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

Acknowledgement

Batteries Europe Secretariat is an EU-funded project that has received funding from the European Union's Horizon Europe Research and Innovation Programme under Grant Agreement N. 101069676.

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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. The energy crisis resulting from Russia's invasion of Ukraine has given a powerful boost to Europe's resolve in attaining net-zero emissions. Faced with the urgency of securing its energy independence and resilience, Europe has rapidly escalated its efforts to transition towards sustainable energy sources and enhance energy efficiency. Electrification of both the transport and energy sectors can expedite the transition with batteries serving as a key enabling technology to support the electrification of the economy[1,2].

The ambitious objectives of electrification of the mobility, energy production, and industrial sector can be reached by fostering the growth of **battery cell manufacturing** in Europe, while providing competitive and sustainable solutions. The **combined production capacity** from battery cell companies and startups is **expected to amount up to 886 GWh/year in Europe by 2030**[3]. In response to increasing needs, Europe must bolster its capabilities in materials development, digitalisation, and applications engineering to establish a solid foundation for sustainable and innovative battery cell manufacturing and position itself against the established players in the global market.

The future success of establishing **large-scale battery cell production** in Europe is tied to the imperative of **reducing raw material dependency and fostering the strategic autonomy of the European Union**. Currently, the refining and processing facilities are predominantly situated outside of Europe, with Asia holding a dominant position in the supply chain. This geographical disparity exposes Europe to vulnerabilities in its resource access, particularly in cases where political instability jeopardizes reliable supply or ethical and sustainable mining practices are compromised. By fostering higher levels of circularity, sustainability, and resource efficiency, Europe aims to **ensure a more resilient supply chain** while concurrently addressing environmental concerns, including the use of critical raw materials. This objective can be realised through an **expansion of recycling alternatives**, increase of recovery efficiency (targeting 95% Cobalt, 95% Nickel, and 90% Lithium metal recovery by 2030). This approach aligns with Europe's commitment to a greener future, fortifying its position as a global leader in responsible resource management. **Achieving lower costs (<75 €/kWh at pack level by 2030), and higher sustainability** in raw materials processing and advanced materials manufacturing is also crucial for Europe to maintain its competitive edge on the global stage. By streamlining production processes, optimizing resource utilization, and integrating eco-friendly practices, Europe can not only reduce operational expenses but also position itself as a frontrunner in environmentally conscious manufacturing. Additionally, the rapid growth of the battery industry highlights the **urgent requirement for a diverse and highly skilled workforce across the**

[1] A Vision for a Sustainable Battery Value Chain in 2030, Global Battery Alliance, 2019
[2] STRATEGIC RESEARCH AGENDA FOR BATTERIES, Batteries Europe ETIP, 2020
[3] Batteries for energy storage in the EU - Status Report on technology development, trends, value chains and markets, JRC 2022

value chain and across disciplines (research, professional, vocational, etc.). The shortage of sector specific skills and education is already recognised as a significant challenge for the years to come. To meet the growing workforce demand in line with the industry's rapid pace, it is crucial to foster a robust collaboration between relevant stakeholders (industry, academia, education and training providers, lab facilities, etc.) so as to provide several opportunities for upskilling and reskilling.

To compete globally, Europe must establish the most advanced innovation ecosystem for batteries worldwide by 2030. This ecosystem should strive for cutting-edge research throughout the entire battery development process, spanning from conceptualisation and design to product realisation and market introduction. Immediate **prioritisation of battery research** is necessary and a comprehensive approach must be adopted, encompassing the entire battery value chain and receiving support from relevant stakeholders, including European, National, and Regional Research & Innovation (R&I) agencies. Significant and continuous investments in battery research and associated research infrastructure are imperative, addressing both **short-term** and **long-term research priorities**. This research should focus on enhancing sustainability, reducing costs, improving performance and ensuring the high quality and safety of products and processes across the entire 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** provides an initial view of the needs and plans underway to address the development of the whole battery value chain and is followed by a comprehensive overview of the principal research areas which we, the battery research community, engaged in Batteries Europe, have determined should be further investigated. The vision sections cover the main EU initiatives of the ecosystem, define the objectives of the roadmap and ends pointing the urgency of reinforcing the education and skills needed to push the research and industry development on batteries related fields. The section highlights the main areas that require adaptation in mid- and long-term as well as necessary measures to address this increasing demand.

Research and Innovation priorities across the entire battery value chain, are addressed in each of the six segments covered by the dedicated Working Group (WG), with the support of the transversal Task Forces (TF). **The experts have identified the main strategic research areas** in each domain, pointed **the transversal challenges** and concluded with **key recommendations** for the battery community, all framed in short (2027) to medium (2030) and long term (2030+) needs.

1. New and Emerging technologies. The chapter suggests strategic research necessary on a broad series of promising 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.** The identified strategic research areas include advanced redox flow batteries, metal air batteries, metal sulfur batteries, aqueous based batteries, anode less batteries, multivalent non-aqueous systems and hybrid supercapacitor batteries. The section also focuses on enabling technologies including multimodal correlative characterisation which can enhance our understanding of battery operations along with the use of biomimetics as smart functionalities for batteries. The final research area addresses Sustainability by Design (SbD) for Battery Materials and Cells which considers a holistic sustainable approach integrating material design, manufacturability, recyclability and sustainability evaluation methodologies. Throughout the process of technological exploration and research, the focal point extends beyond mere performance and cost considerations. As highlighted in the transversal research topics, sustainability aspects and intelligent material selection are equally paramount. In this context, the availability and cost of raw materials are anticipated to play a significant influence on the trajectory of new and emerging battery chemistries. The R&I activities can be expected to also benefit from uptake of digitalisation tools, modelling, and development of relevant infrastructures, allowing for accelerated and cost-efficient discovery, facilitating further technology uptake by the industry.

2. Raw Materials and Recycling. Reducing raw material dependency and fostering the strategic autonomy of the European Union are the main driving force of this section. Batteries Europe identified several research areas necessary to **improve the logistics and the pre-treatments of End of Life** (EoL) batteries, and **to adapt the existing recycling processes to the emerging technologies**, including Li Metal and all-solid-state batteries. The section also focuses on the efforts to ensure a more profitable raw materials supply chain for Europe, even in case of non-Li technologies (e.g., SIBs), that is obtained by means of several strategies, as for example i) integration of secondary raw materials, ii) more efficient and sustainable materials extraction and refining and iii) vertical integration of European mining. The chapter concludes with the transversal challenges that suggest research on the implementation of the tools for the sustainability assessment and on the development of a Safe and Sustainable by Design (SSbD) holistic approach that should integrate safety, circularity and functionality of materials and processes. A special focus is finally devoted to the importance of the digitalisation methods (e.g., digital twins) to optimise the recycling technologies.

3. Advanced Materials. The section is concerned with identifying the promising existing cell chemistries which can be further developed to **enable more cost-efficient, better performing, safer and more sustainable batteries.** The evaluation focuses on battery chemistries with a medium to high maturity level (TRL ≥ 5 [4]). This section covers a selected range of battery technologies such as Li-ion (Gen3 and Gen4[5]), Na-ion and vanadium redox flow batteries. The

[4] Technology Readiness Level: https://ec.europa.eu/research/participants/data/ref/h2020/wp/2014_2015/annexes/h2020-wp1415-annex-g-trl_en.pdf

[5] LiB cell chemistries classification: Roadmap integrierte Zell- und Batterieproduktion Deutschland. Autor / Herausgeber: AG 2 – Batterietechnologie / Nationale Plattform Elektromobilität (NPE) Format: Nationale Plattform Elektromobilität (NPE) Veröffentlicht: January 2016

specific battery chemistries developed may vary depending on the application, whether it is for mobility or stationary purposes. In the mobility sector, the primary advancements are expected to concentrate around Li-ion battery chemistries. The necessary research & development (R&D) efforts are focused on liquid-state batteries (Gen3) with a transition towards solid-state battery chemistries (Gen4). In the stationary storage sector, along with Li-ion, there are expected developments that will emphasise Na-ion chemistries, in both liquid (Gen3) and solid state (Gen4), as well as Vanadium Redox Flow Batteries (VRFBs). Finally, the chapter highlights the transversal research topics concerning Advanced Materials, with a focus on sustainability, safety and digitalisation.developed may vary depending on the application, whether it is for mobility or stationary purposes. In the mobility sector, the primary advancements are expected to concentrate around Li-ion battery chemistries. The necessary research & development (R&D) efforts are focused on liquid-state batteries (Gen3) with a transition towards solid-state battery chemistries (Gen4), as well as Na-ion as a promising alternative to enable affordable electro-mobility. In the stationary storage sector, along with Li-ion, there are expected developments that will emphasise Na-ion chemistries, in both liquid (Gen3) and solid state (Gen4), as well as Vanadium Redox Flow Batteries (VRFBs). Finally, the chapter highlights the transversal research topics concerning Advanced Materials, with a focus on sustainability, safety and digitalisation.

4. Cell Design and Manufacturing. As the market for batteries grows, **innovative cell design** is critical not just from a cost perspective but also towards the realisation of environmentally friendly, high-performance, and long-life batteries. The section looks at the necessary advances for the success of large-scale battery production of todays and the future technologies in Europe. The first research area addresses cells and battery design in relation to sustainability, which considers the actions required to make 2nd life and recycling of the cell optimised, regardless of cell chemistry. In response to several factors, including the obligations of reducing the carbon footprint and the higher energy prices, the second area looks closely at enhanced sustainability of production of cells and batteries in the manufacturing process itself. **Flexibility of future battery factories** is another important aspect for facilitating the transition of early-stage technologies to large scale production and **adapting to the changing supply chains.** This is addressed in the third area, which investigates how to develop flexible production technologies to serve future technological developments while making simple alterations to production lines. The fourth area addresses process and product scaling and industrialisation of battery technology. The chapter concludes with a look at transversal research areas of sustainability regarding the use of recycled materials in the processing, safety looking at implications for cell design and manufacturing, and finally and most significantly digitisation in which digital twins can have a great influence on battery cell and manufacturing development.

5. Application and Integration: Mobile highlights the key requirements identified to facilitate the widespread electrification of the mobility sector. The essential research activities are proposed for various modes of transport including, road, waterborne, airborne, railway as well as off-road machineries. The specific battery requirements to enable widespread adoption will vary depending on the mode of transport being advanced and this section has, therefore, been structured accordingly. The proposed research needs are described in terms of both the **performance-related developments** needed as well as other critical considerations such as **systems, safety, recycling**, etc. Additionally, the section concludes with the address of transversal research topics, such as fast charging, battery swapping and State of X (SoX) prediction, which have been identified as essential for unlocking widespread battery acceptance within the mobility sector.

6. Application and Integration: Stationary storage gathers the research needs in three main strategic areas: the first two topics tackle with the different applications enclosed in **“behind-the-meter”** and in **“front-of-the-meter”** respectively. The last area is related to the **medium-to-long duration batteries**, as a standalone area of great importance for the **better exploitation of renewable resources.** Moreover, three transversal challenges are defined dealing with: i) the potential for digitalisation, with focus on Advanced Battery Management Systems, new algorithms for battery operation, SoX evaluation and prediction and decision-making tools; ii) the potential for sustainability with a focus on second-life battery systems and iii) the potential of safety, suggesting research on safety, efficiency and extended lifetime for Battery Energy Storage systems.

In conclusion, in this **Roadmap** the experts engaged in Batteries Europe have **identified 33 specific strategic research areas along with 17 additional specific transversal challenges** across the entire battery value chain, providing timelines for when it is suggested this research should be underway. We expect these suggested research areas will serve as a guidance to those preparing research programs, both for public and industry programs, and for strategic planning in the battery research sector. **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. However, 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. For instance, **extraction technologies as described in the raw materials research areas** are not part of the scope of BATT4EU and hence could be adopted by other initiatives such as EIT Raw Materials. Another sector of the value chain, not covered by the Partnership, is the **integration of the battery systems into the final application.** However, BATT4EU works together with partnerships covering research on different transport applications, namely: 2Zero (road transport), ZEWT (waterborne), Clean Aviation and Europe’s Rail.

In order to constantly support the entire battery value chain by a holistic approach, Batteries Europe will deliver future Roadmaps and KPIs, which can be used to track the developments of the technologies mentioned in the document and will identify further R&I actions that need to be carried out. Should Batteries Europe, as a community, be successful in the investigation of such research areas and in having the results implemented by industry, the outcome will be a cleaner and healthier environment, with lower carbon emissions, and increased opportunities of sustainable employment in the battery sector in Europe.

Acknowledgements

The publication of the Technology Roadmap has been made possible by the work of the six **Integrated Working Groups** and the **four Cross-Cutting Task Forces**, with the support of the Secretariat of Batteries Europe. We would also like to acknowledge the inputs and considerations from the European Commission, the National and Regional Coordination Group and the BEPA (Batteries Europe Partnership Association) secretariat.

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List of acronyms

AI	Artificial Intelligence	LCC	Life Cycle Costing
ALBATTS	Alliance for Batteries, Technology, Training and Skills	LCI	Life Cycle Inventory
AORFB	All-Organic Based Redox Flow Batteries	LDES	Long Duration Energy Storage
ASSB	All Solid-State Battery	LFP	Lithium Iron Phosphate
B2C	Business to Consumer	LIB	Lithium Ion Battery
BAT	Best Available Technique	$LiPF_6$	Lithium hexafluorophosphate
BattINFO	Battery InterFace Ontology	LMB	Lithium Metal Battery
BEPA	Batteries European Partnership Association	LMFP	Lithium Manganese Iron Phosphate
BESS	Battery Energy Storage Systems	LMO	Lithium Manganese Oxide
BEV	Battery Electric Vehicle	LNMO	Lithium Nickel Manganese Oxide
BIG-MAP	Battery Interface Genome – Materials Acceleration Platform	LTMO	Layered Transition Metal Oxide
BIP	Business Investment Platform	LTO	Lithium-Titanate Oxide
BMS	Battery Management System	MAB	Metal Air Batteries
BREFs	BAT Reference Documents	MAP	Material Acceleration Platform
BTM	Behind-The-Meter	ML	Machine Learning
BVCO	Battery Value Chain Ontology	Mn-HCF	Manganese Hexacyanoferrate
C&I	Commercial and Industry	MTTF	Mean Time To Failure
C2C	Chassis-to-Chassis	MTTR	Mean Time To Repair
C2V	Cell-to-Vehicle	NCA	Lithium Nickel Cobalt Aluminium Oxide
CAN	Control Area Network	NECPs	National Energy and Climate Plans
CAPEX	CAPital EXpenditure	NMC	Lithium Nickel Manganese Cobalt Oxide
CCD	Critical Current Density	NO_x	Nitrogen Oxides
CO_2	Carbon Dioxide	NRMM	Non-Road Mobile Machinery
CRM	Critical Raw Material	OPEX	Operational Expenditure
Cu-HCF	Copper Hexacyanoferrate	P/E	Power/Energy
DBP	Digital Battery Passport	PBA	Prussian Blue Analogues
DoD	Depth of Discharge	PEFCR	Product Environmental Footprint Category Rules
DPP	Digital Product Passport	PFAS	Per- And Polyfluorinated Substances
DSO	Distribution Systems Operator	PHES	Pumped Hydroelectric Energy Storage
DSS	Decision Support System	PINN	Physics-Informed Neural Network

EBA	European Battery Alliance	**PM**	Particulate Matter
EC	European Commission	**PV**	Photovoltaic
EMC	Electromagnetic Compatibility	**PVGIS**	Photovoltaic Geographical Information System
EMS	Energy Management System	**PWA**	Prussian White Analogues
EoL	End of Life	**QRL**	Quality, Reliability and Life
EQF	European Qualifications Framework	**R&D**	Research & Development
ESS	Energy Storage Systems	**R&I**	Research & Innovation
EU	European Union	**REACH**	Registration, Evaluation, Authorisation and Restriction of Chemicals
EUBatin	European Battery Innovation IPCEI	**REE**	Rare Earth Element
EV	Electric Vehicle	**RES**	Renewable Energy Storage
e-VTOL	Electric-Vehicle Take-Off and Landing	**RFB**	Redox Flow Battery
FAIR	Findability, Accessibility, Interoperability, Reusability	**RFID**	Radio-Frequency Identification
FTM	Front-of-The-Meter	**ROI**	Return On Investment
GHG	Green House Gasses	**ROM**	Reduced Order Model
GLAD	Global LCA Access Database	**SbD**	Safe By Design
HCV	Heavy Commercial Vehicle	**SE**	Solid Electrolyte
HER	Hybrid Electric Regional	**SEI**	Solid Electrolyte Interphase
HESS	Hybrid Energy Storage Systems	**SET**	Strategic Energy Technology
HLM	High Lithium, Manganese	**SIB**	Sodium Ion Battery
HPA	Hydrogen-Powered Aircraft	**SMR**	Short and Medium Range
HW	Hardware	**SoX**	State-of-X where X = Charge (C), Health (H), Power (P), Temperature (T)
ICE	Internal Combustion Engine	**SRA**	Strategic Research Area
IoT	Internet of Things	**SRIA**	Strategic Research and Innovation Agenda
IPCEI	Important Projects of European Common Interest	**SSbD**	Safe and Sustainable by Design
IVET	Initial Vocational Education and Training	**SW**	Software
IWG	International Working Group	**TRL**	Technology Readiness Levels
JRC	Joint Research Centre	**V2X**	Vehicle-to-Everything
KPI	Key Performance Indicator	**VRFB**	Vanadium Redox Flow Battery
LBA	Local Balancing Area	**WG**	Working Group
LCA	Life Cycle Assessment	**ZEWT**	Zero-Emission Waterborne Transport

1. Vision

In the future, all that can be electrified will be electrified, for the sake of both the recovery of our planet from excessive greenhouse gas emissions and for our everyday convenience. Energy will be generated from renewable resources and our waste from mobile devices to solar cells, cars and planes will be recycled at the end of their useable lifetime. This will facilitate minimum resource extraction and hence enhance the recovery of natural environments and ecosystems globally. By 2050 Europe can be the first climate-neutral continent, however this will require a long-term maintained focus on sustainability and emissions reductions, while encouraging growth of new markets and provision of high-quality education and jobs for all. Batteries will be a facilitating technology for much of this growth enabling the green transition of both transport and energy storage sectors.

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.

To compete globally, Europe must bolster its capabilities in materials development, digitalisation, and applications engineering to establish a solid foundation for sustainable and innovative battery cell manufacturing and position itself against the established players in the global market. **Reducing raw material dependency** by fostering higher levels of circularity, sustainability, and resource efficiency and reducing the use of CRMs, while concurrently addressing environmental concerns is the key to **establishing a resilient supply chain, which will boost Europe's strategic autonomy.** This objective should be realised through an **expansion of recycling alternatives** and increase of recovery efficiency (targeting 95% Cobalt, 95% Nickel, and 90% Lithium metal recovery by 2030) as listed in the new Batteries Regulation. **Achieving lower costs (<75 €/kWh at pack level by 2030)** and **higher sustainability** in raw materials processing and advanced materials manufacturing is also crucial for Europe to maintain its competitive edge on the global stage.

Additionally, the rapid growth of the battery industry (projected **combined production capacity up to 886 GWh/year in Europe by 2030**) highlights t**he urgent requirement for a diverse and highly skilled workforce across the value chain** and across disciplines (research, professional, vocational, etc.). The shortage of sector specific skills and education is already recognised as a significant challenge for the years to come. To meet the growing workforce demand in line with the industry's rapid pace, it is crucial to foster a robust collaboration between relevant stakeholders (industry, academia, education and training providers, lab facilities, etc.) so as to provide several opportunities for upskilling and reskilling.

To achieve these objective, immediate **prioritisation of battery research in Europe** is necessary, and a comprehensive approach must be adopted, encompassing the entire battery value chain and receiving support from relevant stakeholders, including European, National, and Regional Research & Innovation (R&I) agencies. Significant and continuous investments in battery research and associated research infrastructure are imperative, addressing **both short-term** and **long-term research priorities.**

1.1 The European policies on batteries and related technologies

In 2019, European Commission's President U. von der Leyen presented the European Green Deal, Europe's masterplan to fight climate change by becoming the first climate-neutral continent by 2050 while making the most of the socio-economic opportunities offered by the green transition (Europe's new growth strategy). The European Green Deal has effectively placed decarbonisation at the core of all European policies. In 2021, this approach materialised into the **Fit-for-55 Package**, a package of 12 legislative proposals, aimed at adapting the European climate and energy policy to the new objective of reducing the EU's GHG emissions by 55% by 2030. It sets a number of legally binding targets, strengths EU's industry innovation and competitiveness, creates an enabling framework for the deployment of sustainable solutions, and provides financial incentives. These dimensions concur to reinforce the business case for batteries in key applications, namely electric mobility (road transport, shipping and aviation) and stationary energy storage. The European Commission estimates that *"global demand for batteries is increasing rapidly and is set to increase 14 times by 2030. The EU could account for 17% of that demand"*[6].

Key points in the Fit-for-55 Package:

- Targets for the decarbonisation of power production and transport in the Renewable Energy Directive, Energy Performance of Buildings Directive, and Alternative Fuels Infrastructure Regulation;
- De facto ban on the sale of new ICE (Internal Combustion Engine) vehicles by 2035 in the CO2 Standards for Cars and Vans Regulation;

In 2020, in this context of regulatory effort to improve Europe's footprint on the climate and the environment and keep up with the progress and increasing competitive edge of the European battery industry, the Commission proposed a **revision of the Battery Directive.**
This revision is in the form of a Regulation, hence the text will be directly applicable, with no need for a transposition into national legislation in each Member State. The revised directive aims at improving the sustainability of the entire battery value-chain and at mitigating the risks, notably linked to the availability of critical raw materials, in the supply-chain. The **Battery Regulation** (formally adopted by the European Parliament and by the Council and whose publication is pending in the Official Journal of the European Union) will greatly shape the decisions and actions of the industry in the coming decade. Moreover, it will be complemented by a series of technical texts (secondary legislation) in order to detail the obligations that the industry will have to comply with.

Key points in the Battery Regulation:

- Mandatory sustainability and safety requirements for the placing of batteries on the European

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

market, including restrictions of certain substances, carbon footprint requirements, performance and durability requirements, etc;
- Recycled content requirements;
- Traceability through labelling, marking, and information requirements, notably with the creation of the digital battery passport;
- Mandatory implementation of due diligence policies;
- Extended producer responsibility;
- Targets for the collection of waste batteries, and provisions regarding the treatment, reuse, and recycling of batteries, notably materials recovery targets;
- Green public procurement;

In 2022, following Russia's attack on Ukraine and the subsequent energy crisis in Europe, the Commission proposed the **REPowerEU** Plan in order to rapidly phase-out Europe's dependency on Russia in the energy sector. Strategic autonomy, a concept that had already gained visibility with the new Industrial Strategy for Europe, marking a change in approach with regards to industrial policy, came to the forefront of the European climate and energy policy. In addition, in response to the US Inflation Reduction Act, the Commission proposed a **European Green Deal Industrial Plan** to secure manufacturing of "net-zero technologies" (including batteries) in Europe. This Plan includes new or re-channelled financial support for manufacturing projects, an improved framework for such projects, for instance by facilitating permitting, an improved access to skills, and stronger support from Europe's trade policy.

Key points in the European Green Deal Industrial Plan:

- Support for battery manufacturing projects in the **Net-Zero Industry Act**;
- Launch of Net-Zero Academies, based on the EBA Academy, to help train the workforce needed in the net-zero technologies value-chains, proposed in the Net-Zero Industry Act;
- Support for projects regarding the extraction, processing, and recycling of strategic raw materials for the battery industry in the **Critical Raw Materials Act**;
- Improved integration of flexibility solutions (including mobile and stationary battery storage in the revision of the electricity market design;

Important changes in the regulatory framework for the upstream part of the battery value-chain will stem from the Critical Raw Materials Act and from the measures put forward under the European Green Deal objective "a zero-pollution ambition for a toxic-free environment". The Critical Raw Materials Act proposed by the Commission would complement the current list of critical raw materials with a list of strategic raw materials deemed crucial for the twin transition (digital and green). This list would notably include Cobalt, Copper, Lithium, Manganese, natural graphite, and Nickel. The Act aims at mitigating the risk of supply-chain disruptions for these materials though diversification of import sources, domestic production, and circularity. In parallel, the Commission is progressing on the implementation of the "Chemicals Strategy for Sustainability" adopted in 2020 which had announced a phase-out of the use of per- and polyfluoroalkyl substances (PFAS) in Europe "unless it is proven essential for society". The use of PFAS in battery manufacturing will therefore come under particular scrutiny in the review of REACH secondary legislation to happen by 2024. The battery R&I community will play a crucial role in accompanying the industry with these possible regulatory evolutions. R&I activities will be funded under Horizon Europe to develop innovation to substitute PFAS where needed.

