SWEDISH BATTERY ROADMAP

A Proposal for a Swedish Battery Research and Innovation Roadmap





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1. FOREWORD

Sweden’s transition to a more sustainable and electrified society is highly dependent on access to modern advanced batteries. Batteries are a crucial enabler of the climate transition, industrial development, and the stability of our energy system. At the same time, access to raw materials, advanced materials, battery manufacturing equipment, and high-performance batteries is characterized and affected by geopolitical uncertainty and intense global competition.

This proposal for a roadmap for Swedish battery research and innovation has been developed through broad collaboration between academia, industry, and societal stakeholders in Sweden, with the ambition of providing a comprehensive overview of the current situation, needs, and opportunities. Through a common approach and coordinated action, we aim to lay the foundation for long-term investments that strengthen Sweden’s position in battery research and innovation, to ensure Sweden’s sovereignty and significantly enhance our competitiveness and resilience.

The roadmap’s definition of the battery field encompasses the entire battery value chain, from raw materials, through new and advanced battery materials, battery concepts, and battery technologies, to battery cell manufacturing and the smart implementation of batteries in various applications. In order to accelerate research and enable innovations to be implemented more rapidly than today, new tools such as AI and ML algorithms must be integrated, and real battery data must be usable in a traceable and shareable manner while maintaining protection for commercial actors. For a long-term more sustainable society, reuse and recycling are considered and integrated from a circular perspective.

This work has been made possible through the strong commitment of stakeholders across the entire battery value chain, as well as financial support from the Swedish Research Council and the Swedish Energy Agency.

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2. INTRODUCTION

Batteries are a key technology in our increasingly electrified society. Since the early 1990s, modern batteries, primarily lithium-ion batteries, have been a prerequisite for all portable electronics and thereby for how our modern society functions and is structured. Today, batteries are also absolutely essential for reducing emissions from the transport sector and improving its energy efficiency, on and under land, at sea, and in the future also in the air.

In addition, there are large-scale battery energy storage systems for the optimization and balancing of renewable energy and for improving the quality of the electricity distribution system. They are also vital components in partly new applications and areas of use such as data centres, robotics, drones, agriculture and forestry, among others.

This broad range of socially important applications clearly demonstrates why batteries are absolutely essential for Swedish industry and, in a broader sense, for prosperity, resilience, security, and the reduction of greenhouse gas emissions.

Geopolitical uncertainty and intense global competition in particular create major challenges today for the development and production of batteries. Significant investments have been made and continue to be made in recent years to ensure a European battery value chain, including raw materials, production, system integration, and recycling. This should also be reflected in the investments made in Sweden.

Sweden has a high level of expertise as well as access to important raw materials across large parts of the battery value chain and can therefore play a relatively significant role both within the EU and globally, but only given political prioritization and even stronger collaboration and coordination between academia, industry, and society at large.

3. METHODOLOGY

The development of this roadmap was coordinated by Uppsala University and carried out by representatives of the Swedish battery ecosystem spanning the entire battery value chain.

The starting point was a major workshop held in Stockholm on 27 November 2025, with the objective of placing the *Roadmap* developed within the European Battery 2030+[1] initiative into a Swedish context. Representatives from across the Swedish battery landscape participated in the workshop, including stakeholders from industry, academia, and government agencies.

[1] https://battery2030.eu/wp-content/uploads/2025/11/Deliverable-2.2_Roadmap_4th-edition_final_-2025.10.31.pdf



Six key thematic areas of need were identified and developed during the workshop. These subsequently formed the basis for six dedicated focus working groups. During spring 2026, the groups further elaborated these themes into the present roadmap (Appendix 1).

Based on the outcomes of the workshop and the work carried out by the focus groups, an overarching vision, purpose and objectives, as well as concrete short- and long-term needs, were developed within three strategic action areas. A preliminary version of the roadmap was presented at Almedalen Week 2026, and the feedback received there has also been incorporated into the final document.

The work has furthermore drawn upon previous strategic documents, including Fossil Free Sweden's *Strategies for a Sustainable Battery Value Chain* (2020)[2], as well as reports from the Swedish Energy Agency, the Swedish Environmental Protection Agency, and the Geological Survey of Sweden (SGU) (2022-2025)[3]. These documents particularly emphasize the need for research, skills development, and a holistic perspective on the battery value chain.

