures. **Vision assessment** to evaluate the feasibility and sustainability of future visions.	Evaluation of viability, sustainability and desirability of **future visions**, and definition of **pathways** for achieving these. Knowledge about the **impacts of the visions** for more evidence based individual decision making.
Methods, metrics, and guiding frameworks	Advance existing **s-LCA** methods towards higher granularity and representativeness. Develop **metrics** for assessing inclusion and enabling of affected communities to take part in a low carbon transition. Develop **metrics** that capture aspects of **global and local justice, ethics** and beyond the existing s-LCA framework. **Citizen science**, open data, living labs	Advanced S-LCA approaches. Metrics that measure not only social impacts, but also the **good life**, allowing to assess the contribution of technology to improving **quality of life** and to achieving a desirable future. **Social Readiness Level,** integration of **Responsible Research and Innovation** (RRI) processes. Interplay between social and environmental sustainability. Use of **social conflict resolution** methodologies to identify potential sources of conflict and involve all the stakeholders (promotion of social acceptance)

Impact
(SSH) research is essential for understanding stakeholder concerns and expectations and the potential impact or benefit that battery technology production and deployment has on them. This, in turn, is a key prerequisite for acceptance and thus for a smooth transition towards a carbon neutral global economy, where the required speed of change often leads to economic and social disruptions.

The following section outlines the expected impacts in advancing best practices, fostering community acceptance, and reinforcing supportive policy frameworks for battery adoption. These recommendations aim to address the diverse needs of stakeholders, from policymakers to end-users:

- Best practice recommendations, enhanced community acceptance and policy frameworks
- Stakeholders' satisfaction and participation into the battery deployment process
- Adoption of batteries-as-a-service models and prosumer engagement
- Promotion of circular business models for batteries
- Interdisciplinary collaboration and alignment with societal needs
- Understanding of second-life battery applications

Increased stakeholder awareness of future challenges
By enhancing stakeholder engagement, supporting circular economy models, and building awareness of future challenges, this framework encourages responsible and resilient energy solutions that align with societal goals and set new standards for sustainable energy storage.

2. Research and Innovation areas across the European battery value chain

2.1 New and Emerging Technologies – Strategic Research Areas

This section of the roadmap highlights the R&D needs required at low TRL to advance promising technologies into the next stage of market uptake for a wide range of applications. This Roadmap update 2025 builds on the foundation from Roadmap 2023, emphasizing advancements in material development, digitalization, sustainability and manufacturability (aligned with Battery2030+) to advance their progress while allowing flexibility to accelerate the adoption of sustainable battery systems across Europe.

2.1.1 Next-generation Flow Batteries

This section of the roadmap highlights the R&D needs required at low TRL to advance promising technologies into the next stage of market uptake for a wide range of applications. This Roadmap update 2025 builds on the foundation from Roadmap 2023, emphasizing advancements in material development, digitalization, sustainability and manufacturability (aligned with Battery2030+) to advance their progress while allowing flexibility to accelerate the adoption of sustainable battery systems across Europe.

Redox Flow Batteries (RFBs) encompass a broad spectrum of chemistries and technologies, as discussed in Roadmap 2023, with efforts focused on low-cost inorganics such as iron-, sulfur-, zinc-, manganese or copper-based electrolytes and all-organic based redox flow batteries (AORFBs). Common challenges, including extending the durability, controlling membrane crossover, finding alternatives to PFSA-based ion exchange membranes, reducing parasitic reactions and increasing the energy density of the electrolytes remain a focal point. This Roadmap update 2025 also prioritizes sustainability and recyclability to meet evolving regulations, while maintaining a focus on reducing costs.

R&D activities needed

The challenges identified in Roadmap 2023 (advanced materials, efficient membranes (including fluorine-free options), and disruptive concepts like solid boosters; implement computational tools and validate cost-effective systems, exploring dual-application chemistries) remain and should be urgently addressed. Additionally:

Short-term needs (2029):

- Design of novel active materials and advanced components for low TRL technologies (for example: low-cost inorganics, new organic and organometallic compounds), should include optimised chemistry-specific electrodes and low-cost catalysts to improve power performances.

Mid-term needs (2035):

- Develop robust production processes that support the commercialization of sustainable RFB components and systems.

Impact

Addressing these priorities will significantly advance RFBs' competitiveness, enabling them to fulfill their potential as a key technology for LDES, meaning 10 to 100 hours discharge at nominal power, capable of supporting grid stability and facilitating the transition to renewable energy sources.

2.1.2 Metal-air batteries for high performance and safety, for mobility and energy storage

Metal-air batteries offer lightweight designs and high energy density, utilizing metal anodes (e.g., lithium, zinc, aluminium) and ambient oxygen as the cathode reactant. Challenges include anolyte-catholyte incompatibility, electrolyte stability, and limited performance due to poor rechargeability, dendrite formation, air electrode degradation, and short cycle life. Hybrid designs with ion-conducting membranes help mitigate these issues, but scalability faces hurdles such as electrolyte replenishment and anode slurry management.

R&D activities needed

Roadmap 2023 focuses on addressing rechargeability, parasitic reactions, and electrolyte stability, this update 2025 expands the vision to market-specific implementations and novel technological solutions.

Short-term needs (2029):

- Develop cost-effective catalysts (e.g., Mn(II)O/N-doped carbon, single-atom catalysts, high entropy materials).
- Engineer solid-state (or quasi solid-state) MABs to address stability, oxygen crossover, dendrite growth and parasitic reactions.
- Development of 3D-printed electrodes for enhanced energy density and durability
- Create scalable designs for grid integration and consumer electronics.
- Improve zinc-air systems for grid and compact applications.

Mid-term needs (2035):

- Enhance power density and cycle life through optimize system designs
- Expand applications to wearables, medical devices, and electronics.

Impact

Metal-air batteries can revolutionize renewable energy storage, enabling greater integration of wind and solar. In transportation, their energy density could transform EV batteries, while in electronics, they promise lightweight, long-lasting solutions for devices like sensors and wearables.

2.1.3 Durable Metal–sulfur batteries with enhanced gravimetric energy density

Metal–sulfur batteries utilizing a sulfur-based cathode and a metal anode (e.g. lithium, sodium, magnesium), promise high theoretical specific energies compared to Li ion batteries due to multi-electron redox reactions. These batteries can achieve high specific energy densities beyond 400 Wh/kg for lithium–sulfur (Li–S) batteries, and 200-440 Wh/kg for other metal systems. While the 2023 roadmap detailed limitations like sluggish sulfur conversion kinetics, polysulfide shuttling, and electrolyte consumption over cycling, this 2025 update expands on these themes, emphasizing solutions to tackle the insulating nature of sulfur and Li2S, polysulfide shuttling and significant cathode volume changes causing capacity fading, and safety issues related to pure metallic anodes. It also incorporates strategies for resolving manufacturing complexities to make these batteries viable for commercial applications.

R&D activities needed

All the challenges identified in Roadmap 2023 remain, with additional needs identified including:

Short-term needs (2029):

- Development of low-cost, sustainably sourced sulfur host material and electrocatalyst nanoparticles.
- Development and adapting production technologies for pilot scale pouch cell manufacturing (e.g. Lithium anode and sulfur cathode handling)

Mid-term needs (2035):

- Upscaling the synthesis of sulfur host materials, ideally from precursors which are low-cost, sustainably produced and abundant in the European Union
- Development of composite polymer and gel polymer electrolytes which are specifically tailored to address issues related to metal–sulfur batteries.

Impact

Metal–sulfur batteries are expected to exceed LIB performance limitations, enabling new applications such as ultralight batteries for electric aviation, drones and low cost and sustainable batteries for energy storage. The abundance and low cost of sulfur may significantly reduce our reliance on scarce and expensive electrode materials such as cobalt and nickel.

2.1.4 Next-generation Flow Batteries

Aqueous batteries offer high safety, low production costs and sustainability due the use of non-toxic and non-flammable electrolyte and abundant and low-cost materials. Zinc-ion and sodium-ion chemistries are promising with high specific power, high reversibility and sustainability. Nonetheless, other types of aqueous batteries are also being addressed. Challenges include the limited voltage window of the electrolytes and electrode dissolution, as finding a single electrolyte compatible with both the anode and cathode remains difficult. The solution to these stability problems can potentially be addressed not only through materials solutions, but also through alternative cell design concepts.

R&D activities needed

The most significant research need is establishing material systems that are sufficiently stable in the electrolyte, thus avoiding parasitic reactions which ultimately limits the cyclability and lifetime. In addition to the needs identified in Roadmap 2023, the following must be addressed:

Short-term needs (2029):

- Electrolyte development and impact of concentration and pH innovate gel and compartment-specific electrolytes to address low voltage windows and reduce electrode solubility, alongside developing cheaper and recyclable electrolyte salts.
- Coatings of electrode materials to improve electrolyte stability and to prevent dissolution.
- Recyclable cell components, including electrolytes

Mid-term needs (2035):

- Cell designs to circumvent material stability issues, differing in compact and purged systems.
- Development of recycling processes for cell components, including the electrolyte.

Impact

Batteries with increased power and energy density, safety, lower critical raw material content towards (quasi)-zero metal excess, simplified manufacturing processes (no drying), reduced manufacturing costs and carbon footprint. These advancements, with improved recyclability, accelerate market acceptance in safety-critical applications and stationary market applications, such as frequency regulation, fast charging etc. Especially for Zinc batteries, the recycling procedures are highly advanced.

2.1.5 Zero Li / Na excess battery technologies

Zero Li or Na excess batteries are advanced energy storage systems that use a metal negative electrode and a positive active material in the discharged state. These batteries eliminate the need for additional metal reservoirs, enabling an anode-free configuration. This innovative approach has the potential to achieve the highest retrievable energy density and specific energy compared to traditional batteries, while significantly reducing manufacturing costs. Additionally, the concept aligns with sustainability goals by reducing critical raw material use and lowering environmental impact. However, the development of zero Li-excess (or zero Na-excess) batteries faces significant challenges, such as minimizing metal loss during operation, ensuring interface stability, and scaling up manufacturing processes. Addressing these challenges will unlock the potential for safer, more efficient, and cost-competitive batteries.

R&D activities needed

Although significant progress has been made, with improved understanding of Li nucleation and growth processes as well as the effects of interfaces, several challenges persist. In addition to the challenges identified in the 2023 Roadmap, the following aspects should also be addressed:

Short-term needs (2029):

- Develop thin (<20 microns) lightweight and more sustainable Li/Na-philic current collectors that ensure homogeneous Li plating/stripping processes at moderate to high current densities (> 1mA/cm2), and depth of cycling (> 3mAh/cm2).

- Propose and evaluate interfaces and coating solutions to generate (ex situ or in situ) a stable solid-electrolyte interphase (SEI), improve reversibility and minimize lithium corrosion. Accelerate the discovery of suitable solutions by means of high throughput experimentation.
- Formulate electrolytes to improve cyclability efficiency, limit Li losses and prevent impedance increase.

Mid-term needs (2035):
Optimise the cell design, formation and/or activation and operational conditions through AI techniques and physics-based models (e.g., temperature, pressure) with respect to all the cell components to meet cyclability and high energy density objectives.

- Achieve >1000 cycle life with improved safety, low-pressure operation, and high energy density.
- Reduce costs to €75/kWh and ensure materials are recyclable under Batteries Regulation.
- Conduct safety benchmarking and validate designs with a minimum 1 Ah capacity for regulatory compliance.

Impact
Zero Li-excess batteries will deliver higher energy density, improved safety, and lower environmental impact while reducing reliance on critical materials. Streamlined manufacturing and recyclability will cut costs, support sustainability, and enable scalability, positioning these batteries as a key solution for a greener, more efficient energy future.

2.1.6 Multivalent non-aqueous battery systems (Ca, Mg, Al, Zn etc.)

Rechargeable batteries based on multivalent metals (Mg, Ca, Al, Zn) promise higher energy density, better resource availability, safer, non-flammable electrolytes and a lower tendency for dendrite formation compared to Li-based systems. They show enormous potential for applications ranging from stationary storage and electro-mobility to aviation. However, significant challenges in material, electrode, and cell development limit their practical realization like anode passivation, limited cyclability, and reduced energy density in certain chemistries that use monovalent charge carriers (e.g., Al dual-ion). Upscaling processes with respect to electrode and cell manufacturing technologies are still at an early stage.

R&D activities needed
The sluggish kinetics and high polarisation of these systems caused by the higher charge of the charge carrier ions require research into electrode- and electrolyte development for all metals considered. In addition to metal-anode passivation strategies and electrolyte development, as identified as priority research areas in Roadmap 2023, the following should be considered:

Short-term needs (2029):

- Development of new liquid electrolytes should focus on costs, safety, ionic conductivity, transference number and temperature stability
- To mitigate the corrosive nature of current electrolytes, suitable stable and cost-efficient passive materials (current collector, separator, casing) are required.
- Investigate organic cathode-active materials as a promising solution to address the slow kinetics of multivalent ions.

Mid-term needs (2035):

- Advance the development of solid electrolytes for multivalent batteries, currently at an early stage, to improve performance and reliability.
- Focus on cathode development through the discovery of new active materials, optimized electrode formulations, and binders, alongside research into charge insertion/extraction mechanisms to enhance kinetics and overall performance to make them competitive with existing Li-ion technology.
- Explore conversion cathodes based on sulfur as offer the highest capacities at low cost, leveraging synergies across different metal/sulfur battery systems.
- Address cell manufacturability and recyclability by developing suitable cell manufacturing technologies, new recycling concepts and designs optimized for recycling.

Impact

The compounded advantages of multivalent batteries can render them viable for a broader range of applications at much reduced monetary and environmental cost. The goal is to advance the current TRL (2-4) to a level that constitutes an incentive for self-sustained industrial R&D.

2.1.7 Hybrid supercapacitor-batteries

Hybrid supercapacitor-batteries aim to combine the high energy of batteries and the high power capability of supercapacitors. The desired characteristics could be achieved through combination of high-capacity battery-type negative electrode with a fast-capacitive positive supercapacitor electrode. Other research efforts are focused on redox-active electrolytes. Both areas require more investigation to ensure desired performance and commercial uptake. The efforts should also be focused on avoiding critical raw materials, and this need has also fostered important research beyond lithium metal ion capacitors, e.g. sodium, potassium and zinc, although these are less mature.

R&D activities needed

R&D activities needed are associated to the development of advanced novel cell components and pre-metallation strategies enabling fabrication processes that are cost-effective and scalable. In addition to the needs identified in Roadmap 2023, which still require more research (e.g. development of highly performant redox-active electrolytes, new generation of more energetic and powerful materials etc.), the following must be addressed:

Short-term needs (2029):

- High-voltage and wide-temperature operation.
- Advanced current collectors to improve electrical conductivities and decrease contact resistance. Methods such as laser patterning and etching to enhance heat transfer, mechanical stability, and cell weight reduction. Ensure compatibility with upscaled, industrial production processes.
- Develop novel, cost-effective strategies for pre-metallation that are compatible with roll-to-roll production systems. These strategies should prioritize air-stability and solution processability to enable seamless integration into scalable manufacturing processes.

Mid-term needs (2035):

- Implement sustainable production and recycling methods such as dry or aqueous processing for high mass loading carbon-based electrodes and eliminate the use of fluorinated binders and toxic solvents.

Impact

Incorporating novel advanced materials and designs to increase energy density will enable high-power systems with fast response rates, even in a fraction of a minute, prolonged cycle life, and low cost of ownership. Possible applications include stationary storage, such as grid services or more efficient renewables thanks to fast charging/discharging capabilities, and mobility such as two and three wheelers, public transport (hybridised with other batteries/fuel cells or on their own), or industrial mobility (heavy machinery, forklifts, Unmanned Aerial Vehicles).

2.1.1.8 Multimodal multiscale correlative characterisation

As highlighted in the previous roadmap, achieving next-generation battery technologies requires a comprehensive approach to material discovery, optimization, and validation. Multimodal characterization plays a pivotal role by integrating advanced, multi-technique, multiscale, and in operando methods to analyse and optimize battery materials providing unprecedented insights. These methods are essential for addressing industry demands for energy-dense, durable, and sustainable battery solutions. To support these efforts, the establishment of a collaborative framework—such as a European Battery HUB—is critical. This hub would streamline access to large-scale European infrastructures, including synchrotrons and neutron facilities, enabling shared experimental programs, standardized methods, and efficient data exchange, thereby fostering collaboration across sectors and accelerating innovation.

R&D activities needed

Short-Term Needs (2029):

- Develop guidelines for reproducible and correlative analysis across various characterization techniques to standardize multimodal characterization protocols.
- Launch the European Battery Hub as a collaborative platform for community-organized experimental programs and centralized data sharing.
- Improve multi-technique, multiscale, and in operando methods to enable real-time analysis

of battery materials and interfaces, refining advanced characterization techniques.
- Create open-access data repositories and analysis tools to facilitate the integration of experimental results across academia and industry.

Mid-term needs (2035):
- Transition insights from advanced characterization methods into market-ready battery technologies to industrialize multimodal characterization outputs.
- Scale the European Battery Hub to support large-scale industrial R&D with seamless access to state-of-the-art infrastructures and expert networks.

Impact

Multimodal characterization and the establishment of a European Battery HUB are transformative steps that will not only advance battery material discovery but also strengthen Europe's leadership in sustainable energy storage technologies, driving innovation, collaboration, and competitiveness.

2.1.1.9 Biomimetics as smart functionalities for batteries – a transversal challenge

Building on the priorities outlined in **Roadmap 2023**, biomimetic and biobased materials continue to offer transformative potential for battery design by replacing conventional non-active battery components, such as separators, binders current collectors, housing, and tabs. These materials now incorporate advanced functionalities, such as self-healing, controlled transport at interfaces, and embedded "medicament" storage for on-demand release, enhancing battery performance, extending lifespan, and reducing CO2 emissions. The integration of additional functionalities, such as sensors, redox mediators, etc., in the non-active materials expands batteries' capabilities beyond conventional energy storage.

R&D activities needed

Short-term needs (2029):
- Explore utilisation of biomimetic and biobased materials with self-healing functionalities in advanced battery cells.
- Design smart separators, binders, and current collectors incorporating microcapsules with embedded "medicaments" to extend battery cell lifetime.
- Demonstrate advantages of embedding smart functionalities in battery cells, including improved performance and prolonged lifespan.

Mid-term needs (2035):
- Target various battery chemistries aligned with the Strategic Energy Technology (SET) plan, prioritising critical degradation processes.
- Ensure adaptability to mass production processes of battery cells and compatibility with subsequent recycling processes.
- Evaluate Quality, Reliability, and Longevity (QRL) over the battery cells' lifespan.

- Showcase competitive advantages over alternative methods such as replacement, recycling, or second-use strategies.

Impact

Advancing biomimetic materials in battery design will extend system lifespan, reduce CO2 footprints, and delay recycling needs, fostering sustainability in European battery production. Additionally, integrating biomass and biowaste into material development will create industrial opportunities in rural and agricultural regions, supporting job creation and advancing the circular economy.

2.1.10 Accelerated material discovery and multiscale modeling for emerging battery technologies – a transversal challenge

Building on the priorities outlined in Roadmap 2023, significant progress has been made in replacing traditional trial-and-error methods with integrated approaches combining physics-based and data-driven (e.g., deep learning) models. These models enable the prediction of material properties across multiple scales and times, as demonstrated in initiatives such as BIG-MAP. This integration has accelerated the discovery of novel materials while addressing manufacturability, integration into prototypes, and end-of-life considerations. However, to fully realize the potential of emerging battery technologies, further advancements in predictive modeling, data interoperability, and automation are needed, coupling computational models with self-driving laboratories and advancing "manufacturability by design" to ensure scalability and sustainability.

R&D activities needed

In addition to the activities highlighted in Roadmap 2023 related such as data infrastructure development, enhanced machine learning models, and multiscale modeling, the following should be prioritized:

Short-term needs (2029):

- Integration of multiscale models with self-driving laboratories developing high-performance materials acceleration platforms.
- Development of the concept and models to predict "manufacturability by design", allowing for design materials from the early stages of their use to their end-of-life.
- Expand frameworks for seamless integration of multi-source, multi-fidelity data to support model scalability and accuracy.

Mid-term needs (2035):

- Scale materials acceleration platforms from laboratory to industrial levels, ensuring predictive models and computational tools align with real-world manufacturing constraints.
- Develop hybrid models combining physics-based approaches with AI-driven insights to improve performance, sustainability, and recyclability in battery technologies

Impact

By accelerating the development of new materials by 5–10 times, these efforts will enable a 2–3 fold increase in the speed of advancing new battery technologies. Additionally, establishing comprehensive materials acceleration platforms will drive innovation beyond batteries, benefiting other fields reliant on high-performance materials.

2.1.11 Sustainable Batteries via Design-for-X (Manufacturability, Circularity, etc.) Strategies – a transversal challenge

Sustainability encompasses social, environmental and economic aspects, requiring a holistic approach from the beginning of technology development. By aligning with the R9 Framework (Rethink and Reduce), the focus is on Design for Manufacturability and Design for Circularity, ensuring new technologies are both sustainable and circular. This includes prioritizing non-critical raw materials (e.g., Na, K, Ca, Mg, Zn, Al), addressing supply chain constraints, and incorporating prospective sustainability assessments. The results of these prospective assessments will guide further developments of new and current technologies that show better performance, not only in technical aspects, but also in their sustainability performance.