1.2 The European battery research ecosystem

The European Green Deal and European Green Deal Industrial Plan have had a significant impact on the regulatory framework for batteries, as described in the section above and summarised in the table below. Implementation and further evolutions are expected (notably with the secondary legislation stemming from the Battery Regulation and with the possible restriction of the use of PFAS in batteries).

In this dynamic context, the battery R&I community are called to support the industry in the effective implementation of this new regulatory landscape.

Impact	Policies
Business Case	**Electricity Market Design** **Fit-for-55 Package**- relevant texts for battery technology Renewable Energy Directive (mobile & stationary storage) Energy Performance of Buildings Directive (mobile & stationary storage) Alternative Fuels Infrastructure Regulation (mobile storage) CO_2 Standards for Cars and Vans (electric vehicles)
Manufacturing	Critical Raw Materials Act Net-Zero Industry Act Battery Regulation REACH secondary legislation (PFAS)

Table 1: Overview of the New Regulatory Landscape for Batteries

The European Strategic Energy Technology Plan (SET Plan), since its inception in 2007, has become the reference framework for addressing clean energy R&I developments in Europe. It facilitates the cooperation among EU countries, companies and research institutions in R&I activities for low-carbon energy technologies and supports the alignment of national R&I programmes with the EU R&I agenda. Through the work of its 14 Implementation Working Groups (IWG), it has been successful in setting common EU, national and industrial research priorities to influence R&I agendas, leveraging also resources at both European and national level.

In this landscape, Batteries Europe (BE) is implementing the Action 7 of the SET Plan. In order to monitor the developments in each IWG (and the SET Plan as a whole) and track the progress towards the achievement of their objectives, EC services have established an annual reporting exercise. The process invites all IWG representatives to share information with the EC services about the progress of their IWG. A part of the outcome of this exercise is presented annually in the SET Plan progress report.

The revised structure of the SET Plan (Q4 2023) will become a key tool in improving how the National Energy and Climate Plans (NECPs) are updated and monitored. In parallel it will enable a more efficient connection of the activities of its member countries with the EC, speed up the development and deployment of clean energy technology, while addressing cross-cutting environmental and social sustainability issues.

The effective collaboration of all actors of the Batteries IWG with all stakeholders within the battery R&I community is crucial for reaching the short and long-term objectives of the European batteries industry.

The European Battery Alliance (EBA) is the key player in this landscape which was launched in October 2017 by European Commission Vice President Maroš Šefčovič. Its purpose is to ensure that all Europeans benefit from safer traffic, cleaner vehicles and more sustainable technological solutions. This is achieved by creating a competitive and sustainable battery cell manufacturing value chain in Europe. The industrial development programme of the European Battery Alliance is referred to the EBA250, which is driven by EIT InnoEnergy. The EBA2050 brings together more than 800 European and non-European stakeholders representing the entire battery value chain. The EBA250 provide an overview of EU legislation and directives related to batteries, useful market insights and a Business Investment Platform (BIP). EIT InnoEnergy has co-designed the BIP together with financial institutions – public and private – and several core industrial partners to accelerate transactions between investee and investor along the entire battery value chain. The work of the EBA250 is delivering 43 necessary actions including R&I, to set up a dynamic and efficient European Battery Alliance and to capture a significant share of the rapidly expanding global battery market. The establishment of the European Battery Academy (now InnoEnergy Skills Institute) fulfils one of these actions, which will reduce the cost to train and reskill workers while drastically increasing the efficiency and quality of training led by industry insight. The goal is to develop and produce exceptional programmes and learning content to address skill gaps, including online learning modules, in-person training and training manuals.

To support the implementation of the new regulatory framework and achieve the ambitions of the EBA, the European battery R&I community has organised itself in various interlinking initiatives. These initiatives cover the entire battery R&I community ecosystem, with a wide range of fields representing different R&I interests across the battery value chain. Over the past years, these initiatives have intensified their cooperation to form a well-structured ecosystem of complementary organisations which are summarised below.
Figure 1 provides a graphical representation of the different initiatives and their focus area.

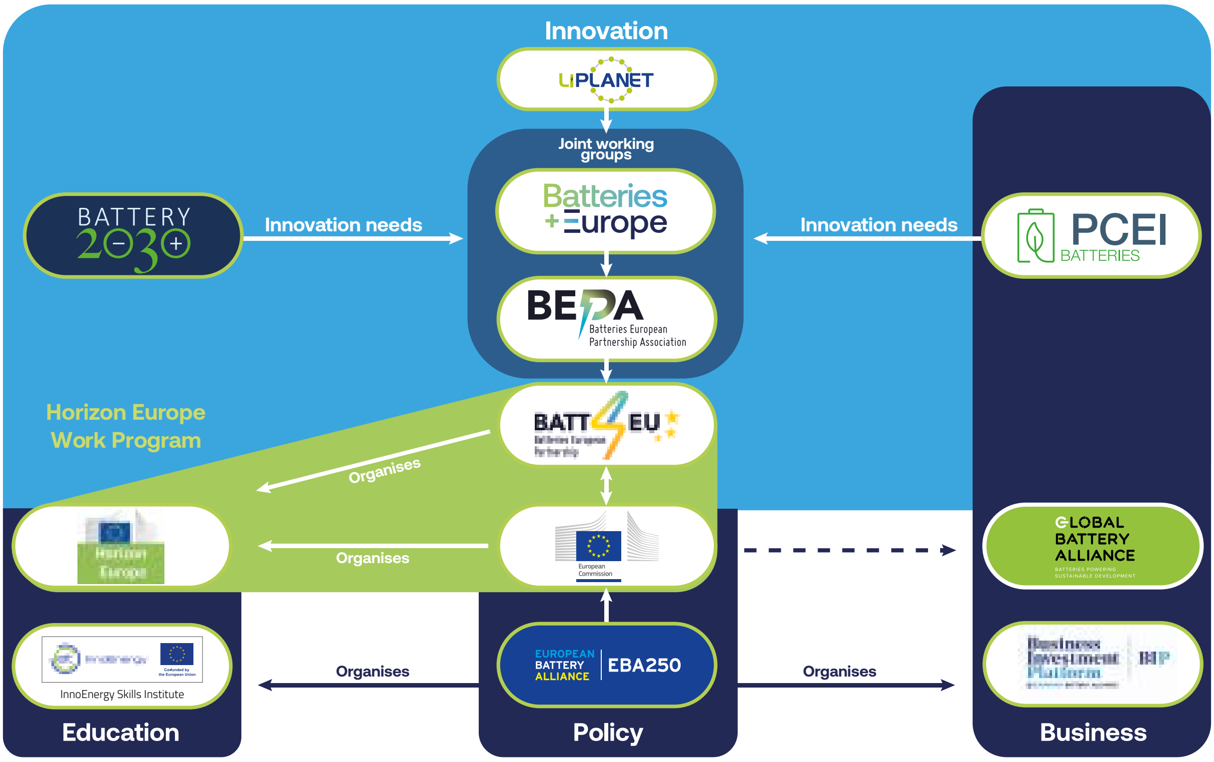


Figure 1: Overview of the entire European battery R&I ecosystem, from Business to Education

To support the establishment of a competitive battery value chain in Europe and to answer the demands of the industry across this new value chain, several institutional initiatives have been set up, aiming to unite the involved stakeholders and ensure a structured support from basic research to industry application.

Batteries Europe was launched as a European Technology and Innovation Platform (ETIP), established with support of the European Commission in 2019. Since its inception it has evolved to be an open and inclusive think tank that aims to represent the entire battery value chain by bringing together experts from research, industry and academia. The aim of the think tank includes preparing KPI & KPI targets and roadmaps for battery R&I community and beyond, while considering technology developments both inside and outside of Europe. BE also participates in the implementation of the SET plan Action 7 on Batteries and works closely with BEPA to develop the Strategic Research and Innovation Agenda for Europe. Batteries Europe also has a focus to develop and implement a uniform Reporting Methodology across Europe and eventually globally so to support the definition of a unified language for researchers in the sector.

Battery 2030+ was set up in 2017 to provide a long-term perspective on the battery research needs in Europe, with a focus on the digital technologies that will create smarter, better, and longer-lasting batteries and that will change the way battery research is being done. Battery2030+ has been key in clustering innovative European projects to create a European community of excellent scientists, who all agree on certain methodologies and the use of FAIR (Findability, Accessibility, Interoperability, Reusability) data. Battery 2030+ also provides a clear long-term perspective through a roadmap of its own, which underpins some of the longer-term recommendations in this Roadmap and the SRIA.

IPCEI is the abbreviation of "Important Project of Common European Interest". It's a transnational project with an important contribution to the growth, employment and competitiveness of the European Union industry and economy funded by state aid. Part of the implementation programme to mark the kick-off for the development of the European battery industry, are the two IPCEIs; the first one on Batteries and the second IPCEI on European Battery Innovation (EuBatIn). They are designed to bring together the public and private sector and undertake large-scale projects that provide significant benefits to the Union and its citizens. More than 50 companies from 12 EU Member States are developing new technologies along the entire battery value chain and bringing them into first industrial deployment. The participating EU Member States are providing up to 6.1 billion euros in funding. In addition, up to 14 billion euros in private investments are being made available. To create a European battery ecosystem, the funded companies are encouraged to establish European supply relationships and share knowledge in spill-over activities. The first IPCEI on batteries is coordinated by the French government, while the second IPCEI on European Battery Innovation (EUBatIN) is coordinated by the German government and its project management agency, VDI/VDE Innovation + Technik GmbH. The IPCEI instrument gives EU Member States the opportunity to fund large-volume projects aimed at setting up production facilities for innovative products. The EU Commission sets the framework conditions and monitors compliance with these. The Member States are allowed to fund projects within this framework, but each project must be notified individually by the EU Commission. This ensures compliance with international trade rules.

LiPLANET is a network of Li batteries pilot lines in Europe. It initially brought together 12 facilities, but it is now ever-growing. LiPLANET started as a European funded project with the aim to create a competitive European innovation and production ecosystem and reinforce the position of the EU in the lithium battery cell manufacturing market. LiPLANET has contributed to increase the production of lithium battery cells towards industrial scale by bringing together the most relevant European lithium battery cell pilot lines. The LiPLANET network has continued as an independent association which allows for the exploitation of synergies between pilot line operators, identification of knowledge and equipment gaps, organisation of joint trainings, collaboration with industry and academia, and facilitation of market access to pilot lines.

As part of the Horizon Europe framework programme, the Commission and stakeholders from the battery value chain launched BATT4EU in 2021. BATT4EU is a public-private partnership, whose main aim is to ensure that the 925 million earmarked in Horizon Europe for research on batteries is spent in the best way possible. To this end, specific goals for the battery value chain have been set out in a Strategic Research and Innovation Agenda (SRIA), which guides the development of the calls in the Work Programmes under Horizon Europe. The partnership will also support other activities, like standardisation efforts and the development of the battery regulation, ensuring a wide dissemination of the research results and contributions to the education and upskilling of the workforce. The battery value chain is represented by BEPA, an association of over 220 members as of July 2023, uniting industry and research actors across the value chain. The BATT4EU Partnership cooperates with other partnership to cover the whole value chain, such as raw materials extraction and production with European Raw Materials Alliance or with application-oriented initiatives, namely 2Zero (road transport), ZEWT (waterborne), Clean Aviation and Europe's Rail. Other collaborations with more cross-cutting topics like manufacturing, processing and digital technologies are also being explored.

To create a continuous workflow between the road mapping exercises by Batteries Europe and the preparation of the Horizon Europe Work Programme by BATT4EU, the expert working groups of BEPA and Batteries Europe have been integrated with a joint governance structure and shared strategy to gain efficiency and synergies among the initiatives.

1.3 Scope and Objectives of the Technology Roadmap

The Batteries Europe Technology Roadmap is a document designed with the objective to support strategic planning of research and innovation by identifying and elaborating the short-, mid-, and long-term needs for supporting the establishment and development of a European battery ecosystem across the whole value chain. It reviews the research required to satisfy those needs and provides a mechanism to help forecast technology developments.

This roadmap is designed to target all communities concerned with battery development (Member States, policymakers, industry & start-up companies, the research community, the general public and associations & communities) with the goal to assess and propose key **strategic research areas** in each segment of the value chain that require R&I support.

For each of the segments, the **6 Working Groups and 4 Task Forces** describe the **state-of-the-art and challenges, research and development needs**, and impact of the strategic research areas and technologies. The working groups worked with members of the task forces to develop **transversal challenges** research areas also. Where there is a **timeline** included, it is expected that the research work in the area should be underway and yielding results towards a solution. The working groups also provide a list of **key recommendations** for all the communities concerned with the final goal of turning new knowledge into a socio-economic viable and sustainable innovation in the battery ecosystem.

1.4 Methodology

Batteries Europe has **6 Working Groups (WGs)** and **4 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 who generally know each other by interactions at earlier meeting, hence hosting meetings online was not a challenge. As the task forces represent transversal issues, they had participants in each of the working group meetings to introduce the relevant transversal research areas.

Research and Innovation priorities across the entire battery value chain were addressed in each of the six segments covered by the dedicated working group, with the support of task forces. Each working group had 4-5 online meetings and one face-to-face or hybrid meeting to prepare the material for the Batteries Europe Roadmap. Initially, the **working groups** identified a number of strategic research areas of interest. Subsequently, a selection process was conducted **to narrow down the strategic research areas to about five per group**, except for WG1 where a larger number of strategic areas was identified considering the long-term vision. Generally, each strategic research area was appointed a separate smaller drafting team who worked with the technical advisor of Batteries Europe secretariat to create a first version of the text. The text was then discussed by the specific working group at online meetings and modifications made accordingly.

The transversal **Task Forces** contributed to the identification of the **transversal challenges** in each segment. At least one member per Task Force was involved in the working group meetings to ensure that the vision of the TFs was well-embedded in each section. As the task forces were split during this exercise, there was a meeting to ensure alignment among the members of the task forces on the transversal research areas selected.

The **final face-to-face Roadmap meeting** was held on at the beginning of **June 2023** to validate the first full draft of this Roadmap and to provide additional comments and improvements. After this point, the feedback and guidance from Batteries Europe Steering Board, Secretariat, and EC officials has been instrumental in giving it its final shape.

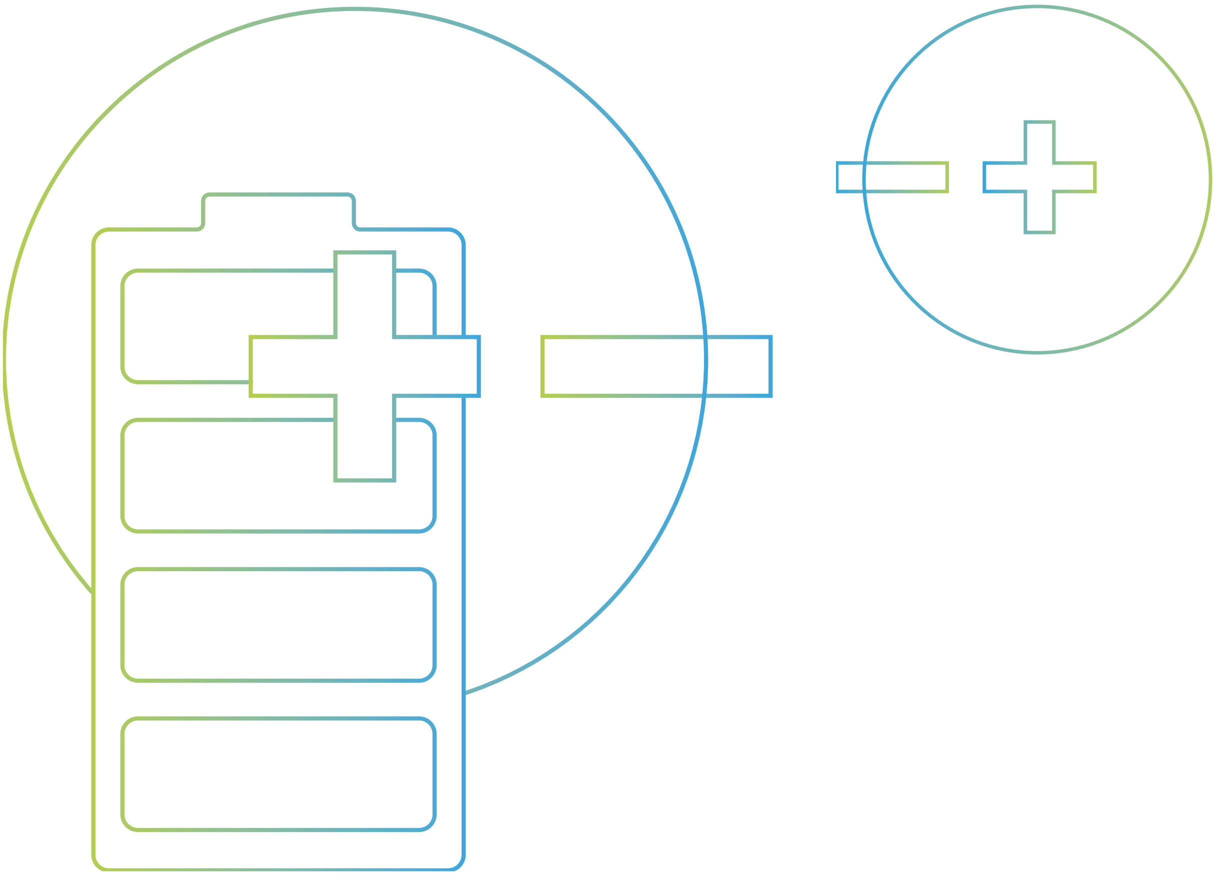
1.5 Needed Education and Skills to address the industry

Battery cell production is a new fast expanding activity in Europe. To ensure skilled workforce and researchers for this development is a major challenge, and qualified workforce is needed both for the white-collar and blue-collar jobs. As a baseline, education and training are demonstrated to be fundamental both for expanding the rather new European battery cell production sector and achieving competitive functionality of the whole value chain of batteries and electromobility in Europe. Europe is now facing a critical phase of expansion of the battery ecosystem: it is time to roll it out. This challenge and need are transversal to all WGs of Batteries Europe.

In fact, batteries are a multidisciplinary field, and we need to educate people on raw materials, new materials development, on recycling, as well as on cell and battery pack production for both automotive and stationary applications, without excluding any other actual current and future needs. The gap of skills is obvious, but there is also an attractiveness gap, a geographical and a timing gap to consider for ensuring competent workforce for this expansion.

In addition, the important concept of Train-the trainers has to be set and strongly developed starting immediately and continuing in the future, to assure well skilled people are teaching future generations of workers and scientists. The quality of training activities must also be certified.

Important work is already completed: the existing education activities have been mapped and the European needs, new job roles, learning objectives and education concepts for the sector have been examined also. This has been done with the help of multiple initiatives and projects, such as the research initiative Battery2030 plus[7], in the position paper of ETIP Batteries Europe[8], a report by Fraunhofer and EIT Raw Materials[9], by ALBATTS through multiple updated skills intelligence reports[10], and through a 4.5-year research led by the EIT InnoEnergy (now via InnoEnergy Skills Institute)[11]. Updates are required, but there are many activities running in Europe to educate people and future workers. This education, skilling and re-skilling of workers must consider all the levels, from blue-collars and vocational levels to professionals to master and PhD students and post-doc.



[7] battery2030.eu
[8] https://batterieseurope.eu/wp-content/uploads/2022/09/education_and_skills_task_force_position_paper_0.pdf
[9] https://eitrawmaterials.eu/eit-rawmaterials-and-fraunhofer-publish-a-report-on-future-expert-needs-in-the-battery-sector/
[10] https://www.project-albatts.eu/en/publications
[11] https://www.innoenergy.com/skillsinstitute/

Baseline (2023-2025)
Academic level
• Attractive grants for early-stage researchers. • Adoption of curricula (specific degrees). • Cross-disciplinary knowledge transfer R&D infrastructures (e.g., pilot lines) as the nucleus for networking between industry and academia (joint programs).
Professional/vocational level
• Initial work in place for identifying industry needs (surveys, expert interviews, job posting crawling, desktop research). • Some work has been done in curriculum development, with few national curricula still in IVET and some EU wide curricula available for professional re/upskilling. • Public learning labs are under construction in a few places; few training simulation tools available and certain lab trainings available for hands-on practice. • Vocational programs started around rising gigafactories or Fraunhofer Battery Facility (FBF); limited capacity. • On professional re/upskilling InnoEnergy Skills Institute (former EBA Academy) and other projects (e.g., European Battery Business Club) and initiatives started; some national development projects; Pact for Skills Automotive Skills Alliance established. • Gigafactories have more onboarding experiences for filling skills gaps but still largely confidential; younger gigafactories still rely on support. • Some work started on sector attractiveness, mostly by gigafactories recruiting; additional work has been done by Batteries Europe, Battery 2030+ and BEPA. • Onsite, online, blended teaching methods used, but mostly in the form of static programmes. • Modular approach under development and followed by certain content providers; constructivism.
Public/user level
• Increase acceptance, awareness, and attractiveness of this sector to the general public (e.g., information, battery safety, handling to recycling etc.). • Specific funding programs for adaptation and expansion of educational systems. • Programs targeted for awareness for battery users, also for people that might be affected by battery production e.g., localities near gigafactories. • Implement EU wide information and monitoring platform on educational offers available for different audiences. Accelerate regulatory aspects.

Mid-term (<2030)

Academic level

- EU wide standards for adapted curricula and creation of interdisciplinary courses covering the whole value chain of battery production/usage and recycling, available for all interested students.
- Encourage establishment of new groups based on early career researchers in the Member States with lower academic activity in the field of battery research.
- Development of trainings based on digital tools.
- Internships offered within industry to mobilise workforce to locations with battery production facilities with dedicated fundings.
- Increase the number and capacity of courses/programs available for all interested students.
- Increase mobility of researchers across Europe, with an increasing number of R&D centres and infrastructures.
- Create fundings for students to increase mobility and attendance to specific courses.

Professional/vocational level

- Continued work to analyse future skill and workforce requirements based on empirical data and in closer collaboration with the industry; assist industry to express detailed needs towards educational providers.
- Internships offered in industry mobilising workforce to battery production facilities locations with dedicated fundings.
- Progressed work in curriculum development, with EU wide acceptance and local adaptations covering the entire battery value chain and multiple European Qualification Framework levels.
- Public learning Labs in most EU countries and dedicated facilities ideally integrated into academic (e.g., FBF) or industrial battery sites (national and EU-wide access).
- Vocational programmes benchmarked and developed into continuous offerings in most EU countries.
- Roll-out of standardised qualification programmes based on industry needs and wider accessibility; Pact for Skills model established; collaboration among industry, training providers, academia, vocational schools, and lab facilities.
- Methods developed for in-house industry training in collaboration with CVET and re/upskilling training providers.
- Train-the-trainer concept developed EU-wide in collaboration with the industry.
- Battery value chain becoming very attractive, mobilising the workforce to relevant locations (e.g., gigafactories).
- More established adaptive and flexible learning for individual needs; Initial VR-based courses/ trainings to complement traditional methods; balance constructivism/ constructionism.

Public/user level
• Support expansion of adapted educational systems across Europe. Provide additional opportunities (digital or onsite) for the public to receive information and training in terms of awareness, safety, and regulatory aspects (if possible, in multiple languages).
Long-term (2030+)
Academic level
• EU wide established educational network/systems (Battery Value Chain and ecosystem). • Large number of young people interested in studying along the value chain and trained/ available for industry. • Adapt curricula based on changing needs. • Long-life learning courses and Massive Open Online Courses available. • Use of specific fundings for the mobility of master, PhD students.
Professional/vocational level
• European collaborative work model (education – industry) in place with review of changing needs and increase in demand; Needs well represented in vocational/ professional education. • Collaborative models between industry – schools are mainstream, and a high number of relevant curricula are available. • Learning labs, both physical and virtual, are widespread. • Continuous and flexible IVET accessibility for the sector. • Continuing education is normal, frequent and flexible for the entire workforce based on industry needs. • Validated and flexible pathways for learning, career development at the workplace, and beyond. • Training trainers/teachers continuously is part of the mainstream sector practice. • Battery industry is known for its clean and interesting workplaces, with many career opportunities. • Digital tools for training are used and effective with modular and adaptive trainings; constructionism more dominating.
Professional/vocational level
• Broad acceptance and awareness of the topic by the public. • Understanding of battery usage and safe handling for users achieved. • No regulatory barriers.