In addition to the roadmap produced within the EU flagship initiative Battery 2030+[1], the European Union's *Strategic Research & Innovation Agenda (SRIA) for Batteries (2024)*[4] and the EU's *SET Plan Action 7*[5] have guided both the direction and design of the roadmap, in order to optimize Sweden’s opportunities to act in alignment with European initiatives.

[2] https://fossilfrittsverige.se/strategier/hallbar-batterivardekedja/
[3] Energimyndigheten, Naturvårdsverket och SGU: Fortsatt samverkan kring Sveriges delar av en hållbar europeisk batterivärdekedja, ER 2023:24, dec 2023
Energimyndigheten, Naturvårdsverket, SGU, Utveckla myndighetssamverkan för Sveriges delar av en hållbar europeisk värdekedja för batterier, ER 2022:14, okt 2022
[4] https://horizoneuropencpportal.eu/sites/default/files/2025-07/batt4eu-strategic-research-and-innovation-agenda-sria-2024.pdf
[5] https://setis.ec.europa.eu/working-groups/batteries_en



4. EXECUTIVE SUMMARY

This roadmap presents a coherent strategy for strengthening Swedish battery research and innovation, and thereby also our industrial competitiveness, over a ten-year perspective. Batteries are a key technology for electrification, the climate transition, and the development of a secure, robust, and sustainable energy system, while also constituting a strategic component for Sweden's prosperity, security, and resilience.

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Despite Sweden's limited size, there is a strong knowledge base and presence across large parts of the battery value chain, from the extraction of raw materials and advanced materials development to optimized system integration and recycling processes. To fully realize this potential, clear political priorities and stronger coordination between academia, industry, and society are required, as well as long-term investments to keep pace with comparable countries in the Western world and to meet the rapid developments in East Asia.

With this in mind, the roadmap identifies six central thematic areas of need: new battery chemistries and technologies, accelerated materials development, battery management and smart systems, manufacturing and digital twins, circular and sustainable value chains, and the interaction between science and society. These areas reflect the need for a holistic approach in which research, innovation, and industrialization are developed in parallel and in an integrated manner.

A central conclusion is that development must take place in a coordinated, long-term manner and across the entire battery value chain, rather than through short-term projects that result in isolated segments. Sweden should deliberately pursue two parallel initiatives.

The first is a long-term investment in next-generation battery chemistries[6] and technologies[7], where fundamental materials research, process development, system integration and management, modelling, diagnostics, and sustainability analysis are developed in an integrated manner and in parallel at an early stage to ensure that new technologies can be scaled up and implemented. At the same time, a balance is required between long-term, excellent, and exploratory research and more short-term, application-oriented innovation initiatives to meet industry's needs to make the best possible use of today's commercial batteries, thereby ensuring continued competitiveness in the short and medium term.

[6] Battery chemistries refer to differences in the materials used within a specific battery technology, such as NMC or $LiFePO_4$ as cathode materials in lithium-ion batteries.
[7] Battery technologies refer to differences in fundamental concepts, operating mechanisms, functions, and architectures, such as lithium-ion batteries, lithium-sulfur (Li-S) batteries, or solid-state batteries.



The roadmap particularly emphasizes the importance of leveraging the opportunities offered by digitalization, including AI, machine learning (ML), and digital twins, to accelerate the development of new and advanced materials, processes, and systems. Data-driven approaches, shared data platforms, and integrated models are considered crucial for reducing development times and strengthening Sweden's competitive conditions.

To enable this development, the roadmap identifies three cross-cutting areas of action:

1. **Collaboration and Coordination** through a national battery research and innovation platform that brings together stakeholders, strengthens strategic direction and interaction, and enables more efficient use of resources.
2. **Accelerated Research, Development, and Scale-up** through research and technology infrastructures, such as large-scale research facilities, data infrastructures, and pilot lines, that reduce the gap between laboratory research and industrial production while advancing knowledge of battery materials through advanced and unique experiments and computational methods.
3. **Education and Skills Supply** where the need for both specialized expertise and broader education throughout the entire value chain is highlighted as a critical factor.

Furthermore, the roadmap addresses the importance of long-term fundamental research on next-generation battery materials and battery concepts, circularity, resource efficiency, and life-cycle perspectives, where recycling, reuse, and sustainable raw material supply are integrated at an early stage in the research and innovation processes. There is significant potential in leveraging advances in multiscale modelling (MSM), artificial intelligence (AI), and machine learning (ML) for the development of battery management systems (BMS) with cloud-based applications, as well as future manufacturing methods for battery cells. At the same time, significant challenges related to global supply chains, data availability, regulations, and skills shortages are identified.