R&D activities needed
Short-term needs (2029):

- Develop sustainable materials and electrodes incorporating non-critical raw materials.
- Develop prospective sustainability evaluation frameworks for low TRL chemistries and materials, taking into account the high uncertainty of the data and the limitation in the information available. Commonly agree on data formats or data transfer protocols to promote a wider utilization of the data.
- Incorporate testing of potential processing methods to identify and address potential pitfalls during materials development (Design for Manufacturability).

Mid-Term Needs (2035):

- Advance circularity strategies, including reusable and dissolvable materials, to align with circular economy goals.
- Scale processes for manufacturability and sustainability to ensure broad adoption of emerging battery technologies.

Impact

The inclusion of Design-for-X strategies combined with prospective sustainability assessments during the early stages of technology development will enable new battery technologies that are sustainable, circular, and aligned with global environmental and economic goals.

Current battery manufacturing processes, especially for Li-ion chemistries, face challenges like high energy consumption, long production times, and costly CAPEX/OPEX. Innovations such as artificial SEI to eliminate formation cycles, advanced analytical methods to identify low quality cells without the need for aging, gradient electrode production to enable tailored performance characteristics within a single electrode and advanced surface structuring technologies show promise but require further development for industrial scalability. Next-generation batteries will also need entirely new manufacturing processes to address these inefficiencies and enable sustainable production.

2.1.12 Low TRL disruptive manufacturing technologies – a transversal challenge

Current battery manufacturing processes, especially for Li-ion chemistries, face challenges like high energy consumption, long production times, and costly CAPEX/OPEX. Innovations such as artificial SEI to eliminate formation cycles, advanced analytical methods to identify low quality cells without the need for aging, gradient electrode production to enable tailored performance characteristics within a single electrode and advanced surface structuring technologies show promise but require further development for industrial scalability. Next-generation batteries will also need entirely new manufacturing processes to address these inefficiencies and enable sustainable production.

R&D activities needed

Short-term needs (2029):

- The development of novel manufacturing processes to produce high performance electrodes while reducing the energy consumption, production footprint (space), time and cost.
- Develop tailored manufacturing methods for next-generation batteries, such as gradient electrodes.

Mid-term needs (2035):

- Automate processes using robotics, AI, and digital twins for enhanced control and efficiency.
- Scale these technologies from the lab to pilot scale and beyond using advanced modeling to optimize processes and enable pilot-to-full-scale production.

Impact

Innovative manufacturing will reduce production times and costs, reduce environmental footprint and accelerate the production of more affordable, and sustainable battery technologies.

2.2 Key Recommendations

Advancing new battery technologies is a vital part of the innovation process that requires a coordinated effort across research, industry, and policy makers. Long-term research is essential for achieving groundbreaking discoveries and improvements at early stages of technological development. These efforts have the potential to significantly shape a future society rooted in sustainability, circularity, enhanced safety, and low-carbon manufacturing.

The identification of new materials that are cost-effective, sustainable, and recyclable is key to progress across all battery technologies. Digital tools and artificial intelligence will be instrumental in accelerating material discovery and optimization, while a deeper scientific understanding of degradation processes will enable iterative improvements. These advances must be supported by large-scale infrastructures and open data repositories to foster collaboration and innovation. To accelerate market adoption, substantial efforts and funding must focus on developing innovative and more sustainable manufacturing and recycling processes that can adapt to various battery chemistries. These efforts will enable innovation, sustainability, and scalability in battery technologies for a low-carbon future.

Strategic Research Area	Short term	Medium term	Long term
Advanced Redox Flow Batteries	Novel active materials and disruptive concepts for cost reduction and sustainability increase and performance enhancement Implementation of computational models and/or artificial intelligence for novel cell components Validation at devices and systems level	New chemistries or electrolyte formulations to enable dual applications	
High-performance safe Metal-air batteries for mobility and grid energy storage	Novel electrode/electrolyte materials, catalysts and topologies Solid state configurations addressing challenges at the interface Scalable cell concepts and design for grid scale and power electronics applications.	System optimization for broader application ranges including EV integration, grid scale and off-grid Alternative design s for wearable electronics	
Durable Metal sulfur batteries with enhanced power capability	Advanced electrolyte enabling low electrolyte to sulphur ratio Stable interphase and metal anode for solid state configurations Adapting production technologies of sulphur and metal anode for pilot scale uptake	Upscaled synthesis of sulphur from sustainable and European based resources Solid-state concepts including also polymer electrolytes System level demonstration	

Strategic Research Area	Short term	Medium term	Long term
Safe & sustainable aqueous batteries	Advanced materials and cell components with lower cost and recyclability. Operational conditions for improved performance	Cell design Scale-up	
Anode less battery technologies	Stable interfaces Pre-metallation strategies Current collector design Improved understanding of processes via advanced characterisation tools and non-invasive methods	Cell design and operational condition optimization Safety assessment Cost reduction and improved cycle life	
Multivalent non-aqueous systems (Ca, Mg, Al, Zn etc.)	Metal anode passivation strategies Non-corrosive electrolytes Organic cathode active materials	Improve the rate performance and capacity Solid-state concepts New cathode active materials (including conversion) Manufacturability and recyclability	
Hybrid supercapacitor -batteries	More energetic and powerful materials. New electrolytes (incl. redox active). Novel current collectors Solvent-free electrode manufacturing processes.	Pre-metallation strategies compatible with manufacturing processes	

Strategic Research Area	Short term	Medium term	Long term
Transversal Challenges			
Multimodal multiscale correlative characterisation	High throughput pipelines with semi-automated data acquisition and analysis, standardised protocols Large-scale facilities hubs Correlative multimodal characterisations and integrated multi-scale workflows Open access data repositories	Scale the European Battery Hub	
Biomimetics as smart functionalities for batteries	Biomimetic and biobased materials with self-healing functionalities Demonstrate advantages for improved performance and lifespan	Demonstrate adaptability to various battery chemistries Evaluate advantages compared to recycling and second-use	
Accelerated material discovery and multiscale modeling for emerging battery technologies	Data infrastructures Multiscale, high-fidelity models integration Machine learning models with predictive power	Self driving laboratories Prediction of “manufacturability by design”	
Sustainability by Design for Battery Materials and Cells	Use of MAPs for sustainable design Shared data infrastructure Shared standards, protocols, and ontologies		New ground-breaking discoveries
Sustainable Batteries via Design-for-X (Manufacturability, Circularity, etc.) Strategies	Novel sustainable materials Sustainability evaluation frameworks Develop and test circularity strategies		
Accelerated material discovery and multiscale modeling for emerging battery technologies	Reduction of energy consumption and carbon footprint	Scale-up Modelling and data-driven approaches Automation and digital twins	

2.3 Raw Materials and Recycling Strategic Research Areas

2.3.1 Hybrid supercapacitor-batteries

Lithium (Li) ion streams represent > 10% of the mixed portable batteries collected, however the composition is changing, with increasing numbers of Li ion batteries due to B2C applications such as Light Mean Transportation (eg. el-bikes, el-scooters) and household storage. This requires different take back and collection models. Safe and environmentally sustainable, post-consumer battery management which is capable of continuously and quantitatively feeding the innovative recycling pathways must be ensured to meet the future Battery Regulation targets. New reverse logistics solutions and collection models need to be developed to i) reduce the potential risks of handling damaged /defective batteries (priority), ii) digitize the waste supply chain for more efficient waste traceability and certified collection of diagnostic and technical data, iii) improve the quality of the waste stream for streamlined materials recovery, reuse and recycling.

Recent developments from the implementation of Horizon Europe (HE) projects (e.g. REINFORCE, BattReverse, Rebellion, Recirculate) are demonstrating advancement in safe and improved battery diagnostics and monitoring systems, faster discharging strategies, innovative traceability approaches and smart logistics solutions (e.g., sensing) for safe transportation, handling and storage of EoL batteries. The use of robotics, AI and industry 4.0 will be demonstrated in real environment at TRL6 to support the automation of adaptable dismantling and sorting (e.g. by SoX) of EoL batteries and components. Blockchain-based platforms are also designed to enable unique battery passport to track key-battery data also for 2nd and 3rd life battery reuse.

R&D activities needed
Short-term needs (2029):
All the R&D needs detailed in the Roadmap 2023 are still relevant and should be further implemented. Taking into consideration the developments from the HE projects funded in the same domain, the research activities are targeted for TRL≥7. Additionally:

- The R&I community should also focus on the sorting of other types of batteries and scraps (from other applications, including electro electronic scraps from WEEE). This action is important in terms of “safety for recycling” perspective.

Impact
The development of a highly efficient, safe and innovative take-back, collection and reverse logistics solutions will impact the development of an organised system of battery handling across the EU and will enable high quality and fully integrated business models in the circular economy of the battery value chain. A sustainable and profitable growth of the batteries recycling European industry will be also ensured.

2.3.2 Adaptability and tolerance of the existing recycling processes to new technologies

The conventional recycling methods (pre-treatment, shredding, hydro- and pyrometallurgical processes) are likely to be easily transposable to some of the new chemistries. In case of Silicon (Si), metallurgical processes exist in large scale, but they are difficult to be profitably adapted to produce battery grade Si. The direct recycling methods (and others) might be more complicate to transpose.

R&D activities needed
Mid-term needs (2035):
This research area targets a mid-term need at TRL7, as it will be possible to utilise experience from previous recycling activities demonstrated for Li-ion batteries. The R&D needs identified in the Roadmap 2023 are still considered topical however in addition:

- Handling of PFAS and unsafe side-streams generated by the recycling processes (especially in case of hydrometallurgical routes)
- Validation of the sustainability of the recycling technologies (e.g. LCA and other methodologies)
- Needs for technologies to assess the quality of the waste batteries and included components/materials for future recycling.

Impact
A substantial increase in robustness and flexibility of the existing recycling processes, to enable treatment of LIBs with varying chemistries (NMC, NCA, LFP, etc.), will enable the adaptability and tolerance of these processes to new technologies. The benefit of such adaptability will reduce new investment CAPEX for industry and ensure greater competitiveness. Chemistry-agnostic battery recycling processes will reduce the impact of battery chemistry market share evolution.

2.3.3 Recycling processes for LFP recycling

Lithium Iron Phosphate batteries are quickly overtaking the NMC technology, especially in the stationary energy storage market. With their increasing market share globally, the need for recycling technology specific to LFP is necessary. Despite this urgency, LFP recycling is still seeing large regional disparities and challenges in its establishment mostly due to the high operational costs compared to the low value of the recovered materials. However, growing legal pressure (especially due to the Battery Regulation) and the sheer size of the market encourages LFP battery recycling. The inclusion of LFP batteries in mandatory recycling will result in significant decrease of residual waste to landfill with positive impacts on the overall sustainability of the Li-battery industry. Additionally, the risk of a Phosphorus supply shortfall can be avoided by taking into consideration opportunities for cross-sector circularity, which means not only mined materials as primary supply to electrification but also closed loop recycling capacity. Horizon Europe projects of low TRL recycling technologies for LFP-based batteries (manufacturing scraps as well as EoL) (Renovate, ReUse and Revitalise) aim to address issues related to the process's techno-economic challenges and sustainability.

R&D activities needed
Medium/Long-term needs (2035+):

- Development of specific recycling processes for LFP, to reduce the Carbon Footprint (CF) by recovering more materials and enhancing the recycling efficiency target, that means:
- innovative hydrometallurgical approaches for the recovery of Lithium, Iron and Phosphorus as intermediates/precursors
- tackling circularity to close the loop by regeneration and direct recycling of the active materials.

Impact

Innovative solutions for LFP batteries recycling technologies for will decrease the EU dependency on importing raw materials from outside the EU and will consider also Phosphorous and Phosphate when securing CRMs for electrification (both stationary and transport applications). Additionally, these measures will enhance the competitiveness of the European recycling industry.
LFP recycling will contribute to ensure the recycling efficiency target in the Battery regulation is achieved and will result in a positive impact towards the reduction of the Carbon Footprint by recovering more materials and increasing the sustainability of the entire European battery value chain.

2.3.4 New recycling processes for Li Metal batteries and other emerging chemistries

Lithium Metal Batteries (LMB) are quite different from Li ion batteries when it comes to the negative electrode (Li). Unlike graphite, Lithium (Li) management will require more care and specific processing which is not used in the case of graphite-based batteries. All Solid- State Batteries (ASSB) and other emerging technologies have no "ancestors" and are likely to require building new recycling techniques to ensure supply. Due to safety concerns, the known separation methods cannot be used, and electrolyte chemistry will have a huge impact on the choice of the recycling approach. A similar situation exists for new emerging technologies, for example Vanadium Redox Flow batteries, for which new technical and feasible processes are needed to ensure supply.

R&D activities needed
Long-term needs (2040+):
All the R&D activities highlighted and detailed in the Roadmap 2023 are still relevant as long-term needs:
i)recycling of Gen4 batteries (including the discharging/deactivation step for the Li metal);
ii) recycling of redox flow batteries;
iii) engineering challenges related to cell/module/pack, cell design and disassembly processes;

iv) new disassembly and pre-treatment technologies considering the removal of sensors (if any), epoxy systems/glues and the separation valuable components.

Impact

The development of efficient recycling processes for the new generation batteries will impact the market growth and European competitiveness by sustainable, safe and scalable solutions that will prepare the battery industry to meet new regulatory targets for recovery and recycling. As the LMBs and Vanadium Redox Flow batteries contain critical raw materials, the recycling processes and recyclability need to be considered already in the early stage. This will ensure that the next generation batteries can be recycled, and the secondary raw material supply secured also in future.

2.3.6 The Sodium-ion and other new chemistries battery supply chain

Sustainable, green and low-cost production of SIB and other non-Lithium emerging technologies are of vital importance towards the next generation of energy storage systems. Such chemistries are at various stages of development and demonstration, as outlined in the sections on New and Emerging technologies and Advance materials. To achieve scale-up potential, synthetic methods and the environmental impact of corresponding manufacturing process should be improved. The raw materials should be cheap and abundant.

R&D activities needed
Short-term needs (2029):
All the R&D activities highlighted and detailed in the technology Roadmap 2023 are still relevant as short-term needs at TRL7:
i)ensure a European supply chain for SIBs (e.g. Na salts and hard carbon, Prussian analogues);
ii) production of bio-based carbons;
iii) focus on other chemistries (e.g. multivalent systems).

Impact

A non-Lithium European based supply chain will reduce the EU dependence on CRMs by substituting with abundant, cheap, non-toxic materials by decreasing the negative impacts generated by potential trade disruptions.

2.3.7 Sustainable sourcing and processing of raw materials

Efficient extraction and processing of battery grade raw materials is a key element in securing the European leadership in energy storage markets, but the production volumes in EU are still marginal. There is a high level of urgency to develop new sustainable and cost-efficient processing solutions for Lithium (Li), Nickel (Ni), Cobalt (Co), Manganese (Mn), Rare-Earth Elements (REEs), Vanadium (V), Silicon (Si) and graphite (both natural and synthetic) from current and emerging materials streams. Several European projects (e.g. Source, Licorne, Grafite3) are implementing technologies that would lead to lower environmental impacts, reduced CO2 emissions, water and energy saving.

R&D activities needed

Short-term needs (2029):

All the R&D activities highlighted and detailed in the technology Roadmap 2023 are still relevant as short-term needs at TRL7:

i)cost- and sustainable carbon-based anode production processes;

ii) use of extracted materials or RMs deposits as sources for battery materials;

iii) reduction/handling of wastes (e.g. Sodium Sulphate);

iv) vertical integration of European mining; v) efficient refining processes of blended RMs.

Impact

Innovation in raw materials sourcing, refining and processing will impact the securing of future EU supply for next generation technologies and a more competitive and decarbonised battery industry. The activities will also contribute to decrease the EU dependency on imported battery chemicals and raw materials.

2.3.8 Generative AI for new predictive models - transversal challenge

Development of new predictive models leveraging advanced generative AI tools enable early and accurate predictions of battery performance across key metrics such as safety, cyclability, and recyclability.

2.3.9 Objective sustainability assessment methodologies – transversal challenge

Develop objective assessment methodologies to get a preliminary estimate of the sustainability of a cell design. This should include a circularity assessment before production, considering the technology characteristics to assist in process development.

2.3.10 Physics-based and AI models with automated data collection - transversal challenge

Development of a digital solution that aims at integrating physics-based and AI models, combined with automated data collection throughout the entire value chain, from manufacturing to recycling. Databased control enables a link between the single processes as well as the production and recycling chains to utilize synergies and enhance cross-process understanding.

2.4 Key Recommendations

Member States (National Authorities). The battery value chains will spread across countries and continents. Thus, national authorities are invited to join the discussions at European level, both to give insights from national impacts and specialties, and to learn how to collaborate. This will ensure fair sourcing and utilisation of raw materials across Europe and create European circular economy industry.

Policymakers. As stated in the Critical Raw Materials Act, increasing the European critical raw material supply is urgently needed. The proposed actions are highly relevant to support the goals in the twin transition. In addition, substitution of critical raw materials is also highly relevant. Both directions are needed to ensure the sufficiency of raw materials for batteries.

Industry & Start-up. Adaptable processes of recycling are needed to decrease new investment CAPEX and increase competitiveness. The development of strong circular economy business models is necessary to ensure a profitable raw materials supply chain in Europe. Efficient and innovative solutions of collection and logistics are also needed to ensure the growth of the batteries recycling European industry.

Research Community. Europe needs battery raw materials, and an active research community is the key to develop methods to ensure material sufficiency. Recycling research is needed at different TRLs, both to ensure safe handling/collecting and cost-efficient recycling of used Li-ion batteries that are now on the market, and to be ready for recycling the new battery types, which will be ready to be recycled in future. Even though recycling of e.g., solid-state batteries will be relevant only in the long term, research needs to be done already now to ensure that we are not developing batteries, which can't be recycled in future either at all or at too high cost. Raw materials also need strong research efforts. The main target is to ensure a sustainable and cost-efficient supply of materials. At the same time, there needs to be a decrease in European dependency on other continents. Research is needed especially to support development of more sustainable options for raw materials and utilisation of secondary raw materials, with consistent quality.

General Public, Association & Communities. Batteries will, for their part, help to build resilient and carbon-neutral societies. This won't happen unless there is strong support from the citizens. We encourage the public to get familiar with new technical solutions, and to actively follow and participate the discussions regarding battery raw materials and recycling. Getting feedback from the public about the new solutions and regulations is essential to speed up the twin transition and to understand the challenges that might not be realised by the research community or policy makers.

Strategic Research Area	Short term	Medium term	Long term
Logistics, sorting, collection and discharging/deactivation	Safe, fast and cost-efficient ways for discharging/ deactivation Innovative waste collection systems Upstream EoL processes Advanced systems for sorting Active monitoring systems for high level of safety Integration of inputs from recycling for sorting stages		
Adaptability and tolerance of the existing recycling processes to the new technologies		More flexible and adaptable recycling processes for LIBs Flexible recycling processes for the treatment of black mass including blended chemistries Adaptability of existing technologies to some new chemistries Adaptability of the existing technologies to the recovery of graphite from the Si-based anodes batteries Implementation of existing technologies to enhance the Li recovery rate Direct recycling for emerging chemistries	
New Recycling processes for Lithium (Li) metal batteries and other emerging new technologies			New recycling processes for gen 4 batteries (including solid electrolytes) and V-RFBs BREFS for specific technology and battery chemistry Address engineering challenges for efficient recycling Improved pre-treatment and separation strategies (including streams of different chemistries) Discharging/deactivation processes for new chemistries batteries (e.g., LMBs)

Strategic Research Area	Short term	Medium term	Long term
Integration of secondary raw materials		Battery-grade materials from mining and industrial wastes Closed loop for batteries and increase of symbiosis with other sectors Raw Materials integration from direct recycling processes and manufacturing scrap into battery manufacturing	
The Sodium-ion and other new chemistries battery supply chain	Ensure EU supply chain for SIBs Production of bio-based hard carbon for SIBs Focus on other chemistries (e.g., multivalent cations)		
The Sodium-ion and other new chemistries battery supply chain	Alternative route to replace graphite Use of extracted or underutilised battery Raw Materials deposits as battery materials sources More environmentally friendly sourcing Vertical integration of EU mining with materials and battery chemicals production Efficient refining processe		
Transversal Challenges			
Sustainability / Digitalisation	Implemented Tools for sustainability assessment		
Sustainability / Safety	Safe and Sustainable by design		
Digitalisation	Digital twins with hybrid models for the optimisation of recycling processes		

2.5 Advanced Materials Strategic Research Areas

2.5.1 Li-ion batteries (gen. 3) (driven by mobility)

Focusing on developing advanced materials for higher energy and power density by enhancing capacity and enabling higher operating voltages. Much of the materials focus and challenges remains the same as in the previous roadmap[citation]. In this revision LFP cathodes are excluded while other polyanionic compounds e.g LMFP are still included. Blended cathodes offer the chance to tailor performance to specific cost, market and application targets.

It is acknowledged the urgent need for Sustainably produced European artificial graphite anode that ensures supply chain independence and that graphite's energy density, is increasingly being boosted by addition of silicon. Multiple strategies are in development to make Si-graphite composites (10<Si<50%) and silicon-dominant anodes a practical solution for the future with emphasis on particle size, shape, porosity, doping and compatible binders and electrolyte systems.

The increasing application of thin ceramic coated separators and thinner foil current collectors is to be expected and composite copper foils as the next innovation step. These measures can improve safety, reducing inactive component weight and reducing cost of copper per cell respectively.