2. Research and Innovation priorities across the battery value chain

2.1 New and Emerging Technologies

The energy transition will create new opportunities for different battery technologies to match safety, sustainability, circularity, cycle lifetime, performance, and cost requirements. This part of the roadmap describes these expected emerging and new battery technologies at TRL < 4 for a diverse range of present and future applications. The needs to develop tools and methods to enable the acceleration of the battery development have been considered. This includes both high throughput experiments and exploring the full potential of digitalisation developments. This is also described in depth in the Battery 2030+ roadmap. The strategic research areas (SRAs) described are all selected on the vision to reach as far as 2050 but with the short-term needs to 2027, and mid-term needs (2030) specifically highlighted. The SRAs are not reported in order of priority.

2.1.1 Strategic Research Areas

2.1.1.1 Advanced Redox Flow Batteries

Advanced Redox Flow Batteries (RFBs) involve a wide variety of cell technologies and chemistries. Among them, low-cost inorganic RFB with iron-, copper- or zinc-based electrolytes or all organic based redox flow batteries (AORFBs) are worth mentioning. Efforts toward commercialisation are underway, especially for iron based RFB, although there is still potential for improvement at the material level. A wide variety of options are included within the term AORFB, for which the highest maturity has been reached by quinone based technologies up to TRL5-6. A less developed approach (TRL3-4), that is conceptually different from standard RFB and transversal to different chemistries (both organic and inorganic), is based on the use of solid boosters with redox potentials coupled to the active species in the electrolytes to increase energy densities. Challenges vary for different RFB technologies, however there are several common areas for improvement including extending the durability of the active species, a better control of crossover processes through the membrane, reduction of parasitic reactions to increase energy efficiency and increasing the energy density of the electrolytes.

R&D activities needed

R&D activities should ultimately target cost reduction increasing the performance, sustainability and increased safety, including environmental impact and materials availability analysis. These should include:

Short-term needs (2027):

- Design of novel active materials and advanced components especially for (but not only) low TRL level technologies; for example, new organic and organometallic compounds, and more

efficient membranes (which involves a careful balance between selectivity, resistance, and environmental impact), including fluorine-free membranes which still represent a challenge for Vanadium Redox Flow Batteries (VRFB).
- Research on disruptive concepts (solid boosters, membrane free, etc.) that allow lowering costs and increasing sustainability.
- Development and implementation of computational models and/or artificial intelligence methods for the discovery and/or engineering of redox active materials for flow batteries.
- Validation of devices and systems for low-cost inorganic (e.g., Fe, Zn, Cu, etc.) and AORFBs.

Mid-term needs (2030):
- Investigation on new chemistries or electrolyte formulations to enable dual applications (redox-mediated hydrogen production or thermal management) or the coupling with other systems such as photo electrochemical solar cells.
- Design developments are highly relevant but also chemistry dependent and should be addressed at a later stage.

Impact

Low-cost and sustainable RFBs will be more competitive than Li-ion batteries (LIBs) for Long Duration Energy Storage (LDES), meaning 8 to 100 hours discharge at nominal power. While LIBs are suitable for intraday storage, the ability to store energy for multiple days is crucial for addressing overnight power needs and periods of poor conditions for variable renewables, such as storms (traditionally covered by conventional power plants and energy curtailment).

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

Metal-air batteries (MABs) are considered promising electrochemical energy storage systems in view of their high theoretical energy density, potential low cost, and environmental friendliness. Indeed, the utilisation of oxygen from ambient air as a cathode has the benefit of lowering not only the weight but also the cost. Metal electrodes include zinc, iron, lithium, sodium, magnesium, aluminium, and their alloys with other metals to potentially mitigate corrosion issues, tune the working potential and improve mechanical properties.

The main drawback of MABs is their rechargeability mainly due to parasitic chemical reactions. As an example, the precipitation of the solid discharge product may block the oxygen flow in presence of aprotic solvents and low porosity cathode, lowering the achievable energy density. Another challenge is the lack of stability of the liquid electrolyte, indeed in most chemistries non-aqueous liquid electrolytes, often lack electrochemical stability; and aqueous electrolytes are susceptible to evaporation, electrolysis, and carbonation. Oxygen crossover from the cathode to the anode is yet another fundamental challenge which must be addressed regardless of the metal used as an anode. Shifting from liquid electrolytes to solid or quasi-solid electrolyte is foreseen as a future breakthrough for MABs to alleviate these challenges. The substitution of the metallic anode by alternative more sustainable materials which can supply quasi finite source of metal ions would also be a breakthrough. To increase cycle life and rechargeability, more efficient and economically affordable electrocatalysts, (not including critical raw materials (CRMs) and providing low charge overpotentials, are required to increase the TRL and competitiveness of MABs.

R&D activities needed

Short-term needs (2027):

- In-depth interface studies to better identify and quantify discharge products and therefore enhance reversibility by understanding parasitic reaction paths. Fundamental studies are necessary at materials and cell level.
- New concepts to enhance the performance of electrodes and address oxygen crossover, such as novel structures, catalysts (mainly bifunctional), including focus on surface topologies and airflow/water-electrolyte flow management; always keeping in mind materials sustainability.

Mid-term needs (2030):

- A precise engineering of solid-state (or quasi solid-state) MAB configurations, to address electrolyte electrochemical stability, oxygen crossover, dendrite growth and parasitic reactions.

Impact

Successful implementation of the above suggested activities by 2027 would lead to i) Full cell and system level concepts for feasibility studies to direct further R&D efforts; ii) Broad and consistent understanding of fundamental interfacial phenomena and demonstration of realistic application scenarios and timelines; iii) networking and exchange within the broad scientific community of shared testing protocol for rechargeability. These would result in the development of relevant battery cell prototypes with high energy density that are safe, environmentally friendly (without use of CRMs), and lightweight, addressing mobility and grid energy storage.

2.1.1.3 Durable Metal sulfur batteries with enhanced power capability

Metal sulfur battery cells achieve high gravimetric energy densities beyond 400 Wh/kg for Li-S and 200-440 Wh/kg for other metal systems and are based on low-cost raw materials. Several material and cell concepts have been progressed from small lab experiments (TRL 1-3) to evaluation in pouch cells (TRL5) and even in application systems (TRL ≥ 6). So far, the poor cycle life and power capability of high energy metal-S prototype cells are limiting the broad applicability of this battery technology.

Cycle life is mostly restricted by the consumption of electrolyte and/or the metal anode over cycling, while the sluggish sulfur conversion kinetics and/or the high viscosity of saturated polysulfide solutions is limiting the power capability. To stop the polysulfide shuttle in highly solvating electrolytes, additives are often applied. However, their consumption over cycling leads to gas formation and their limited thermal stability clearly restricts their applicability.

Alternative approaches based on cathodes and electrolytes partially or fully suppressing the polysulfide dissolution have been reported with promising results. The reaction mechanisms of the various electrolyte and cathode concepts can be very different and advanced analytical methods have been developed and applied to achieve an enhanced understanding on the conversion chemistry in liquid, quasi-solid and solid-state concepts.

R&D activities needed
Short-term needs (2027):

- Enhance the understanding on mechanisms in relevant cell configurations under lean electrolyte condition (e.g., via advanced in-operando characterisation).
- Investigation of advanced electrolyte concepts, enabling low electrolyte to sulfur ratios and stabilising the anode/electrolyte interphase
- Enabling efficient solid-state-sulfur conversion via organosulfur compounds or solid electrolyte composite cathodes.
- Developing new catalysts to minimise the shuttle effect and to accelerate the polysulfide redox reactions.
- Enhance metal anode stability (e.g., via surface modifications and electrolyte compositions).

Mid-term needs (2030):

- Implementation of all-solid-state cell concepts.
- Upscaling component and cell manufacturing for cell concepts targeting specific application requirements.
- System level demonstration (including thermal management, SoC monitoring and cell pressurising concepts).

Impact
Research in metal-sulfur technologies is expected to deliver cells with performance criteria exceeding LIB limitations, enabling new applications such as ultralight batteries for electric aviation, drones and low cost and sustainable batteries for energy storage.

2.1.1.4 Safe & Sustainable aqueous batteries

Development of aqueous batteries has been one of the critical areas of research in view of their high safety, low cost of production and sustainability. For example, zinc-ion, sodium-ion and other types of aqueous batteries are particularly attractive due to their non-toxic and non-flammable electrolyte, their high specific power, high reversibility and sustainability, and due to the overall abundant as well as low-cost materials. However, certain challenges still remain and prevent aqueous batteries reaching their full commercial potential. Primary challenges identified are the limited voltage window and the dissolution of employed electrode materials.

R&D activities needed
Short-term needs (2027):

- Electrode material development and evaluation, and scalable production. In the case of

Zn-ion for example, one direction of research is metal zinc anode, which allows for fast cycling. For the cathode side several material classes can be explored, E.g., Prussian-blue analogues (PBA), like copper hexacyanoferrate (Cu-HCF) or manganese hexacyanoferrate (Mn-HCF). Biomass-derived carbons are also attractive electrode materials for various aqueous chemistries.

- Electrolyte development, with focus on overcoming the low voltage window.
- Cell design and manufacturing using sustainable electrode manufacturing processes (e.g., sustainable binder systems robust in aqueous electrolytes) and appropriate separators.
- Operational conditions for enhancing lifetime, cyclability and energy.
- Identification of most promising market potential and competitors.

Mid-term needs (2030):
- Focusing on specific applications and products for faster increase of TRL.
- Scaled-up production processes.

Impact

Development of batteries with increased power and energy density, ultimate safety and lower critical raw material content towards (quasi)-zero metal excess. Benefits of simplified manufacturing processes (no drying), reduced manufacturing costs and carbon footprint. Simplified recycling allows for faster battery uptake in safety-critical applications, as well as provides more competitive offering in the stationary market in applications, such as frequency regulation, fast charging etc.

2.1.1.5 Anode less battery technologies

Cell chemistries assembled with a positive active material at discharged state using metal negative electrodes do not strictly require an additional metal reservoir and can therefore be assembled in an anode-free configuration. This concept, still at early stages of development (TRL<3), allows achieving the highest retrievable energy density and specific energy, however it is extremely sensitive to the inefficiencies of the system. The main challenge is to minimise loss of metal inventory (consumption of metal ions for SEI (Solid Electrolyte Interphase) formation, dead metal deposits), and maximise reversible metal utilisation.

R&D activities needed

Short-term needs (2027):
- Development of stable interfaces, either through ex situ or in situ strategies. This includes the design of protective layers or the use of advanced electrolyte formulations/compositions for stable SEI formation.
- Non-invasive techniques to monitor SoH (sensing approaches) so that self-healing approaches, to avoid dendritic growth and stabilise the interface, are activated externally by the BMS.
- Current collector design. Structuration to enable higher C-rates and mitigate volume changes, and/or functionalisation resulting in advanced interphases to form metalphilic

surfaces that promote homogeneous metal nucleation and ensure low interfacial contact resistance between electrolyte and current collector (wettability in liquid, contact in solid). Strategies should be cost-competitive and minimise energy density and specific energy penalties.

- Explore pre-metalation strategies like small anode reservoirs to compensate for inefficiencies and/or stabilise interfaces.
- Develop advanced characterisation tools to understand metal loss phenomena, buried interfaces, metal electrodeposition and dissolution, and evaluate the impact of external conditions (pressure, temperatures, cycling protocols) to minimise volume changes, reduce contact resistance and overall improve the system performance.
- Develop understanding in metal nucleation processes and material screening in terms of material compatibility, metal-philicity, impact of structuring approaches, etc. using a combination of experimental and modelling approaches.

Mid-term needs (2030):

- Research focused on manufacturing technologies and scalability of areal preparation for mass production and calculating carbon dioxide footprint.

Impact

Development of batteries with increased energy density, better safety and lower critical raw material content towards (quasi)-zero metal excess will benefit both the performance and environmental impact. Benefits in processability (no handling of metal anodes) and reduced manufacturing costs would also benefit the sector.

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

Rechargeable batteries based on multivalent metals (Mg, Ca, Al, Zn) could theoretically offer higher energy density, better resource availability, and a lower tendency for dendrite formation on metal anodes than established Li-based systems. They therefore have enormous potential to meet the demands for current and future applications ranging from stationary storage and electro-mobility to aviation. However, their practical realisation hinges on several significant challenges in material, electrode, and cell development. For instance, metal anode passivation severely limits accessible capacity, and cyclability and represent a significant issue, particularly for Mg-and Ca-anodes.

R&D activities needed

The sluggish kinetics and high polarisation of these systems caused by the higher charge require research into electrode- and electrolyte development for all metals considered.

Short-term needs (2027):

- Metal anode passivation strategies are of high priority for the realisation of multivalent batteries (e.g., Ca and Mg based) whose full potential can only be realised with metal anodes.

- Very few non-corrosive liquid electrolytes are currently available. However, a broader spectrum of electrolytes and additives is urgently required for optimisation in combination with different cathodes.

Mid-term needs (2030):

- The development of solid electrolytes for any kind multivalent batteries is still in its infancy, but progress in the area is warranted.
- Development of cathodes including discovery of new active materials, development of optimised electrode formulation and binder, research into the fundamental charge insertion/extraction mechanisms are required to improve kinetics. Significant research efforts are required to improve the rate performance and capacity of current inorganic insertion cathodes, since these cannot compete with available Li-ion technology at the moment.
- Conversion cathodes based on sulfur offer the highest capacities at low cost. Research in this area is highly relevant for all battery types and synergistic benefits are expected from parallel research in different types of metal/sulfur-systems. The specific challenges associated with M/S-batteries are covered in the corresponding section.
- A promising strategy to alleviate the slow kinetics of multivalent ions is the use of organic cathode-active materials.
- In parallel to the R&D on the materials themselves, aspects related to cell manufacturability and recyclability for the materials being developed, particularly related to new recycling concepts and cell design for recycling, should be addressed.

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 in this area needs to be to advance the current TRL (2-4) to a level that constitutes an incentive for self-sustained industrial R&D.

2.1.1.7 Hybrid supercapacitor-batteries

Hybrid supercapacitor-batteries aim to bridge the gap existing between both technologies while ensuring improved energy (compared to supercapacitors) and power capability (compared to metal-ion batteries). Today, the most common solution to hybridise supercapacitors and batteries on a cell level has been through so-called metal-ion capacitors, where a battery type negative electrode -faradaic in nature- is faced with a positive supercapacitor type electrode -capacitive in nature. Despite recent commercialisation efforts, lithium-ion capacitors still struggle to achieve comparable energy levels to batteries. This limitation poses a significant barrier to their market adoption. The need to avoid any critical raw material usage such as graphite or lithium has also fostered important research beyond lithium metal ion capacitors, e.g sodium and potassium. The maturity level of these technologies' lags behind that of lithium and requires further research and development.
In addition to metal-ion capacitors, another research area in the domain on hybridisation is development of redox-active electrolytes. Redox-active electrolytes should allow an increase

in the energy capacity of supercapacitor systems without significantly compromising power and cyclability inherited from supercapacitors. While some research has been carried out in this domain, more investigation is required into these systems, for example, in electrolyte-electrode interaction for various types of redox-active electrolytes.

R&D activities needed

R&D activities needed are associated to the development of advanced novel materials and pre-metallation strategies enabling fabrication processes that are cost-effective.

Short-term needs (2027):

- A new generation of more energetic and powerful materials is needed. Nano design of faradaic materials is needed to transition from bulky redox reactions towards pseudo capacitance (surface redox reactions) confined into the subsurface of nanomaterials, enabling high energy at high power. Advanced design of capacitive carbon materials is also needed to target higher capacitance. Hybrid positive electrodes combining faradaic and capacitive materials can be a strategy to increase the overall capacity of the system.
- New solvent-salt-additive combinations are needed as electrolytes, moving beyond fluorinated salts and carbonate-based solvents, in the search of more sustainable technology that can operate at higher voltage.
- Development of redox-active electrolytes (aqueous, ionic liquids, organic etc.) and combination of best electrolyte/electrode to ensure performance characteristics satisfying the application needs.

Mid-term needs (2030):

- Current fabrication technologies require the use of metal anodes to accomplish pre-metallation. Novel strategies compatible with roll-to-roll production systems, air-stable, solution processable and cost-effective need to be developed.
- Relevant production and recycling technologies.

Impact

Increasing the energy density of current systems by incorporating novel advanced materials and designs will unlock opportunities in the power batteries market. These systems could operate at much higher power regimes and fast response rates, even in a fraction of a minute, with prolonged cycle life, offering the best cost of ownership solution. Possible applications include stationary storage, such as grid services, or with renewables where fast charging / discharging capabilities could increase the energetic efficiency of photovoltaics and windmills, and mobility such as powering two and three wheelers, public transport (hybridised with other batteries/fuel cells or on their own), industrial mobility (heavy machinery, forklifts, Unmanned Aerial Vehicles).

2.1.1.8 Multimodal multiscale correlative characterisation

Europe has shown strong and early efforts of exploring new chemistries at low TRLs. The methodologies proposed by MAP (Materials Acceleration Platform) on the development of modelling tools and high throughput experimental methods through the Battery 2030+ initiative need to be democratically spread. The challenge is to get access to both, use and develop tools and sample environments including robotic systems at large-scale facilities to achieve the accelerated development of new battery chemistries. The state-of-the art of battery characterisation relies on the optimisation of single techniques focusing on specific scales and parameters, usually optimised for a given chemistry and employing methods and protocols that are not transferable beyond specific scopes. The challenge is to enable multiplexing infrastructures and community-driven platforms to accelerate time- and space-resolved investigations of materials and devices, adapted to provide fast multiscale evaluation of battery concepts and systems, covering both low and high TRL levels.

R&D activities needed
Short-term needs (2027):

- Experimental characterisation beyond single-shot measurements is required to understand the complexity of reaction processes and mechanisms in battery components.
- Holistic approaches involving correlative multimodal characterisations and integrated multi-scale workflows are necessary to explore the full chemical space.
- High throughput pipelines with semi-automated data acquisition and analysis, standardised protocols, and new access modes are crucial for fast, data-centric discovery of new materials and technologies.
- Community-driven large-scale facilities hubs are needed to cover different scales and address various questions related to novel materials development.

Mid-term needs (2030):

- A European hub with coordinated access to synchrotrons and potential links to neutron facilities can serve as a battery meta-hub. This will act as a collaborative framework and experimental platform for community-organised experimental programs, facilitating the sharing of methods and data. Its purpose is to accelerate the multi-technique and multiscale advanced characterisation of battery materials and devices.

Impact
A community-driven hub will allow a democratised access to high-throughput multimodal multiscale experimental platform to the battery community, where the need to accelerate research in this field to be globally competitive for new battery chemistries with tailored properties and special markets at the industrial level. A European synchrotron-based meta-hub will boost the multidimensional quality control of new materials and diagnosis of device architectures, enabling novel capabilities to detect defects, analysis failure modes, enable micro-to-macro knowledge-based modelling-aided innovation across the TRL scale.

2.1.1.9 Biomimetics as smart functionalities for batteries

Batteries consist of a significant proportion of non-active components, including separators, current collectors, housing, tabs, binders, and additives which are used in the energy intensive production processes. With the development of advanced battery systems, a step further in design of non-active components must be taken as a possibility to elongating the lifetime of batteries, which in turn reduces the CO2 footprint and cost. This transition should be done by implementation of additional smart functionalities.

Biomimetic and biobased components offer the potential for incorporating such functionalities. These materials can be designed to control transport at interfaces, repair damage that occurs within the battery cell, and even store “battery medicaments” that can be released on demand. This will contribute to cell development with much higher quality, better reliability and longer cycle life and it will have a significant impact on sustainability and decreased CO2 footprint. Furthermore, the integration of additional functionalities, such as sensors, redox mediators, etc., in supporting materials enables batteries to go beyond their conventional energy storage capabilities. This advancement can lead to batteries with enhanced performance, improved safety, and greater versatility in various applications.

R&D activities needed

Short-term needs (2027):

- Explore utilisation of biomimetic and biobased materials with self-healing functionalities in advanced battery cells.
- Replace high energy demanding battery cell parts with natural and sustainable biobased materials to reduce CO2 footprint.
- Design smart separators, binders, and current collectors incorporating microcapsules with embedded “medicaments” to extend battery cell lifetime.

Mid-term needs (2030):

- Target various battery chemistries aligned with the Strategic Energy Technology (SET) plan, prioritising critical degradation processes.
- Demonstrate advantages of embedding smart functionalities in battery cells, including improved performance and prolonged lifespan.
- 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

- Increased quality, reliability, and life (QRL) of the battery system by extending the lifetime of the battery cells and maximising their performance.
- Improved sustainability of batteries produced in Europe, lower CO2 footprint.
- Industrial opportunities for exploiting new concepts and technologies for integrating self-healing capabilities in the battery cell.

2.1.1.10 Sustainability by Design for Battery Materials and Cells

To enhance the sustainability of future battery materials and cell designs, it is important not only to limit the dependence on Critical Raw Materials (CRMs) like cobalt and lithium but also to improve the environmental sustainability of European battery production itself. This can be partially achieved by using more abundant materials, more efficient material utilisation, and circular economy principles, aiming to develop new battery materials, components and cell designs that are both environmentally sustainable and economically viable. Still, it is also necessary to focus on novel material scalability and absolute sustainability, i.e., identify the operating space for a battery production that respects the carrying capacities of the planet's ecosystems and climate regulation system and ensure a fact-based understanding and evaluation of routes to sustainability, meticulously analysing new battery materials, membranes, solvents, salts, binders together with the electrode and cell designs' role as enablers or barriers. It is necessary to incorporate a more holistic approach ensuring "absolute sustainability by design" building upon the activities in manufacturability and recyclability by design, ensuring novel material scalability and making it possible to accelerate the development of new battery materials and cell designs that minimise environmental impact, promote resource efficiency and reliance on domestically sourced materials, and contribute to a sustainable energy ecosystem.

R&D activities needed
Short-term needs (2027):

- R&D activities are needed to utilise and extend existing concepts and chemistry-neutral infrastructure e.g., BATTERY 2030+ and BIG-MAP, for AI-accelerated inverse materials design of battery material, cells and production processes to optimise them towards absolute sustainability.
- Development of an interoperable and shared data infrastructure is crucial for seamless collaboration and data sharing across the European battery value chain.
- Shared standards, protocols, and ontologies like BattINFO will facilitate data integration and utilisation from various research disciplines.

Mid-term needs (2030):

- Multi-sourced and multi-fidelity data streams, including experimental data, computational models, and machine learning, need to be integrated and utilised. Improved and consensual sustainability evaluation methodologies should also be considered. Comprehensive data analysis will provide valuable insights into the performa nce, sustainability, and safety aspects of battery materials and cells.

Impact
The proposed activities for absolute sustainability by design for future battery materials, electrodes and cells will place Europe in a unique position to design battery technologies that are not just more sustainable than the present but sustainable in absolute terms and to develop a sustainable and secure domestic production of future batteries.

2.1.2 Transversal challenges

2.1.2.1 Batteries based on cheap, abundant, and easily recyclable materials

The use of low-cost metal ions alternative to Li-ion batteries is one of the main research areas of interest. Na, K, Ca, Mg and Zn ions are being investigated. The selected materials should be easily recyclable and as cheap and abundant as possible. What is abundant will depend on the definitions and criteria defined in the directive and other applicable regulations, following the definition of Critical Material. Environmental and social constraints associated with the supply chain (extraction, processing, and disposal) should be considered (possibly favouring EU sourced active material).
Another significant challenge is how to assess the sustainability of new chemistries. Adequate assessment methodologies need to be defined, and transparent data from various sources (experiments, simulation, artificial intelligence tools, among others) should be used. The results of these prospective assessments will guide the further developments of new chemistries that show better performance, not only in technical aspects, but also in their sustainability performance, allowing the R&D activities to focus on more targeted aspects and challenges.