R&D activities needed

Short-term needs (2029):

- Stable cathodes and electrolytes for high-voltage (4.8 V) batteries with ≥2,000 cycles
- Durable cycling for Li- and Ni-rich, low-Co cathodes with up to 2,000 cycles
- Optimization of manganese-rich HLM, LMFP materials for low cost and high safety
- Advanced Si/C materials, additives, and electrolytes supporting up to 20 wt% Si (~1000mAh/g) for fast charging and reduced degradation
- Cathode materials designed for solvent-free or dry processing
- Blended Cathode Active Materials
- Stable electrode / electrolyte interfaces
- Optimization of materials from direct recycling
- Ceramic coated separators for increased performance and safety

Long-term needs (2040)

- Develop cathode materials with capacities over 300 mAh/g, coulombic efficiencies of 99.98%, and lifespans of at least 1,000 cycles, paired with anode capacities of ≥1,200 mAh/g.
- Create lithium-ion batteries with minimized use of critical materials (excluding lithium).

Impact

Technological impact: Lithium-ion battery materials will pave the way towards their fundamental limits by 2030 and enable adoption of EVs.

Economic impact: Innovative solutions are needed to decrease the dependency on importing raw materials and components from outside the EU, but also to develop competitive technologies in Europe.

Environmental impact: The proposed measures will have a direct environmental impact by keeping the materials in the value chain, using less critical raw materials, increasing energy density and lifetime of battery.

2.5.2 Li-ion batteries (gen. 3) (driven by mobility)

This strategic area is devoted to the development of solid-state electrolytes, cathode materials, and anode materials (including additives) that enhance thermal and electrochemical stability and compatibility. The goal is to achieve higher energy and power densities, faster charging capabilities, improved cyclability, and enhanced safety. Much of the focus remains the same as in Roadmap 2023 to which we refer readers for generational classification.

Solid-state lithium-ion batteries (SSBs) are a significant milestone in original equipment manufacturers' (OEMs) roadmaps, as they can double driving range due to their higher energy density. They also offer enhanced intrinsic safety but still face challenges such as lower cyclic performance and high interfacial resistance. New chemistries, materials, and production technologies are needed, to strengthen the European industry.

Though the most advanced technology is polymer-based electrolyte, it has been noted that inorganic solid electrolyte technology at OEMs is moving towards sulfide4,5 based electrolytes aided by semi-solid/hybrid6 application deployed in pouch789, prismatic and cylindrical10 formats and in cars11.

As the technology begins entering commercial deployment in the field an emphasis is placed on the development of safety assessments, active materials, electrode and external fixtures for cells under lower compression force operations.

R&D activities needed

Short-term needs (2029)

- Active materials, including coatings to reduce interfacial resistance with electrolyte and catholyte.
- Reducing the thickness of the anode.
- Developing thin solid electrolytes (e.g. multilayer and composite electrolytes) that exhibit high ionic conductivity across a wide temperature range and less sensitivity to humidity during processing.
- Manufacturing new solid electrolyte interlayers (i.e. interlayers stable against metallic Lithium).
- Developing of stable electrolyte compositions with high ionic conductivity for use in composite cathodes (catholytes)
- Creating solutions for manufacturing and handling lithium metal sheets in a dry atmosphere.
- Improving interface design for efficient charge transfer, along with electrochemical and mechanical stability.

- Designing materials and cells for low-pressure solid-state battery operations.
- Conducting safety assessments in Generation 4, to better understand the mechanisms that initiate thermal runaway.

Mid-term (2035) & long-term (2040)

- Development of new materials and chemistries that can operate at higher voltages.
- Application of coatings for these materials, particularly at the cathode electrode, to stabilize the interface between the electrode and electrolyte and reduce its resistance to be able to operate at higher C-rates.
- Innovative approaches for low-cost, solvent-free manufacturing of electrodes and deposition of solid electrolytes.
- Key development targets include reducing the interface resistance with solid electrolytes on the cathode and anode side, preventing dendrite formation at high charge and discharge rates.
- Design of new cells that are compatible with the developed components.
- Research on formation protocols for solid state, semi solid state/composite systems
- Strategies for mitigating thermal runaway initiation in Generation 4 batteries.

Impact

Technological impact: Solid state batteries to be the most promising technology for use in EVs for the next decades.

Economic impact: As the share of advanced materials represents a dominant share of battery cell cost structure, innovation in solid state battery materials will be a powerful lever for European competitiveness.

Environmental impact: Developments will enable a carbon-neutral and circular approach of Mobility.

2.5.3 Na-ion batteries (driven by mobility) – Mid-term / Long-term

This strategic research area has the most potential for materials advancement, IP generation, technology development and supply chain independence for Europe. Details of the various challenges and chemistries can be found in the previous roadmap[citation].

There is no lack of diversity in cathode materials for SIB's including presence of European producers, unlike on the anode side that's limited to hard carbons typically having a lower12 tap density of <0.9g/cm3 compared to graphite13 at >1 g/cm3 and no European production. An emphasis on European produced hard carbon anodes and other types of anodes should be placed. Chemistries with reduced CRM content should be preferred. SIBs14 have recently achieved a price parity with LFP based batteries considering recent price drops ($50/kWh15) of LFP. However large OEM players already producing16 or are constructing1718 multi GWh plants and, hybrid Na-ion-LFP battery packs have been deployed in unique solutions19 for mobility applications.

R&D activities needed
Short-term needs (2029)
Gen 3 (SIBs with liquid electrolyte)

- Cathodes: Stable Co-free and low Ni-content LTMO cathodes with capacity of ≥160 Ah/kg for PBA, and 120Ah/kg for other chemistries, operation at ≥3.6V, fading < 5% over ≥ 500 cycles
- Modified polyanionic-based electrodes with improved electronic conductivity and ionic mobility
- Reduction of manufacturing costs and enhancement of durability for PBA cathodes
- Anodes with enhanced capacity of ≥350 Ah/kg, FCE >90% fading < 5% over ≥ 500 cycles.
- Hybrid electrolyte concepts with high ionic conductivity, enhanced safety, wide operating windows and improved SEI stability (e.g., reduced SEI solubility).
- Interface optimization to enable low interface resistance and improve stability, long lifetime,
- Cost-, material- and energy efficient production processes including. recycling concept for rejected material streams in production process.
- Cells with ≥180 Wh/L and cycling stability of 2000+ cycles (< 10% fading with DoD 80% at 1C).
- Towards no CRM in cells.

Gen 4 (Na-based SSB)

- Tools for Screening (modelling and simulation combined with experiment) of materials and material development strategies to obtain higher conductivity, higher capacity/lifetime, and reduced CRM content.
- Composite cathodes with capacity of ≥120 Ah/kg (total composite cathode weight) and cycle life of > 500 cycles (< 5% fading at DoD 80%) (active material, catholyte and interfaces).
- Electrolytes with enhanced resistance against dendrite formation for Na-metal anode (>1000 cycles)
- Interface design to enable a critical current density (CCD) of at least 2 mA/cm^2.
- Techno-economic assessment to elaborate concepts showing competitiveness with LIBs.
- Proof of concept for cells with solid-state electrolyte demonstrating energy density of at least ≥200 Wh/L and cycle life > 500 cycles.
- Safety aspects and mitigation strategies for thermal runaway initiation in Gen 3
- Materials and cell designs for low-pressure solid-state batteries operations
- Material strategies to minimize mechanical stress (e.g., due to volume expansion)
- Mid- (2035) and Long-term needs (2040+)

Gen 3 (SIBs with liquid electrolyte)

- Anodes with enhanced capacity of ≥400 Ah/kg, FCE >92% fading < 5% over ≥ 500 cycles.
- Cathodes ≥120Wh/kg for other chemistries, operation at ≥3.6V, fading < 5% over ≥ 500 cycles
- Design and integration of advanced materials to realize “design for recycling” cell and battery strategies after end-of-life (EOL).

- Upscaled cost & energy-efficient manufacturing technology for cell materials recognizing recycling aspects.
- Cells with hybrid electrolyte concepts with cycling stability of 2000+ cycles and CCD >2 mA/cm^2.
- Cell level techno-economic assessment of reaching ≤ 100 €/kWh in case of mass production.
- No CRM in cells.
- Cells with ≥300Wh/L and cycling stability of 4000-6000+ cycles (< 10% fading with DoD 80% at 1-2C).
- Safety aspects and mitigation strategies for thermal runaway initiation in Gen 4
- Gen 4 (Na-based SSB)
- Composite cathodes with capacity of 160-300 Ah/kg (total composite cathode weight) and cycle life of > 1000 cycles (< 10% fading at DoD 80% and 1C) (active material, catholyte and interfaces).
- Strategies to mitigate mechanical stress during cycling (e.g., due to volume expansion)
- Cells with Na-metal anode with critical current density of 2+ mA/cm^2 and cycling life >1000 cycles.
- Design and integration of advanced materials to realize “design for recycling” strategies after EOL.
- Cells with solid state electrolyte demonstrating capacity of at least ≥300 Wh/L and cycle life 1000-4000+ cycles (< 10% fading with DoD 80% at 1C).
- Formation protocols for solid state, semi solid state/composite systems for proper interface formation during initialization phase, with scope transitioning WG3 to WG4
- Safety aspects and mitigation strategies for thermal runaway initiation in Gen 4
- No CRM in cells.

2.5.4 Long-lasting batteries (driven by stationary)

Long lasting batteries (Cycle life ≥6000cycles) SRA is dedicated to the development of various materials systems (such as cathodes, anodes, electrolytes, and binders) to enable stationary lithium-ion and sodium ion batteries, LIBs and SIBs respectively for utility-scale applications (greater than 100 MW, with a power-to-energy ratio less than 1/3) and for commercial high-power applications (less than 100 MW, with a power-to-energy ratio greater than 4). The material strategies are diverse, particularly concerning cathode materials like NMCs, LFP, LMFP, HLM for LIB and Na-LTMO, PBA and polyanionic cathode materials for Sodium ion batteries (NIB). Much of the materials focus and challenges remains the same as in the previous roadmap[citation] to which we refer readers. In this roadmap update we introduce NIBs to this SRA.

Large-scale utility Li-ion/Na-ion energy storage plays a crucial role in integrating renewable energy in various ways. The dramatic cost decrease of Li-ion technologies, specifically LFP based, has made energy storage very competitive. Recently 500MW/4hrs/location tenders at 4 locations have been opened in the middle east20 while Australia has not been left behind with its call for 16GWh21 at multiple locations. To fully leverage the potential of Li-ion/Na-ion batteries in battery energy storage systems (BESS), it is essential to reduce cycle costs, which necessitates significant improvements in both cycle and calendar life while also optimizing reliability and safety through the development of advanced materials (active and inactive) and development of larger capacity cells (>500Ah/cell).

R&D activities needed (All time scales)

Utility-Scale Applications:

- Develop new intercalation compounds with low cycling strain and fatigue for LIBs and SIBs
- Improve the cycle and calendar lifetime of batteries to create reliable, cost-effective products.
- Electrolytes facilitating extended cycle lifetime of batteries
- Develop high-energy-density electrodes with strong ionic and electronic conductivity.
- Create a highly ionic-conductive solid electrolyte for solid-state Li-ion/Na-ion batteries to enhance safety.
- Reduce the content of critical raw materials in existing cathode chemistries.
- Cells demonstrating capacity of at least 250 Wh/l and cycle life 6000+ cycles (< 10% fading with DoD 80% at 0.5C).
- Techno-economic assessment of reaching < 0.05 €/kWh/cycle in case of mass production.

Commercial High-Power Applications:

- Enhance conductivity to increase power by incorporating structured carbons/anodes or 3D structures as additives in electrodes, and by developing power-optimized materials and architectures.
- Create fast-charging Li-ion/Na-ion anode materials.
- Innovate high-capacity technology by integrating materials such as silicon into the anode, or dopants in Hard Carbons, creating high-energy-density cathode materials, and minimizing Li/Na consumption in the solid electrolyte interphase (SEI) on the anode side while maximizing Li/Na use in the cathode.
- Electrolytes facilitating extended cycle lifetime and high-power application of batteries
- Decrease cobalt content in cathodes while improving structural stability through composition adjustments.
- Develop coatings for high-energy-density cathode materials to reduce interfacial resistance.
- Create innovative separators that improve safety and reduce reliance on organic solvents. Incorporate shutdown mechanisms into the design of separators, enhance the structural resilience of separators through new materials, designs, or coatings.
- Cells demonstrating capacity of at least cycle life ≥12000 cycles (< 10% fading with DoD 80% at ≥3C).
- Techno-economic assessment of reaching < 0.05 €/kWh/cycle in case of mass production.

Impact

Technological Impact:- Establish large battery systems with capacities above 100 MW and a power-to-energy ratio of less than 1/3, while ensuring performance, cost, and safety standards suitable for utility-scale applications. Additionally, develop solutions for battery systems with capacities below 100 MW that achieve a power-to-energy ratio > 4, delivering increased lifespan and lower operational (OPEX) and capital expenditures (CAPEX) for commercial high-power applications.

Economic Impact:- Foster the commercial success of European battery material and cell producers supplying lithium-ion battery solutions for both utility-scale and commercial high-power applications. Facilitate multi-MWh deployments of BESS for grid security and stabilization therefore smoothing out sharp rises in electricity costs at critical times

Environmental Impact:- Contribute to the potential partial replacement of gas peaker plants (utility-scale) and promote the accelerated integration of renewable electricity into the grid, facilitating the decarbonization of the industry through green and cost-competitive electricity (utility-scale).

2.5.4 Vanadium-based redox flow batteries (driven by stationary)

This strategic area focuses on developing safe and sustainable materials, including enhanced catalysts, for vanadium-based redox flow batteries (VRFBs). The aim is to achieve high energy density, long cycle life, low cost, and reduced reliance on scarce raw materials. Cost and scalability are the key competitive factors, so advancing VRFB technology requires reducing costs and increasing production scale. Much of the materials focus and challenges remains the same as in the previous roadmap[citation] to which we refer readers. Some reprioritization has been done, moving targets to the short term. Recovery and co-production of Vanadium from unconventional sources, supply chain strengthening of all components together with sensor integration and corrosion mitigation are some of the newly identified priorities.

R&D activities needed

Short-term needs (2029)

- Optimized vanadium electrodes with improved efficiency at high current densities and low cost.
- Novel bipolar plates to meet high performance and durability, high production efficiency, low energy consumption, environmentally friendly, and low cost.
- Low-cost membranes with reduced fluoride for RFB including strategies for upscaling.
- Design cells, stacks with low maintenance and include predictive maintenance.
- Optimize and widen the temperature range for the electrolyte while improving electrochemical activity/capacity through, for example, additives.
- Sustainable electrodes from natural materials & new energy-efficient carbonization processes.
- New (non-fluorinated) low-cost, improved mechanical properties and limited swelling membranes for RFB, including strategies for upscaling.
- Understanding and mapping of global vanadium supply chains including geographical distribution, unconventional sources, recycling, and projected demand/supply
- Recovery of vanadium from unconventional sources including co-production with other critical elements
- Mitigation of corrosion for components in large-scale VFBs
- Sensor integration and AI/ML battery management systems

Mid- and long-term needs (2035+)

- Validate use of recycled electrolytes in new VRFBs demonstrating performance and lifetime.
- Effective end-of-life strategy for all the components
- Quantitative understanding of long-term degradation mechanisms and iterative improvement of battery management systems
- Sustainable and predictable vanadium inventories and mitigation of component supply chain issues (acid-tolerant plastics, alloy design for bipolar plates, first-wall tubing and components)
- Energy efficient recycling processes coupled to clean energy to produce ultra-high-purity electrolyte
- Benchmarking of electrolytes, stack design, operation protocols to standards

Impact

Technological Impact: Better performance, reliability, and efficiency of VRFBs with reduced production and maintenance costs.

Economic Impact: Reduced cost of production of VRFBs will improve the economics of long duration energy storage, accelerate its deployment, contribute to stabilise the energy grid, and reduce the need for expensive upgrades to the grid. Advances in VRFB technology will create economic potential and development of the related value chain in Europe.

Environmental Impact: Technological improvement of VRFBs will further extend their durability and lifespan to over 20 years, which reduces the need for frequent replacements and limits environmental impact. Reduced use of fluorinated materials in VRFBs membranes will lower environmental risks.

2.5.5 Vanadium-based redox flow batteries (driven by stationary)

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R&D activities needed

Short-term needs (2029)

- Optimized vanadium electrodes with improved efficiency at high current densities and low cost.
- Novel bipolar plates to meet high performance and durability, high production efficiency, low energy consumption, environmentally friendly, and low cost.

- Low-cost membranes with reduced fluoride for RFB including strategies for upscaling.
- Design cells, stacks with low maintenance and include predictive maintenance.
- Optimize and widen the temperature range for the electrolyte while improving electrochemical activity/capacity through, for example, additives.
- Sustainable electrodes from natural materials & new energy-efficient carbonization processes.
- New (non-fluorinated) low-cost, improved mechanical properties and limited swelling membranes for RFB, including strategies for upscaling.
- Understanding and mapping of global vanadium supply chains including geographical distribution, unconventional sources, recycling, and projected demand/supply
- Recovery of vanadium from unconventional sources including co-production with other critical elements.
- Mitigation of corrosion for components in large-scale VFBs
- Sensor integration and AI/ML battery management systems
- Mid- and long-term needs (2035+)
- Validate use of recycled electrolytes in new VRFBs demonstrating performance and lifetime.
- Effective end-of-life strategy for all the components.
- Quantitative understanding of long-term degradation mechanisms and iterative improvement of battery management systems.
- Sustainable and predictable vanadium inventories and mitigation of component supply chain issues (acid-tolerant plastics, alloy design for bipolar plates, first-wall tubing and components).
- Energy efficient recycling processes coupled to clean energy to produce ultra-high-purity electrolyte.
- Benchmarking of electrolytes, stack design, operation protocols to standards.

Impact

Technological impact: Better performance, reliability, and efficiency of VRFBs with reduced production and maintenance costs.

Economic impact: Reduced cost of production of VRFBs will improve the economics of long duration. energy storage, accelerate its deployment, contribute to stabilise the energy grid, and reduce the need for expensive upgrades to the grid. Advances in VRFB technology will create economic potential and development of the related value chain in Europe.

Environmental impact: Technological improvement of VRFBs will further extend their durability and lifespan to over 20 years, which reduces the need for frequent replacements and limits environmental impact. Reduced use of fluorinated materials in VRFBs membranes will lower environmental risks.

2.5.6 Sustainability – transversal challenge

Current and emerging battery chemistries show promise, but face sustainability challenges:

- Lithium-ion batteries need to reduce the use of critical raw materials (CRMs) like cobalt and nickel, with lithium also anticipated to decrease in mass applications over time.
  - Lithium iron phosphate (LFP) batteries use no cobalt or nickel, offering economic and environmental benefits, but rely on phosphorus—a CRM—with uncertain recycling economics. Solid-state batteries (SSBs) require more lithium, though they offer better safety. Their recycling also needs technological advances.
  - Sodium-ion batteries could be a sustainable option if technological hurdles are overcome, but their low-value materials may pose recycling challenges, and toxic emissions from PBAs/PWAs fire need addressing.
  - For redox flow batteries (RFBs), vanadium availability may become critical if they gain traction in stationary storage. Life cycle assessment shows good environmental performance, especially with electrolyte recycling, making them potentially more competitive than lithium-ion batteries if renewable energy predominates.
  - For all types of batteries, the concepts for material recycling and re-utilization should be developed and implemented.

2.5.7 Safety – a transversal challenge

Battery materials pose hazards to human health and the environment during manufacturing, transportation, use, and recycling. High energy density and electrochemical potentials introduce risks such as dendrite formation, oxygen loss, and thermal runaway. Hazards include material-specific risks regulated by EU standards and interactions within the cell. Main hazards from material combinations involve leakage of liquids, gases, and particles, venting of toxic gases, and self-heating. The testing methodology for measurement of related KPIs is still in development. It is necessary to harmonize the KPI definitions and measurement methods for safety KPIs in the near future to enable the target-oriented development of safer batteries. In the future the KPIs will be defined by the physical chemical and electrochemical behaviour of materials, with evaluations based on comparisons to internationally agreed reference electro-chemistries. Readers are referred to an in-depth discussion on safety aspects in the recently published position paper on safety by the safety taskforce[22]

2.5.8 Digitalization -a transversal challenge

AI is increasingly utilized to discover new battery materials, optimizing designs more efficiently than traditional methods. By searching vast material databases, AI identifies patterns that humans might miss and aids in fine-tuning designs through simulations of material properties before physical experiments, speeding up discovery and conserving resources. Challenges include the need for high-quality data and access to expert knowledge. Good data and machine-readable expertise are essential for creating accurate AI models. Promoting advanced digital solutions supports research cohesion and positions the EU as a leader in battery technology. Standardized tools, like Material Acceleration Platforms, enhance research capabilities, while collaborative researcher groups and robust FAIR data exchange foster competitive research. Human supervision ensures the right machine learning algorithms are applied, avoiding ineffective optimization. A centralized knowledge base for the battery industry and standardized mechanisms for accessing intellectual property benefit IP owners and expedite technology development and distribution.

2.6 Key Recommendations

Advanced materials account for the >40% of battery manufacturing costs and stand in the value chain between raw materials and battery cells, they are, thus, critical enablers of both the EU's Critical Raw Materials Act and the EU's Net-Zero Industry Act. Therefore, we call for the level of European, national and regional, funding going to Advanced Materials to be increased substantially to fulfil strategic ambitions of the EU for a sustainable battery value chain based on sustainable, high-performance and cost-competitive battery technology. In that respect, we need to step up ambitions in Europe when it comes to solid state batteries while also investing in chemistries relying on less critical raw materials without compromising battery performance. Development of battery chemistries will also have to take more into account elements of sustainability and safety. For instance, recyclability, both technically and economically speaking, of new battery chemistries will need special attention to avoid falling for battery chemistries delivering on cost and raw material criticality but potentially leading to a strong environmental liability, should their recycling not be economically possible

SRA	Short term	Medium term	Long term
Li-ion batteries (gen 3) (driven by mobility)	Stable cathodes and electrolytes for high voltage batteries (4.8 V, ≥ <2.000 cycles Durable cycling for Li- and Ni-rich, low-Co cathodes with up to 2,000 cycles Optimised manganese-rich HLM, LMFP materials for low cost and high safety Advanced Si/C materials, additives, and electrolytes to enable up to 20 wt% Si (~1000mAh/g) with fast charge and reasonable cycling by reducing cell degradation Cathode materials designed for solvent-free or dry processing Blended Cathode Active Materials	Stable cathodes and electrolytes for high-voltage batteries, ≥3,500 cycles at 4.8 V. Reduce CRM content (e.g., natural graphite, cobalt, lithium) and fluorinated compounds per kWh. Long cycle life for low-voltage, high-capacity anodes, such as Si/C composites with over 20% silicon content or pure silicon, reaching capacities of ≥1,000 mAh/g.	Cathode materials with capacities over 300 mAh/g, coulombic efficiencies of 99.98%, and lifespans of at least 1,000 cycles, paired with anode capacities of ≥1,200 mAh/g. Lithium-ion batteries with minimized use of critical materials (excluding lithium).

SRA	Short term	Medium term	Long term
Li-ion batteries (gen 3) (driven by mobility)	Stable electrode / electrolyte interfaces Optimization of materials from direct recycling		

SRA	Short term	Medium term
Solid-state batteries (gen 4) (driven by mobility)	Active materials incl. coatings for reduced interfacial resistance to electrolyte & catholyte Reducing thickness of the anode Developing thin solid electrolytes (such as multilayer and composite electrolytes) that exhibit high ionic conductivity across a wide temperature range and less sensitivity to humidity during processing Manufacturing new solid electrolyte interlayers (i.e. interlayers stable against metallic Lithium). Developing of stable electrolyte compositions with high ionic conductivity for use in composite cathodes (catholytes) Creating solutions for manufacturing and handling lithium metal sheets in a dry atmosphere Improving interface design for efficient charge transfer, along with electrochemical and mechanical stability Designing materials and cells for low-pressure solid-state battery operations Conducting safety assessments in Generation 4, focusing on understanding the mechanisms that initiate thermal runaway	Development of new materials and chemistries that can operate at higher voltages. Application of coatings for these materials, particularly at the cathode electrode, to stabilize the interface between the electrode and electrolyte and **reduce its resistance to be able to operate at higher C-rates.** Innovative approaches for low-cost, solvent-free manufacturing of electrodes and deposition of solid electrolytes Key development targets include reducing the interface resistance with solid electrolytes on the cathode and anode side, preventing dendrite formation at high charge and discharge rates Research on formation protocols for solid state, semi solid state/composite systems, with scope transitioning WG3 to WG4 Strategies for mitigating thermal runaway initiation in Generation 4 batteries

SRA		Short term	Medium term
Na-ion batteries (driven by stationary and mobility)	Gen 3 (SIBs with liquid electrolyte)	Cathodes: Stable Co-free LTMO cathodes with capacity of 160 Ah/kg for operation at 4.0 V, fading <10% over ≥ 500 cycles; Modified polyanionic-based electrodes with improved electronic conductivity and ionic mobility; Reduction of manufacturing costs for PBA cathodes Anodes with enhanced capacity of 300 Ah/kg, fading <10% over ≥ 500 cycles Hybrid electrolyte concepts with high ionic conductivity, enhanced safety and improved SEI stability (e.g., reduced SEI solubility) Interface optimisation to enable low interface resistance and stability, long lifetime, cost- and energy efficient production processes Cells with 160 Wh/kg or/and 300 Wh/L and cycling stability of 2000+ cycles (<10% fading with DoD 80% at 1C) Towards no CRM in cells	Anodes with enhanced capacity of ≥400 Ah/kg, FCE >92% fading < 5% over ≥ 500 cycles Cathodes ≥120Wh/kg for other chemistries, operation at ≥3.6V, fading < 5% over ≥ 500 cycles Design and integration of advanced materials to realize “design for recycling” cell and battery strategies after end-of-life (EOL) Upscaled cost & energy-efficient manufacturing technology for cell materials recognizing recycling aspects Cells with hybrid electrolyte concepts with cycling stability of 2000+ cycles and CCD >2 mA/cm^2 Cell level techno-economic assessment of reaching ≤ 100 €/kWh in case of mass production No CRM in cells Cells with ≥300Wh/L and cycling stability of 4000-6000+ cycles (< 10% fading with DoD 80% at 1-2C). Safety aspects and mitigation strategies for thermal runaway initiation in Gen 4
	Gen 4 (Na-based SSB)	Tools for Screening (modelling and simulation combined with experiment) of materials and material development strategies to obtain higher conductivity, higher capacity/lifetime, and reduced CRM content Composite cathodes with capacity of ≥120 Ah/kg (total composite cathode weight) and cycle life of > 500 cycles (< 5% fading at DoD 80%) (active material, catholyte and interfaces) Electrolytes with enhanced resistance against dendrite formation for Na-metal anode (>1000 cycles) Interface design to enable a critical current density (CCD) of at least 2 mA/cm^2 Techno-economic assessment to elaborate concepts showing competitiveness with LIBs Proof of concept for cells with solid-state electrolyte demonstrating energy density of at least ≥200 Wh/L and cycle life > 500 cycles. Safety aspects and mitigation strategies for thermal runaway initiation in Gen 3 Materials and cell designs for low-pressure solid-state batteries operations Material strategies to minimize mechanical stress (e.g., due to volume expansion)	Composite cathodes with capacity of 160-300 Ah/kg (total cathode weight) and cycle life of >1000 cycles (<10% fading at DoD 80% and 1C) (active material, catholyte and interfaces) Strategies to mitigate mechanical stress during cycling (e.g., due to volume expansion) Cells with Na-metal anode with critical current density of 2+ mA/cm^2 and life >1000 cycles Design and integration of advanced materials to realize “design for recycling” strategies after EOL. Cells with solid state electrolyte demonstrating capacity of at least 220 Wh/kg or/and 500 Wh/L and cycle life 1000-4000+ cycles (<10% fading with DoD 80% at 1C) Formation protocols for solid state, semi solid state/composite systems for proper interface formation during initialization phase, with scope transitioning WG3 to WG4 Safety aspects and mitigation strategies for thermal runaway initiation in Gen 4 Towards no CRM in cells.

SRA	All Time Scales	
	Utility-scale applications:	**Commercial high-power applications:**
Long-lasting Li-ion batteries (driven by stationary)	Develop new intercalation compounds with low cycling strain and fatigue for LIBs and SIBs Improve cycle lifetime & calendar lifetime to develop reliable, cost-effective products Electrolytes facilitating extended cycle lifetime of batteries Create a highly ionic-conductive solid electrolyte for solid-state Li-ion/Na-ion batteries to enhance safety Reduce the content of critical raw materials in existing cathode chemistries Cells demonstrating capacity of at least 250 Wh/l and cycle life 6000+ cycles (< 10% fading with DoD 80% at 0.5C) Techno-economic assessment of reaching < 0.05 €/kWh/cycle in case of mass production.	Enhance conductivity to increase power by incorporating structured carbons/anodes or 3D structures as additives in electrodes, and by developing power-optimized materials and architectures. Create fast-charging Li-ion/Na-ion anode materials Innovate high-capacity technology by integrating materials such as silicon into the anode, or dopants in Hard Carbons, creating high-energy-density cathode materials, and minimizing Li/Na consumption in the solid electrolyte interphase (SEI) on the anode side while maximizing Li/Na use in the cathode Electrolytes facilitating extended cycle lifetime and high-power application of batteries Incorporate shutdown mechanisms into separator materials or separator design and improve structural resilience of separators through new materials, designs or coatings Electrolytes facilitating extended cycle lifetime and high-power application of batteries Decrease cobalt content in cathodes while improving structural stability through composition adjustments Develop coatings for high-energy-density cathode materials to reduce interfacial resistance Create innovative separators that improve safety and reduce reliance on organic solvents. Incorporate shutdown mechanisms into the design of separators, enhance the structural resilience of separators through new materials, designs, or coatings Cells demonstrating capacity of at least cycle life ≥12000 cycles (< 10% fading with DoD 80% at ≥3C). Techno-economic assessment of reaching < 0.05 €/kWh/cycle in case of mass production.

SRA	Short term	Medium term
Vanadium-based redox flow batteries (driven by stationary)	Optimised vanadium electrodes with improved efficiency at high current densities & low cost Novel bipolar plates to meet high performance and durability, high production efficiency, low energy consumption, environmentally friendly, and low cost Low-cost membranes with reduced fluoride for RFB including strategies for upscaling Design cell, stack with low maintenance and include predictive maintenance Optimise and widen the temperature range for the electrolyte while improving electrochemical activity/capacity through for example, additives Understanding and mapping of global vanadium supply chains including geographical distribution, unconventional sources, recycling, and projected demand/supply Recovery of vanadium from unconventional sources including co-production with other critical elements Mitigation of corrosion for components in large-scale VFBs Sensor integration and AI/ML battery management systems	Validate use of recycled electrolytes in new VRFBs demonstrating performance and lifetime Effective end-of-life strategy for all the components Quantitative understanding of long-term degradation mechanisms and iterative improvement of battery management systems Sustainable and predictable vanadium inventories and mitigation of component supply chain issues (acid-tolerant plastics, alloy design for bipolar plates, first-wall tubing and components) Energy efficient recycling processes coupled to clean energy to produce ultra-high-purity electrolyte Benchmarking of electrolytes, stack design, operation protocols to standards

Table 8 Overview of Strategic Research Areas of Advanced Materials developed by the Batteries Europe/BEPA WG3

2.7 Cell Design and Manufacturing Strategic Research Areas

2.7.1 Sustainable innovative cell and battery design

When looking at ecologically sustainable high-performance, long-life batteries, there is a lack of design and testing specifically for second-life applications and recycling especially with respect to easy disassembly. In addition, currently there is little to no recycled content in battery packs, and even less in the cells themselves. Apart from LCA, LCC and circularity analyses, the sustainability of the cell and pack design itself should be also focused. The Cell and module design must enable cost-effective and environmentally friendly, eventually also flexible production. There is a growing need to focus not only on the technical challenges of new generation cells, but also on incorporating sustainability considerations into the material selection and cell design.

R&D activities needed

The cell and battery designs of the future will need to be designed for recycling at every level and to promote circularity in the supply chain. The growing need for large-scale electric mobility also requires an appropriate cost structure for newly developed batteries' designs. Both the new requirements for cell performance and safety, as well as extended lifetime, require functionalisation of the cell design. This should increase not only the efficiency of thermal management and include chemistry-agnostic designs to extend the temperature operational window, but also include reducing the mechanical stress on the cells, especially when using high energy materials, to reduce the overall amount of material required. This holds especially for solid state batteries, which usually are operated at extremely high compression stresses.

Short-term needs (2029)

- Develop objective assessment methodologies not just for LCA but also to assess production process sustainability including environmental impact and externalities cost, thus allowing a preliminary estimate of the sustainability of a cell design. Assess cost impact of re-use/recyclability designs vs. projected life and failure rate of battery packs.
- Design cells with a focus on recyclability, to facilitate material recovery and increase modularity by simplifying assembly and end of life disassembly processes. Battery design should minimize the environmental impacts of battery production (maximizing the incorporation of recycled raw material, overall material efficiency, minimizing the material waste generated in the production processes, etc.).
- Design cells, especially on basis of digital twins, for the increased utilization and incorporation of sustainable, recycled and bio-based materials. Upcycling of waste materials (including plastic waste and bio-based materials, value-added products that may be used or not in battery systems, as for example electrically conductive carbons, etc.).
- Create functional cell design for long cycle life and application-specific cell design, supported by simulations and experimental testing for cell design and respective applications.
- Engage with stakeholders in the supply chain from the start to define what characteristics materials need to have to enhance second life applications or recycling.

- **Mid-term needs (2035)**
- Preliminary or retrofitting cell designs should include sustainability, in particular LCA and LCC studies considering externality costs, circularity and supply chain analysis, based on existing frameworks and guidelines.Digital twins of cells to optimize cell design regarding performance, lifetime, costs and ecological impact
- Specific design for long lifetime and reduced production and maintenance cost.
- Fully circular pack design for re-use or easier recycling of materials.
- Integration of chemistry-agnostic cell designs that extend the operational temperature window.
- SoH and SoC monitoring using Electrochemical Impedance Spectroscopy (EIS), along with the integration of in-cell sensors enables real-time adaptive control, which is crucial for improving efficiency, safety, and lifespan in applications like electric vehicles and grid storage.
- Long-term needs (2040+)
- Development of dynamic decision supporting methodologies and tools, based on artificial intelligence and data science tools that enable optimum materials/design according to application and industry-wide sustainability parameters.
- Enabling smart-cell informed prototyping process using embedded instrumentation as development and validation tool, to establish accurate and efficient development lifecycle. Consequently, supporting rapid deployment of new technologies, while minimising final design monitoring needs supplemented by model based virtual sensors.
- New cell designs with integrated heating/cooling system.

Impact

Focusing on the design for maximized lifetime of cells, modules and packs would deliver a long-term improvement that impacts all industries. Increasing the lifetime per cell increases its overall value and helps to differentiate sustainable cells from others. Safer materials and designs lead to cost reduction in manufacturing and handling. Finally, increased modularity and a circular pack design facilitates usability in second life applications and overall recyclability.

2.7.2 Sustainable production processes of cells and batteries

Current processes are characterised by high energy consumption, use of toxic, harmful, highly polluting materials, large physical footprint, safety issues, which also translate into high operating costs. The optimisation of existing processes and equipment and the development of innovative ones are essential to promote the establishment of safe and sustainable battery mass production. Also relevant is the development and implementation of production information systems that, besides ensuring an efficient resources (materials and energy) utilization and improving the sustainability of the production process, will facilitate the creation of the Digital Product Passport. Consortia of equipment suppliers delivering the entire process chain need to be formed to establish a reliable European equipment supply chain for current and next-gen technologies.

R&D activities needed
Short-term needs (2029)

It is necessary to improve the efficiency and robustness of processes and equipment and to implement appropriate quality management to minimize production scrap and maximize product quality. Demo installations, optimally the entire process chain, are needed to show and validate the solutions, to gain trust of the battery manufacturers regarding the capabilities of the European equipment suppliers.

Minimize specific energy consumption and emissions, minimise the use of hazardous chemicals, improve process safety, reduce cost and increase materials and energy efficiency:

- Develop mechanisms for (non-competitive) best-practice sharing across different battery chemistries /industries.
- Determine which are relevant materials to be recycled and at what level. Consistent quality supply of recycled materials should be ensured. Determination of what is the impact of adding recycled material in a new cell regarding performance and manufacturing process stability.
- Minimizing production scrap by intelligent automatisation and quality control as well as implement direct scrap recycling.
- The utilization of bio-based materials, intrinsically renewable, should be promoted.
- Use of processing techniques that have lower environmental condition requirements. e.g. dry coating with a smaller footprint than wet coating.

Quality and production control and management:

- Identify correlations between off-line and on-line measurement techniques towards a fully automated quality control process chain.
- Leveraging AI to predict potential defects and optimize manufacturing processes (predictive quality control). By integrating real-time data analysis from sensors strategically placed along the roll-to-roll production lines within the factory, AI models can anticipate production flaws, allowing for immediate adjustments resulting in high quality standards and reduced material waste.
- Virtual production - develop digital twins to optimise production processes, reduce commissioning time, and mitigate project risk.
- EU cross-industry dataset for batteries that can be used in advanced decision making (incl. AI).
- Data sets must follow data formats that facilitate data traceability, data transfer and its utilization for different purposes, including process and quality control, or support the creation of DPPs for the cell and/or packs FAIR principle.

Cost efficiency - Overall reduction in CAPEX:

- The reduction in OPEX must be quantified and compared with the possible higher CAPEX, taking into account potential costs of externalities

Digital passport policy definition:

- Development of data storage exchange, traceability, protocols and applicable regulations and standards, e.g. Product Category Rules and data quality requirements for implementation of the digital battery passport at the battery production scale. Standards and protocols should be open source, to facilitate implementation in particular for SME.

- Standardisation of hardware and software interfaces, for later focusing on specific data formats and/or procedures for traceability and data integrity.
- Grey-market battery traceability: Digital signature associated with battery passport to minimise lost units.
- Full standardization for LCA, Social-LCA and LCC and widespread implementation should be pursued focussing on refining data collection, ensuring interoperability and conducting pilot testing to ensure the KPI's practical applicability across the value chain.

Development equipment and demonstration projects:

- Development of equipment with improved efficiency and quality compared to competitors with high ability to be integrated into full process chains.
- A strong network and relationship among the European equipment providers has to be established to realize full process chains, if possible leading to joint demonstration projects, comprehensive of several process steps / developments to gain customer trust.

Mid-term needs (2035)

- Develop/implement new production technologies and/or procedures based on the results of LCA and/or LCC studies, including externalities costs for the latter.
- Digital twin of full process chain predicting product performance, product quality, costs and ecological impact.
- Trade-off between scrap reduction vs. ease of scrap reuse
- Development of manufacturing for battery chemistries that are compatible with pre-existing Li-ion battery infrastructure (e.g. for for metal-sulfur batteries, Na-ion, solid-state, multivalent etc.) as well as development of improved and higher energy density chemistries (e.g. RFBs, multivalent chemistries) aimed at long duration energy storage.
- Development of production technologies and equipment for new generation batteries, e.g. solid-state batteries, which require new process chains
- The incorporation of sustainable materials into electrodes, for example using carbons prepared from waste streams including biomass and plastic waste.
- Sensors should be developed for manufacturing equipment and process tracking to ensure process quality and performance standards.
- Printed Sensors in cells and batteries.
- AI tools for battery manufacturing, eventually combined with physical models (grey box model), aimed for identification and modelling of influencing factors on the process enhanced quality and reduced cost by implementing virtual inspections
- Increase the utilization of renewable energy directly in the production process, e.g. by process electrification.

Impact

The activities will lead to the development of advanced solutions with higher efficiency and reduced carbon footprint, fitting the overall sustainability targets set in the EU. This includes the increase of productivity while reducing the floor occupation and the energy consumption.

2.7.3 Flexible production technologies

As the market for batteries grows, the demand for safe, flexible and adaptable battery cell production technologies becomes paramount. Flexible production technologies plays a critical role in reducing production costs, improving efficiency, and minimising waste. Manufacturing lines are often highly specialised and lack the flexibility needed to adapt to new formats, chemistries, and production processes. Future battery factories need to be highly adaptable to keep up with the manifold technological innovations within the product itself, for example solid state batteries, as well as within the production system and changing supply chains. Digital models and on this basis digital twins can serve as essential tools for understanding, assessing, and implementing flexibility in battery production.

R&D activities needed
Short-term needs (2029)

- Analyse the interconnection between production processes and the factory system like the interplay between production processes and the factory environment.
- Develop digital models for understanding, assessing, and implementing flexibility in battery production. A digital model can help design, control and optimise a production line. High-fidelity comprehensive digital models can simulate how the line behaves with different materials, electrode designs, cell formats, and cell chemistries, without disrupting the production. Digital models should also consider explicitly the data generated in the process (hybrid modelling), be flexible enough to account for process variation and should be periodically validated. Standardised models for processes are needed that can work with new battery materials, cell chemistries and components. Develop hybrid physics-based digital models of production steps fusing with data-driven methods to create digital twins for new machinery and process configurations based on sparse data sets, or data obtained from the process.
- Development of manufacturing processes for alternative battery chemistries with an emphasis on raw materials that are cheap and can be easily obtained within Europe.
- Implement and automate the creation of Digital Produce Passports based on the digital models/twins taking into account also the process data and the adequate calculations methodologies.
- Production technologies need to be designed with flexibility with respect to chemistries used to address possible future raw material unavailability.
- Development of flexible, eventually highly automated machinery and tools for varying lot sizes and cell designs
- Adaptable and interchangeable production equipment.
- Collaboration with other industries to define equipment that can be adaptable for new processes and materials for the battery industry (for example for solid state cell manufacturing).

Mid-term (2035) and long-term (2035+) needs

- Advance from digital models to digital twins, directly interacting with the production system, enabling innovations while minimising risks by virtual installation of new equipment, upscaling production, or integration of new materials into existing process chains. Validation methodologies should be developed based on process data or external certified data sets.
- Leveraging production environment digital twins to improve quality assurance and defects (waste) reduction, as well as enhancing employee training and skills development.
- Multipurpose production platforms for manufacturing pouch, cylindrical and flexible cells.

Impact

The impact of R&D on the flexibility of battery cell production and design enables manufacturers to adapt rapidly to market trends and innovations, resulting in a reduction of time-to-market. Given the constant evolution of cell chemistries, such as the introduction of Si, solid state and Na-ion, the flexibility in battery production and design is critical for keeping up with these changes without building new production lines. Increased flexibility enables the production of small batch sizes for customised products, allowing for greater differentiation and competition in the market. Moreover, it expands opportunities for smaller players to enter the market, promoting increased competition and innovation. Enhanced flexibility of battery cell production is key to Europe's competitive position.