R&D activities needed

- Focus on the design and development of new sustainable materials using non-critical raw materials including novel inorganic-based materials and redox polymer electrodes which can incorporate Na, K, Ca, Mg, Zn or Al ions, which represent potential low-cost alternatives to existing M-ion chemistries.
- Develop sustainability evaluation frameworks for low TRL chemistries, taking into account the high uncertainty of the data and the limitation in the information available.
- Commonly agree data formats or data transfer protocols, hence promoting a wider utilisation of the data. This aspect is also relevant for future battery passports associated with new chemistries.

Impact

Reduced environmental footprint of battery production, more stable and reliable supply chain for battery manufacturing, more affordable and accessible battery technologies, accelerated transition to a more sustainable energy system.

2.1.2.2 Accelerated material discovery & multiscale modeling for emerging battery technologies

Digitalisation can strongly accelerate the development of emerging battery technologies though advanced digital solutions for the discovery of novel materials, the design of the battery and its optimal management. Currently available state-of-the-art solutions have been developed for consolidated battery technologies such as Li-ion. Significant R&D is needed for adapting these tools for novel chemistries and validating them for industrial use. The main challenges regarding digitalisation are related to the development of (i) material acceleration platform (MAP) concepts targeting for increasing the predictive ability of material synthesisability by physics-based computational design and addressing battery technologies not treated in existing MAP projects such as flow batteries, (ii) novel multiphysics-multiscale modelling platforms closing the gap between the atomistic and the macroscopic world (from individual materials to cells).

R&D activities needed
Building upon the shared data infrastructure, standards and protocols developed in the BATTERY 2030+ initiative, the novel MAP aims at improving and integrating advanced multi-scale computational modelling, materials synthesis, and characterisation to perform AI-driven autonomous material discovery.

- Apply the MAP concept to RFBs to accelerate the identification of new sustainable and scalable redox active materials. This new platform also seeks to improve the computational techniques used to predict the redox potential of multi-electron redox processes, particularly in proton-coupled mechanisms, as well as evaluate the electrochemical stability and solubility of novel electrolytes.
- Improve the depiction of phenomena occurring at the electrolyte/membrane and electrolyte/electrode interfaces. The development of novel modelling tools bridging between the different scales (from atomistic to cell) would bring huge benefits to the battery sector accelerating the development of emerging battery technologies and reducing the testing needs. To achieve this target, the combination of atomistic, mesoscale and macroscopic multiphysics simulations has to be performed in an effective way to make it sustainable from the computational point of view. The use of hybrid models, Physics-Informed Neural Networks (PINNs) and Reduced Order Models (ROMs) combining physics-based and data-driven approaches can support this complex task.

Impact
The proposed activities will accelerate the development and design of emerging battery technologies, such as RFBs, reducing the time-to-market and placing Europe in a competitive position regarding mid- to long-term energy storage needs. The proposed developments will enable to improve currently available technologies due to improved accuracy and reduction of testing needs.

2.1.3 Key Recommendations

Development of performant new battery technologies, answering the application needs, is crucial in achieving the carbon neutrality goals of the EU. In the process of technology discovery and research, it is essential to focus not only on the performance and cost, but also on safety and selection of the materials. Exploration of more sustainable materials, including of biobased and biomimetic materials, is therefore considered crucial for all the chemistries. The abundancy of the raw material and their cost will play a role in the development of new and emerging battery chemistries.

The R&I activities can be expected to also benefit from uptake of digitalisation tools, modelling, and development of relevant infrastructures, allowing for accelerated and cost-efficient discovery. While development of new chemistries is important, it is critical to facilitate further technology uptake by the industry, by means of close collaboration between research and industry and facilitation of investments into technological scale-up (incl. relevant production and recycling processes). To facilitate the communication and succession between research and industry, it is also recommended to develop battery-specific TRL standardisation framework, as development of battery technologies is not always as direct and straightforward to be easily classified in accordance with the existing NASA-based TRL system (due to different levels of development (cell, material, module, etc.) and associated challenges (including manufacturability).

Strategic Research Area	Short term	Medium term	Long term
Advanced Redox Flow Batteries	Advanced materials and disruptive concepts for cost reduction and sustainability Computational models Validation of devices and systems	New chemistries or electrolyte formulations to enable dual applications	
High-performance safe Metal-air batteries for mobility and grid energy storage	Novel structures, catalysts and topologies Interface understanding	Solid-state configurations	
Durable Metal sulfur batteries with enhanced power capability	Low electrolyte to sulfur ratios Stable interphase and metal anode New catalysts	System level demonstration Solid-state concepts	
Safe & sustainable aqueous batteries	Advanced materials Cell design Operational conditions	Scale-up	
Anode less battery technologies	Stable interfaces Pre-metallation strategies Current collector design Improved understanding and characterisation tools	Scale-up	

Strategic Research Area	Short term	Medium term	Long term
Multivalent non-aqueous systems (Ca, Mg, Al, Zn etc.)	Metal anode passivation strategies Non-corrosive electrolytes	Improve the rate performance and capacity Solid-state concepts New active materials	
Hybrid supercapacitor-batteries	More energetic and powerful materials New electrolytes (incl. redox active)	Pre-metallation strategies compatible with manufacturing processes	
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	Battery meta-hub	
Biomimetics as smart functionalities for batteries	Biomimetic and biobased materials with self-healing functionalities	Demonstrate advantages and manufacturability	
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
Transversal Challenges	**All times scale**		
Sustainability	Batteries based on cheap, abundant, and easily recyclable material		
Digitalisation	Accelerated material discovery and multiscale modelling for emerging battery technologies		

Table 2: Overview of Strategic Research Areas of the New and emerging technologies roadmap developed by Batteries Europe/ BEPA WG1

2.2 Raw Materials and Recycling

2.2.1 Strategic Research Areas

2.2.1.1 Logistics, sorting, collection and discharging / deactivation

Lithium (Li) ion streams represent > 10% of the mixed portable batteries collected. The waste is changing in terms of composition, with the introduction of emerging B2C applications such as Light Mean Transportation and household storage that require different and innovative take back and collection models. Safe and environmentally sustainable post-consumer battery management should be ensured, capable of continuously and quantitatively feeding the innovative recycling pathways that meets the targets of the forthcoming Battery Regulation. New reverse logistics solutions and collection models need to be developed to i) reduce the potential risks of handling damaged /defective batteries (priority), ii) digitise the waste supply chain in favour of more efficient waste traceability and certified collection of diagnostic and technical data, iii) improve the quality of the waste stream for more selective and streamlined materials recovery, reuse and recycling.

R&D activities needed
Short-term needs (2027):
Research activities are targeted for TRL7, and they should be started urgently.

- Safe, fast, and cost-efficient ways for discharging/deactivation the end-of-life batteries, including also damaged batteries and scrap manufacturing from Gigafactories. Focusing especially on the large-scale discharging (as the number of batteries that need to be recycled becomes high).
- Improve the quantity, the quality, and the safety of the stored EoL batteries through the development of innovative waste collection systems (from new packaging solutions to innovative structures for waste facilities, public collection points, etc.), advanced monitoring systems, and related new policies and innovative and clear regulatory standards, including also means to keep the used batteries in the European circular value chain.
- Upstream end-of-life processes: digitise and secure the collection of spent batteries towards net-zero risks by introducing systems for the segregated and separated collection of unstable batteries (for transport, handling, recycling purposes) using simple diagnostic systems.
- Materials management: development of advanced systems for sorting, characterisation and selection of spent batteries based on dimensional/application parameters, state of preservation and other digitisable parameters (e.g., diagnostic, chemical, especially those included in DPP/DBP, etc.) capable of generating predictive 3R embedded processes.
- Active monitoring systems to ensure a high level of safety throughout the value chain: dynamisation of “state of preservation” diagnostics and other safety KPIs (e.g., precursors of thermal runaway) through robust, efficient, and highly effective multi-application detection systems, enabling new extinguishing systems. Contributions to new regulatory standards.
- Integration of inputs from recycling processes to develop sorting stages.

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.

2.2.1.2 Adaptability and tolerance of the existing recycling processes to the 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 new optimisation is needed for battery grade Si. The direct recycling methods (and others) might be more complicate to transpose due to the early stage of such technology.

R&D activities needed
Mid-term needs (2030):
This research area targets a mid-term need at TRL7, as it will be possible to utilise experience from previous recycling activities for Li-ion batteries.

- Design and development of more flexible and adaptable recycling processes for Lithium-ion batteries providing a solution for the constantly evolving composition and formulation of cathodes, anodes and electrolytes and for the reduction of CAPEX investment. As an example: common workshop between LFP and NMC in the same plant using the same facilities.
- Development of flexible recycling processes for the treatment of black mass including mixed chemistries (e.g., blended cathode active materials).
- New chemistries, such as Sodium-ion, will benefit from the progress achieved in Lithium-ion batteries recycling technologies. However, the tolerance and adaptability of such technologies to other chemistries still need to be demonstrated.
- In particular, the evolution of the anode chemistry will strongly impact the recycling technologies. For example, Li ion batteries contain Silicon/graphite in variable proportions. In such case, R&D actions will be required to address how the existing technologies could be adapted to recover graphite.
- Implementation of the existing processes to enhance the recovery rate of Lithium from other chemistries.
- The feasibility of the direct recycling technologies (namely routes avoiding any metal separation) also for the emerging chemistries needs to be investigated depending on the active materials, cell shape and size, manufacturing processes, etc.

Impact
A substantial increase of the robustness and flexibility of the existing recycling processes, in order to make them capable of treating LIBs of 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 more competitiveness. Chemistry-agnostic battery recycling processes should reduce the impact of battery chemistry market share evolution.

2.2.1.3 New Recycling processes for Lithium (Li) metal batteries and other new emerging technologies

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 (2030+):

This research area targets a long-term need. However, research activities should be started now at low TRL (targeting TRL4), to ensure that the new battery types will be designed to be recycled.

- Generation 4 Lithium-based batteries (e.g., Lithium metal, LMB, and all solid state, ASSB) will contain critical and strategic raw materials; the recycling processes shall be different from the Lithium (Li) ion batteries, especially in case of LMBs, mostly because of safety issues. Therefore, new methods need to be developed, with safety-enhancing steps added.
- Apart from the needs that the Lithium metal anodes imply, the different chemistries of solid electrolytes (ceramic and polymeric) of all solid-state batteries (ASSB) will require the development of different recycling alternatives.
- Depending on the new chemistry involved specific References Documents (BREFS) presenting the Best Available Techniques (BATs) for a specific technology and/or battery chemistry should be developed and/or implemented.
- Vanadium-based Redox Flow Batteries (RFBs) need different approaches from LIBs, in terms of mechanical pre-treatments and chemical processes (e.g., for the Vanadium recovery from the electrolyte). Similarly, for potentially low-cost inorganic and organic electrolytes recycling processes (different from Vanadium) are needed with potentially strong constraints on recycling economics due to low cost of materials.
- Engineering challenges, related to the cell/module/pack design, the cell geometry or the disassembly processes need to be also addressed to develop efficient recycling technologies.
- Disassembly should also consider the removal of the smart functionalities, as internal

battery sensing, actuators, and self-healing tools, if any.

- Improvement of pre-treatment should be achieved for efficient hydrometallurgical processes, including effective separation of valuable components, black mass, epoxy systems, glues.
- Good separation strategies of incoming streams of batteries with different chemistries will be necessary. They will be supported by the information included in the battery passport.
- Development of discharging/deactivation processes for the batteries based on new chemistries (especially Li Metal ones).

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 early stage. This will ensure that the next generation batteries can be recycled, and the secondary raw material supply secured also in future.

2.2.1.4 Integration of secondary raw materials

Increasing the circularity of the battery business through specific targets for the incorporation of secondary raw materials in manufacturing processes is necessary to contribute to the circular economy and align with the Battery Regulation. Among several quality criteria to be considered, the substitution of high-quality raw materials/precursors (especially to have a future proof concept) is an important issue that is strictly related to the chemistry involved.

R&D activities needed

Mid-term needs (2030):

This research area targets a mid-term goal as there will be more secondary raw materials coming from recycling feeds.

- The recovery and production of battery-grade materials from mining and industrial wastes (e.g., tailings, slags, sludges, etc.) for reintroduction into the battery value chain. Some virtuous examples (e.g., Copper, Cobalt, Iron) show that there are several business opportunities in reuse, repurposing and recycling of mineral residuals and metal production chains that also make clear how to contribute to the mining sustainability by enhancing the total resource efficiency.
- Closed loop-based recycling technology (as in the new Battery Regulation): the integration of process streams and/or by-products from the battery recycling processes (as raw materials or utility chemicals/reagents) can increase the circularity.
- Integrate secondary raw materials from direct recycling routes into battery manufacturing, especially in case of materials with lower economic value such as the $LiFePO_4$ (LFP) chemistry. In this specific case, direct recycling is considered today as the only method

to keep the promise of being economically viable. Even though a more precise economic evaluation needs to be done at least at the pilot scale, many academic reports tend to demonstrate the higher revenue expected from regeneration methods compared to conventional methods.
- Beyond the closed loop for batteries: increase the symbiosis with other sectors (e.g., metallurgy of Copper (Cu), Nickel (Ni) and other metals, solid electrolytes manufacturing, etc.).
- The recovery of the raw materials from the manufacturing scrap should be ever considered as well as their integration into the new batteries production.

Impact
The development of a strong circular economy business model for battery industry that ensures a sustainable and profitable raw materials supply chain for Europe. The industry will get access more easily to the raw materials and will secure their activity decreasing their dependency of supply from outside Europe.

2.2.1.5 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 next generation of energy storage systems. Such chemistries are at various stage of development and demonstration, as outlined in the roadmap prepared by WG1 and WG3. In order 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 (2027):
This research area targets a short-term goal as the SIB industry is already becoming active. It is important to scale up the material supply towards TRL7.

- Efforts are still required to ensure a European supply chain in operation for the Sodium-ion batteries, for the electrolytes (e.g., Na salts), the anode materials (e.g., hard carbon) and cathode materials that do not benefit from the LIBs value chain (e.g., Prussian White, Blue and other analogues).
- Research on producing bio-based hard carbon for Sodium-ion batteries is needed as it is a sustainable and locally available alternative to non-renewable resources.
- The focus on other chemistries, including the multivalent systems (e.g., Magnesium (Mg), Aluminum (Al), Calcium (Ca), Zinc (Zn)), is another needed strategic action.

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.

2.2.1.6 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 from current and emerging materials streams. Several European projects work to develop technologies that would lead to lower environmental impacts, reduced CO2 emissions, water and energy saving.

R&D activities needed
Short-term needs (2027):
This research area targets a short-term need as there is urgency to increase European production of sustainable battery raw materials towards TRL7.

- Developing sustainable and cost-effective carbon-based anode production processes, using other options as raw materials (e.g., bio-based carbon or other organic materials). Ensuring homogeneous quality of the produced carbon material, regardless of the variations in the bio-based/organic feedstock.
- The utilisation of extracted materials or underutilised battery raw materials deposits as sources of battery materials should be promoted. An example is the extraction of Lithium from brine obtained from deep geothermal energy generation, or from brine obtained from water desalination. Other non-standard sources of raw materials should be considered, in particular waste materials, reducing the potential need for mining. The valorisation of waste materials generated by the battery materials beneficiation and refining industry/processes should be addressed to achieve a zero-waste strategy.
- Sourcing processes should be developed and/or optimised to ensure its energy and material efficiency. Aspects such as the utilisation of more environmentally friendly and milder conditions, should be considered when defining them. Best Available Techniques (BAT) should be defined, for example via the creation of specific BREFs that will include them.
- The vertical integration of European mining operations with materials and even battery chemicals production will reduce transportation, lowering carbon emissions, and minimise environmental impacts. Moreover, it will create jobs and promote local economies, making it easy the public acceptance of mining.
- Development of efficient refining processes of blended (primary/secondary) raw materials.

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.

2.2.2 Transeveral challenges

2.2.2.1 Implemented Tools for sustainability assessment (reference data availability and methodology framework). Sustainability and digitalisation:

Life Cycle Assessment is a standardised methodology for assessing potential environmental, social and economic impacts associated to a product, a process or a system, along its life cycle, namely from the extraction of raw materials to the end of life. Although it is standardised by ISO 14040:2006/ ISO 14044:2006 and the EC has developed PEFCR on rechargeable batteries, many assumptions are needed, and different methodologies can be employed when it comes to quantifying environmental impacts. These facts increase the uncertainties of the environmental impact results and hinder comparison between different products. In this sense there is a need for more and reliable primary data to support more robust LCA studies. Moreover, PEFCR should be extended from the battery product to the components and materials level including secondary data from recycling of battery components too.
Additionally, taking into account a wide variety of output materials and different process TRLs, a more consistent and ontology-based methodological approach should be developed for levelled comparison of the environmental impacts of different recycling processes.

R&D activities needed

- Implementation of the LCI databases that should be based as much as possible on real life data for both mining and recycling activities, including social impacts. The data should be made public and made available, for example through the European platform on LCA or GLAD.
- There is a need for further combination of different methodological frameworks (Life Cycle Assessment LCA and Safe-By-Design SBD) to assess products environmental impacts (Carbon footprint, water consumption, energy efficiency, etc.).
- There is also a need for more complete and representative datasets for reference processes and mainstream processes. This is required to be able to compare new EU products with competition, in order to promote environmentally-best-in-class products (Raw materials, batteries, etc.).
- Currently, for graphite anode materials, there is no public dataset of market mainstream products that are complete and process-representative. It is thus difficult to compare and promote the European alternatives.
- Ensure the traceability of the data and information, via the implementation of chains of custody for the various materials involved. Protocols such as blockchain or others with lower environmental footprint specifically adapted to the battery supply chain.
- Digitalisation of the whole recycling process, including tracking and tracing, to protect from fraud and collect data by means of: i) digital identifiers to track and trace materials and batteries, giving information on the materials (“speaking names”); ii) tracking technology such as blockchains, RFID (Radio-Frequency Identification), etc.
- LCA outputs should be considered for the scale-up of the production/recycling technologies, not only for research purposes.

- Achieving interoperability of LCA standards (OpenLCA) with material science and process engineering standards by the following actions: i) use of the same ontology in the LCA documents for both chemical aspects at cell level and engineering/production process domain (e.g., Carbon dioxide vs CO2); ii) direct integration of the LCA information from engineering and production to the database for the lifecycle.
- Provide rules on how to update and check the databases (e.g., adding new info, fixing wrong data, versioning, etc.).
- Implement the digital passport also for battery materials and parts within the supply chain, in particular in recycling materials, develop a common ontology for battery passport (and digital twins) based on existing ontologies like BattINFO and BVCO.

Impact

Developing clear rules and high-quality data which would allow a robust assessment and comparability of the carbon footprint of batteries. Harmonised, interoperable and transparent LCA/LCI approach and tools with a commonly accepted ontology will improve the environmental performances and designs of the batteries along the value chain and over the full life cycle. Furthermore, improved data and tool interoperability through semantic technology will provide access to sustainability aspects early the material science research process and establish a fast feedback loop for sustainability by design.

2.2.2.2 Safe and Sustainable by design

The Safe and Sustainable by Design (SSbD) concept promotes a holistic approach which integrates safety, circularity and functionality of chemicals, materials and products during the entire life cycle minimising their environmental footprint. It requires thus the integration of safety- based considerations with life- cycle considerations to ensure sustainability along the entire value chain. Therefore, safety needs to be considered as one of the sustainability dimensions along with environmental, social and economic. The SSbD framework involves two components: a (re) design phase where design guiding principles are proposed to support the design of chemicals and materials, and a safety and sustainability assessment phase. Regarding the design phase different aspects are considered such as: materials efficiency, minimising the use of hazardous materials, designing for energy efficiency, using renewable sources, preventing and avoiding hazardous emissions, reducing exposure to hazardous substances, designing for end- of- life and considering the whole life cycle.

It supports then the design and development of materials with research and innovation activities. This methodology is relevant for batteries development to overcome challenges they are facing in order to develop next generation batteries, as for example challenges related to raw materials extraction and manipulation (cobalt, manganese or nickel).

In conclusion, there is a need to develop a SSbD framework focused specifically on batteries to face all challenges involved in batteries life cycle, taking also into consideration the information reviewed by JRC and others.

R&D activities needed

- A focus should be given to the utilisation of abundant and/or cheap materials (including Na-ion cathode materials, hard carbon, etc.). Goal conflicts regarding the recycling of low value batteries (like Na-based systems) needs to be addressed.
- As changes in the materials will impact the overall battery performance, all life cycle stages should be considered as a whole. Therefore, a life cycle-based view (and/or along the value chain) is necessary.
- Design for sustainability, considering production, potential use and end of life.
- Design for recycling: to move to a more circular economy requires a better design of the overall battery and its components. This involves various aspects, as for example simplified processes of battery disassembly, (e.g., robotics to replace workers and achieve economic benefit), utilisation of recyclable and reusable components/materials, use of not flammable/ toxic materials.
- Batteries also need to be standardised in terms of shape and size to facilitate disassembly and recycling, especially in the case of large batteries. It could be also envisaged the design of standardised disassembly/recycling plants working on specific battery shapes.
- High focus on the workers protection: significant reduction of the safety risks for the workers by developing less dangerous and less poisoning recycling processes.
- Regarding the Critical Raw Material (CRM) act the following should be examined: 1) How to ensure the European availability for CRMs from used batteries (e.g., black mass) and manufacturing processes (e.g., scrap); 2) Develop new and/or optimise CRM recycling methods, minimising as much as possible CRM losses; 3) Increase the share of raw material sourcing in Europe by the adoption of both primary and secondary raw materials; 4) Focus on raw materials that are already on the CRM list, but also on the strategic raw materials, characterised by high importance for relevant technologies (e.g. renewable energy, digital, defence and aerospace). Indeed, the strategic raw materials will have increased supply demand in future and might thus become part of CRM (unless something is done about it in advance); 5) Increase European processing capabilities for CRM.
- In parallel, find alternative processing routes to replace CRM, e.g., biobased carbon or other organic materials.

Impact

The development of a framework to define safe and sustainable by design criteria for batteries development will go beyond current regulatory compliance. The safe and sustainable by design approach will contribute to develop technologies where important categories will be considered at the earliest stage minimising the risks of undesirable substitutions. This SSbD approach will support the development of an integrated value chain from recycling to use of secondary raw materials by decreasing the cost of recycling and material treatment. Dismantling, disassembly and recycling issue will be integrated in the battery design in order to simplify and reduce the step of treatment.

2.2.2.3 Digital twins with hybrid models for the optimisation of recycling processes

Currently, many processes have been developed to recycle battery materials, in particular those of LIBs. However, their successful application requires improvements in several aspects such as scalability, recovery efficiency and flexibility. In this regard, notable challenges include the fast dynamics of the battery market, emerging new technologies and chemistries, confidential information on commercial battery materials, and missing knowledge on the effect of degradation phenomena.

R&D activities needed

- Developing models for the optimisation and scale-up of LIBs recycling processes, also considering the effect of the degraded materials.
- Creating Digital Twins for real-time control of the recycling process based on the properties of waste material streams.
- Successful implementation and pilot-scale demonstration of novel digital solutions in control systems for recycling processes.
- Optimisation of material outcome of the recycling process using digital models that combine physical and economical views. For example: i) compare the purity of the outcome materials in real time (or daily) to market data to evaluate the economic feasibility of their recycling; ii) also, use info from battery lifecycle as input data.
- Combining AI and machine-readable expert knowledge in a hybrid way to discover and boost new recycling technologies.
- Semantic integration of the battery passport in different phases of battery recycling or reusing to take advantage of the information.
- Data driven process and quality control, for real time or even predictive control. Hybrid modelling may be relevant for complex and hard to model systems, in which the incorporation of real data may be valuable.

Impact

Improve competitiveness of EU battery industry by applying an extended traceability of batteries (and thus their component materials). This shall contribute to making sure the material does not leave the EU through uncontrolled channels. Achieve a higher process yield and dynamic adaption for recycling processes by a hybrid model that makes stakeholders engaged in tracing and recycling. Overall, this contributes to an implementation of independent, safe and sustainable supply of Europe’s battery production.