2.7.4 Process and product scaling and industrialisation

Current approaches for industrialisation rely highly on physical testing in laboratories and pilot lines, which is time-consuming and requires high CAPEX and OPEX costs. Equipment is currently optimised for giga-scale production, while smaller-scale equipment is not as efficient in terms of price and environmental sustainability. Although there is a wealth of knowledge in Europe from academia, research institutes with pilot line capabilities and experienced equipment manufacturers, for economic reasons, cell manufacturers tend to rely on equipment manufacturers from suppliers with large-scale experience, which are mainly located in Asia.

R&D activities needed

Short-term needs (2029)

- Develop and implement universal standards for data collection and reporting throughout the battery lifecycle to ensure that data from various stakeholders is compatible and traceable.
- Strategy to use of pilot and demonstration lines to scale new innovative European production technologies to realize a fast and reliable scaling
- Process chain orientated development of production equipment (and not process step based), at best by trustful European equipment supplier consortia
- Incorporate scale-up tools (e.g., digital twins, IoT for real-time monitoring, predictive analytics) into current pilot projects.
- Work with regulatory bodies to ensure compliance standards are clear and achievable at the pilot stage.

- Plan cell design well in advance vs. buying cell production equipment by looking min. 5 years forward into OEM's tech roadmaps.
- Combined AI-powered physics-based models for accelerating the scaling up process from lab to pilot and from pilot to giga (LIB and solid state based).
- Encourage transparent information sharing between industry and academia to reduce the prevalence of 'secret ingredient' solutions in R&D, which hinder informed, reproducible research.

Mid-term needs (2035)

- Expansion of standardization to include and follow constantly evolving quality and safety protocols.
- Scaling digital infrastructure.
- Pilot testing of integrated scale-up tools.
- AI-enhanced physics-based models of the process chain where the impact of machine parameters is also considered at material and component level.
- Collect worldwide data for training existing AI models.

Long-term needs (2040+)

- Work towards international standardisation and certification frameworks.
- Deploy advanced scale-up tools (such as fully autonomous digital twins and AI-driven analytics) across the entire production line.
- Transferable AI-enhanced physics-based models among new emerging technologies
- R&D funding is cyclical, whereas prototyping equipment requires ongoing maintenance. Bridging the gap to ensure facilities continuity would ensure resilience of the development chain.

Impact

A strong European ecosystem of cell producers, equipment suppliers and pilot lines operators is necessary to close the gap to other global manufactures and suppliers. By a trustful cooperation, solutions of entire production chains based on European knowledge and technology can be implemented. New digital tools will play a great role to allow fast process and product up-scaling, enabling more flexibility on the development of new materials and technologies without recurring to physical assets, reducing CAPEX and OPEX cost and facilitating compatibility with possible future green regulations.

2.8 Key Recommendations

Policymakers and Member States (National Authorities)

Stronger sustainability focus should be put on cell and pack design level. LCA, LCC and circularity analyses are an important part of determining the viability of novel materials and design. Flexibility should be promoted for adapting to new chemistries, while at the same time addressing raw materials with no or limited availability due to export restrictions. Due to increasing digitalisation and virtualisation, cyber security aspects are of high priority to ensure a safe operation of digital systems involved in battery production. The protocols to be developed should be ideally open source to simplify implementation and reduce costs for SMEs.

Industry & Start-ups

European R&D institutes and industry must cooperate closely and develop solutions for the entire process/production chain which can only be achieved in a trustful cooperation of cell producers, equipment suppliers and research institutions running pilot lines, in particular for the virtual production development. Transparent information sharing between industry and academia should be pursued to reduce the prevalence of 'secret ingredient' solutions in R&D, which hinder informed and reproducible research. Research pilot lines can serve as basis to deliver a large data pool. To enhance the quality of battery production, AI can be leveraged to predict potential defects and optimize manufacturing processes. The entire cell production process should be prepared for the digital battery passport. Efficiency can be also improved by intelligent automatization to minimize production scrap. Also, changeable production equipment is important for adapting to novel cell chemistries and increasing flexibility for varying lot sizes. Active participation from the stakeholders in the various standardisation processes is recommended. Partnerships with global suppliers who comply with standardized protocols for ethical sourcing and traceability should be established, supporting sustainable practices as production scales. Finally, cells should be designed with a focus on recycling, to facilitate material recovery and increase modularity by simplifying assembly and end of life disassembly processes.

Research Community

Collaboration with industries should begin at the early stage of development of new technologies. By that, deep knowledge and experience with new technology in pilot lines and data can be achieved for further scaling up. Research should focus even more on sustainability, including the development of measurable sustainability KPIs, and start considering cell designs for next generation cells. Standardised models for processes are needed that can work with new battery materials, cell chemistries and components. Digital models need to be developed that serve as essential tools for understanding, assessing, and implementing flexibility in battery production. Hybrid physics-based digital models of production steps fused with data-driven methods should be developed to create digital twins for new machinery and process configurations based on sparse data sets. Data acquired in European pilot lines can be a strong basis for the model and digital twin development. Objective assessment methodologies for estimating the sustainability of a cell design should be developed. This should include a circularity assessment before production, considering the technology characteristics to assist in process development. Focus should not be only on high purity recycled raw materials but also the impact of lower quality material on cell performance and safety.

SRA	Short term	Medium term	Long term
SRA1 Sustainable cell and battery design	Objective assessment methodologies for sustainability before production Design with focus on recyclability and increase modularity Increase utilization of recycled or up-cycled material	Materials selection based on sustainability evaluation LCA, LCC, circularity and supply chain analyses to chose most suitable option Design for long lifetime	AI- and data-driven decision supporting in design and material selection. Embedded instrumentation for continuous monitoring for performance optimisation
SRA2 Sustainable production of cells and batteries	Improve production efficiency, among others by new innovative processes Analysis on impact of using recycled materials w.r.t. battery performance Intelligent automatization for scrap reduction and recycling Focus on cheap/abundant materials (e.g. Sodium) Automated quality control processes and cross-industry data sets Prepare for digital battery passport implementation	Flexible production processes Trade-off between scrap reduction and reuse Sensors for manufacturing equipment and process tracking AI-based tools for battery manufacturing	
SRA3 Flexible (production) technologies	Digital models for production line assessment before using new materials Digital twins for new machinery and process configurations Automatic creation of digital battery passports from process data Flexibility regarding new (e.g. SSB) or no longer available chemistries Flexible and adaptable tools for varying lot sizes and interchangeable production equipment	Advance from digital models to digital twins directly interacting with production Data platform standardisation Multi-purpose platforms for pouch, cylindrical and flexible cells	

SRA	Short term	Medium term	Long term
SRA4 Process and product scaling and industrialization	Standardisation for data collection and reporting	Scaling digital infrastructure	Work towards international standardization and certification frameworks
	Integration of scale-up tools at pilot level	Pilot testing of integrated scale-up tools	Full integration of scale-up tools for mass production
	Regulatory alignment at pilot level to ensure achievable compliance	AI-enhanced physics-based models	Transferable AI-enhanced physics-based models among new emerging technologies
	Cell design should take into account OEM tech roadmaps	Collection of worldwide data for training existing AI models	
	AI- and physics-based models for accelerating scale-up		
Transversal Challenges			
	Formation of a trustful European ecosystem in which knowledge and technology is developed for the entire process chain and is shared to achieve a competitiveness European Battery Industry.		

Table 9: Overview of Strategic Research Areas of the Cell design and manufacturing roadmap, developed by Batteries Europe/ BEPA WG4

2.9. Application and Integration: Mobile: Strategic Research Areas

The mobility sector includes several forms of transport, each of which have some of their own unique demands and particular areas of focus for battery technology research to ensure batteries can serve as part of the drivetrain. Even within the individual sections of the sector there are different demands, for example road transport includes everything from electric bicycles and scooters to passenger cars to heavy duty trucks each with differing demands. However, regardless of the sector there are some overlapping research needs for battery technology which you will see echoed throughout the chapters below. These include:

- Reduced cost for batteries in particular with regard to manufacturing processes.
- Increasing gravimetric and volumetric energy density of battery cells
- Facilite fast and super-fast recharge cycles
- Extend the calendar and cycle lifetime of batteries
- Enable first life reparability and refurbishing of batteries.

2.9.1 Road transport

Road transport has a significant economic and environmental impact, remaining the largest and most important market for batteries in Europe, and, therefore, a crucial area of focus for policymakers. According to the European Environment Agency, road transport is responsible for approximately one-fourth of anthropogenic CO2 emissions in Europe. To mitigate these emissions, the electrification of cars, vans, and trucks is gaining momentum as a primary strategy, and in this context, batteries play a pivotal role as a key enabling technology. For electrified vehicles, the battery must strike a balance between performance and cost. As performance in EVs we mainly refer to a blend of energy storage capacity (kWh), sustained power rating (charge and discharge, (kW)), weight (Wh/kg) and volume (Wh/l), while, as cost, we merely refer to the production cost of the battery pack (cell, module, systems, sensors) in €/kWh. Currently, state-of-the-art market-available Li-ion technology offers energy density up to 250 Wh/kg at the cell level and up to 175-180 Wh/kg at the pack level, with a cost of approximately 150 €/kWh.

Concerning light duty passenger cars and commercial vehicles, in 2024 the European car market is navigating a period of transformation driven by tightening emissions regulations, economic pressures, and evolving consumer preferences. In this framework EVs continue gaining ground against conventional fueled cars; however, the European EV market is facing severe challenges with high inflation and supply chain disruptions, particularly in battery materials, as well as an increasing and upcoming competition from Chinese manufacturers. It is a fact that today electric vehicles are mature products, and battery performance of current state-of-the-art market reference products are deemed satisfactory in most use cases, with EVs' real-world driving range of 400+ km and battery capacities above 60 kWh. Consequently, research should prioritize cost reduction, specifically aiming to lower battery pack costs below 100 €/kWh to make European EVs more affordable and competitive with Chinese and Korean alternatives. While current gravimetric and volumetric energy densities are sufficient for light-duty markets, further improvements in energy density, such as reducing material use per kWh, and enhancing charging capabilities to support frequent fast-charging with minimal degradation, are key to reducing costs. A target of 300 Wh/kg at the pack level and 3-5 C sustained fast-charging could enable new use cases, extend battery life, and reduce total cost of ownership. Cost pressures are likely to shift European focus toward smaller, lighter EVs optimized for urban and suburban use, such as compact "European key-cars". Affordable battery technologies tailored to these applications, with fast-charging capability, could serve as a primary area of research to meet future market demands.

Concerning medium and heavy-duty vehicles' electrification, the adoption of batteries together with fuel cells is still seen as an option for covering diverse use cases, i.e. regional delivery vs. long-haul trucks. However, there are elements in the market suggestive of batteries to be fit in future for long-haul applications too. Also here, cost reduction is essential, both in terms of reduction of battery cost as well as extension of the lifetime, and hence reduction of the vehicle's total cost of ownership. The latter, in the case of medium and heavy duty, is deemed a priority. Ability to sustain fast charging and super-fast charging (up to 1 MW) is also key in medium and heavy-duty market.

Furthermore, to enable the large-scale deployment of fully electric vehicles, several essential factors must be considered as transversal to the light, medium and heavy-duty markets. These include interoperability and standardization, new and flexible manufacturing approaches, refurbishment, second life and recyclability, and the integration of in-vehicle batteries with the electricity network and infrastructure to unlock the potential for bidirectional recharging services. Developing new business models for enhancing affordability is important too. In addition to performance, capability of operating under extended user-profiles and diverse environmental conditions (e.g., cold/warm climates) is also of importance.

R&D activities needed

Research needs for road transport batteries can be summarised along the following areas and time frames:

Short-term needs (2029):

- Reducing battery cost, both in terms of manufacturing cost and retail price, as well as extending lifetime as a measure to reduce the total cost of ownership of the vehicle.
- Increase the cell energy density performance, while avoiding critical materials (e.g., Co) still keeping other requirements like lifetime ability, pushing for the transition to solid-state Gen. 4 Li-ion batteries on the mid-term targeting 300+ Wh/kg at pack level.Automotive grade safety (e.g., crash safety, adoption of flame-retardant materials), cyclability, lifetime, sustainability, and recyclability must be ensured.
- Progress on the batteries' thermal management, extended lifetime under sustained fast and super-fast charge cycles, and integration into vehicles' platforms, exploiting, where applicable, multi-functionality as a cost reduction measure.

Mid-term needs (2035):

- Investigate new battery architectural and housing designs, including multi-type pack arrangements (e.g. high-voltage LNMO / high-capacity NMC packs co-existing in the same system, only if applicable according to the requirements of the specific end-user application), high-voltage and current (i.e. above or equal to 800 V and 500 A), increasing performance through enhanced integration (i.e. Cell-to-Chassis (C2C) and Cell-to-Vehicle (C2V)) while ensuring repairability and failure safe operation (e.g. containment of the thermal runaway).
- Encompassing first life reparability and refurbishing, second life (either in mobile or stationary applications), battery cell, module and pack dismantling and recyclability, including tracking of relevant battery data, in full alignment with the Battery Regulation and Battery Passport prescriptions. For niche applications (e.g. contract fleet, and very light duty vehicles) further exploration on how to facilitate battery swapping has also its own interest.

Impact

The advancements in batteries for road transport will have a significant impact, accelerating the deployment of fully electric light and heavy-duty vehicles. This transition will effectively reduce the environmental impact of transportation, leading to a decrease in CO2 emissions and an improvement in air quality, particularly in cities and densely populated areas. These advancements will unlock substantial environmental and social benefits. It is worth noting that even with several carbon-intensive electricity grids across Europe, electric cars already outperform fossil-fuel cars in terms of life-cycle CO2 emissions. As the EU continues to decarbonise its electricity grid, this situation will further improve in the future. From an economic perspective, the development of batteries as a key enabling technology in road transport will strengthen the European automotive industry. Simultaneously, it will create new business opportunities in the transport and energy sectors. By implementing smart charging strategies and exploring vehicle-to-grid capabilities, electric vehicles can become valuable assets, providing flexibility services to the electricity distribution network. They can function as intermittent storage solutions for renewable energy sources, enhancing the overall efficiency and sustainability of the energy system. Overall, the progress in battery technology for road transport will not only contribute to environmental goals but also drive economic growth and innovation, positioning Europe at the forefront of the automotive industry while facilitating the integration of clean energy solutions into the transportation sector.

2.9.1 Airborne Transport

Batteries are recognized as a key technology for delivering the next generation aircraft, supporting the vision to achieve carbon neutral aviation by 2050, as per the European Green Deal Action Plan. Strategically, the EU has identified four synergistic pillars to achieve this objective: adoption of sustainable aviation fuel, implementation of economic measures, better air traffic management and new technologies (energy storage, carrier, and conversion systems). Solely focusing on the technology improvement dimension, this is expected to contribute 38% to the overall carbon cut by 2050, while its implementation is framed within the Clean Aviation Strategic Research and Innovation Agenda (SRIA). The latter identifies the three main "thrusts" along which the Clean Aviation programme and the Horizon Europe programme unfold: SMR (Short and Medium Range, 150-200 pax.), HER (Hybrid Electric Regional, 50-100 pax.) and HPA (Hydrogen-Powered Aircraft). An update of the SRIA was published in autumn 2024 where the role of hybrid electric propulsion, and therefore of batteries, is better framed within the HER thrust. Specifically, the SRIA refers to the next generation "ultra-efficient regional aircraft" engineered to meet the industry's growing demand for sustainable and efficient air travel, specifically catering to regional routes. This is targeted to serve regional routes between 500 and 1,500 kilometers (i.e. short-to-medium range), accommodating up to 72-78 passengers. Primarily it combines an ultra-efficient thermal engine re-designed for full compatibility with sustainable aviation fuel, with a battery-powered electrical motor mechanically connected to the propeller gearbox (parallel hybrid), to optimize the engine core size using electrical power. The targeted thermal-electric power split of the 4 MWh drivetrain is not disclosed, however, in normal operations, it is envisioned electrical energy providing up to 20% of the power for the top-of-climb segment and initial cruise, with recharging from the thermal engines potentially occurring later in the cruise and during descent, as well as on the ground between flights. This should result in a DoH between 10 and 20%, requiring a sizing of the battery in the range of few hundreds kWh (two battery packs capable of combined 300-500 kWh), aiming at exploiting the electric powertrain as a booster in a mild-hybrid architecture. As such the ultra-efficient regional aircraft targets a 20% fuel and CO2 reduction against the baseline aircraft, possibly achieving up to 30% by implementing additional innovations (e.g. optimized wingtips, redesigned nacelles, lightweight materials, and electric auxiliaries, etc.). Entry into service is envisaged by 2035.

Beyond the ultra-efficient regional aircraft, the market is also targeting a smaller class of passenger aircraft for regional transport, capable of a flight range between 200 and 800 km accommodating 25-30 passengers. Here, full electric flight is doable for the lower mark range, with hybridization intervening in a range extender configuration (series hybrid), resulting in a DoH of 50-to-100%.

Additionally, where batteries will not act as a propulsion energy storage device, they will continue to increasingly serving the deployment of more electric secondary systems within the HER and SMR thrusts. For HER and SMR more-electric aircraft systems (i.e., electrification of all main aircraft subsystems, such as electric ice protection systems, landing gear, electric aerodynamic surfaces' actuators, and electric cabin environmental control system), batteries are expected to function as their main energy storage, accounting for approximately 3-5% of the overall energy demand on a typical short-to-medium range aircraft segment, and 1% in the long-range segment (i.e. in the range of 2 MWh capacity size). Moreover, batteries are seen as the primary solution for powering upcoming unmanned aerial vehicles, such as cargo delivery drones, capable of electric Vertical Take-Off and Landing (e-VTOL) and future urban air mobility applications.

Currently, Li-ion batteries are used in the aeronautic field in support to on-board electric systems on large passenger aircraft, e.g., avionics and, still in a very limited manner, as main propulsion energy storage in the general aviation segment. Current market available battery technology for aeronautic applications consists of high-capacity NMC either in cylindrical or in a pouch cell format. The main challenge for further developing batteries for air transport consists of designing lightweight systems that natively adopts Generation 4 solid-state cell, capitalizing on the improved performance and safety inherent to such technology, while complying with the recent framework disclosed under the EASA SC-VTOL MOC3 (June 2023), signaled to be adopted as baseline for future Part-25 airworthiness specifications (Dec. 2023).

R&D activities needed

Research needs for airborne batteries can be summarised along the following five areas:
Short-term needs (2029):

- Increase the performance for density (energy and power) and safety of cells (e.g. EUCAR level ≤ 2 at cell level only), by focusing on inherently safe active materials, electrodes, and electrolytes, delivering (semi-)solid-state Gen. 4 cells in pouch format, achieving 450+ Wh/kg at cell level and 2.5C, with capability up to 5C for fast charging. Research should target calendar and cycling ageing performance compatible with aircraft maintenance cycles (e.g., 2,000 cycles over 12-18 months, aircraft C-check).
- Design and prototype safe, light weight and airworthy battery modules and packs (including cooling systems and thermal conditioning systems, also relevant to battery safety, BMS, on-cell sensors) capable of 400+ Wh/kg at module level and fit for the 800V Ultra-Efficient Regional Aircraft architecture (liaison with Clean Aviation), with the possibility of stepping up to higher voltage architectures in the longer term.
- Enhance European testing capabilities in support of the module and/or pack airworthiness certification of large-scale passenger hybrid electric aircraft batteries (specifically targeting EASA SC-VTOL MOC3 and upcoming CS-25).
- Deploy a MWh-scale battery system demonstration at the test bench level (liaison with Clean Aviation).

Mid-term needs (2035):

- Advance battery integration concepts into composites, such as multi-functional energy storage structures with embedded multi-purpose sensing capabilities capable of significantly increasing on the performance of mono-functional references, while maintaining aeronautical-grade structural safety uncompromised and targeting secondary and primary fuselage structural components.
- Develop new airworthiness certification procedures capable of capitalising on fast technology development cycles (together with EASA), alongside with on-ground and in-flight operational procedures for airborne batteries in the aircraft, i.e., battery check, recharging or quick and safe replacement, maintenance and/or refurbishment procedures, informed by on-cell and in-module sensors, for continuous monitoring.
- Cost reduction, which is a driver for all other mobile applications, is significantly less relevant for airborne batteries. The aeronautic market can, provided its key safety and energy

density requirements are met, afford a production cost per kWh in the order of 5-to-10 times higher than its surface transport counterpart.

Impact

Impact-wise, batteries are expected to function as the main energy storage for airborne applications in the categories of full electric general aviation, E-VTOL, and in the lower segment of regional passenger transport. Additionally, they are expected to functioning as co-primary energy storage, together with sustainable aviation fuel, across the full spectrum of regional passenger applications, while supporting more electric aircraft architectures in the short-and-medium range and long-range aircraft segments.

Airborne batteries are expected to contribute to a carbon cut compared to aviation 2020 state-of-the-art directly proportional to their actual use as no GHG (Greenhouse Gases) energy source. In more details, between 20 and 100% of carbon emissions reductions are expected in the regional aircraft segment, up to 5% in the short-and-medium range segment and up to 2% in the long-range segment. By considering fleet-level reduction, this sums up to 3.5% of total emission reduction from airborne transport by electrification, i.e. approximately 10% of what is deemed achievable technology wise. Moreover, the airborne battery market (global) is estimated at 55-110 GWh/year (new deliveries and refurbishment combined), with benefits for all transport modes that will leverage on the high-level technological challenges and safety standards expected in this sector.

2.9.3 Waterborne Transport

In 2020, marine electrification involved over 200 vessels, with more than 170 still under construction, but this represents only 0.5% of the world fleet. The battery demand accounts for less than 1% of the global annual production of lithium-ion batteries. Batteries are primarily used in passenger ferries, car ferries, and offshore supply vessels, and the sector is growing in coastal and short-distance shipping. For long-distance navigation, hybrid systems are employed to enhance fuel efficiency. The main challenges are safety, reliability, efficiency, and lifespan. Compared to road transport, marine safety regulations are much stricter.

Lithium technology dominates due to its balance between safety, energy density, power, and lifespan. The most common chemistries are NMC and LFP, while LTO is used for high-power, long-cycle applications. Research will mainly focus on the integration of battery systems into ships or offshore platforms and safety aspects, which are also the main cost drivers for waterborne applications. Marine systems must cope with harsh environmental conditions, such as humidity and salinity, making corrosion-resistant materials and proper thermal management essential. Applications vary widely, requiring customized solutions and the integration of energy harvesting technologies. As a subject of note, the exploitation of the “container form factor” as an on-board battery modular element could be useful for electrified container ships.

R&D activities needed

Battery research for waterborne applications will benefit from advancements in other transport modes, regarding performances and enabling fast charging. Tailored requirements for waterborne applications will consider high energy density to support long voyages and heavy loads typical in maritime operations. Waterborne-specific research needs are listed below.

Short-term needs (2029):

- Enhance energy and power capabilities, with a focus on improved system integration and thermal management. This includes advanced solutions like direct liquid cooling (partial or full immersion) and innovative Battery Management Systems (BMS) leveraging AI technologies for real-time optimization.
- Develop battery packs and systems with advanced materials and coatings to resist corrosion, ensuring durability and reliability in challenging operating environments. Ensure robust battery designs that can withstand harsh marine environments, including exposure to saltwater and extreme temperatures, while maintaining a long operational life.
- Enhance safety measures to address specific maritime risks, such as fire prevention and thermal runaway containment in confined spaces onboard vessels.
- Design modular and scalable battery systems to meet the diverse energy demands of various vessel types, from small ferries to large cargo ships.

Mid-term needs (2035):

- Implement adaptable functional safety rules for emerging technologies, such as novel chemistries, advanced communication hardware/software, and integrated thermal conditioning systems. Develop standardized functional safety guidelines tailored to waterborne applications.
- Enhance fast charging capabilities to support the specific requirements of waterborne transport: fast-charging solutions suitable for ports and remote locations, ensuring seamless integration into existing maritime operations. Promote the development of vessel-to-grid technology, enabling large ship batteries to provide grid services, fostering green ports, and integrating renewable energy resources.
- Advance hybrid solutions combining batteries and fuel cells to accommodate diverse operational modes. Design systems with retrofit capabilities to integrate future battery advancements seamlessly.
- Establish a robust framework of regulations and standards developed in collaboration with private and public stakeholders. Ensure these are globally applicable to facilitate the transition to zero-emission marine transport.

Impact

In the waterborne sector, emissions in densely populated areas, such as coastal regions and ports, have a more significant impact compared to those in open sea areas. Achieving zero emissions in urban environments by using fully electric vessels is particularly valuable in cities like Istanbul, Venice, Copenhagen, and Amsterdam. Promoting waterborne transport as an alternative to road transport is a key strategy for reducing urban pollution.

The electrification of waterborne transport will not only benefit the environment but also stimulate economic growth by creating job opportunities in both retrofit and new construction markets. Moreover, it will enhance the integration of different transport modes, contributing to Europe's competitiveness in delivering a safe, reliable, cost-effective, circular, and sustainable battery industry.

2.9.4 Rail Transport

Rail transport plays a key role in achieving the Paris Climate Agreement goals. Around 60% of railway lines are electrified, and 80% of traffic uses electric traction. However, diesel still powers 20% of EU rail traction on non-electrified lines. To address this, innovative solutions include hydrogen fuel cell trains with lithium-ion batteries and hybrid diesel-electric locomotives. Hydrogen fuel cell trains typically have batteries with capacities around 200 kWh. For battery-electric trains, common lithium-ion technologies include NMC (e.g., Bombardier, iLint) and LTO (e.g., Siemens, Stadler). These batteries offer 80-120 km autonomy and 7-10 years lifespan, with energy capacities up to 800 kWh. R&D is essential to overcome limited available space on board, efficiency, and performance constraints, advancing battery technology for rail applications.

R&D activities needed

Battery research priorities for rail applications align with broader transport needs, focusing on increased energy density, cost reduction, enhanced safety, and fast charging capabilities. However, rail-specific requirements can be summarized as follows:

- Develop batteries with higher energy storage to extend train autonomy, especially for long non-electrified routes, while exploiting discontinuous catenaries for intermittent charges.
- Lower production and maintenance costs to make battery-powered solutions more economically viable for the rail industry.
- Ensure robust safety standards for high-capacity batteries, addressing thermal stability, fire resistance, and failure prevention in railway environments.
- Enable rapid charging systems to minimize downtime and support high-frequency train operations.
- Harmonizing EU-level standards for trains is essential to enhance interoperability, reduce costs, and streamline certification processes.

Impact

These measures aim to create a cohesive rail network, driving innovation and sustainability while supporting the EU's broader climate and mobility goals. Storing large amounts of clean energy onboard trains, combined with ground storage, enables more flexible and cost-effective electrification of infrastructure in challenging areas like tunnels and bridges. This on-board self-sufficiency also ensures uninterrupted operation during power outages, maintaining passenger comfort and allowing the train to reach the nearest station safely. Additionally, electrifying freight transport, especially for last-mile operations, will become simpler and more efficient, enhancing sustainability across the entire rail network.

2.9.5 Off-road Transport

Non-Road Mobile Machinery (NRMM) includes mobile machines and industrial equipment with internal combustion engines, not designed for road transport. Used in sectors like mining, forestry, and agriculture, NRMM operates in demanding environments requiring rugged, high-power solutions. Electrification potential varies by application, with priorities on power density, cyclability, and safety, while energy density and cost are secondary. Fast charging is crucial due to continuous operations. NRMM faces challenges like remote sites with limited grid access and is shaped by emissions standards, notably Regulation (EU) 2016/1628, which excludes CO2. Market competitiveness depends on local zero-emission subsidies, competing with traditional powertrains in a fragmented market.

R&D activities needed

Battery research for Non-Road Mobile Machinery (NRMM) can benefit significantly from advancements in other transport modes, focusing on enhancing performance, safety, enabling fast charging, and reducing costs. The specific needs for NRMM can be outlined as follows:

- Advance the design of battery modules and packs, integrating efficient cooling and heating solutions to ensure reliable operation in extreme environments. Leverage digital twin models to accelerate development through agile and virtual design loops, enabling faster innovation and optimization.
- Improve the accessibility, repairability, and reusability of battery packs by enabling the replacement of individual cells or modules as needed. This approach enhances sustainability, promotes circularity, maximizes battery lifetime, and reduces cost per cycle.
- Conduct pre-normative research specific to NRMM batteries to establish standards and foster synergies within the off-road sector, while aligning with heavy-duty on-road applications. This alignment aims to achieve economies of scale and drive cost efficiencies across the battery industry.

Impact

CO2 emissions from NRMMs—including construction and agricultural machinery, gardening equipment, rail vehicles, and inland waterway vessels—are estimated at 100 million tons annually within the EU27. This accounts for approximately 2% of the region's total greenhouse gas emissions, highlighting their significant environmental impact. Electrification offers a promising solution, potentially eliminating emissions and improving local air quality. It also promises a substantial reduction in energy consumption, projected to drop from the current 395 TWh to 165 TWh if the entire fleet transitions from diesel to fully electric power.

2.9.6 Fast charging – Transversal challenge

The ability of fast charging is a major aspect influencing consumer choices and electrification of transport, often treated as a main barrier for adoption and connected to range anxiety, as far as electric passenger cars are concerned. Additionally, the perception of not having enough driving range and/or not being able to fast charge pushes consumers towards vehicles with batteries often larger than what is needed in most real-world use cases, exacerbating costs, and constituting a further barrier to adoption. Therefore, the deployment of fast charging is functional to the cost reduction, allowing to downsize the battery capacity without hampering the ability of the vehicle to serve certain use cases.

Li-ion batteries fast charging has made significant progress in recent years, with chargers capable of 10-to-80% battery pack SoC increase in about 30 minutes. However, real-life performance at vehicle level lags the one demonstrated at cell level, indicating cell-to-system adaptation challenges. As most prominent limiting factors to adoption and further development of fast charging, cell degradation (i.e., cycling capacity fade) and heat dissipation are to be mentioned, with the latter constituting a safety risk too. Fast charge performance is strictly entwined with the specific battery pack designs, as the requirements for high-energy applications differ from high-power systems. R&I in the area of fast charging is expected to focus on mainly at system level, i.e. modules and battery pack level, delivery system designs capable of increasing the charging power while limiting degradation targeting to double the actual charging speed, i.e., from 10-to-80% battery pack SoC increase in 15 minutes. Similarly fast charging is key in industries other than automotive too. Concerning the aeronautic industry, with charging time that need to be compatible with the aircraft Turnaround time (TAT), i.e. from 20-to-95% battery pack SoC increase in 20-30 minutes, while, concerning the waterborne industry, charging needs to be compatible with port infrastructure and vessel resident time. Safety issues, standardisation of the connectivity and control between the battery and the charging infrastructure, and the regulatory framework (including payment systems) are also important aspects to enable the deployment of the fast charge. On the latter, compatibility across different vehicle categories, and across different transport modes need to be considered. Deploying fast charging capabilities is seen as necessary to unlock the potential of electric vehicles, while enabling electrification of sectors such as long-range heavy-duty transport or regional aircraft applications, where the short charging time is essential to operate the business model. Infrastructure-driven fast charge and V2X (affecting grid balance) are also relevant aspects to be considered.

2.9.7 Battery refurbishing – Transversal challenge

Battery refurbishing is an essential strategy for enhancing sustainability, reducing waste, and extending the lifecycle of batteries across various applications. Addressing the research needs in this domain is critical to overcome existing challenges and unlock the potential of circular economy practices in the battery industry. A primary research focus is on advanced diagnostics to accurately assess the state of health (SoH) and state of charge (SoC) of used batteries. Innovative tools and algorithms are required to identify individual cell or module performance, ensuring reliable sorting of reusable components. This diagnostic capability is vital for creating standardized refurbishing processes that maintain safety and performance standards.
Another key area is the development of modular battery designs to simplify disassembly and

replacement. Research should prioritize designing batteries with replaceable components, such as cells or modules, without compromising structural integrity. Improving automation in refurbishing processes is also crucial. Robotic systems and AI-driven tools could streamline disassembly, cleaning, and reassembly, reducing manual labor and ensuring precision. Enhanced automation would make large-scale refurbishing economically viable. Additionally, research into sustainable material recovery is necessary to recycle or reuse battery components that cannot be refurbished. For instance, innovative chemical or mechanical processes could enable the recovery of critical materials like lithium, cobalt, and nickel, minimizing environmental impact. Finally, policy and standardization efforts are needed to establish clear guidelines for refurbishing practices, ensuring safety, and fostering consumer trust. Collaboration between industry, academia, and regulatory bodies can align refurbishing technologies with market demands. In conclusion, addressing these research needs will enable efficient, cost-effective, and sustainable battery refurbishing, supporting a resilient and environmentally responsible energy ecosystem.

2.9.8 SoX prediction and smart sensors – Transversal challenge

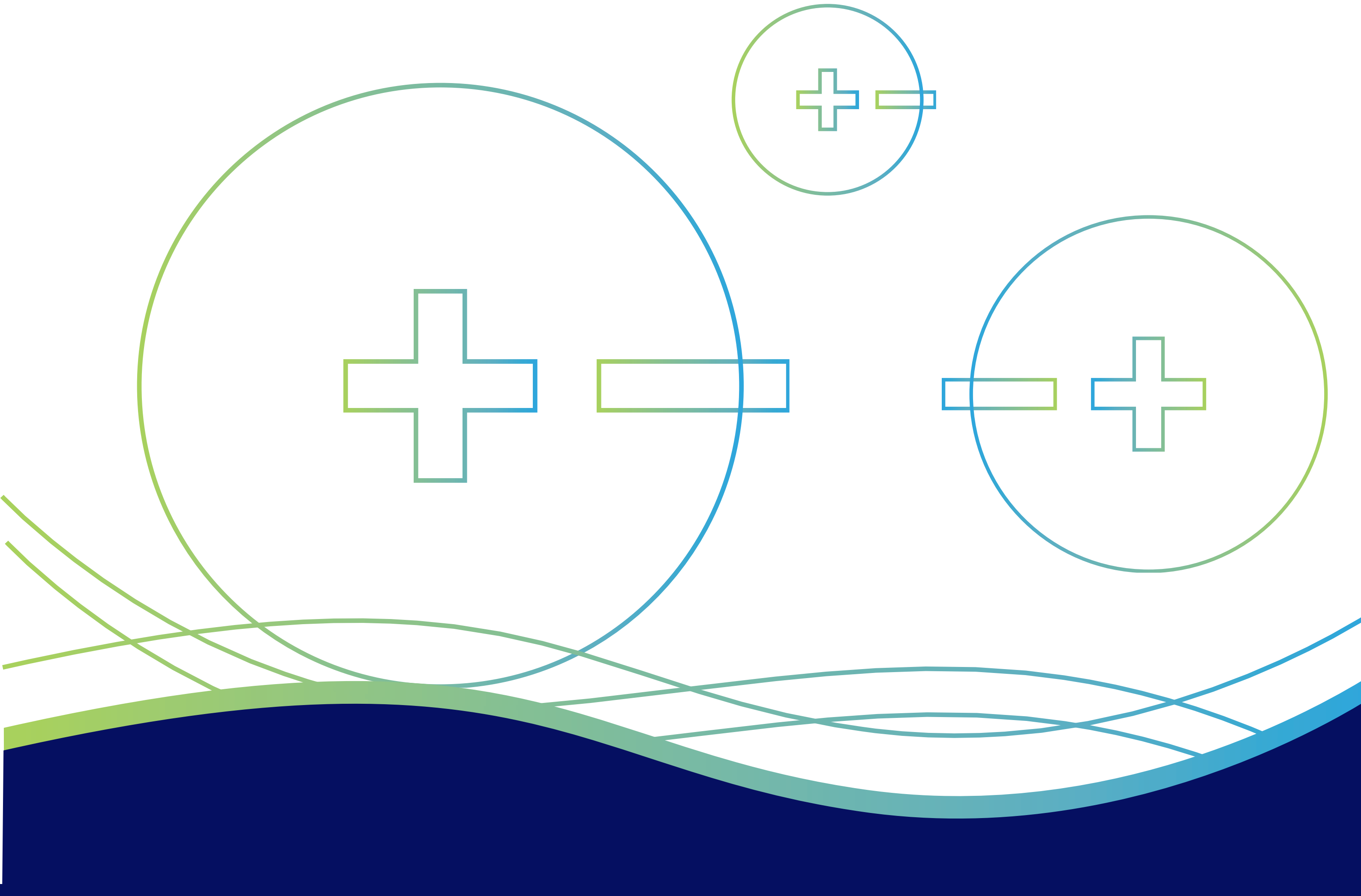
The accurate measurement and estimation of key battery indicators such as State of Charge (SoC), State of Health (SoH), State of Temperature (SoT) and State of Power (SoP) is crucial for implementing the correct and safe operation of the battery and hence extract the maximum performance from the technology as well as for ensuring adequate safety in aeronautical applications. Additionally, accurate failure prediction, prognostics and diagnostics are essential to extend the lifetime of the battery, and these functions need to be enabled via fewer multifunctional embedded sensors and Battery Management Systems (BMS) which are both low power and low cost. The set of key indicators (SoX) must be, therefore, uniquely defined, applicable to different battery chemistries, and implementable in all BMS systems. The main challenges to address in this field are: (i) identification of sensors for estimating SoX according to a prescribed reference (established through pre-normative research), (ii) establishment of methodologies for SoX estimation which are fast, accurate and reliable making use of data (e.g. manufacturing data from the battery passport, usage data pattern recognition, charging data), and (iii) integration and demonstration of SoX models fit to run on the existing battery electronics and/or connected platforms. Impact wise, robust, accurate and reliable SoX prediction is crucial to correctly operate the battery, extend service life, and implement effective use profile, as well as to perform robust comparison between different technologies and applications. SoX methods must be open, enabling better use and hence decreasing the environmental impact of the technology.

2.9.9 Key Recommendations

Investments in battery technologies research and innovation, on European, national, and regional levels will enhance the competitiveness of Europe and empower a circular battery value and supply chain. It is extremely important to promote collaboration along the entire value chain (horizontal) / cross-sectoral (vertical) enabling synergy and circular economy (production).

From the perspective of mobile applications, it is crucial to address the gap between the cell and the system, implementing the specifications of the vehicles in terms of performance, operational environment and mission profile. Bolstering performance, while reducing the cell-to-system penalty is key. Among the applications, automotive and aeronautics are considered those which are mostly gaining traction and will drive the market in the short and medium future. Hence it is advised to invest most of the efforts on these. Automotive drives volume applications and cost reduction, while aeronautics drives performance and safety. The other applications, i.e. waterborne, rail and off-road, follows, benefitting from the advancements of the first two while introducing additional requirement specific to the interested vehicles.

Moreover, policymakers and national authorities should encourage and foster pre-normative research to define battery system requirements in (emerging) applications, battery system design bases, interoperable BMS and IoT, improve sustainability and aiming at reaching scale benefits in battery industry. New standards are strongly needed to couple with the emerging new technologies and tools for batteries applied on all transport modes. A common strategy is to be recommended for improved performance, lifetime, and safety (including control monitoring, common protocols, learning prognostics).



SRA	**Short term**	**Medium term**	**Long term**
SRA1 Road transport	Reduction of battery costs and extension of the usable battery life, achieving a cost mark below 100 €/kWh		
	Increase the cell energy density performance while avoiding critical materials (towards Gen. 4) and ensure automotive grade safety		
	Progress on batteries' thermal management for extended lifetime and fast charging capabilities		
		Increase performance for density (energy and power) and safety of Gen 5 cells	
		Encompassing first life reparability and refurbishing, second life and recyclability	
	Increase the cell energy density performance Gen 3b		
	Advance in cooling systems, and digital twin models		
	Advance Battery Management Systems		
		Increase the cell energy density performance Gen 4	
		Investigate new battery architectural and housing designs	
		Encompassing first life reparability and refurbishing, second life	
	Reduction of battery costs and extension of the usable battery life, achieving a cost mark below 100 €/kWh		
	Increase the cell energy density performance while avoiding critical materials (towards Gen. 4) and ensure automotive grade safety		
	Increase the cell energy density performance while avoiding critical materials (towards Gen. 4) and ensure automotive grade safety		
		Investigate new battery architectural and housing designs (e.g. C2C, C2V)	
		Encompassing first life reparability and refurbishing, second life eycyclability	

<table>
<tr><th>SRA</th><th>Short term</th><th>Medium term</th><th>Long term</th></tr>
<tr><td rowspan="15">SRA2
Airborne Transport</td><td colspan="2">Increase the cell energy density performance Gen 3b</td><td></td></tr>
<tr><td colspan="2">Advance in cooling systems, and digital twin models</td><td></td></tr>
<tr><td colspan="2">Advance Battery Management Systems</td><td></td></tr>
<tr><td></td><td colspan="2">Increase the cell energy density performance Gen 4</td></tr>
<tr><td></td><td colspan="2">Investigate new battery architectural and housing designs</td></tr>
<tr><td></td><td colspan="2">Encompassing first life reparability and refurbishing, second life</td></tr>
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<tr><td>Progress on batteries' thermal management for extended lifetime and fast charging capabilities</td><td></td><td></td></tr>
<tr><td></td><td colspan="2">Investigate high voltage systems (800V+) in new battery architectural designs (e.g. C2C, C2V)</td></tr>
<tr><td></td><td colspan="2">Encompassing first life reparability and refurbishing, second life and recyclability</td></tr>
<tr><td colspan="2">Increase performance for density (energy and power) and safety of Gen 4 cells, achieving 450+ Wh/kg at cell level and 2.5C, with capability up to 5C for fast charging and 2,000 cycles.</td><td></td></tr>
<tr><td colspan="2">Design and prototype safe, light weight and airworthy battery modules and packs, capable of capable of 400+ Wh/kg at module level and fit for the 800V Ultra-Efficient Regional Aircraft architecture (liaison with Clean Aviation)</td><td></td></tr>
<tr><td colspan="2">Enhance European testing capabilities in support of the module and/or pack airworthiness certification (as per EASA SC-VTOL MOC3 / upcoming CS-25)</td><td></td></tr>
<tr><td colspan="2">Deploy a MWh-scale battery system demonstration at the test bench level (liaison with Clean Aviation)</td><td></td></tr>
</table>