2.2.3 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	
Adaptability and tolerance of the existing recycling processes to the new technologies	Ensure EU supply chain for SIBs Production of bio-based hard carbon for SIBs Focus on other chemistries (e.g., multivalent cations)		
Sustainable sourcing and processing of raw materials	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 processes of blended Raw Materials		
Transversal Challenges	**All times scale**		
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		

Table 3: Overview of Strategic Research Areas of the Raw materials and recycling roadmap developed by the Batteries Europe/ BEPA WG2

2.3 Advanced Materials

2.3.1 Strategic Research Areas

2.3.1.1 Li-ion batteries (gen 3) (driven by mobility) – Short-term / Mid-term

This strategic area is concerned with developing advanced materials enabling higher energy/ power density thanks to higher capacity and/or operating at a higher voltage. Focus is on adapting the cathode materials for capacity including high-nickel NMCs and for high voltage nickel-rich layered oxides, lithium-rich layered oxides, high-voltage spinel oxides and high-voltage polyanionic compounds, the anode materials with silicon-based materials (silicon carbon composites with Si > 10 wt.%, silicon oxide composites, or pure silicon materials), the electrolytes (salts, solvents, additives) which can maintain good stability both with silicon anode materials and high voltage cathode materials (stabilised formulations), the binders and their interplay. Next to these "design-to-performance" chemistries and processes, there is a need to innovate on "design-to-cost" chemistries and processes (manganese-rich HLM, improved LFP, ...) delivering lower energy density with a reduced amount of CRMs.

Electromobility has become the preferred solution for decarbonisation in the transportation sector with BEVs projected to reach ca 120 million worldwide by 2030. Advanced materials used in cathode, anode, separator, and electrolyte make up 50 to 70% of the cost of Li-ion battery cells used to power these vehicles. The requirements for lower cost batteries still guaranteeing high energy density, long cycle life and rapid charging capability need sustainable R&I in advanced battery materials to continuously solve these challenges. Besides the technical R&I challenges of cost, energy and power density, and cycle life, other factors like safety, sustainability and criticality of the battery raw materials are becoming more and more pronounced. A solution is needed to enable EU's competitiveness in the battery industry where Li-ion is expected to remain the dominant technology in EV batteries.

Cathode materials of Generation 3 include Nickel-Manganese-Cobalt Oxides (NMC) of varying Ni content (up to 90+ wt.%), and lower cost materials with strong chemical bonds based on e.g., phosphates. They can be used alone or as a blend. The aim is to reduce Co content, to reduce cations leaching, to increase performance and in general to decrease CRM content. In addition, high-voltage materials such as LMNO spinels and others are available technologies. On the anode side, graphite is the most used material, providing good capacities but consuming significant amounts of Li in the SEI. The addition of silicon to graphite is the main trend of new anode development with the target to increase the energy density on cell level. Premature cell aging and slow charge rates with increased Si amount limit the maximum usable Si fraction to around 5-10 wt.%. Many strategies are being developed for silicon-dominant anodes to become a future reality. For the passive materials, the trend leads towards a reduction in the number of inactive materials to achieve higher energy densities on cell level. Thinner substrate films and separators are more and more common in cells. The electrolyte that usually consists of organic solvents, additives, and a conductive salt, like LiPF6, is adapted via additives.

Lithium-ion batteries with liquid electrolytes can be considered the champions of electrochemical energy storage. Key performance indicators for electric mobility like energy and power density (plus 30% to 50%) and costs (minus 50%) have drastically improved compared to 2015, making battery electric vehicles viable alternatives already today. Still, many challenges need to be addressed.

Challenge	Short Description	Relevance
Cost	Improve cost competitiveness of battery active materials and passive materials	+++
Fast charging	3-5C fast charging in 10 min to 80% SOC	+++
Sustainability	Reduce ecological and social footprint, ensure transparent value chain (battery passport)	+++
Energy density	High energy anodes with high loading and stable capacities of 1200 mAh/g. High energy cathodes with high loading and stable capacities up to 300 mAh/g	++
Resilient sourcing of battery materials	Increase security of supply by enabling alternatives to Co-rich battery materials	++
Increase lifetime and cycle life	Improve cycle life of high voltage (500+) and high-capacity batteries (1000) to allow viable 2nd life applications	+

R&D activities needed

Short-term needs (2027):

- Stable cathodes and electrolytes for high voltage batteries (4.8 V, <2.000 cycles).
- Stable cycling of Li-rich and Ni-rich, low Co cathode materials (<2.000 cycles).
- Optimisation of low cost and high safety phosphate-based materials (e.g., LFP, LFMP).
- Optimisation of low cost and high safety manganese rich HLM based materials.
- Advanced Si/C materials, additives, and electrolytes to enable up to 20 wt.% Si (~1000 mAh/g) with fast charge and reasonable cycling by reducing cell degradation.
- Cathode (active and inactive) materials designed for organic-solvent-free, or quasi-dry/dry production processes.
- Stable electrodes-electrolyte interfaces.

Mid-term needs (2030):

- Stable cathodes and electrolytes for high voltage batteries (≥ 1000 cycles at 4.8 V).
- Decrease specific amounts of critical materials (Natural Graphite, Co, Li) per kWh stored energy in line with EU battery regulation considering recycling and use of secondary raw materials.
- Large cycle life in low voltage, high-capacity anodes ≥ 1000 mAh/g, e.g., Si/C composites with above 20 wt.% Si, or pure Si.

Long-term needs (2030+):

- Cathode materials capacities beyond 300 mAh/g with efficiencies of 99%, ≥ 1000 cycles,

and specific anode capacities of ≥ 1200 mAh/g.
- Lithium-ion battery with reduced use of critical materials (other than 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.

2.3.1.2 Solid-state batteries (gen 4) (driven by mobility) – Mid-term / Long –term

This strategic area is about developing solid-state electrolytes, cathode materials and anode materials (including additives) enabling higher thermal and electrochemical stability while targeting higher energy/power densities, fast charging, cyclability and improved safety. Developments should range from using conventional materials (Gen. 4a) to using Li metal-based anode without high voltage cathode materials (Gen. 4b) or with high voltage cathode materials (Gen. 4c).

With a rapid implementation of electrification of transport, deployment of EVs soars, with estimated ca. 1800 GWh capacity by 2030. Improved Li- ion batteries are expected to remain the technology of choice. New chemistries, materials and production technologies must, however, be developed to strengthen European industry. Solid State Li-ion batteries (SSB) are a major step in OEMs roadmaps as they enable doubling of the driving distance due to higher energy density. Additionally, they provide enhanced intrinsic safety, but still suffer from lower cyclic performance and high interface resistance.

Solid state technology is known to be classified in 3 consequent generations:
- Generation 4a with conventional Li-ion materials (NMC cathode vs. C/Si anode).
- Generation 4b with Li-metal as anode (NMC cathode).
- Generation 4c with Li- metal as anode and high voltage cathode (≥ 4.75 V) combining a solid electrolyte with newly developed stable high voltage, high capacity and high-rate capability cathode materials such as Li-rich NMCs or spinels.

Different solid electrolyte compositions are in development by battery and materials producers, including within the EU. They are based on polymer, inorganic and inorganic/polymer composites. Organic solid electrolytes cover dry, plasticised polymers, composite, hybrid, heterophasic and single ion conducting electrolytes. Inorganic solid electrolytes belong to the following classes: Sulfide Glass Ceramics, Oxide Glass Ceramics, Hydrides, and others.

Challenge	High energy	High power
Creating stable electrolyte chemical interfaces	+++	+++
Improve ionic conductivity of solid electrolyte	+++	+++
Improve processibility of solid electrolyte	+++	+++
Improve stability of solid electrolyte towards mechanical stress	++	++
Enhance thermal operation window	++	++
High Li-ion transference number (tLi+ up to 1)	++	++
Reduce costs for raw material, cell manufacturing and recycling	++	++
Increase volumetric gravimetric and volumetric energy density on cell level	+++	
Increase power density of battery cells		+++
Improve anode towards homogenous Li deposition		++
Reduce Li-metal anode thickness for lower material cost and higher volumetric/gravimetric energy density	++	++
Reduce the ecological footprint in production and recycling	++	++

Challenges relate to the development of solid-state electrolytes, cathode materials and anode materials, enabling higher thermal and electrochemical stability while targeting higher energy / power density, fast charging, high-rate capability, cyclability and improved safety. Attention on raw material availability and recycling / environmental / safety impact must be considered.

R&D activities needed

Short-term needs (2027) for Generation 4a/4b

- Active materials incl. coatings for reduced interfacial resistance to electrolyte & catholyte.
- Reducing thickness of the anode.
- Developing thin solid electrolytes (e.g., multilayer and composite electrolytes) with high ionic conductivity over a wide range of temperatures.
- Manufacturing of new solid electrolyte interlayers.
- Solutions for manufacturing and handling Li metal sheets in dry atmosphere.
- Improved interface design for efficient charge-transfer and electrochemical & mechanical stability.

Mid-term (2030) & long-term needs (2030+) for Generation 4c

- New materials and/or chemistries at higher voltage.

- Coating for these materials to stabilise the electrode and electrolyte interface.
- Novel solutions for low-cost solvent-free electrode manufacturing and solid electrolyte deposition.
- Important targets of development are the reduction of interface resistance to solid electrolyte and avoidance of dendrite formation at high C-rates.
- New cell design compatible with the developed components.

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

2.3.1.3 Long-lasting Li-ion batteries (driven by stationary) – Short-term / Mid-term

This strategic area is focused on developing the various materials systems (cathode, anode, electrolyte, binders, etc.) to enable stationary Li-ion batteries to be used in utility-scale applications (> 100 MW, P/E < 1/3) and in commercial high-power applications (< 100 MW, P/E > 4). Material strategies are very diverse (including for the cathode materials a.o. NMCs, LFP, LMFP, HLM.) and range from improving conductivity to improving energy density and the lifetime in utility-scale applications, while also improving conductivity and capacity for high-power applications.

Utility-scale applications (> 100 MW) - Large scale utility Li-ion energy storage assists renewable energy integration in several ways. As the cost of Li-ion technologies decreases, storage will become increasingly competitive. Plant capacities increased in the multi MW/MWh size and grew to dimensions never seen before requiring energy storage for longer periods. Evidence is growing that large Li-ion plants can replace gas peakers to provide power on days of high demand. To fully exploit the potential of Li-ion batteries, cycle cost has f to be decreased meaning further drastic improvements in cycle and calendar life whilst, at the same time, optimising reliability and safety by developing advanced materials.

Commercial high-power applications (< 100 MW) - Existing power grids will reach their limits in coping with situations of temporary high loads caused by fast charging EVs. To promote the use of EVs, fast charging stations must be distributed across the road network, including areas with limited grid power capacities. This challenge can be met by fitting fast charging stations with suitable LiB systems capable of balancing loads. Standalone stations with RES are usually not capable of producing uninterruptable electrical power due to the intermittent of renewable sources. Energy storage is thus the solution to enable EV charging in these areas and/or these conditions.

R&D activities needed

Utility-scale applications:

- Develop new intercalation compounds with low cycling strain and fatigue for Li-ion batteries.
- Improve cycle lifetime and calendar lifetime to develop reliable, cost-effective products
- Develop fast-charging Li-ion anode materials other than lithium titanate
- Develop high-energy-density electrodes with high ionic and electronic conductivity
- Develop a highly ionic-conductive solid electrolyte for solid-state Li-ion batteries for safety
- Decrease content of critical raw materials in used cathode chemistries

Commercial high-power applications:

- Improve conductivity to increase power e.g., by incorporating structured carbons or 3D-structures as additives into electrodes, and through the development of power optimised materials and architectures.
- Develop high-capacity technology by incorporating for instance, Si into the anode, developing high-energy density cathode materials, reducing Li consumption in SEI on anode side with higher use of Li in the cathode.
- Decrease cathode's Co content, improving structural stability by composition adjustment.
- Develop coatings for cathode materials with high energy density for lower interfacial resistance.
- Develop innovative separators, improving safety & reducing use of organic solvents.
- Incorporate shutdown mechanisms into separator materials or separator design and improve structural resilience of separators through new materials, designs, or coatings.

Impact

Technological impact: Large energy Li-ion battery systems above 100 MW with P/E ratio < 1/3 and delivering on performance, cost and safety suitable for utility scale applications. In addition, solutions enabling Li-ion battery systems (below 100 MW) with P/E ratio > 4 and delivering increased lifetime, lower OPEX and CAPEX for commercial high-power applications.

Economic impact: Commercial success of European battery material and cell producers supplying Li-ion battery solutions for utility-scale & commercial high-power applications.

Environmental impact: Contribution to potential partial replacement of Gas Peaker Plants (utility-scale) and an accelerated uptake of renewable electricity into the grid and decarbonisation of the industry through green & cost-competitive electricity (utility-scale).

2.3.1.4 Na-ion batteries (driven by stationary and mobility) – Mid-term / Long-term

This strategic area is about developing safe and sustainable materials systems to enable low-temperature Na-ion batteries (SIBs) to deliver on energy density, long cycle life and low cost, and a reduced dependence on critical raw materials. They include liquid and solid-state options with different types of cathode materials: liquid electrolyte batteries with carbonaceous or Ti-based anode (Gen 3) and solid-state electrolyte (polymer, sulfide and oxide) batteries with carbonaceous, Ti-based and Na metal-based anodes (Gen 4) with corresponding KPIs.

The positive electrode materials operating at low temperatures, as used in industry, belong to three main categories: layered transition metal oxides (LTMO), Prussian blue/white analogues (PBAs/PWAs), and polyanionic compounds. LTMO and PBAs can provide higher specific capacities, 120-160 and 100-190 Ah/kg, respectively, but with poor cycle life, especially LTMO due to structural degradations and deactivation. Nonetheless, oxide-based electrodes are the most common in industry, mainly due to manufacture processes comparable to LIBs, whereas PBA production has proved to be more complex. Polyanionic cathodes can reach longer cyclability (> 4000 cycles) but with only 80-140 Ah/kg. They can operate at ~ 4.0 V (vs Na+|Na) as with LTMOs, while PBAs operate at 3.8 V (vs Na+|Na).

At the negative electrode side, the material options for SIBs are limited. Hard carbons are currently the material of choice with specific capacity in the 250-350 Ah/kg range, still below the graphite benchmark in LIBs. TiO2-based negative electrodes show good cycling stability but lower capacities (<100 Ah/kg) compared to HCs, while alloying and conversion materials can provide higher capacities but limited cycling stability due to poor ionic/electric conductivity and severe expansion.

SIBs commercial landscape is centered around China and focused on Gen 3 (liquid electrolyte). HiNa Battery Technology alone has a 1 GWh production line with cells claiming 140-155 Wh/kg and 2000-6000 cycles. Additionally, CATL, Natrium, LiFUN and Farasis are set to begin their battery production in 2023. In Europe, Faradion and Tiamat can produce SIBs with 160 and 75 Wh/kg, respectively, but in a small-scale manufacturing. From the US, Natron Energy is set to start producing symmetrical SIBs with aqueous electrolyte and 30 Wh/kg in 2023.

R&D activities needed
Short-term needs (2027
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 improve 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).

Gen 4 (Na-based SSB)
- Screening (modelling and simulation combined with experiment) of materials and material development strategies to obtain higher conductivity, higher capacity/lifetime, and reduced critical element contents.
- Composite cathodes with capacity of 120 Ah/kg (total cathode weight) and cycle life of >

500 cycles (< 10% 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 of elaborate concepts showing competitiveness with LIBs.
- Proof of concept for cells with solid-state electrolyte demonstrating capacity of at least 60 Wh/kg and cycle life > 500 cycles.

Mid- (2030) and Long-term needs (2030+)
Gen 3 (SIBs with liquid electrolyte)
- Design and integration of advanced materials to realise "design for recycling" strategies.
- Cost & energy-efficient manufacturing technology for cell materials recognising recycling aspects.
- Cells with hybrid electrolyte concepts with cycling stability of 2000+ cycles and CCD > 2 mA/cm^2.
- Techno-economic assessment of reaching < 0.05 €/kWh/cycle in case of mass production.
- Cells with 170-200 Wh/kg and/or 400-500+ Wh/L and cycling stability of 4000-6000+ cycles (< 10% fading with DoD 80% at 1-2C).

Gen 4 (Na-based SSB)
- 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).
- Material strategies to minimise mechanical stress (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.
- Manufacturing concepts for SSSBs demonstrated TRL4.
- Design and integration of advanced materials to realise "design for recycling" strategies.
- Cells with solid state electrolyte demonstrating capacity of at least 100-200 Wh/kg or/and 250 Wh/L and cycle life 1000-4000+ cycles (< 10% fading with DoD 80% at 1C).

Impact
Technological impact: Establishment of value chain for Na-ion battery manufacturing in EU, utilisation of manufacturing synergies with LIB, and elaboration of recycling strategies/technologies.
Economic impact: Avoidance of CRM dependence from developing countries and elaboration of cost-efficient alternatives to LIB and reduction of global risks of shortage of Li-supply for EU energy system.
Environmental impact: Use of common, non-toxic and cheap materials with less energetical effort needed for mining, recycling and waste treatment.

2.3.1.5 Vanadium-based redox flow batteries (driven by stationary) – Short-term / Mid-term

This strategic area is about developing the various safe and sustainable materials systems including improved catalysts to enable Vanadium-based redox flow batteries to deliver on high energy density, very long cycle life, low cost, and a reduced dependence on scarce raw materials. The key points where RFBs can compete are cost and scale. Therefore, the most crucial point to advance VRFBs is to focus on reducing costs and scaling production (which itself brings economies of scale).

Vanadium-based redox flow batteries (VRFBs) are currently state-of-the-art flow batteries considering their performance, safety, and long-duration energy storage. In VRFBs, the electrolytes on each side are flown through the corresponding electrodes when the flow battery is charged and discharged. The energy storage capacity of flow batteries can easily be scaled up or down by changing the size of the external electrolyte reservoirs, allowing for a high level of scalability and flexibility. The external electrolyte tanks allow flow batteries to be recharged more often and for a longer period.

However, the round-trip efficiency and cost of VRFBs are challenges for grid-scale energy storage. The crucial elements of VRFBs are redox couples and electrolytes, as they play a significant role in determining the energy density and cost of grid-scale systems. Nonetheless, other components (electrodes, membranes, etc.) also impact battery longevity, efficiency, and cost. To deploy RFBs at large scale, efficient systems based on inexpensive, sustainable, scalable substances are needed.

R&D activities needed

Short-term needs (2027)

- Optimised 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.
- Optimise and widen the temperature range for the electrolyte while improving electrochemical activity/capacity through, for example, additives.

Mid-term needs (2030) and Long-term needs (2030+)

- Sustainable electrodes from natural materials & new energy-efficient carbonisation processes.
- New (non-fluorinated) low-cost, improved mechanical properties and limited swelling membranes for RFB, including strategies for upscaling.
- Validate use of recycled electrolytes in new VRFBs demonstrating performance and lifetime.
- Effective end-of-life strategy for all the components.

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.

2.3.2 Transversal challenges

2.3.2.1 Sustainability

Much promise exists for current and emerging battery chemistries. However, many challenges remain from a sustainability perspective including:

- The usage of critical raw materials (CRMs) should be reduced in lithium-ion batteries. Both cobalt and nickel (e.g., in NMC) are considered critical, and lithium should also see decreased use in mass applications in the long-term future.

- To produce LFP batteries, no Co and Ni are used, which is a big economic (when considering low energy density systems) and environmental advantage. However, phosphorous is also a CRM and the economics of LFP recycling (with low value materials) is not yet established, potentially leading to a significant environmental legacy.

With SSBs, we face a similar CRM situation with more Li being needed at, however, a better safety profile. Recycling of SSBs will also require further technological developments.

Na-ion batteries could be a sustainable alternative, provided the technological promises are met and the limited energy density is not seen as a problem. As far as the recycling of Na-ion batteries is concerned, the low value materials contained in the battery could create similar concerns as those highlighted for LFP recycling. In case of fire, the potential toxic emissions by PBAs/PWAs should be tackled.

For RFBs, the availability of vanadium could become critical if RFBs would penetrate successfully into the stationary storage market. LCA results indicate a good environmental performance, especially if the recycling of the electrolyte is considered. Vanadium-based RFBs could be more competitive than LiBs, if renewable energy dominates in the mix, given their lower round-trip efficiency.

2.3.2.2 Safety

Battery materials can cause hazards for human health and environment during manufacturing, transportation, use and recycling. Because of the high energy density of active materials as well as possible high electrochemical potentials, additional risks / unwanted processes (onset for Li-dendrite formation, oxygen loss, (electro)chemical instabilities, exothermic reactions) should be considered besides standard physical and chemical features of singular materials.
At the material level, the hazards of the material itself (which are expected to be regulated by specific EU regulations), and the hazards caused by the interactions of materials in the cell should be considered. Therefore, KPIs at material level must be related to their testing in "concept" cells (e.g.: semi-cells or small full cells). The main hazards coming from specific material combinations are potentially induced by (1) liquids, gas, and particles leakage into environment, (2) venting of toxic gases, and (3) heat release caused by self-heating, potentially leading to thermal runaway. The characteristics related to material combinations in different chemistries and their behaviour regarding the issues due to electrochemical reactions, excluding combustion processes, are covered by the definition of safety KPIs. The evaluation and classification of safety related properties must be performed by comparing measured values to ones for reference chemistries for a corresponding cell concept.

2.3.2.3 Digitalisation

AI is increasingly used to discover new battery materials, optimising designs faster and more accurately than traditional methods. It searches vast material databases, identifying patterns missed by humans and focusing efforts. AI simulations of material properties and performance help fine-tune designs before physical experiments, greatly accelerating the discovery process and saving resources. Challenges include acquiring high-quality data and providing AI access to physics and expert knowledge. Good data and machine-readable human expertise are crucial for designing relevant and accurate AI models, reducing the search parameter space. Encouraging advanced digital solutions aids research defragmentation and positions the EU as a battery technology leader. Standardised digital tools and shared infrastructure, such as Material Acceleration Platforms, enhance battery research capabilities. Dynamic mixed researcher groups and fluent FAIR data exchange promote globally competitive research actions in the short and mid-term. Human-supervised approaches determine suitable ML algorithms for physical problems, avoiding misguided AI optimisation. A common knowledge base for the battery industry provides information on materials used in batteries, along with their pros and cons. Digitally supported standardised mechanisms facilitate access and use of intellectual property (IP) within the EU, benefiting IP owners and expediting development time and technology distribution.

2.3.3 Key Recommendations

Advanced materials 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 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	Stable cathodes and electrolytes for high voltage batteries (≥ 2000 cycles at 4.8 V)	Cathode materials capacities beyond 300 mAh/g with coulombic efficiencies of 99,98%, ≥ 1.000 cycles, and specific anode capacities of ≥1200 mAh/g
	Stable cycling of Li- and Ni-rich, low Co cathode materials (<2.000 cycles)	Decrease specific number of critical materials (Natural Graphite, Co, Li) and materials with F per kWh stored energy in line with EU battery regulation considering recycling and use of secondary raw materials	Lithium-ion battery with reduced use of critical materials (other than Lithium)
	Optimisation of low cost and high safety phosphate-based materials (e.g., LFP, LFMP)	Large cycle life in low voltage, high-capacity anodes ≥ 1000 mAh/g, e. g. Si/C composites with above 20 wt.% Si, or pure Si	
	Optimisation of low cost and high safety manganese rich HLM based materials		
	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 (active and inactive) materials designed for solvent-free or dry production processes		

SRA	Short term	Medium term
Solid-state batteries (gen 4) (driven by mobility)	Active materials incl. coatings for reduced interfacial resistance to electrolyte & catholyte	New materials and/or chemistries at higher voltage
	Reducing thickness of the anode	Coating for these materials to stabilise the electrode and electrolyte interface
	Developing thin solid electrolyte (e.g., multilayer and composite electrolytes) with high ionic conductivity over a wide range of temperatures	Novel solutions for low-cost solvent-free electrode manufacturing and solid electrolyte deposition
	Manufacturing of new solid electrolyte interlayers	

SRA	Short term	Medium term
Solid-state batteries (gen 4) (driven by mobility)	Solutions for manufacturing and handling Li metal sheet in dry atmosphere	Important targets of development are the reduction of interface resistance to solid electrolyte and avoidance of dendrite formation at high C-rates
	Improved interface design for efficient charge-transfer and electrochemical & mechanical stability	New cell design compatible with the developed components

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 Li-ion batteries	Improve conductivity to increase power by e.g., incorporating structured carbons or 3D-structures as additive into electrodes and by the development of power optimised materials and architecture
	Improve cycle lifetime & calendar lifetime to develop reliable, cost-effective products	Develop high-capacity technology by incorporating Si into anode, developing high-energy density cathode materials, reducing Li consumption in SEI on anode side with higher use of Li in cathode
	Develop fast-charging Li-ion anode materials other than lithium titanate	Decrease cathode's Co content improving structural stability by composition adjustment
	Develop high-energy-density electrodes with high ionic and electronic conductivity	Develop coatings for cathode materials with high energy density for lower interfacial resistance
	Develop a highly ionic-conductive solid electrolyte for solid-state Li-ion batteries for safety	Develop innovative separators improving safety & reducing use of organic solvents
	Decrease content of critical raw materials in used cathode chemistries	Incorporate shutdown mechanisms into separator materials or separator design and improve structural resilience of separators through new materials, designs or coatings

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	Design and integration of advanced materials to realise "design for recycling" strategies
		Anodes with enhanced capacity of 300 Ah/kg, fading <10% over ≥ 500 cycles	Cost & energy-efficient manufacturing for cell materials recognising recycling aspects
		Hybrid electrolyte concepts with high ionic conductivity, enhanced safety and improved SEI stability (e.g., reduced SEI solubility	Cells with hybrid electrolyte concepts with cycling stability of 2000+ cycles and CCD >2 mA/cm^2
		Interface optimisation to enable low interface resistance and stability, long lifetime, cost- and energy efficient production processes	Cells with 170-200 Wh/kg or/and 400-500+ Wh/L and cycling stability of 4000-6000+ cycles (<10% fading with DoD 80% at 1-2C)
		Cells with 160 Wh/kg or/and 300 Wh/L and cycling stability of 2000+ cycles (<10% fading with DoD 80% at 1C).	