SRA	Short term	Medium term	Long term
SRA2 Airborne Transport		Advance battery integration concepts into composites, such as multi-functional energy storage structures with embedded multi-purpose sensing capabilities	
		Develop new airworthiness certification procedures capable of capitalising on fast technology development cycles	
	Increase performance for density (energy and power) and safety of Gen 4 cells		
	Prototype light weight, integrated, airworthy battery modules and packs		
			Increase performance for density (energy and power) and safety of Gen 5 cells
			Increase the cell energy density performance Gen 3b
			I Advanced battery integration concepts
			Develop a sustainable circular economy for batteries
	Increase performance for density (energy and power) and safety of Gen 4 cells, achieving 450+ Wh/kg at cell level and 2.5C, with capability up to 5C for fast charging and 2,000 cycles		
	Design and prototype safe, light weight and airworthy battery modules and packs, capable of capable of 400+ Wh/kg at module level and fit for the 800V Ultra-Efficient Regional Aircraft architecture (liaison with Clean Aviation)		
	Enhance European testing capabilities in support of the module and/or pack airworthiness certification (as per EASA SC-VTOL MOC3 / upcoming CS-25)		
	Deploy a MWh-scale battery system demonstration at the test bench level (liaison with Clean Aviation)		
		Advance battery integration concepts into composites, such as multi-functional energy storage structures with embedded multi-purpose sensing capabilities	
		Develop new airworthiness certification procedures capable of capitalizing on fast technology development cycles	

<table>
<tr><th>SRA</th><th>Short term</th><th>Medium term</th><th>Long term</th></tr>
<tr><td rowspan="13">SRA3
Waterborne Transport</td><td colspan="3">Improve battery performance, in term of energy/power, including systems integration, thermal management while addressing specific maritime requirements (e.g. withstanding harsh marine environments).</td></tr>
<tr><td></td><td colspan="2">Implement adaptable functional safety rules for emerging technologies</td></tr>
<tr><td></td><td colspan="2">Enhancing fast charging as a key enabler for waterborne applications and develop hybrid systems</td></tr>
<tr><td></td><td colspan="2">Establishing a reliable framework of regulations and standards linked to private and public stakeholders</td></tr>
<tr><td colspan="3">Improving battery performance, in term of energy/power, including systems integration, thermal management</td></tr>
<tr><td></td><td colspan="2">Improving battery safety by deploying functional safety rules</td></tr>
<tr><td></td><td colspan="2">Enhancing fast charging as a key enabler for waterborne applications</td></tr>
<tr><td></td><td colspan="2">Develop hybrid systems (e.g., battery and fuel cells) to cover different operation modes</td></tr>
<tr><td></td><td colspan="2">Establishing a reliable framework of regulations and standards linked to private and public stakeholders</td></tr>
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<tr><td></td><td colspan="2">Establishing a reliable framework of regulations and standards linked to private and public stakeholders</td></tr>
<tr><td rowspan="5">SRA4
Waterborne Transport</td><td colspan="3">Improve technical performances at system level increasing the energy density for higher train autonomy, capitalizing on the developments in other transport modes</td></tr>
<tr><td colspan="3">Harmonize the standards applicable to train at the EU level</td></tr>
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<table>
<tr><th>SRA</th><th>Short term</th><th>Medium term</th><th>Long term</th></tr>
<tr><td rowspan="5">SRA4
Waterborne Transport</td><td></td><td colspan="2">Deliver systems characterised by a lower life-cycle cost</td></tr>
<tr><td></td><td colspan="2">Improve battery cycling characteristics, developing accurate lifetime modelling</td></tr>
<tr><td></td><td colspan="2">Improve battery packaging safety</td></tr>
<tr><td colspan="3">Improve technical performances at system level increasing the energy density for higher train autonomy, capitalizing on the developments in other transport modes</td></tr>
<tr><td colspan="3">Harmonize the standards applicable to train at the EU level</td></tr>
<tr><td rowspan="9">SRA5
Off-road Transport</td><td colspan="3">Improve the power performance at cell, module, and pack level, ensuring high charge and discharge rate capabilities, capitalizing on the developments in other transport modes</td></tr>
<tr><td colspan="3">Conduct pre-normative research specific to NRMM batteries</td></tr>
<tr><td colspan="3">Improve the power performance at cell, module, and pack level, ensuring high charge and discharge rate capabilities</td></tr>
<tr><td colspan="3">Advance the system design of battery modules and packs; Digital twin models for accelerating the development within design loops</td></tr>
<tr><td colspan="3">Increase the safety of the battery systems</td></tr>
<tr><td></td><td colspan="2">Enhance accessibility, repairability and re-use of battery packs</td></tr>
<tr><td></td><td colspan="2">Encompass pre-normative research for NRMM batteries, for defining standards</td></tr>
<tr><td colspan="3">Improve the power performance at cell, module, and pack level, ensuring high charge and discharge rate capabilities, capitalizing on the developments in other transport modes</td></tr>
<tr><td colspan="3">Conduct pre-normative research specific to NRMM batteries</td></tr>
<tr><td colspan="4">Transversal Challenges</td></tr>
<tr><td rowspan="2">Fast charge</td><td colspan="3">Focus on cells, modules and battery pack design capable of increasing the charging power while limiting degradation (10-to-80% battery pack SoC increase in 15 minutes for automotive, 20-to-95% battery pack SoC increase in 20-30 minutes for aeronautics)</td></tr>
<tr><td colspan="3">Safety issues, standardisation of the control between the battery and the charging infrastructure, and the regulatory framework</td></tr>
</table>

<table>
<tr><th>SRA</th><th>Short term</th><th>Medium term</th><th>Long term</th></tr>
<tr><td rowspan="3">Battery swapping</td><td colspan="3">Advanced diagnostics to accurately assess the state of health (SoH) and state of charge (SoC) of used batteries</td></tr>
<tr><td colspan="3">Modular battery designs to simplify disassembly and replacement</td></tr>
<tr><td colspan="3">Policy and standardization efforts to establish clear guidelines for refurbishing practices</td></tr>
<tr><td rowspan="4">SoX prediction</td><td colspan="3">Identification of sensors for estimating SoX according to a prescribed reference</td></tr>
<tr><td colspan="3">Establishment of methodologies for SoX estimation which are fast, accurate and reliable making use of data</td></tr>
<tr><td colspan="3">Accurate measurement and estimation of key battery indicators such as State of Charge (SoC), State of Health (SoH), State of Temperature (SoT) and State of Power (SoP) with integration and demonstration of SoX models fit to run on existing battery electronics/ connected platforms</td></tr>
<tr><td colspan="3">Accurate failure prediction, prognostic, and diagnostic methodologies.</td></tr>
<tr><td rowspan="3">Fast charge</td><td colspan="3">Focus on cells, modules and battery pack design capable of increasing the charging power while limiting degradation</td></tr>
<tr><td colspan="3">Safety issues, standardisation of the control between the battery and the charging infrastructure, and the regulatory framework</td></tr>
<tr><td colspan="3">Compatibility across different vehicle categories, and across different transport mode</td></tr>
<tr><td rowspan="4">Battery swapping</td><td colspan="3">Compatibility across different vehicle categories, and across different transport mode</td></tr>
<tr><td colspan="3">Development of mechanics and connection of swappable modules, ensuring safety, robustness, acceptable costs, and durability</td></tr>
<tr><td colspan="3">Electronics and battery management system developed for operating different chemistries and adapt different SoX indicators</td></tr>
<tr><td colspan="3">Recharge infrastructure and logistics of the swappable battery modules and packs, and standardisation and interoperability of the swappable modules across different vehicles and vehicles' categories</td></tr>
</table>

Table 10: Overview of Strategic Research Areas of the Mobility applications and integration roadmap, developed by Batteries Europe/BEPA WG5.

2.10 Safety, efficiency and extended lifetime for BESS

The framework of the 2025 roadmap remains substantially similar to the previous one in both content and structure, with the exception of the inclusion of a new transversal challenge regarding Vehicle to Grid (V2G) and Vehicle to Home (V2H) which, in an incremental perspective of the spread of electric cars, may assume significant relevance in the near future. Finally, other minor technological needs have also been included, such as the need to demonstrate the maturity of LDES technology even in an industrial context, or the request to include research in the field of Balance-of-Plant, as it is an important component for management. On this revision, the political and social aspect of the Clean Industrial Deal has been emphasized, highlighting how, with regulatory and financial incentives, politicians and stakeholders can create a favourable environment to drive innovation, promote industrial competitiveness, and achieve a fair and sustainable energy transition.

What remained unchanged in the previous document has been summarized.

2.10.1 Front-of-the-meter (FTM) Battery energy storage systems (BESS)

Front-of-the-meter (FTM) battery energy storage systems (BESS) are essential for grid-connected and renewable-powered microgrids due to their flexibility, scalability, and adaptability. When combined with other technologies, they form Hybrid Energy Storage Systems (HESS). These systems, increasingly integrated with generation assets, provide services to balance energy demand in Local Balancing Areas (LBA). Optimal market performance should require coordination among batteries, distributed generation, and other storage technologies like pumped hydro, thermal, and hydrogen systems.

For this reason, key challenges include digitalizing BESS management, developing advanced optimization algorithms for multiservice functionality, and ensuring interoperability between systems for seamless integration and efficient operation.

Moreover, FTM BESS R&I projects should integrate the following further key elements to drive innovation, promote industrial competitiveness, and achieve an equitable and sustainable energy transition.

- R&I projects should evaluate taxation models that support equitable growth while incentivizing BESS adoption
- Design of funding mechanisms within R&I projects to focus on BESS solutions that enhance long-term energy resilience and stabilize the economy.
- Integrate social justice metrics into BESS R&I methodologies to track progress on equity and environmental goals.
- Embed participatory processes in R&I projects by actively involving citizens, communities, and industries affected by the energy transition. This approach fosters social acceptance and ensures equitable outcomes.

- Develop standards and protocols within R&I efforts to ensure interoperability between BESS and other energy storage technologies.
- Establish clear Key Performance Indicators (KPIs) in BESS R&I projects to measure material circularity, energy efficiency, environmental and societal impact.

R&D activities needed
Short-term needs (2029):

- Development of Digital Energy Management Algorithms:
- Create advanced algorithms for managing energy systems using BESS/HESS in combination with, i.e., renewable energy sources and customize the digitization to meet specific goals based on algorithm integration levels.

Virtual Power Plants (VPPs):

- Develop district storage systems for distribution system operators (DSOs) and implement with real-time integration of energy production data from conventional generation, distributed systems, and energy storage systems (ESS)

Mini-Grid System Control:

- Development of algorithms to control FTM BESS within mini-grids operating in island mode or connected to the main grid, defining the energy priority of household appliances or energy-intensive activities to minimize consumption during isolation

BESS Monitoring and Control:

- Enhance algorithms for (i) monitoring and controlling BESS to ensure optimal performance by managing parameters like Depth of Discharge (DoD), State of Charge (SoC), C-rate, and operating temperature limits; (ii) to predict key operational parameters or degradation factors affecting capacity and efficiency; (iii) Enhance BESS reliability while minimizing MTTR, OPEX, and disconnection costs

Mid-term needs (2035):

- Develop a digital twin for both the BESS and the energy system (or mini-grid) to collect measurement and forecast data and to predict, monitor and optimize energy systems.
- Focus on integrating BESS/HESS with distributed generation assets for multiservice functionality in Local Balancing Areas (LBAs) like mini-grids. Key priorities included standardize communication protocols, develop middleware to unify diverse communication standards and resolve EMC issues caused by power electronic converters in BESS and generation assets
- Design advanced algorithms to support shared ownership and operation of storage facilities between grid operators and third parties, maximizing asset utilization and market flexibility.
    - Focus on developing efficient data management systems, certified digital platforms, and battery readiness for integration into these systems, supporting innovative market models and the circular economy concept.

- Develop strategies for selecting the optimal location, power, and capacity of BESS installations to minimize Capital Expenditures (CAPEX) while maximizing system performance.
- Direct the research on Balance of Plant, especially for power electronics and thermal management, for the optimal operation and cost of the FTM BESS. Direct BoP research, particularly for power electronics and thermal management, for optimal FTM BESS operation and cost.
- The BESS specifications, in fact, depend on the network operator and can vary in terms of power and voltage, so it is important to develop serial power conversion systems that are scalable, modular and easily adaptable to different voltage and peak power levels. Also for thermal management (in particular for hybrid systems) it should be studied how to make it more flexible so that it can meet the needs of different types of batteries and work in different climatic conditions (which depend on the location). Greater reliability, repairability and cost efficiency would be desirable.

Impact

- The development of FTM-BESS will improve the integration of renewable energy sources (RES), supporting the electricity grid in times of congestion and tension. Furthermore, FTM-BESS will enable a more sustainable and cost-effective energy transition while maximizing the benefits of renewable energy and modernizing local energy systems

2.10.2 Behind-the-meter (BTM) Battery Energy Storage Systems (BESS)

Behind-the-Meter (BTM), Battery Storage Systems operate within consumer premises to balance energy flows, reduce costs, and integrate renewable energy sources like solar and wind. They store energy during low-price periods and redistribute it as needed, with battery size and cost depending on demand and local production.

A new storage opportuny can come from the V2X technology (see section 2.10.7 “Transversal Challenge Vehicle to Grid (V2G) and Vehicle to Home (V2H) “)”, which is also a possibility for larger and smaller installations. The control of the energy flow is very important for the implementation of specific business models as well as interaction with the grid and aggregators, but since the vehicle is not always connected to the grid this makes the business case more complex.

A well-designed Energy Management System (EMS) is crucial for optimizing energy flows, balancing internal and grid-supplied energy, and providing surplus energy to address grid congestion. EMS must ensure battery safety, efficient energy flow management, and accurate forecasting, delivering cost savings, resilience, and grid support.

BTM systems, with effective EMS integration, offer both cost-saving and grid-supporting benefits, advancing energy resilience and efficiency.

R&D activities needed
All timescale (2029-2035+)

- Development of battery hardware and software enabling the safety, low maintainability, and long life of the battery storage system.
- Improving energy balancing BTM for predict energy demand, shifting consumption based on availability and also improving component and system performance to enhance efficiency and cycle life, optimizing response time, and reliability metrics (MTTF, MTTR).
- Concerning Energy Flow Management, develop algorithms to optimize energy production, consumption, and storage at the customer level, integrating local controls with cloud/edge aggregator platforms. These systems should identify market demands, propose energy services (type, kWh, duration), and ensure grid support aligned with customer preferences.

A new research need was identified that becomes relevant with the increase of number of machines in circulation, that is the V2X technology. As it concerns about research need, will be important evaluate the impact of V2X (BTM) and V2G (FTM) services on grid needs, to maximize the impact of truly stationary BESS installations. There are both business, control and resilience implications, on the question;
Since bidirectional charging infrastructure represents an opportunity to improve network performance, it is important to direct research to improve scalability and efficiency for energy transfer for use in V2H and V2G.

Impact
Technological impacts include an Increased security of supply (power and energy related), along with the opportunity for the re-use of batteries (2nd life) in BTM applications. Economic impacts include new opportunities for customers to offer their capacity as local services for grid operators and participation in energy markets (intraday, day ahead, others), gaining additional benefits. This will optimise customer cost and welfare maximalisation. The environmental benefits included increased opportunities for consumers to increase their energy independence, thus accelerating the decarbonisation process, along with circularity and resilience strategies of the batteries.

2.10.3 Medium-to-Long Duration Battery Storage

Medium and long duration energy storage systems are essential to build fully decarbonized, reliable, safe and affordable electricity grids. To achieve the goal of net zero emissions it is necessary to eliminate emissions from the energy sector, since the effectiveness of the electrification of energy demand in other sectors also depends on this assumption. While the expansion of variable renewable energy sources is ongoing and expected to continue until at least 2030, it is critical to invest in and develop advanced storage technologies now to ensure their future availability. Globally, various long-duration energy storage (LDES) technologies are under development, spanning mechanical, thermal, chemical and electrochemical systems. Pumped hydroelectric energy storage (PHES) remains the most established, but interest in medium-duration battery energy storage systems (BESS) and funding for LDES innovations have grown significantly in recent years.

Short-term (2029):

Develop innovative approaches for consolidated battery technologies (e.g., VRFB, NaS/NaNiCl2, Li-ion) and upcoming ones (e.g., Na-ion, all-iron flow battery): innovate consolidated battery technologies adapting them to medium or long duration storage also through improved electrochemistry, custom design and hybridisation, also demonstrating capacity expansion during the BESS lifetime through advanced design and management.

In order to achieve the cost target most of the LDES technologies should be based on low-cost and abundant materials. Here the short-term research needs for long-duration BESS should focus on:

- Accelerating the technology maturation and upscaling of BESS suitable for LDES (e.g., flow batteries, metal-air, etc.) and based on low-cost earth abundant materials (e.g., Fe, S, Na, Mn, Zn, Cr, Mg) or organic materials aiming at closing the gap with worldwide competitors while improving technical performances and reducing costs.
- Analysing how LDES can contribute to the creation of a reliable, resilient and green European power grids by providing additional flexibility and considering current status and future evolution of EU power system and energy markets
- Developing advanced tools for long-duration BESS techno-economic assessment (under different scenarios and time horizons) and optimal management, also exploiting advanced AI solutions.

Mid-term needs (2035):

Considering a longer timeframe, the emerging long-duration BESS technologies need to be demonstrated in industrially relevant or operational environment at a relevant scale. The demonstrations should clearly prove maturity of LDES technologies and highlight the benefits of LDES, for example by:

- demonstrating 24/7 clean power enabled by renewables and medium-to-long duration BESS at a relevant scale (e.g., large industry, island);
- demonstrating multi-purpose grid-scale long duration BESS with advanced management systems supporting the creation of solid business cases even for long-duration BESS.

2.10.4 Digitalisation, hybridisation and interoperability – standardisation of data sharing and communication (BMS inverter) – Transversal challenge

Digitalisation improves the safety, reliability and efficiency of battery energy storage systems (BESS). Both digital twins and AI-based EMS optimize operations, face challenges such as interoperability and barriers in data sharing. Battery management systems (BMS) are vital for battery monitoring and control, but lack standardized communication interfaces and protocols, limiting their flexibility. Decision tools that help optimize battery use have been developed in recent years, but diverse applications and uncertain lifetimes complicate design and operation. Therefore, addressing standardization, improving algorithms and integrating real-time forecasts can unlock the full potential of BESS. Furthering the digitalisation of the EU energy sector and of BESS is a key target that could be reached tackling the following research needs in different digitalisation areas:

R&D activities needed

Developing advanced energy management systems for BESS/HESS focuses on optimizing distributed assets and hybrid power plants through standardized BMS interfaces, communication protocols, and testing procedures. Open, flexible systems for diverse battery technologies, supported by prototypes and clear data access strategies, will enhance interoperability, efficiency, and safety.

New algorithms for battery operation prioritize accurate SoX evaluation and prediction, using hybrid approaches that combine data-driven and theoretical models. Advanced sensing technologies and digital twins can boost performance, while open-source tools and intuitive algorithms will empower stakeholders to optimize battery operation sustainably.

Decision-making tools must leverage hybrid algorithms integrating real data with models to improve data quality, detect degradation, and enable real-time decisions. Advanced BMS should monitor at multiple levels, integrate with digital twins for predictive maintenance, and support tools like PVGIS to enhance accessibility and customization. Predictive battery models for Remaining Useful Life (RUL) will guide efficient, cost-effective, and scalable energy storage solutions.

The digitalisation of battery storage will be able to improve efficiency, safety and flexibility. Standardized battery management systems (BMS) and communication protocols will enable modular designs, predictive maintenance and integration with smart grids. Finally, decision support systems (DSS) will optimize energy storage solutions, while advanced data analytics will improve safety, support second-life applications, promoting sustainable and economical energy systems.

2.10.5 Design for 2nd life – Transversal challenge

Battery design focus has been primarily on first-life applications, prioritizing vehicle safety, durability and performance, with little consideration for second-life scenarios such as repair and reuse. It will therefore be important that this aspect is also developed in the preliminary stages of production. Second life, in fact, requires “design for disassembly” and detailed SoX (state of health, state of safety) data to enable efficient processes. While the European battery passport is promising, its suitability for second-life needs is uncertain, as it may lack granular, standardized data critical for logistics and reuse. Difficulties lie in the availability of inconsistent SoX prediction methods, poor data transparency, and disassembly difficulties due to compact first-life designs. Research and development should focus on modular designs, cost-effective joining techniques, SoX rapid evaluation tools, and cloud-based platforms for data access. Achieving these goals would unlock the potential of second-life batteries, creating safe, reliable and affordable energy storage, improving sustainability, aligning with EU regulations and facilitating the creation of universal standards for battery lifecycle management.

Second-life lithium-ion batteries in electric vehicles offer high energy density for stationary storage, enhancing electrification efforts. Research should ensure that high levels of safety, reliability and convenience can also be achieved for second life. Advancements will extend battery life, promote sustainability, optimize CRM use and align with regulations. Designing batteries for use throughout their entire life cycle ensures wider social acceptance, market growth and universal standards.

2.10.6 Safety, efficiency and extended lifetime for BESS – Transversal challenge

Safe operation throughout a battery's lifecycle is critical to promoting stationary battery systems for homes and production facilities. System efficiency, longevity, and cost-effectiveness are key factors in adoption. Key R&D Need should be focused on:

- Developing codes, standards, and best practices for safe operation and emergency response.
- Addressing lithium-ion battery thermal runaway hazards through public testing and analysis to design mitigation strategies.
- Using fire hazard modeling to lower testing costs and inform lifecycle stages, from design to incident response.
- Establishing protocols for assessing risks of second-life batteries with varied usage histories.
- Studying safety profiles of emerging storage technologies for effective risk management.