SRA	Short term	Medium term
Gen 4 (Na-based SSB)	Screening (modelling and simulation combined with experiment) of materials and material development strategies to obtain higher conductivity, higher capacity/lifetime, and reduced critical element contents Composite cathodes with capacity of 120 Ah/kg (total cathode weight) and cycle life of >500 cycles (<10% 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. Proof of concept for cells with solid-state electrolyte demonstrating capacity of at least 60 Wh/kg and cycle life >500 cycles	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) Material strategies to minimise mechanical stress (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 realise "design for recycling" strategies 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)
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	Sustainable electrodes from natural materials & new energy-efficient carbonisation processes New (non-fluorinated) low-cost membranes for RFB including strategies for upscaling Validate use of recycled electrolytes in new VRFBs demonstrating performance and lifetime Effective end-of-life strategy for all the components

Table 4: Overview of Strategic Research Areas of the Advanced materials roadmap, developed by Batteries Europe/BEPA WG3

2.4 Cell Design and Manufacturing

2.4.1 Strategic Research Areas

2.4.1.1 Sustainable cell and battery design

With the increasing need for advanced battery cells, innovative cell design is critical not just from a cost perspective but also towards the realisation of environmentally friendly, high-performance and long-life batteries. At present, there is little to no recycled content in battery packs, and even less in the cells themselves, which are notoriously focused on the use of high purity materials. In addition, the design of cells has largely been based on first life applications –there is a lack of design and testing specifically for second-life applications. There is a lack of vision on how to design for 2nd life applications, making it clear that there is a need for easy disassembly of packs. LCA and LCC analyses are an important part of determining the economic and environmental viability of novel materials and designs – but there is a limited focus on the sustainability of the cell and pack design itself. As part of efficient and sustainable manufacturing processes, cell and module design must also enable cost-effective and environmentally friendly production. With the rise of new generations of cells, there is a growing need to focus not only on their technical challenges, but also on incorporating sustainability considerations into the material selection and cell design.

R&D activities needed

The above challenges lend themselves to specific activities to address future cell manufacturing in Europe and to bring cell, module and pack technology to the forefront of sustainable and economic production processes. 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. This includes simplifying and promoting recyclability of raw materials and finished products, reducing the cost associated with recycling and using recycled materials. The growing need for large-scale electric mobility also requires an appropriate cost structure for newly developed batteries. Starting with the cells, these products must be suitable for the mass market, but this means not only low cost, but also low cost of ownership over the entire life cycle. Both the new requirements for cell performance and safety, as well as extended lifetime, require functionalisation of the cell design. This should increase the efficiency of thermal management, 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 translates into concrete R&I needs in the short-, mid- and long-term as follows:

Short-term needs (2027)

Cell Design to promote circularity

- Focus on higher energy densities to promote using fewer materials overall.
- Cell design for high-power applications with different overall performance requirements.
- Quasi-solid-state cells as an intermediate solution for large-scale manufacturing.

Low-Cost designs and processes

- Safer disassembly processes for 2nd life applications with non-destructive/non-invasive safety assessment.
- Changing modularity of design for fast release of modules and cost-effective disassembly.

Abundant, easy to recycle and sustainable

- Use of recycled and recyclable materials as active and inactive components.
- Minimise as much as possible their consumption of CRMs.

Functionalised cell design

- Functional cell design for cycle life and application-specific cell design, supported by simulation for cell design and respective application.
- Design for safety on cell, module, and pack level during manufacturing, application, 2nd life and recycling.
- Reducing the gap between power and energy cell design including improving the flow paths of the electrical current to reduce the internal resistance, Electrode design, heat dissipation strategies, etc.

Mid-term needs (2030)

Cell Design to promote circularity

- Sustainable cell design, including materials selection, for solid-state and quasi-solid-state cells.

Low-Cost designs and processes

- Easy to disassemble packs, including ease of SoH determination for 2nd life use.
- Testing for 2nd life applications as standardised process and “certify” 2nd life capability.
- Standardisation efforts for cell form factor, especially for mass market applications.
- Specific design for lifetime cost.

Abundant, easy to recycle and sustainable

- Fully circular pack design for re-use, easier recycle.

Functionalised cell design

- Structural batteries (cell-to-body-concept) and distributed cell/energy storage solutions.
- Integration of smart functionalities and sensors in cells.

Long-term needs (2030+)

Cell Design to promote circularity

- Focus on cell design for new technologies, including scalable production methods, e.g., Bipolar stacking, Redox-flow cells, Metal-air cell designs.
- Full focus on sustainability of (quasi-) solid-state cell manufacturing process.

Low-Cost designs and processes

- Cell to pack designs.

Abundant, easy to recycle and sustainable

- Alternative ion technology with a focus on the sustainability of cells.

Functionalised cell design

- Optimised smart functionalities and sensors in cells.

Impact

Focusing on the design for life of cells, modules and packs would deliver a long-term improvement that impacts all industries. Increasing the lifetime per cell increases its value from the factory and helps to differentiate sustainable cells from others. This also facilitates sustainable production by reducing the need for large numbers of cells per application, including improved safety and reduced cost of ownership. Control of the technology drives the long-term improvement of the life cycle and therefore the cost of ownership, including 2nd life applications and recycling of cells and packs. Safer materials and designs lead to cost reduction in manufacturing and handling.

2.4.1.2 Sustainable production of cells and batteries

Sustainability in production is a key issue in battery manufacturing, particularly in cell preparation. Current processes are characterised by high energy consumption (dry rooms, electrode drying, cell formation), use of toxic / harmful / highly polluting materials (e.g., solvents in electrode preparation), large physical footprint (long ovens for electrode drying, large warehouses for cell formation and ageing), safety issues (flammable liquid electrolyte, large number of cells under charge/discharge), which also translate into high operating costs. The optimisation of existing processes and equipment and the development of innovative ones are therefore essential to promote the establishment of safe battery mass production in Europe.

Several aspects and solutions need to be considered to achieve this goal, such as: reducing the use of critical materials by using safer, more abundant and less polluting materials; reducing the consumption of energy and resources by using more efficient and/or innovative processes and equipment, rework, reuse, recycling; improving quality control; digitalisation. There is no single solution, but only a combination of all/most of them can achieve the objectives.

R&D activities needed

Short-term needs (2027)

Li-ion is expected to remain the winning technology in the short term. The R&I needs reported in this section are related to improvements in the production of current and advanced Li-ion technology. To achieve more sustainable cell and battery production, it is necessary to improve the efficiency of processes and equipment and to implement appropriate quality management.

- Reduce specific energy consumption and emissions, minimise the use of chemicals and improving process safety, reduce cost and increase efficiency. Examples:

- Development of processes that require less restrictive environmental conditions, such as water processing to reduce the use of dry rooms.
- Electrode preparation: reduction / elimination of the solvent use, more efficient solvent recovery, water processing, dry processing.
- Improve machines and implement systems to reuse energy in the plant (e.g., recirculation of electrical energy to charge / discharge cells, reuse of thermal energy in the plant).
- Explore the potential of coupling/integrating battery production processes with other

production/manufacturing processes.

- Reduce scrap and improve plant performance:

- Implement rework strategies to reduce the scrap while maintaining high-quality.

- Improve integration among processes: automation, optimisation of the plant logistics, reduction of dead times, etc.

- Quality and production control and management:

- Clearly identify and define quality gates, i.e., the critical points in production system that are key to ensure the final product quality.

- Digital solutions and technologies to be developed: e.g., sensors, on-line non-destructive measurement techniques for each production step (focusing on the quality gates).

- Virtual production - develop digital twins to optimise production processes, reduce commissioning time, and mitigate project risk.
- Cost efficiency - Overall reduction in CAPEX

- The reduction in OPEX must be quantified and compared with the possible higher CAPEX, to demonstrate the benefits in terms of economic, environmental sustainability and safety.

- Evaluate the potential synergies of integration with manufacturing and/or industrial processes, in the context of industrial symbiosis.

- Digital passport policy definition:

- IP and data ownership are key to identify how to protect data of individual companies while allowing the sharing of the proper information in the context of large multi-supplier projects, e.g., with blockchain or related protocols with lower energy consumption.
- Standardisation of hardware and software interfaces.
- Full product traceability throughout the production process.

Mid-term needs (2030)

- Validation of the solutions previously developed, through their implementation at pilot level and the consequent optimisation to be ready for mass production.
- Development of innovative processes and related equipment that assure sustainability in terms of environment, efficiency, safety, and economics for GEN 3B, 4 and 5.

- Development of processes that can use as many as possible state-of-the-art machines, to enable a smooth transition to new technologies. Li-ion and Na-ion have similar production processes, RFB and solid state may require specific developments.

- Increasing flexibility, for example to handle simultaneously different chemistries, e.g., in-situ crosslinking, low solvent high speed coating or separator supported solid electrolyte.

- Decrease the specific energy demand and emissions, minimise the usage of chemical and improve process safety:

- Development of additive manufacturing (e.g., 3D printing) technologies.
- Carbon-based materials: new synthetic routes using temperatures < 1000°C.
- Develop/implement new production technologies and/or procedures based on the results of LCA and/or LCC studies.

- Quality control and virtual production:

- Optimisation of sensors and on-line measuring.

- Validation of digital twins.
- Use of digital twins to develop systems of early defect detection, automatic rework, process adjustments, predictive maintenance.
- Data interoperability throughout battery manufacturing process: development of methods to analyse the data and transfer the experience from a project to another.

- Digital passport completely developed and mandatory for established technologies; optimisation and validation for new technologies.
- Equipment and process steps for the integration of sensors into the cells.

Long-term needs (2030+)

The long-term R&D activities will be dedicated to the emergent chemistries currently at low TRL. The main focus will be on the development of industrially feasible production processes for the manufacturing of those cells, transferring the knowledge from very small scale to pilot level and then industrial scale, while maintaining unaltered the product performances. This can be challenging, since, for example, it is already known that some of the studied materials require stringent environment conditions (e.g., inertisation): it is therefore necessary to find solutions that can be technically and economically feasible at large scale, assuring at the same time high quality standards.

Impact

From the technological point of view, the activities will lead to the development of advanced solutions, with higher efficiency and reduced carbon footprint, properly designed for the needs of the EU framework. This includes the increase of productivity while reducing the floor occupation and theenergy consumption. Eventually, it will lead to lower environmental impact of the battery production and reduced operative costs.

2.4.1.3 Flexible production technologies

As the market for batteries grows, the demand for safe, flexible and adaptable battery cell production technologies becomes paramount. In addition to meeting customer needs, flexible production technologies also play a critical role in reducing production costs, improving efficiency, and minimising waste. Battery cell production is in constant evolution. New cell chemistries and material systems are being developed at a rapid pace, which can quickly render existing manufacturing lines obsolete. 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 as well as within the production system. For example, the changing supply chains and the increasing demand for sustainable and environmentally friendly production methods and materials presents a challenge that must be addressed in the development of flexible battery production technologies. The following table provides an overview of challenges considering the broad understanding of “flexibility”.

Area	Examples for challenges that call for increased flexibility
(active) Materials processed	• Innovative anode materials (e.g., Si vs. Graphite) • Changing active materials (e.g., high Ni content vs. LFP/LMO) • Future battery generations (e.g., LiB vs. ASSB vs. post-LiB) • Integration of recycled and safer components and materials
Cell Design	• Changing cell dimensions and design (axial vs. radial) • Housing concepts (e.g., safety mechanisms, cell contacting terminals)
Process technology	• Slurry production (e.g., aqueous vs. non-aqueous) • Electrode production (e.g., wet vs. dry electrode coating) • Cell assembly (e.g., stacking vs. winding) • Process integration (e.g., lamination, pre-lithiation) • Innovative material feeding (e.g., from coil vs. from sheet buffer) • Changing process design (continuous vs. discrete processes)
Process chain design and factory configuration	• Resilient process chain design (e.g., regarding supply chain disturbances and material from different suppliers) • Reduced ramp-up times to decrease time-to-market • Investment-optimised factory configuration for flexible investments in small increments • Flexible process feeding and process transfer (routing flexibility, format flexibility, latency, throughput)
Factory operation and production infrastructure	• Changeable building design (e.g., relocation of dry room) • Modular technical building services (e.g., modular dry room design vs. mini environments) • Energy flexibility (e.g., handling of volatility of renewable energy) • Cost-efficient production (max. throughput vs. max energy efficiency) • Implementation of safety protocols for the new technology and process

R&D activities needed

As the battery market will constantly evolve in short-, mid- and long-term perspective, the flexibility and changeability of battery production systems must be increased to meet the demands of the ever-evolving battery market. This requires innovations in production processes, machinery, and automation, along with improvements in material and cell design that can be easily implemented and adapted to new requirements.

Short-term needs (2027)

Increasing flexibility requires a deep understanding of the consequences of innovations in battery design and production. The implementation of this knowledge within the battery production process comes with some inertia hence it is vital to begin this R&D as soon as possible.

- Analyse the interconnection between production processes and the factory system, such as the interconnection between processes, dry rooms, and technical building services.
- Develop digital models which serve as essential tools for understanding, assessing, and implementing flexibility in battery production. Digital models can help design and outline a production line, control and operate the line, and optimise its operation. With digital models,

it is possible to simulate how the line behaves with different materials, electrode designs, cell formats, and cell chemistries.
- Develop digital twins that directly interact with the production system which will be necessary to enable innovations like the virtual installation of new equipment and the integration of new materials into existing process chains.
- Standardised models for processes are needed that can work with new materials and components.
- Standardised data interfaces are needed to facilitate the rapid integration of new machines into existing lines as well as the continuous monitoring and control of production processes.

Research activities should focus on increasing the resilience of the production process, developing innovations that reduce and manage the effects of disruptions, and achieve a robust production. The target conflicts between throughput, efficiency, costs, flexibility, and resource efficiency should also be addressed, including the analysis of scalability of innovations.

Mid-term (2030) and long-term (2030+) needs:
- Develop a comprehensive understanding of the relationship between battery cell materials, cell designs, and production processes, which facilitate development of equipment that is interchangeable and modular. This is necessary as there will be a range of new materials introduced into existing production processes for electrodes and cells.
- The standardisation of data platforms is necessary to flexibly integrate new processes with the related manufacturing equipment into existing production lines. Shared access while protecting IP will be one of the success factors.
- Build and develop validation lines to test for fast and safe changes from pilot to industrial mass production. This will allow for the quick and efficient implementation of R&D in real-world production environments.

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 and Na-ion, the flexibility in battery production and design is critical for keeping up with these changes. 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. Overall, the enhanced flexibility of battery cell production is key to Europe's competitive position in the global battery industry.

2.4.1.4 Process and product scaling and industrialisation

In order to promote the industrialisation of battery cells in the EU, it is necessary to develop methods to accelerate the up-scaling from laboratory to pilot lines and finally to mass production. Several technical challenges slow down this process, including safety concerns, process optimisation with different equipment sizes (e.g., mixing tanks, coating and cell assembly machines) and product design validation on larger cell formats.

Even more mature process such as conventional Li-ion technologies still require significant time (> 5 years) to move from a laboratory prototype to mass production. For new emerging technologies the upscaling time may be even longer. Currently, there is little to no experience in the EU from a large-scale manufacturing perspective. New techniques are needed to speed up the process of product scaling and industrialisation. The state-of-the-art approach relies 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. This creates a bottleneck for the whole industry to develop at the required speed.

R&D activities needed
Short-term needs (2027):

- The development and implementation of digital twins can greatly support process and product designers to rapidly scale up machines and production lines. Digital twins can be implemented at different levels of computational complexity. These models are already in use and can be optimised in the short term to speed up the commissioning of equipment, thereby reducing the time to scale-up.
- Developing validation methods to analyse the up-scaling effects (environmental conditions, changes in process parameters, etc.) on product performance.
- Introduction of standard methods and protocols for evaluating the quality of the final product and by standardising process definition and quality criteria.
- An automated material handling system is required and should be developed for large-scale productions. Logistics and safety aspects are to be carefully considered.

Mid-term needs (2030):

- Large cell formats compatible with Gigafactory throughput should be developed at pilot level (e.g., prismatic cell with capacity > 100 Ah). To support this production, pilot line concepts should be representative of mass production equipment, but flexible enough to accept new materials and allow experimentation with processes.
- Design of manufacturing equipment for higher efficiency, as high energy and resource consumption, low availability and contamination are responsible for slowing down the manufacturing up-scaling process.

New materials and new emerging technologies require special efforts to validate the potential up-scaling and manufacturability. Specific digital tools need to be used and adapted to support early-stage development to assess their industrialisation. Specific machines can be developed in a second phase.

Long-term needs (2030+)

- Develop cell designs and manufacturing processes for next generation cell chemistries which are where possible compatible with current Li-ion technology. As mentioned in Section 2.4.1.2, particular attention should be paid to the environmental operation conditions for new materials.

Impact

From a technological perspective, 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. These new digital technologies will reduce the commissioning time for the manufacturing equipment and therefore the time-to-market.
From an economic standpoint, CAPEX and OPEX for up-scaling battery production will be reduced. However, allowing higher CAPEX costs for the implementation of advanced process controlling sensors in pilot lines may result in a convenient return of investment by reducing the time necessary to achieve mass production targets. More flexible manufacturing equipment with process monitoring capabilities may overall improve the development cycle to reach giga-factory level production (e.g., < 5 years).

From an environmental standpoint, lower energy consumption, less resource intensive, higher production efficiency and a reduced scrap rate are important targets to achieve an environmentally sustainable production. Moreover, innovative processes will be compatible with possible future green regulations (e.g., reduction of fluorine content or dismissal of NMP or toxic solvents).

2.4.2 Transversal challenges

2.4.2.1 Sustainability: Implications due to recycled raw material on cell design, manufacturing, material selection and application

Further improving the environmental, economic and social sustainability of batteries and their manufacturing process is crucial for the future of the battery evolution. Therefore, the related challenges and potential R&D activities are included in all the Strategic Research Areas above. Research areas which should be highlighted include:

R&D activities needed

- Developing tools for enhancing cell manufacturing throughput and sustainability.
- Track and tracing tools for cell manufacturing process from material to cell.

2.4.2.2 Safety: Safety Implications on cell design, material selection and recyclability

Safety issues of batteries remain a crucial topic for battery manufacturers and users. Recent incidents have raised concerns. Critical battery incidents include cell openings that lead to the release of toxic gasses (including hydrofluoric acid), internal short circuits and fires. Manufacturers are making considerable efforts to maintain the safety of their batteries while ramping up new production capacity with a new workforce. Safer materials and designs with lower requirements lead to significant cost reduction in manufacturing and handling during all stages of the battery life. Safety related challenges and potential R&D activities are included in all the Strategic Research Areas above. Research areas which should be highlighted include:

R&D activities needed
- Incorporation of smart functionalities in the current sensor technologies of the manufacturing facilities, e.g., sensor data fusion.
- Virtual safety, early prediction of unsafe situations.

2.4.2.3 Digitalisation: Digital twins for sustainable design and manufacturing of batteries

Digitalisation plays a crucial role in the battery sector, enabling significant advancements in cell design and manufacturing. By digitalising cell design and manufacturing processes, sustainability, optimisation, and flexibility solutions can be greatly supported. One of the key aspects of digitalisation is the use of hybrid, both knowledge and data-driven models, which are instrumental in process and quality control. The data and information generated throughout the production process together with accurate and efficient models are highly valuable for enhancing real-time control and even enabling predictive process control. By harnessing this data, manufacturers can make informed decisions and improve the efficiency and effectiveness of their operations. Furthermore, digitalisation facilitates the integration of various aspects of the battery manufacturing process, enabling seamless communication between different stages and optimising overall productivity.

Numerous models have been developed to describe the performance of batteries or to optimise the manufacturing processes, however, their usefulness for the development of sustainable and flexible production lines remains limited unless digital twins are created to link the performance of batteries with material properties, cell design and manufacturing processes. The development of such digital twins is highly challenging as it involves coupling diverse models that describe phenomena of distinct nature at different scales.

R&D activities needed
- Development of a material acceleration platform suitable for different battery technologies.
- Developing multi-physics multi-scale digital twins for the production line of batteries using semantic frameworks to link multiple models.
- A semantic layer connecting digital twins with the physical machines and automatise the

deployment of complex digital twins.
- Accelerate the upscaling procedure from lab to pilot scale by means of AI.
- Efficient multiscale models (e.g., PINNS and ROM models) for new cell configurations focusing on coupled mechanical and electrochemical durability and ageing.
- Optimise critical steps in the manufacturing process such as formation step by means of modelling tools (advanced physics- based as well as hybrid models).
- Modelling of advanced manufacturing routes (extrusion, dry process, etc.) for properly understanding their parameters impact on the electrode properties.
- Battery twins linked to the battery passport, to follow the batteries' lifecycle and providing critical input data for digital twins in the recycling industry.

Impact
Multiscale multiphysics models together with AI-enforced models should enable the optimisation of the material development, cell manufacturing and recycling minimising current limitations (e.g., lithium plating). Combined modelling and advanced characterisation techniques are required for properly understanding technology limitations with special focus on the interfaces, and to guide on new routes of development.

Digital twins for manufacturing processes can improve the competitiveness of the EU battery industry from several aspects as they are useful for fast and cost-effective design, scaling and control of production processes. Therefore, they improve the flexibility of the battery industry in implementing emerging technologies, hence reducing the time-to-market of products. Moreover, they can be integrated with sustainability analysis tools to improve the sustainable production of batteries. Furthermore, they can be leveraged to assess manufacturability and sustainability of new materials.

2.4.3 Key Recommendations

From the perspective of sustainable, flexible and safe cell design and manufacturing the following key recommendations for policy and authorities, industry and research can be derived.

Policymakers and Member States (National Authorities)
To prevent falling behind, new secondary EU regulations to support the Battery Regulation, on recycling, new manufacturing processes should already be developed considering the use of recycled materials. Additionally, the use of renewable energies, improvement of efficiency and exploitation of flexibility potential needs to be encouraged at factory-level. To improve interoperability and technology openness, standardisation and data exchange need to be supported with clear definition of rules, e.g., for the digital passport implementation, as well as easier access to BMS functions for 3rd parties, especially for 2nd life use.
Effective collaboration between academia, large cell makers and research institutes with pilot scale production capabilities may be key to improve production up-scaling of new technologies. Therefore, larger public investments should be issued to boost the development

of such research facilities. Also, dedicated funding and collaboration with other partnerships would be beneficial to spread the effort and enable the development of digital tools and virtual production.

Industry & Start-ups

The European battery industry will benefit greatly from focusing on the optimisation of efficiency for equipment and processes, both for giga and for mega scale, the development of equipment specific for next-gen processes and the upscaling of the recycling process. The processes throughout the production line, including material and energy recovery, need to be integrated.

Strong collaboration between R&D institutes and industry, with industry leading the activity, is required, in particular for the virtual production development. Here real representative industrial data is required in large quantities.

Active participation from the stakeholders in the various standardisation processes is recommended, particularly regarding cell form factors and machine interfaces.

Research Community

Battery R&D is more dynamic than ever. A strong and creative research community, sharing knowledge and working together with the various stakeholders of the battery ecosystem, is an enormous advantage. Collaboration with industries should begin at the early stage of development of new technologies. Further recommendations for the research community are to focus even more on sustainability, including the development of measurable sustainability KPIs, and start considering cell designs for next generation cells. The usage of recycled and recyclable materials in cells needs to be evaluated, as well as battery cost regarding the entire life cycle and longer cycle life, also for applications beyond 10k cycles. Another field is the faster charging to enable smaller battery design.

SRA	Short term	Medium term	Long term
SRA1 Sustainable cell and battery design			
Cell Design to promote circularity	Simplifying recyclability	Reducing the cost of recycling and using recycled material	Full focus on sustainability in new technologies
Low-Cost designs and processes	Safer and easier disassembly processes	Standardisation, low cost over entire life cycle	Cell to pack design and optimisation
Abundant, easy to recycle and sustainable	Use of recycled and recyclable materials	Fully circular pack design for re-use	Alternative technologies

Functionalised cell design (for improved efficiency and lifetime)	Design for safety, Reducing the gap between power and energy cell design	Structural cells and distributed storage solutions	Smart functionalities and sensors in cells
SRA2 Sustainable production of cells and batteries			
Improve plant performance and reduce scrap	Better integration among processes	Processes and equipment for transition to new technologies	Maintain high production performances with emerging chemistries
Reduce environmental impact & cost	Less restrictive environmental conditions	Additive manu-facturing, Carbon-based materials	
Quality and production control	Identify and define quality gates	Sensor optimisation	
Virtual production	Strong collaboration, representative industry data	Validation of digital twins, data interoperability	
Cost efficiency	Demonstrate economic benefits	Continue optimisation and synergies	
Digital passport	Policy definition	Completely developed	New business models
SRA3 Flexible (production) technologies			
Interconnection between production processes and the factory system	Analyse the interconnection between processes and system	Develop interchangeable and modular equipment	
Standardisation	...of data interfaces	...of data platforms. Shared access while protecting IP	
Digital models	Simulate the flexible lines behaviour		
Increased resilience and flexibility	Flexibility towards supply chain disruptions and fluctuating energy supply	Validation line for fast and safe changes	
SRA4 Process and product scaling and industrialisation			
Digital tools / digital twins	Accelerate commissioning and scale-up	Simulate material behaviour during the manufacturing process	Develop tools for up-scaling validation of emerging technologies

Reduce the gap between the lab/ pilot scale to mass production	Development of validation methods to analyse the upscaling effects	Develop large cell formats at pilot level	Down-scaling the equipment to mega-scale
Promotion of collaboration between research and mass production	Data exchange methods, standardisation of process definition and quality criteria	Mass production equipment in pilot lines	Develop new materials and process validation methods
Equipment improvement	Rise equipment efficiency	Evaluate compatibility and challenges of upcoming with current technology	Develop upcoming processes compatible with Li-ion technology
Transversal Challenges			
Sustainability	Improving the environmental, economic and social sustainability		
Safety	Safer materials and designs with lower requirements lead to significant cost reduction in manufacturing and handling		
Digitalisation	Digital twins and multiscale models for sustainable production and design		

Table 5: Overview of Strategic Research Areas of the Cell design and manufacturing roadmap, developed by Batteries Europe/ BEPA WG4

2.5 Application and Integration: Mobile

2.5.1 Strategic Research Areas

2.5.1.1 Road transport

Road transport has a significant environmental impact, making it 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. In this context, batteries play a pivotal role as a key enabling technology. For electrified vehicles, the battery must strike a balance between high-power performance, energy storage capacity, weight, volume, lifetime, and cost. Additionally, it must adhere to automotive-grade safety standards while being recyclable and environmentally sustainable.

Currently, state-of-the-art market-available Li-ion NMC (either 622 or 811) technology offers energy density up to 250 Wh/kg at the cell level, and around 175 Wh/kg at the pack level, with a cost ranging from 100 to 150 €/kWh. This translates to a range of approximately 400 km for most fully electric passenger cars on the market, with an expected lifetime exceeding 150,000 km. However, there is room for improvement in terms of increasing energy density, reducing costs, ensuring safety, and emphasising the second life and recyclability of spent automotive batteries.

To enable the large-scale deployment of fully electric vehicles, several essential factors must be considered. These include interoperability and standardisation, new and flexible manufacturing approaches, the ability to swap battery modules, 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 and enhancing affordability are critical aspects as well. Focusing on heavy commercial vehicles (HCVs), it's important to note that they require larger battery capacities compared to passenger vehicles. Higher gravimetric energy densities, both at the cell and system levels, are needed to enable higher payloads and more cost-efficient utilisation of the entire vehicle. In addition to performance, factors such as cycle life and total cost of ownership are crucial considerations for HCVs. These vehicles must be capable of operating under extended user-profiles, such as long-haul missions, and diverse environmental conditions (e.g., cold/warm climates).

R&D activities needed

Research needs for road transport batteries can be summarised along the following five areas that could be addressed at different time frame:

Short-term needs (2027):

- Increase the cell energy density performance, while avoiding critical materials (e.g., Co), reducing costs and focusing on Gen. 3b on the **short-term** and on solid-state Gen. 4

Li-ion batteries on the **mid-term.** 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, advanced cooling systems, and digital twin models for improving performance understanding under sustained fast and super-fast charge cycles, while informing the end-user on optimal usage profiles (driving/charging) for minimal capacity and performance degradation.
- Advance Battery Management Systems (BMS), embedding sensors for diagnostics and early failure prediction, remote upgrade, and maintenance (ensuring cyber security for remote and cloud-based functions), lifetime-optimised operation management, (capitalising on fleet-learning, artificial intelligence).

Mid-term needs (2030):
- Investigate new battery architectural and housing designs, including multi-type cell arrangements (e.g. high-voltage LNMO / high-capacity NMC), high-voltage and current (i.e. above 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.

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. On average, in the EU, the life-cycle CO2 emissions of an electric car are nearly three times lower than those of an equivalent fossil-fuel car. 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.

2.5.1.2 Airborne Transport

Batteries are recognised 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). Batteries act as primary propulsion energy storage within the HER thrust, providing 30-to-50% of the energy demand to fly a typical regional mission, and as energy storage for 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, electric environmental control cabin system), batteries are expected to function as their main energy storage, accounting for approximately 3-5% of the overall SMR energy demand on a typical short-to-medium range mission. Beyond these, batteries are also 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).

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 622 or 811) with Si/C anode (5-10% wt.), either in cylindrical or in a pouch cell format. The main challenge for further developing batteries for air transport consists of capitalising on recent Li-ion technology advances for increasing energy and power densities (e.g., high-voltage Gen. 3b and solid-state Gen. 4), while allowing for systems which are safe in an aeronautic context. There is, in fact, consensus within the aeronautic industry that Gen. 3b batteries will be the enabler for moving from fully electric general aviation to fully/hybrid electric commuter aircraft and electric VTOL vehicles (i.e., CS-23, CS-VTOL), with Gen. 4 being the enabler for the hybrid electric regional aircraft segment (CS-25).

R&D activities needed
Research needs for airborne batteries can be summarised along the following five thrusts along the timeline:
Short-term needs (2027):
- Increase the performance for density (energy and power) and safety of cells, by focusing on inherently safe active materials, electrodes, and electrolytes, for all solid-state Gen. 4b, including Li-metal anode, and Gen. 5 in a mid-to-long-term perspective, with calendar and

cycling ageing performance compatible with aircraft maintenance cycles (e.g., C-check).
- Design and prototype safe, light weight and airworthy battery modules and packs (including cooling systems, BMS, in/on-cell sensors, including digital twin), fit for the high voltage and power requirements of reference airframes (e.g., high C-rates for power boost in take-off and go-around scenarios), including theirintegration in relevant electric architectures and interface with electric conversion systems.

Mid-term needs (2030):
- Develop new airworthiness certification procedures capable of capitalising on fast technology development cycles, 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.
- Advanced battery integration concepts, such as multi-functional energy storage structures with embedded multi-purpose sensing capabilities, maintaining aeronautical-grade safety uncompromised.
- Develop a sustainable circular economy for batteries for airborne applications (including material sourcing, manufacturing, dismantling, and recycling).

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 and e-VTOL, while functioning as co-primary energy storage, together with sustainable aviation fuel and/or hydrogen (either cryo-compressed or liquified), in the categories of commuter (19 pax) and hybrid regional aircraft (50-100 pax). Moreover, batteries are expected to be the main energy storage solution for all non-propulsive systems on board large passenger aircraft. 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, up to 50% of the overall carbon cut is expected by hybrid-electric supplied by batteries in case of a regional aircraft, or up to 5% of SMR emissions are foreseen in case batteries supply the on-board systems energy demand. Moreover, all transport modes are expected to capitalise on advanced airborne batteries, leveraging the high-level technological challenges and safety standards expected in this sector.

2.5.1.3 Waterborne Transport

In 2020, marine electrification involved more than 200 vessels, with over 170 currently under construction. However, this represents only about 0.5% of the world fleet, with a battery demand accounting for less than 1% of the annual global production of lithium-ion batteries. Most battery systems are integrated into car and passenger ferries, as well as offshore supply vessels. Nevertheless, the sector is experiencing growth and expansion in coastal and short-distance shipping. For long-distance shipping, hybrid systems are employed to enhance fuel efficiency and reduce redundancy by keeping fuel engine generators online. The main challenges faced by marine electrification include safety, reliability, efficiency, and lifespan. It is important to note that compared to road transport and stationary energy storage system (ESS) standards, marine safety regulations are much more stringent.

Lithium technology currently dominates the marine electrification sector due to its ability to strike a good balance between safety, specific energy/energy density, specific power/power density, and lifespan. The most common chemistries used in waterborne applications are Nickel Manganese Cobalt Oxide (NMC) (111 or 532) or Lithium Iron Phosphate (LFP). Hybrid and high-power applications utilise the same cell technology but restrict the usable capacity window to achieve high cycle life and power output. Lithium-Titanate Oxide (LTO) is also a valuable solution for high cycle life and high-power requirements.

Research and development (R&D) efforts in the waterborne sector are not expected to focus primarily on battery technology itself but rather on the system integration of different battery systems into ships or offshore platforms and the safety aspects associated with these installations. Safety considerations are also the main cost driver for these applications. Waterborne systems are not anticipated to encounter significant regenerative conditions but will be subjected to continuous discharge with a power requirement close to peak power. Therefore, reliability and thermal management are crucial. Additionally, waterborne systems are exposed to high levels of humidity and salt ions while being expected to deliver a long lifespan. Hence, materials used must be durable and corrosion resistant. Furthermore, waterborne applications encompass a wide range of vessel types, including jet skis, small boats, ferries for short-distance transportation (such as coast-to-coast lake and river applications), fishing boats, recreational yachts, large vessels, and open sea transportation (e.g., large passenger or cargo ships). The diversity of these applications necessitates a significant level of customisation in the adopted solutions, as well as the integration of renewables (e.g., solar panels) where feasible.

R&D activities needed

Battery research needs for waterborne applications can be summarised as follows:

Short-term needs (2027):

- Improving battery performance, in term of energy/power, including systems integration, thermal management, such as direct liquid cooling (either partial or full immersion) and novel BMS technologies (e.g., implementing AI).

Mid-term needs (2030):

- Improving battery safety by deploying functional safety rules adaptable to ground-breaking concepts or ideas (e.g., new chemistries, new communication HW and SW, built-in thermal conditioning systems), while building standardised functional approach guidelines for waterborne.
- Enhancing fast charging as a key enabler for waterborne applications. This also opens the way to develop a vessel-to-grid technology, where large batteries used onboard ships could provide services to the electric grid, supporting the deployment of green ports and improving the integration with renewable resources.
- Develop hybrid systems (e.g., battery and fuel cells) to cover different operation modes, envisaging retrofitting by design to benefit of the latest development as the battery industry develops.
- Establishing a reliable framework of regulations and standards linked to private and public stakeholders, applicable world-wide, to facilitate the transition to a zero-emission marine transport.

Impact

In the waterborne sector, emissions in densely populated areas such as coastal regions and ports have a greater impact than those in open sea areas. Therefore, achieving zero emissions in or around cities by utilising fully electric vessels and promoting waterborne transport as an alternative to road transport is highly desirable in cities like Istanbul, Venice, Copenhagen, and Amsterdam. The electrification of waterborne transport will have a positive impact on the industry, creating job opportunities in both the retrofit and new construction markets. Furthermore, it will synergise with other modes of transportation, enhancing European competitiveness in providing a safe, reliable, cost-effective, circular, and sustainable battery industry.

2.5.1.4 Rail Transport

In the landscape of mobility, rail transport stands on an advantageous position in achieving the climate goals of the Paris Climate Agreement. Indeed, almost 60% of railway lines are electrified and 80% of traffic is running using electric traction. For non-electrified railway lines, however, diesel accounts for around 20% of EU rail traction. In substitution, new vehicle concepts are being developed with fuel cell drives - with a lithium-ion battery storage system compensating for the low power rate of the fuel cell or hybrid diesel-electric locomotives. The lithium-ion battery of the hydrogen fuel cell trains in service is in range of 200 kWh.

For battery electric train the most used lithium technologies are NMC (Bombardier Nanjing tramway and BEMU demonstrator, iLint fuel cell train) and LTO (Siemens Desiro, CAF, Stadler Flirt). The required autonomy of the battery systems is of about 80-120 km and 7-10 years of lifetime, the useful energy around 500 kWh (installed is up to 800 kWh depending on the technology).

The main constraints for battery storage systems currently installed are the limited available space onboard (mass and volume) and performance (efficiency, lifetime). An interesting but challenging approach could be providing the whole rolling stock by the onboard energy sources and improve the train subsystems (comfort auxiliary's consumption, energy efficiency, tones per axel). R&D is necessary to improve battery technology and to develop batteries and hybrid solutions suitable to serve the rail industry.

R&D activities needed
Battery research needs for rail applications can be summarised as follows:
Short-term needs (2027):

- Improve technical performances at system level increasing the energy density for higher train autonomy. Allow fast recharge without degrading the battery, including requested cooling systems, that must be implemented to reduce weight, volume, size, and energy consumption.
- Harmonise the standards applicable to train at the EU level at different levels: (i) for railway rolling stocks, unify technology standards, vehicle interfaces for electricity supply and data protocols; standardise where possible batteries technical solutions, safety requirements, and recharge systems to support interoperability across Europe, reduce costs thanks to scale effect on serial products; standardise virtual certification, simplify the validation and train certification process to reduce cost and duration of certification across Europe.

Mid-term needs (2030):

- Deliver systems characterised by a lower life-cycle cost (covering initial investment cost, maintenance cost, energy efficiency, simplification of electrotechnics and cooling devices).
- Improve battery cycling characteristics while developing accurate lifetime modelling considering micro-cycles (1 to 2% for energy cells and 4 to 5% for power cells DoD and the power charge during the recovery laps of time). Synthetic railway mission profile(s) provide information about the cycling characteristics at operational usage performance as requested at battery level (such as EN 50591 or according to its update with hybrid usage).
- Improve battery packaging safety to avoid explosion, gassing, and intoxication.

Impact
The replacement of diesel trains, which currently account for approximately 20% of train mobility, will lead to a significant reduction in greenhouse gas (GHG) emissions, nitrous oxide (NOx) emissions, and particulate matter (PM) emissions. This shift in mobility aims to achieve zero emissions while minimising noise pollution. By storing large quantities of clean energy onboard trains and utilising ground storage, it becomes possible to optimise electrification infrastructure in challenging or high-cost areas such as tunnels or bridges. Moreover, on-board self-sufficiency allows for better control of peak load consumption, ensuring reliable operation of the train even in the event of a power failure. This ensures passenger comfort and facilitates traction to the nearest station. Additionally, the electrification of freight transport, particularly for last-mile operations, will be simplified and made more efficient.

2.5.1.5 Off-road Transport

Non-Road Mobile Machinery (NRMM) is a broad category encompassing mobile machines and transportable industrial equipment or vehicles that are equipped with internal combustion engines and not intended for transporting goods or passengers on roads. It represents a diverse group of vehicles with various use cases and a fragmented market, presenting significant potential for hybridisation and electrification. The key sectors involved in NRMM include mining, materials, cargo handling (with a focus on green ports and airports), forestry, and agriculture. The electrification and battery requirements of NRMM strongly depend on the specific application and operational strategy, reflecting the diverse nature of these vehicles. Compared to road transport applications, NRMM operates in harsh and demanding environments, including extreme temperatures, necessitating charging and operation capabilities in rugged environmental conditions. Given the high-power characteristics of NRMM, aspects such as power density, cyclability, and safety are of paramount importance, while considerations such as energy density, cost, and calendar life are considered secondary. Furthermore, due to the continuous operation of NRMM, fast charging capability is crucial. The development of NRMM is guided by emission standards, specifically Regulation (EU) 2016/162835, which currently does not cover CO2 emissions. In the absence of specific regulations for NRMM, the market competitiveness of electrified off-road vehicles relies on local zero-emission subsidies and competes with conventional powertrains. Additionally, it should be noted that the electrification of NRMM may face challenges due to the remote locations of work sites and limited access to the electricity grid.

R&D activities needed

Short-term needs (2027):

- Improve the power performance at cell, module, and pack level, ensuring high charge and discharge rate capabilities, regardless of the environmental conditions.
- Advance the system design of battery modules and packs, including cooling/heating solutions allowing for operation in extreme environments. Digital twin models for accelerating the development within agile and virtual design loops.
- Increase the safety of the battery systems, encompassing: (i) safety of the materials and electrode, (ii) safety and mechanical robustness of the battery module, and (iii) safety of the operation. Sensors, data collection, remote data management, diagnostics, prognostics and BMS are also in-scope.

Mid-term needs (2030):

- Enhance accessibility, repairability and re-use of battery packs, ensuring the ability to replace battery cells and/or modules when needed, addressing sustainability and circularity, maximising the useful lifetime while reducing their cost per cycle.
- Encompass pre-normative research for NRMM batteries, for defining standards and synergies within the off-road sector as well as interplay with heavy-duty on-road applications, aiming at reaching scale benefits in the battery industry.

Impact

CO_2 emissions from NRMMs (including construction machinery and equipment, agricultural machinery and equipment, gardening equipment, rail, and inland waterway vessels) are estimated at 100 million tonnes per year equivalent emissions in the EU27, corresponds to approximately 2% of the EU27's total greenhouse gas emissions. Hence, the NRMMs have a non-negligible impact on the environment. Electrification is expected to decrease or eliminate emissions, with immediate benefits on the air quality at local level, while decreasing the energy consumption, which is expected to decrease from the actual 395 TWh down to 165 TWh assuming a full conversion of the fleet from diesel to full electric.

2.5.2 Strategic Research Areas

2.5.2.1 Fast charging

Charging speed and C-rate of Li-ion batteries is a major aspect influencing consumer choices and electrification of transport, often treated as a main barrier for adopting electric vehicles in substitution to conventionally fueled vehicles. 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, the performance at vehicle level lags behind 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. The latter, moreover, constitutes 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 more power-density systems. On the opposite side, safe fast charging in low temperatures requires the adoption of specific strategies, such as pre-conditioning, to preserve system resistance and internal cell kinetics. In addition, inductive (wireless) charging poses its own challenges, in terms of energy efficiency, electromagnetic compatibility and infrastructure. R&I in the area of fast charging is expected to focus on cells, modules and battery pack design capable of increasing the charging power while limiting degradation (by increasing voltage), targeting to double the actual charging speed, i.e., from 10-to-80% battery pack SoC increase in about 15 minutes, for road transport applications. Safety issues, standardisation of the 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 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 are also relevant aspects to be considered.

2.5.2.2 Battery swapping

The concept of swappable batteries is attracting an increasing interest, given the ability to flexibly adapt the transported battery capacity to the end-user real-world need, while detaching the use of the battery from its charge. Of course, this is a solution that generates most of its benefits in applications where the battery is reasonably small and easy to handle/transport (e.g., electric motorcycles with up to 2 kWh battery swappable modules). The main challenges to address in this field are: (i) mechanics and connection of swappable modules, ensuring safety, robustness, acceptable costs, and durability, (ii) associated electronics and battery management system, allowing for operating different chemistries and adapt different SoX indicators, (iii) recharge infrastructure and logistics of the swappable battery modules and packs, and (iv) standardisation and interoperability of the swappable modules across different vehicles and vehicles' categories. Impact wise, swappable batteries allow for rightsizing the battery capacity depending on the specific needs of the end user, also adapting them to evolving needs, reducing the total capacity needed at fleet level, as well as allowing the implementation of V2X and smart recharge strategies, while eliminating in full the range anxiety.

2.5.2.3 SoX prediction

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. Additionally, accurate failure prediction, prognostics and diagnostics are essential to extend the lifetime of the battery, and these functions need to be enabled via 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 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.

2.5.3 Key Recommendations

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

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: control monitoring, common protocols, learning prognostics.

By employing intuitive foresight, both the European Commission and Member States can effectively embrace the forthcoming diversifications that will inevitably emerge as a result of different chemistries and their hybridisation, in the future.

A key point is also to promote and share citizen awareness participation in electrification of the energy system context.

<table>
<tr><th>SRA</th><th>Short term</th><th>Medium term</th><th>Long term</th></tr>
<tr><td rowspan="6">SRA1
Road transport</td><td colspan="2">Increase the cell energy density performance Gen 3b</td><td></td></tr>
<tr><td colspan="3">Advance in cooling systems, and digital twin models</td></tr>
<tr><td colspan="3">Advance Battery Management Systems</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>
<tr><td rowspan="6">SRA2
Airborne Transport</td><td colspan="3">Increase performance for density (energy and power) and safety of Gen 4 cells</td></tr>
<tr><td colspan="3">Prototype light weight, integrated, airworthy battery modules and packs</td></tr>
<tr><td></td><td colspan="2">Increase performance for density (energy and power) and safety of Gen 5 cells</td></tr>
<tr><td></td><td colspan="2">Develop new airworthiness certification</td></tr>
<tr><td></td><td colspan="2">Advanced battery integration concepts</td></tr>
<tr><td></td><td colspan="2">Develop a sustainable circular economy for batteries</td></tr>
<tr><td rowspan="5">SRA3
Waterborne Transport</td><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>
<tr><td rowspan="5">SRA4
Rail Transport</td><td colspan="3">Improve technical performances at system level increasing the energy density for higher train autonomy</td></tr>
<tr><td colspan="3">Harmonise the standards applicable to train at the EU level</td></tr>
<tr><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 rowspan="2">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</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>
</table>

SRA	Short term	Medium term	Long term
SRA5 Off-road Transport	Increase the safety of the battery systems		
		Enhance accessibility, repairability and re-use of battery packs	
		Encompass pre-normative research for NRMM batteries, for defining standards	
Transversal Challenges			
Fast charge	Focus on cells, modules and battery pack design capable of increasing the charging power while limiting degradation		
	Safety issues, standardisation of the control between the battery and the charging infrastructure, and the regulatory framework		
	Compatibility across different vehicle categories, and across different transport mode		
Battery swapping	Development of mechanics and connection of swappable modules, ensuring safety, robustness, acceptable costs, and durability		
	Electronics and battery management system developed for operating different chemistries and adapt different SoX indicators		
	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		
SoX prediction	Identification of sensors for estimating SoX according to a prescribed reference		
	Establishment of methodologies for SoX estimation which are fast, accurate and reliable making use of data		
	Integration and demonstration SoX models fit to run on the existing battery electronics and/or connected platforms		

Table 6: Overview of Strategic Research Areas of the Mobility applications and integration roadmap, developed by Batteries Europe/BEPA WG5

2.6 Application and Integration: Stationary

Electrochemical storage is undoubtedly one of the relevant levers to provide greater flexibility to our electricity system and thus allow higher percentages of renewable energy penetration. The challenges facing the development of battery-based storage stem from the current structure of the electricity markets, regulatory challenges, technological and economic challenges, as well as other challenges related to safety, standardisation and recycling. Different application areas can be defined for stationary storage: home storage systems, district storage systems, large-scale battery storage plant, Commercial & Industrial (C&I) storage systems. Each area could have different specific targets and requirements for an optimal use of the battery system. Research is needed to fulfil the application-specific requirements.