Prioritizing safety enhances social acceptance, reduces costs (e.g., safety controls), and extends battery lifetimes. Lower costs and safer systems can improve grid efficiency, support renewable energy integration, and accelerate energy system electrification.

2.10.7 Vehicle to Grid (V2G) and Vehicle to Home (V2H) – Transversal challenge

Concerning V2G, the possibility of thousands (eventually hundreds of thousands) of vehicles feeding energy back into the electrical grid during peak consumption hours (when workers return home in the evening), thereby limiting peak consumption, is an exciting prospect for future grid management. V2G is foreseen to be operated at low power as the impact on battery aging would be lower and the battery efficiency is better. The aggregation of thousands of EVs in cities or local regions can potentially offer a relatively large reinjection of power to the grid. To offset this, the overnight charging of EVs, outside of peak hours, will be encouraged, like also charging of vehicles during any favourable time of the day in line with grid conditions, market prices or specific site opportunities and needs.
Despite the absence of technological barriers on bi-directional chargers in vehicles, V2H and V2G solutions are still very marginal in the world of electric vehicles. This technology has not been widely embraced, bi-directional charging has the potential to offer value to both vehicle owners and electricity grid operators

Concerning V2H, being able to use the energy from its own vehicle at home, would make it possible to:

- maintain power in their home during electrical grid power outages or where the grid load is maxed out and cannot deliver by using battery as back up. The latter case could be very relevant in rural areas or island communities
- use energy, which was stored in EV battery packs, during any favourable time of the day or night at lower-cost off peak times.
- potentially reduce the overall power usage from the electrical grid, thereby reducing the cost of electricity bills

Currently the introduction of V2H and/or V2G technology in Europe is mainly hindered by politics. Furthermore, it is unclear who has legal responsibility for electrical management as this is bidirectional and requires bidirectional power electronics. The V2G business model should be based on strategies aimed at improving collaboration between different stakeholders by developing collaborative business models for this type of applications.

The adoption of V2G may require revising the specifications and design costs of electric vehicle batteries. Therefore, unless incentives are provided for offering network services, OEMs may not pay attention to this business. Complementing the suggested research, therefore, the main focus to accelerate the implementation of V2X solutions should be placed on policies capable of combining financial incentives and adequate market system design (in which business models can be defined).

This could be possible by using smart metering infrastructure and providing subsidies and tax credits, to create an enabling environment that promotes the deployment of BTM BESS for V2G development purposes.

Research needs:
Short terms needs (2029)

- Advancement and demonstration of bidirectional batteries in vehicles for use in V2H and V2G;
- Analysis of the impact on SoH of battery systems over extended cycling
- Demonstration of V2G in real world use cases with large vehicle fleets to have significant impact on the grid.
- Stablish financial incentive schemes and tariffs to validate business models
- Smart charging and V2X strategies aiming to maximise positive benefits on the grid while reducing negative impacts on battery lifetime
- Improve the efficiency of bi-directional chargers especially at low power (around 2-3kW).

Mid-terms needs (2035)

- Research on communication protocols on the vehicle – grid aggregator interface for optimization of the V2G implementation (For Instance, research on the how to keep the vehicle alert, without consuming too much energy, while waiting for the V2X demand on energy delivery).

- Development of a collaborative business models to create, capture, deliver and share value between different stakeholders
- Technology, including new sensors to enable practical real time testing of State of Health (SoH) of battery.
- Interoperable and standardised communication protocols (and interfaces) for interaction with the EV user, the grid operator(s) and potential aggregators of energy storage.

To see these solutions adapted on a large scale, it will be necessary to measure more precisely the impact of these additional charging/discharging cycles on battery ageing, and then evaluate and subsequently reward the contribution of the end-user to the grid.

2.11. Key Recommendations

Affordable, safe, reliable, and environmentally friendly battery chemistries for stationary storage are promising areas of research. Focus should be placed on improving both existing and novel chemistries to enable long-term energy storage, boost renewable energy generation, and enhance grid adaptability.

Technology plays a vital role in creating a circular supply chain and fostering global competitiveness. Investment in research is needed at European, national, and regional levels. Encouraging collaboration across the entire value chain—both horizontally and vertically—can drive synergies and support a circular economy.

Pre-normative research is essential to establish requirements for emerging battery applications, optimize system design, develop interoperable battery management systems (BMS) and IoT, and enhance sustainability. Pilot projects within regulatory frameworks are crucial for scaling from low TRL to real-world applications, such as small grids or RES-integrated plants. Knowledge-sharing among stakeholders is key to overcoming regulatory and business model challenges while driving innovation.

To more efficiently exploit the EU's RES and BESS resources, it is important to promote interoperability to bridge the gap between the European electrified automotive industry and BESSs used in BTM and FTM applications. An efficient approach between these two fields to meet circularity, for example related to the second life of BESS, and a joint sharing of many aspects of modeling, simulation and hardware-related approaches would make the EU more efficient and competitive.

Finally, the need to stabilize and unify European legislation by unifying the operational rules for BESS in the different EU members must be underlined. This would facilitate cross-operation and collaboration between researchers/industries across the EU. It is important to shift attention from the “Green” concept to the “Deal” concept if we want to have greater competitiveness and independence of the EU compared to external countries.

<table>
<tr><th>SRA</th><th>Short term</th><th>Medium term</th><th>Long term</th></tr>
<tr><td rowspan="9">SRA1 Front-of-the-meter (FTM) Battery energy storage systems (BESS)</td><td colspan="3">Develop digital energy management algorithms using BESS or HESS and distributed generation assets, especially for multi-use concepts (revenue stacking)</td></tr>
<tr><td></td><td colspan="2">Create a digital twin of both the BESS and the increasingly large parts of the power system</td></tr>
<tr><td colspan="3">Interoperability of BESS or HESS and distributed generation assets to provide multiservice on the power (grid services) and energy market</td></tr>
<tr><td></td><td colspan="2">Advanced algorithms to enable shared ownership</td></tr>
<tr><td></td><td colspan="2">Robust methodologies for measuring and evaluating circular economy</td></tr>
<tr><td colspan="3">Prediction algorithms of BESS operational parameters, including prediction of remaining useful lifetime (RUL). And algorithms for prediction / early-stage identification of safety / reliability critical states of aged batteries</td></tr>
<tr><td colspan="3">Develop methods of dimensioning power and capacity as well as the place of installation / grid connection of the BESS</td></tr>
<tr><td colspan="3">Develop battery hardware enabling the safety, reliability, low maintainability, and long life of the BESS</td></tr>
<tr><td></td><td colspan="2">Invest in Balance of Plant, especially power electronics and thermal management, for optimal operation and cost of the FTM BESS</td></tr>
<tr><td rowspan="6">SRA2 Behind-the-meter (BTM) Battery Energy Storage Systems (BESS)</td><td colspan="3">Develop battery hardware enabling the safety, reliability, low maintainability, and long life of the BESS</td></tr>
<tr><td colspan="3">Identification of critical limits which will be chemistry dependent, biasing research on specific cell chemistries for stationary storage applications</td></tr>
<tr><td colspan="3">Enable the balancing of energy and predict the energy behind the meter to optimise and maximise the overall usage of the BESS including multi-use concepts (e.g., PV self-sufficiency, peak-shaving, and additionally grid services)</td></tr>
<tr><td colspan="3">Improve component and system level performances</td></tr>
<tr><td colspan="3">Development of integrated algorithms to manage energy flows, production, consumption and storage capacity at the individual customer level (integration with IoT)</td></tr>
<tr><td colspan="3">Capability to analyse the reported needs of the grid operator and aggregators in providing flexibility services</td></tr>
<tr><td rowspan="2">SRA3 Medium-to-Long Duration Battery Storage</td><td>Develop innovative approaches for consolidated battery technologies for medium or long duration storage</td><td></td><td></td></tr>
<tr><td>Demonstration of the benefits of LDES</td><td></td><td></td></tr>
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<table>
<tr><th>SRA</th><th>Short term</th><th>Medium term</th><th>Long term</th></tr>
<tr><td rowspan="2">SRA3 Medium-to-Long Duration Battery Storage</td><td>Accelerate technology maturation and upscaling of BESS based on low-cost materials and organic materials</td><td></td><td></td></tr>
<tr><td colspan="3">Analysing how LDES can contribute to the creation of a reliable, resilient and green European power grids by providing additional flexibility under different scenarios and time horizons. Development of operating / business models for LDES</td></tr>
<tr><th colspan="4">Transversal Challenges</th></tr>
<tr><td rowspan="11">Digitalisation – Advanced BMS</td><td colspan="2">Review of existing battery related standards</td><td></td></tr>
<tr><td colspan="2">Identify gaps in BMS standardisation</td><td></td></tr>
<tr><td colspan="2">Definition of key BMS parameters and functionalities including definition of battery states, which are standardised and useful for the application</td><td></td></tr>
<tr><td colspan="2">Definition of data and information to be transmitted</td><td></td></tr>
<tr><td colspan="2">Analysis of existing communication protocols for BMS</td><td></td></tr>
<tr><td colspan="2">Definition of internal/external standardised interfaces</td><td></td></tr>
<tr><td colspan="3">Proposal of data formats and communication interfaces for BMS standards</td></tr>
<tr><td></td><td colspan="2">Definition of testing procedures to validate BMS standards</td></tr>
<tr><td></td><td colspan="2">Dissemination actions among relevant stakeholders and standardisation push</td></tr>
<tr><td colspan="3">Proof of open BMS interface effectiveness: prototype implementation demonstrating BMS advanced interoperability</td></tr>
<tr><td colspan="3">Define communication protocols for the safe, reliable, and efficient exchange of data between the BMS and external devices</td></tr>
<tr><td rowspan="4">Digitalisation - New algorithms for battery operation, SoX evaluation and prediction</td><td colspan="3">Accurate and robust estimation of the battery state through hybrid algorithms combining data-driven methods with model-based approaches</td></tr>
<tr><td colspan="3">Focus on open-source tools, based as much as possible on publicly available data/information and/or open-source tools (e.g., PVGIS)</td></tr>
<tr><td colspan="3">Advanced charging and operating control algorithms for optimal battery operation</td></tr>
<tr><td colspan="3">Advanced battery models in combination with ML approaches able to provide lifetime projections (RUL) and the influence of operating control strategies on aging</td></tr>
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<table>
<tr><th>SRA</th><th>Short term</th><th>Medium term</th><th>Long term</th></tr>
<tr><td rowspan="7">Digitalisation - Decision making tools</td><td colspan="2">Definition of main parameters and rules to be considered (cost/ Wh, power density, life cycle, environmental impact, ROI…), application specific annual degradation rates (--> of much higher value than just looking cycle numbers and calendric aging</td><td></td></tr>
<tr><td colspan="2">Study of different DSS models and techniques to be applied.</td><td></td></tr>
<tr><td colspan="2">Study and definition of potential use cases (FTM and BTM)</td><td></td></tr>
<tr><td colspan="2">Development and validation of DSS models for HESS</td><td></td></tr>
<tr><td></td><td colspan="2">Improved ML methods based on previous experience.</td></tr>
<tr><td></td><td colspan="2">Definition of standardised input parameters</td></tr>
<tr><td></td><td colspan="2">Definition of exploitation models for DSS</td></tr>
<tr><td rowspan="6">Digitalisation</td><td colspan="3">Development of a database of models, case studies, and other important information. Consideration of the FAIR principle (“Findable, Accessible, Interoperable, and Re-usable) also for simulation data.</td></tr>
<tr><td colspan="3">Incorporation of local/regional information in the digital tools, based as much as possible in open-source data sources.</td></tr>
<tr><td colspan="3">Integration with existing digital tools.</td></tr>
<tr><td colspan="3">Validation activities, in various geographic and climatic conditions, to assess the robustness and/or uncertainty involved in the development.</td></tr>
<tr><td colspan="3">Digital twin of BESS/HESS extended to connected grid and integrating real-time data aiming at fine-tuning the storage performances and extending its lifetime. Consideration of the FAIR principle (“Findable, Accessible, Interoperable, and Re-usable) also for simulation data.</td></tr>
<tr><td colspan="3">Functional safety to be assessed of the hybrid system (HW and SW)</td></tr>
<tr><td rowspan="5">Design for 2nd life</td><td colspan="3">Explore how to incorporate the concept of designing for second life; design for disassembly, with is also important for the recycling process</td></tr>
<tr><td colspan="3">Develop methods for identification of unusable cells / modules / pack, which is essential for second life applications.</td></tr>
<tr><td colspan="3">Cost efficient joining techniques for first and second life. Including all different levels, cell to pack. Electrical, thermal, and mechanical bonds to be “designed for disassembly”.</td></tr>
<tr><td></td><td colspan="2">Fast assessment and testing (reliability and repeatability of results), keeping up with frequent updates on battery chemistries, materials, and manufacturing processes, and open and versatile SoX measurement.</td></tr>
<tr><td></td><td colspan="2">Developing cloud-based tools and methodologies focused on different requirements for different stakeholders.</td></tr>
</table>

<table>
<tr><th>SRA</th><th>Short term</th><th>Medium term</th><th>Long term</th></tr>
<tr><td rowspan="5">Safety, reliability, efficiency and extended lifetime for BESS</td><td colspan="3">Well-developed codes, standards, and best practices that are applicable for energy storage systems in normal and emergency situations also including the preparation of incident</td></tr>
<tr><td colspan="3">Response protocols and maintenance and repair safety guidelines</td></tr>
<tr><td colspan="3">Understanding thermal runaway and propagation (including the function of propagation inhibiting material), specifically of lithium-ion batteries</td></tr>
<tr><td colspan="3">Fire hazard modelling</td></tr>
<tr><td colspan="3">Emerging storage technology safety and reliability information and analysis to study their hazard profiles and possible mitigation strategies</td></tr>
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<tr><td rowspan="3">Vehicle to Grid (V2G) and Vehicle to Home (V2H)</td><td colspan="3">Technology, including the increasing of the efficiency of bi-directional chargers especially at low power (around 2-3kW) and the development of new sensors to enable practical real time testing of State of Health (SoH) of battery</td></tr>
<tr><td colspan="3">Development of a collaborative business models based on strategies aimed at improving collaboration between different stakeholders</td></tr>
<tr><td colspan="3">Research on communication protocols on the vehicle – grid aggregator interface for optimization of the V2G implementation</td></tr>
</table>

Table 11: Overview of Strategic Research Areas of the Stationary applications and integration roadmap, developed by the Batteries Europe/BEPA WG6

3. Conclusions

The 2025 update of the Batteries Europe Roadmap acknowledges the fast-paced advancements in battery technology and outlines a comprehensive list of research needs and potential timelines. Contributions from experts across six thematic working groups and six task forces have shaped this revised roadmap, identifying 49 strategic research areas throughout the entire battery value chain. This detailed roadmap offers a broad spectrum of research areas without prioritization. Additionally, each working group has provided key recommendations for policymakers, authorities, industry, and researchers.

This roadmap revision takes into account recent global trends in the battery sector, including significant advancements in sodium-ion batteries, the impact of increased use of lithium iron phosphate (LFP) batteries on recycling, the growing focus on solid-state battery production, and the extensive use of batteries in stationary storage systems, among others. Furthermore, the task force for Skills and Education emphasizes the importance of specific recommendations to ensure Europe educates candidates for high-value jobs in the battery sector. Meanwhile, the task force for Social Science and Humanities focuses on understanding the complex socio-cultural, economic, and ethical dimensions of technology deployment and consumption.

This revised roadmap aspires to be an inspirational repository of ideas, offering a wide array of research areas to enhance the competitiveness and sustainability of the European battery value chain. Batteries Europe emphasises the importance of coordinating research through beneficial synergies and collaborates with BEPA (Battery European Partnership Association), Batt4EU, and other stakeholders to ensure the key concepts outlined in this document are translated into research calls, projects, and ultimately, industry innovations.

4. Additional References

The future of European competitiveness Part B In depth analysis and recommendations - Sept 2024 https://commission.europa.eu/document/download/ec1409c1-d4b4-4882-8bdd-3519f86bbb92_en?filename=The%20future%20of%20European%20competitiveness_%20In-depth%20analysis%20and%20recommendations_0.pdf

Regulation of the European Parliament and of the Council concerning batteries and waste batteries, repealing Directive 2006/66/EC and amending Regulation (EU) No 2019/1020.

BAT Reference Documents. https://eippcb.jrc.ec.europa.eu/reference

Batteries Europe Position Paper, Education & Skills Task Force, April 2024. https://batterieseurope.eu/wp-content/uploads/2024/11/Task-Force-Education-Skills_052024.pdf

Some examples of reuse, repurposing and recycling of minerals to improve the resources efficiency in mining. I.V. Kojo, M.A. Reuter K. Heiskanen, 6th Int. Conference on Sustainable Development in the Mineral Industry (2013).

European Platform on LCA/EPLCA. https://eplca.jrc.ec.europa.eu

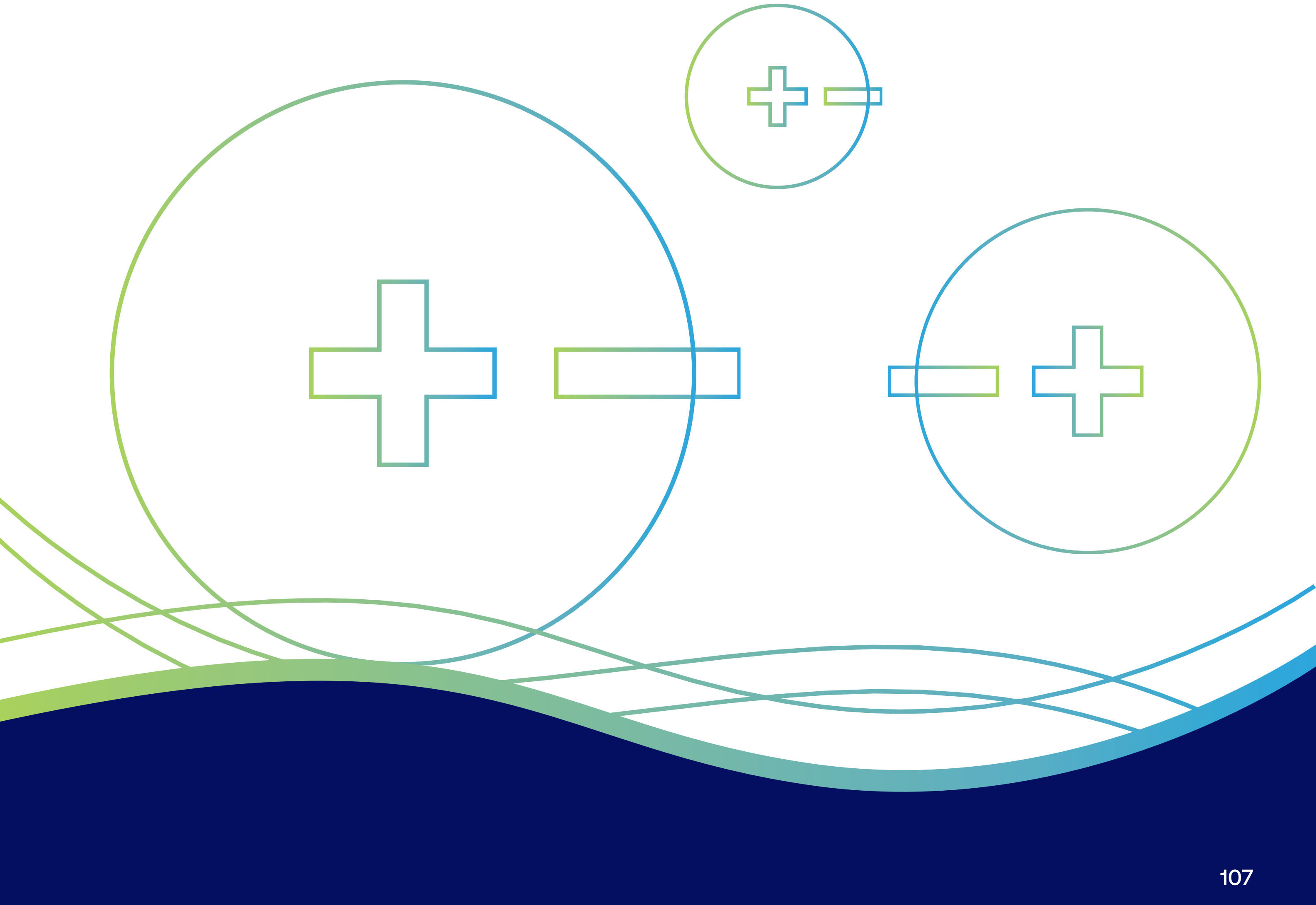
Global LCA data access network. https://www.globallcadataaccess.org

Safe and sustainable by design chemicals and materials – Framework for the definition of criteria and evaluation procedure for chemicals and materials. https://publications.jrc.ec.europa.eu/repository/handle/JRC128591

Supply chain analysis and materials demand forecast in strategic technologies and sectors in the EU. A foresight study. https://publications.jrc.ec.europa.eu/repository/handle/JRC132889

Will the development of a European battery ecosystem fail due to a shortage of skilled labour? https://www.isi.fraunhofer.de/en/blog/2024/batterieforschung-kuerzung-foerderung-folgen-aufbau-oekosystem-europa-deutschland-fachkraefte-mangel.html

World Energy Employment 2024, IEA. https://iea.blob.core.windows.net/assets/7350d894-d250-4455-bb12-0a865f64c193/WorldEnergyEmployment2024.pdf.



Contact us

www.batterieseurope.eu
info@batterieseurope.eu