2.6.1 Strategic Research Areas

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

Front-of-the-meter (FTM) battery energy storage systems (BESS) gather different applications and services to different stakeholders connected to distribution or transmission electric power grids. Energy storage systems are also applicable into mini-grids (or micro-grids) with renewable generation powering a mini-grid with battery energy storage at its heart. BESS have the advantage of location and sizing flexibility and can be easily scaled. The use of various energy storage technologies is referred to as Hybrid Energy Storage Systems (HESS). Hybridisation of BESS (or HESS) with generation assets are becoming more common and provide opportunities for many system services related to balancing the demand for various types of energy in Local Balancing Areas (LBA). Offering the best services in the energy market will require synergies between batteries, distributed generation and other types of energy storage, including pumped storage, thermal energy storage, hydrogen, etc. The challenges for FTM BESS hybridised with generation assets is the digitisation of BESS management and energy balancing with optimised algorithms to provide multiservice. This will require interoperability between different systems to provide services between them.

R&D activities needed
Short-term needs (2027):

- Develop digital energy management algorithms using BESS or HESS and distributed generation assets (especially renewable) to provide multiservice. The digitisation of energy management systems will have different goals depending on the level of integration of the algorithms.
  - Virtual power plants based on distributed FTM e.g., District Storages for DSOs.
  - The second stage would be real-time integration of energy production data from conventional, distributed and ESS systems.
  - The next step in the development and integration of digital algorithms for FTM BESS is the control in the mini-grid system operating in island mode or in connection with the main grid.

o Another level of algorithm digitisation is the control and monitoring of the BESS in order to maintain optimal operating conditions (DoD, SoC, C-rate, Max/Min operating temperature).

- Prediction algorithms of BESS operational parameters, such as: calendar lifetime, mean time to failure (MTTF), and degradation factor related to capacity/efficiency in the context of increasing the reliability of systems with BESS and reducing the mean time to repair (MTTR), Operational Expenditures (OPEX) or disconnection cost.

Mid-term needs (2030):

- Create a digital twin of both the BESS and the power system (or mini grid) using digital algorithms and systems for collecting measurement data and forecasts.
- Interoperability of BESS or HESS and distributed generation assets in order to provide multiservice on the energy market for various types of energy in Local Balancing Areas (LBA), e.g., mini grid. Research in this area should focus on the standardisation of communication protocols as well as the creation of middleware integrating various communication standards. Research should concern interoperability in the field of maintaining electromagnetic compatibility (EMC) related to the use of power electronic converters in BESS and generation assets.
- Advanced algorithms to enable shared ownership and/or operation of the storage facility between grid operator and third parties.
- Develop robust methodologies for measuring and evaluating circular economy concepts through aggregation and sharing of data, towards new market models, efficient data management systems and certified digital platforms, as well as a battery readiness for integration into such systems.
- Develop methods of selecting power and capacity as well as the place of installation of the BESS. This will allow optimisation of Capital Expenditures (CAPEX).

Impact

Developing FTM-BESS will increase the absorption of energy from RES and make the generation and consumption of electricity more flexible in local areas, also providing support for the power system, solving congestion and voltage problems, Furthermore, it will enable the Green and Digital Transition of the electrification process in local areas, leading towards a rationalisation of CAPEX and OPEX of BESS in the context of their optimal operation and increasing the time of use.

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

Behind-the-meter (BTM) battery storage systems are not part of the electrical grid distribution system, but an entity used within the consumers' own premises behind the meter. The purpose is to balance the energy flow and lower the energy cost, i.e., buying electricity when it is cheap. The battery is the energy reservoir that makes redistribution of the energy possible over time. This local ecosystem can interact with energy production equipment, e.g., solar panels or wind turbines, for optimal cost reduction. The cost and size of the battery is determined by the consumers energy demand, in combination with the additional energy produced i.e., by solar or wind. The energy management system (EMS) optimises the energy flow over time from the electrical grid, balancing with the internal production and consumption, with the battery is used as a reservoir.

With proper optimisation of the energy management system, the surplus energy can provide a service to the grid operator for solving congestion and voltage issues. The system can also, when and where possible, provide a storage operation to store additional energy for the grid in the form of local services for grid operators. The possibility of using equipment connected to an internal consumer installation for the benefit of the power system is becoming increasingly important.

The Energy Management System must address three different issues:

- Manage the use of the battery system including safety, reliability, low maintenance and long life.
- Manage the energy flow behind the meter including demands and availability, including possible local production of energy, also taking into consideration the participation to grid services through the interaction with an aggregator.
- Predict the solar generation (in case of combination with PV), energy demand and availability of the consumer and optimise with respect to the energy availability of the grid.

R&D activities needed
All timescale (2027-2030+)

- Development of battery hardware enabling the safety, low maintainability, and long life of the battery storage system, including the software and necessary controls to utilise these points.
- Identification of critical limits which will be chemistry dependent. Such critical limits can be connected to environmental constraints, which may be a driving force for research on specific cell chemistries for stationary storage applications.
- Enabling the balancing of energy behind the meter as well as interacting and predicting the energy demand behind the meter. including time shifting energy demands depending on availability of energy as well as local production of energy, solar panels, windmills etc. Prediction of future energy demand should consider information from external available platforms such as price, weather etc., to optimise the overall usage of the battery storage system and maximise impact for the user/owner.
- Improvement in component and system level performance such as calendar life at system level, equivalent full cycle at module / system level (cycles), energy round trip efficiency, MTTF, MTTR, response time, self-discharge, all are of great importance.

As is the case with FTM, the following is also needed for BTM systems:

- Development of integrated algorithms to manage energy flows, production, consumption and storage capacity at the individual customer level and allow a direct integration between the local control and optimisation layer and cloud (or edge) layer of the aggregator’s

platform.
- The capability to analyse the reported needs of the grid operator and aggregators in providing flexibility services. The result of such analysis would be information for the aggregators as to whether there are market needs for service provision.

In addition, such an algorithm indicated the possibility of such optimisation of production, consumption and storage that would allow local services to be provided to the grid operator through the interaction with an aggregator, in a manner acceptable to the active customer. The system itself should propose the type of service (decrease, increase) and its level (kWh) and duration.

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 strategies of the batteries

2.6.1.3 Medium-to-Long Duration Battery Storage

Medium (5-10h h) and long (>10h, up to 100h or more) duration energy storage will be a key enabler to achieve fully-decarbonised, secure, reliable, and affordable power grids. Driving emissions down to zero is essential to achieve a net-zero economy. The electrification of energy demand in all other sectors is only effective under the assumption that power sector emissions fall to zero. While the deployment of variable renewable resources is still accelerating, and will not reach saturation until at least the 2030s, it is imperative to invest in and develop next-generation storage technologies now so that they are commercially viable by the time they are needed. Currently LDES technologies are being developed worldwide covering different types of storage: mechanical, thermal, chemical and electrochemical. The most mature and deployed LDES technology is still PHES but in the last year deployment of medium duration BESS and research funding dedicated to LDES have been increasing.

R&D activities needed
Short-term (2027):
Concerning medium-duration BESS, research needs are related to:
- Develop innovative approaches for consolidated battery technologies (e.g., VRFB, NaS/NaNiCl2, Li-ion, Lead acid): innovate consolidated battery technologies adapting them to medium or long duration storage also through improved electrochemistry and hybridisation; demonstrate capacity expansion during the BESS lifetime through advanced design and management.

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

To reach the cost target most of the technologies are based on low-cost and earth-abundant materials. Here the research needs should focus on:

- Accelerating the technology maturation and upscaling of BESS suitable for LDES (flow batteries, metal-air, etc.) and based on low-cost earth abundant materials (e.g., Zn, Fe, Mn, S, Na, Mg, Pb, Cr) or organic materials aiming at closing the gap with worldwide competitors.
- 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 and developing advanced tools for BESS and emerging LDES techno-economic assessment under different scenarios and time horizons.

Impact

Long Duration Energy Storage (LDES) development will accelerate the deployment of medium-to-long duration battery storage enabled by significant cost and environmental impact reductions obtained through novel system designs and use of low-cost active materials. It will also create a strong medium-to-long duration BESS EU industry, ideally based on EU-sourced materials, capable to meet the long-term EU storage needs (2040-2050) thus ensuring EU competitiveness and energy security.

LDES will support the transition to fully decarbonised power grids based on RES such as solar and wind and decentralised BESS will also result an energy grid which is more efficient, stable and resilient against potential outages.

2.6.2 Transversal challenges

2.6.2.1 Digitalisation, hybridisation and interoperability – standardisation of data sharing and communication (BMS inverter)

Digitalisation of battery storage plays a central role in enabling enhanced safety and increased reliability and uptime of the system. The effective integration of advanced digital solutions, such as digital twins and AI in novel EMS developed targeting different applications and BESS multi-use can be a major step towards next-gen battery storage for the future grid. Interoperability, access to and sharing of data are issues that have to be addressed considering the future needs of a digitalised EU energy system.

Battery Management Systems (BMS) are crucial for monitoring and control of battery systems. The accurate estimation of the battery state-of-health (SoH) is critical for an efficient and safe battery operation. The development of new promising battery technologies based on novel chemistries or hybridisation of existing systems require the development of new flexible BMS that can be used with a wide variety of battery systems. Currently, the development of flexible BMS is challenging due to a lack of standardised interfaces for the access of sensor data and interaction with actuators.

The integration of BMS with higher-level components is a promising approach to overcome the limited computational resources for model-based battery state-of-health estimation, long-term degradation predictions, or predictive maintenance applications. The interoperability of BMS with external higher-level components is difficult due to the lack of standardised communication protocols.

Currently no standards for data sharing between BMS are released. Every BMS defines its own data format specification, usually, based on CAN Bus communications. Although many batteries related standards exist, especially for electric vehicle applications, most of them are focused on safety, testing, and performances.

The increased utilisation of battery energy storage has resulted in the advancement of specific decision-making tools for battery utilisation. This is not limited to a better understanding of the physical and chemical phenomena, but also concerning the practical application, e.g., which types of batteries (chemistries, capacities) are better suited for a given application and/or operational conditions. A knowledge database is being developed and improved in time, and it can be used to develop tools to support decision regarding battery utilisation, allowing the maximisation of economic return while reducing the operational risks.

The expectation is to be able to develop a robust tool that considers battery models and real-time forecasting information to select the best battery operation as power setpoints to the network system. However, the diversity of use cases, applications and services, chemistries and manufacturing designs, combined with the uncertainty over battery lifetime, makes it challenging to design and operate the battery to maximise the economic return on investment.

R&D activities needed

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:

Advanced BMS

Development of advanced energy management systems for BESS or HESS also considering distributed assets and hybrid power plants generation assets capable of optimal scheduling based on forecasted loads and generation. In this direction steps should be taken:

Short-to-Mid-term needs (2030):

- Review of existing battery related standards.
- Identify gaps in BMS standardisation.

- Definition of key BMS parameters and functionalities.
- Definition of data and information to be transmitted.
- Analysis of existing communication protocols for BMS.
- Definition of internal/external interfaces.

Mid-to-Long-term needs (2030+):
- Proposal of data formats and communication interfaces for BMS standards.
- Definition of testing procedures to validate BMS standards.
- Dissemination actions among relevant stakeholders and standardisation push.

1. More general and flexible approaches to BMS are required that allow the usage of a wide range of battery technologies, such as different chemical systems and applications. Open BMS interface specifications should be developed that:Define an abstraction layer between the lower-level BMS hardware, including sensors and actuators, and the higher-level BMS functionalities, such as state estimation algorithms and
2. Define communication protocols for the safe, reliable, and efficient exchange of data between the BMS and external devices.

The effectiveness of the open BMS interface should be proven by a prototype implementation that demonstrates the advanced interoperability of the BMS. This can include the application to different battery systems or the integration of the battery with external digital devices, e.g., to allow efficient software updates to adapt the battery model. Additionally, a clear strategy should be proposed that describes how the permission rights for access to the battery data, including data for the battery passport, should be handled.

New algorithms for battery operation, SoX evaluation and prediction
- New hybrid algorithms combining data-driven methods with model-based approaches, potentially capable to be deployed and executed directly on the edge (battery premises), are required for an accurate and robust estimation of the battery state. The development and integration of advanced sensing technologies in batteries should be investigated with respect to their potential to improve the accuracy and robustness of state estimation and ability to capture phenomena causing battery degradation. Novel BMS should allow for controlling and monitoring batteries at the cell, stack and system level to increase the overall performance. New battery state estimation and control systems allowing for more accurate long-term predictions of battery state degradation processes and predictive maintenance applications need to be developed, e.g., by combining the embedded BMS with external digital twins.
- Focus on open-source tools, based as much as possible on publicly available data/information and/or open-source tools (e.g., PVGIS).
- Advanced management algorithms for optimal battery operation are needed to develop tools that should be easy to use and be able to rely on commonly available parameters (e.g., from the Battery Passport). It should empower citizens to independently analyse their case and be tailored to different stakeholders, from utility scale operators (e.g., large scale renewable plant management), passing through industrial and commercial users or

aggregators, to small scale residential users.

- Advanced battery models able to provide lifetime projections (RUL) and the influence of operating control strategies on aging are necessary for optimal decision-making tools.

Decision making tools

Designing Decision making tools helps to define hybrid energy storage systems in terms of ESS to be combined, sizing of each single-ESS or control strategies based on the requirements of every specific application. The envisioned steps toward this goal are:

Short-to-Mid-term needs (2027):

- Definition of main parameters and rules to be considered (cost/Wh, power density, life cycle, environmental impact, ROI...)
- Study of different DSS models and techniques to be applied.
- Study and definition of potential use cases
- Development and validation of DSS models for HESS

Mid-to-Long-term needs (2030+):

- Improved ML methods based on previous experience.
- Definition of standardised input parameters
- Definition of exploitation models for DSS

Other more specific research needs are:

- Development of a database of models, case studies, and other important information, that will be used to develop the digital tools as well as to validate and improve it.
- Incorporation of local/regional information in the digital tools, based as much as possible in open-source data sources.
- Integration with existing digital tools. This may involve integration with other digital tools aimed to obtain specific information.
- Validation activities, in various geographic and climatic conditions, to assess the robustness and/or uncertainty involved in the development.
- 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.
- Functional safety to be assessed of the hybrid system (HW and SW)

Impact

Battery storage digitalisation encompasses many aspects, and it will impact widely. Enabling the user to actively follow and accept battery operations will increase social acceptance.

Decision Support Systems (DSS) can be a useful tool to select a combination of energy storage technologies that provides an optimal solution, in terms of performance, cost and environmental impact. Standardising information exchange formats between BMSs would facilitate the integration of HESS with various types of batteries. It would allow modular design approaches, which would facilitate the customisation of HESS to the requirements of each

application and reduce design costs.
Standardised interfaces will lower the technological barrier to develop flexible BMS. Advanced BMS will contribute to lowering the operational costs of BESS, while improving performance, lifetime, reliability, and safety. Integration of BMS with external services will allow for long-term battery state predictions enabling utility operators to determine optimal service intervals, schedule replacements of battery components, and perform long-term simulations of a battery system to optimise the battery usage and minimise their degradation.

Communication with higher-level smart grid control units is important to adapt the energy demand profiles of intelligent electricity consumers to the fluctuating power supply from intermittent energy sources, such as photovoltaics and wind. Furthermore, the ability of large battery data analysis by external services will allow for early detection of abnormal battery behaviour, thus enhancing the safety of operation.

Standardised battery data access protocols coupled with a proper communication architecture /strategy will enable service providers or researchers to access battery data and provide recommendations on battery utilisation and provide required information for repurposing and refurbishing for second life battery utilisation.

2.6.2.2 Design for 2nd life

Design for second life has not been the focus of the cell manufacturing companies, nor the companies' making assemblies or products. The first life scenario has been the focus areas with customer demands such as cell shape, cell size, product quality, weldability, solderability, incorporation of sensors as well as safety and durability. The second life scenario including repair and repurposing requires "design for disassembly" at different levels.

Information about first life state-of-health can be useful and very beneficial for second life applications. This is a question relating to the battery passport that is regulatory EU directive question. For a cost-efficient second life application product development this information is crucial. Is the information in the upcoming battery passport sufficient for providing the necessary data?

The uncertainty on the SoX (e.g., State of Health, State of Safety) of dismissed battery can prevent cost- effective logistics. Assessing the accuracy of different SoX prediction methods and comparing values from different manufacturers can be difficult. There are several bottlenecks that prevent the flow of information, batteries, and components along the value chain of EoL batteries. It is essential that these bottlenecks are addressed in order to enable competitive business cases for 2nd life.

R&D activities needed
Manufacturing products requires great knowledge about the environments that the products are going to be used in. First-life batteries from the car industry are often very compact,

mechanically stable, and well-sealed to withstand the harsh operating environment of the vehicle. This makes the repair and repurpose procedure more difficult for second life applications.

Research activities should focus on:
- Explore how to incorporate the concept of designing for second life; design for disassembly, with is also important for the recycling process.
- Develop methods for identification of defective cells / modules / pack, which is essential for second life applications.
- 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".
- Ensuring fast assessment and testing (e.g., < 10 minutes) with reliability and repeatability of results, keeping up with frequent updates on battery chemistries, materials, and manufacturing processes, and the need for open and versatile approaches to SoX measurement.
- Developing cloud-based tools and methodologies focused on different requirements for different stakeholders (e.g., more user- friendly for vehicle dealer and repair shop operators)

Impact

Second life Li-ion batteries from EV are a potential source of high energy density stationary storage systems. The research focus must concern making these products safe, reliable and affordable on the market for maximum impact on global electrification. Achieving the research goals on the battery design for second life will allow new markets and also longer (safer) life of the batteries. These advantages will lead, on the one hand, to greater social acceptance and, on the other, to an increase in the overall sustainability of batteries, as the CRMs contained will be exploited more efficiently. Furthermore, the design for second life goes in the direction outlined by battery regulation, also facilitating the recovery of materials at the end of their life. Finally, batteries built with whole life in mind (first, second and EoL), will facilitate the definition of universal standards.

2.6.2.3 Safety, efficiency and extended lifetime for BESS

Safe operation during the entire life, including first and second applications, is one of the most crucial points for convincing the owners and commercial operators about using stationary battery systems into the homes and production facilities. The efficiency and the lifetime of the energy storage system are both connected to the cost effectiveness of these products.

R&D activities needed
- Facilitate more effective, safe and reliable operation of energy storage through 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 response protocols and maintenance and repair safety guidelines.
- Understanding thermal runaway, specifically of lithium-ion batteries is an urgent need.

The industry needs broad and public testing of batteries and systems to characterise this hazard of the various chemistries and form factors. A proper understanding of the hazard will enable effective mitigation strategies to be designed, validated, and deployed.

- Fire hazard modeling can also support these activities avoiding the high costs of individual tests. These models can be input into tools that can inform all aspects of the project life cycle, such as sitting, design, construction, operations, and incident response. Second life batteries in new products are difficult to risk assess because of the difference history. Protocols and standards need to be developed to convince the market of their potential and safety.
- Emerging storage technology safety information and analysis to study their hazard profiles and possible mitigation strategies.

Impact

Ensuring safety is important to achieve broader social acceptance and facilitate wider utilisation of BESS, even in non-expert user applications such as home-BESS. By developing intrinsically safer batteries, overall system costs can be reduced by minimising expenses associated with safety control and integrated fire extinguisher systems, within the BESS. Additionally, extending battery lifetime and enhancing efficiency will contribute to a decrease in battery costs, a critical factor in stationary storage applications. Ultimately, the availability of more affordable BESS will enable more efficient grid operations and greater integration of RES, thereby driving the desired electrification of the energy system.

2.6.3 Key Recommendations

Affordable, safe, reliable and green battery chemistries developed for stationary storage are strong research candidates. Special attention is crucial on improving existing or new chemistries for long-term storage, enhancing renewable generation and grid flexibility.

Technology is the key ingredient for circular supply chain in global competitiveness and investment should be taken on research needs from European, national and regional level. It is extremely important to promote collaboration along the entire value chain, horizontally, and vertically on cross-sectoral topics, enabling synergies and circular economy.

Fostering of pre-normative research is necessary to define battery system requirements in (emerging) applications, battery system design bases, interoperable BMS and IoT, improve sustainability and aim at reaching scale benefits in battery industry. Pilot projects operating within the regulatory framework are key for BESS research enabling upscaling from low TRL up to field test in small grid or RES-integrated pilot plant. Sharing values and knowledge between different stakeholders is key to cross boundaries and overcome challenges due to both regulatory barriers and lack of reliable business models.

<table>
<tr><th>SRA</th><th>Short term</th><th>Medium term</th><th>Long term</th></tr>
<tr><td rowspan="7">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 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></td><td colspan="2">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="4">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>
<tr><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>
</table>

<table>
<tr><th>SRA</th><th>Short term</th><th>Medium term</th><th>Long term</th></tr>
<tr><td colspan="4">Transversal Challenges</td></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>
<tr><td rowspan="4">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>
</table>

SRA	Short term	Medium term	Long term
Digitalisation - Decision making tools		Improved ML methods based on previous experience.	
		Definition of standardised input parameters	
		Definition of exploitation models for DSS	
Digitalisation	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.		
	Incorporation of local/regional information in the digital tools, based as much as possible in open-source data sources.		
	Integration with existing digital tools.		
	Validation activities, in various geographic and climatic conditions, to assess the robustness and/or uncertainty involved in the development.		
	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.		
	Functional safety to be assessed of the hybrid system (HW and SW)		
Design for 2nd life	Explore how to incorporate the concept of designing for second life; design for disassembly, with is also important for the recycling process		
	Develop methods for identification of unusable cells / modules / pack, which is essential for second life applications.		
	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".		
		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.	
		Developing cloud-based tools and methodologies focused on different requirements for different stakeholders.	
	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		
Safety, reliability, efficiency and extended lifetime for BESS	Response protocols and maintenance and repair safety guidelines		
	Understanding thermal runaway and propagation (including the function of propagation inhibiting material), specifically of lithium-ion batteries		
	Fire hazard modelling		
	Emerging storage technology safety and reliability information and analysis to study their hazard profiles and possible mitigation strategies		

Table 7: Overview of Strategic Research Areas of the Stationary applications and integration roadmap, developed by the Batteries Europe/BEPA WG6

3. Conclusions

The Batteries Europe (BE) Roadmap is the result of the coordination work of experts involved in the six thematic Working Groups and four Task Forces. The engaged experts have identified 33 strategic research areas along with 17 additional specific transversal topics across the entire battery value chain, for which challenges, R&I needs, and impacts are described. Timelines are also provided that suggest when this research should be underway. Key recommendations for policy and authorities, industry and research are finally derived.

This document aims at serving as a lighthouse for battery research and innovation in order to make Europe ever more competitive, self-sufficient and sustainable in the global battery production scenario. The Battery industry is, in fact, evolving rapidly in Europe. As shown by the EBA, over 40 giga-factories have been announced, several that are in construction phase and some with qualification lines already established.

With this Roadmap, Batteries Europe underlines the importance to coordinate research through beneficial synergies that are welcomed thanks to a fertile European battery research ecosystem. Batt4EU, for example, is an excellent enabling partnership to implement many of the identified research concepts in the Horizon Europe framework program. However, 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. For instance, extraction technologies as described in the raw materials research areas are not part of the scope of BATT4EU and hence could be adopted by other initiatives such as EIT Raw Materials. Another sector of the value chain which is not covered by the BATT4EU Partnership is the integration of the battery systems into the final application. However, BATT4EU works together with partnerships covering research on different transport applications, namely: 2Zero (road transport), ZEWT (waterborne), Clean Aviation and Europe's Rail. Stationary energy storage currently does not have a specific partnership which addresses this topic in Europe and hence it may need attention. Moreover, national and regional research entities may find research areas which are highly relevant to their landscape and may wish to utilise these concepts as a basis to their own research programs.

In order to constantly support the entire battery value chain by a holistic approach, Batteries Europe will deliver future Roadmaps and KPIs, which can be used to track the developments of the technologies mentioned in the document and will identify further R&I actions that need to be carried out. In particular, the BE platform expects that many of the identified concepts now seen in the new and emerging technologies will evolve into the other sectors of the future roadmaps. Moreover, Batteries Europe foresees that the Education and Skills section will demonstrate the upcoming opportunities and hence will become a source of inspiration to those considering a career in the field of battery technology.

Being the hub for battery research in EU, Batteries Europe awaits that these suggested research areas will serve as a guidance to those preparing research programs, both industry and public, and for a strategic plan in the battery research sector. Should Batteries Europe, as a community, be successful in the investigation of such research areas and in having the results implemented by industry, the outcome will be a cleaner and healthier environment, with lower carbon emissions, and increased opportunities of sustainable employment in the battery sector in Europe.

4. Additional References

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