The overall vision is that, within ten years, Sweden should have positioned itself with valuable, unique, and essential cutting-edge expertise within a European system of world-leading, cohesive, and internationally competitive research and innovation environments in the battery field. Through close collaboration between academia, industry, and the public sector, Sweden should be able to develop and produce next-generation sustainable batteries, strengthen its role in the European battery value chain, and contribute to long-term sustainable societal development.



5. VISION

In ten years', time, Sweden will have internationally leading research and innovation in selected parts of the battery value chain and strong, cohesive expertise across the entire value chain (Appendix 2 Battery Value Chain), through academia, industry, and society at large jointly building a cohesive and strong research and development environment as an irreplaceable part of the European battery initiative.

This environment shall enable the development and production of the next generation of more sustainable and environmentally friendly batteries in Sweden, while at the same time strengthening the competitiveness of Swedish industry that depends on battery technology, not least the automotive industry.

6. MISSION

To achieve the vision, Sweden will continue to develop existing strong environments for collaboration between academia and industry with the aim of generating new knowledge and innovations, as well as developing and testing new concepts, components, materials, methods, technologies, and processes within the battery field.

This lays the foundation for Sweden, in the long term, to achieve an internationally strong position in materials and technology within the strategically important battery field by:

- Research programmes with long-term continuity and sustainability, in which long-term "blue-sky" research is balanced with more focused short-term and applied efforts, are implemented to accelerate the pace of innovation.
- Collaboration within the Nordic region and Europe, and knowledge exchange with other leading and collaboration-oriented battery development nations such as Japan and South Korea, are intensified.
- Swedish researchers and the Swedish raw materials industry increase their collaboration with stakeholders in strategically important countries and regions such as Canada, Australia, Africa, and South America.
- Research and development activities for batteries take manufacturing scalability into account, including with respect to raw materials and the potential for cost-effective recycling. The reuse of components is considered at an early stage.
- Regulatory frameworks and business models for a circular economy are developed and become well established.
- Knowledge of climate impact and other sustainability challenges is deepened with regard to different supply pathways for the production of dominant and promising future battery chemistries and technologies.
- Innovations in the battery field are, to a large extent, based on analysis from a life-cycle perspective.



7. UNDERLYING NEEDS

Based on the vision and mission, the six thematic areas of need are presented, together with the analyses and considerations carried out within each area, as well as the conclusions and proposals that have been developed. These form the basis for the roadmap's areas of action and recommendations. Each area of need has unique conditions in both the present and the future, which is reflected in the fact that the material within each description differs in both structure and content. The differences become particularly apparent with regard to time perspectives, as the timescales vary across different areas. This is especially true with respect to research and industrialization, where the progression from successful short- and medium-term research on new battery materials to cell concepts and implementation at industrial scale often takes at least 10 years. There is also an inherent inertia in broader societal transitions that plays a significant role in how quickly knowledge and acceptance of technological shifts spread and are adopted by wider segments of society.

The six thematic areas of need are:

1. New Chemistries and Technologies
2. Accelerated Materials Development
3. Control and Smart Systems
4. Manufacturing and Digital Twins
5. A Circular and Sustainable Value Chain
6. Science and Society

A summary of the actions proposed within the six thematic areas is provided in Appendix 3.

In addition, three cross-cutting priority areas have been identified to address the fundamental needs and prerequisites recurring across all six thematic areas and to support their implementation:

1. Collaboration, a strategic battery research and innovation platform
2. Accelerated research, development and scale-up through large-scale research infrastructures and other technology infrastructures
3. Education and skills supply



THEME 1. NOVEL CHEMISTRIES AND TECHNOLOGIES

With an increasing diversity of battery applications, the range of requirements for what a battery must be able to deliver, as well as the economic and environmental conditions for different battery technologies, is expanding. Although today's dominant lithium-ion battery technology based on NMC or LFP cathodes and graphite anodes is powerful, there is both a need for and development potential in new chemistries and technologies. A number of different concepts exist at varying levels of maturity, and world-leading research is being conducted in Sweden on several of these, which also builds future competence for increased competitiveness.

The Battery 2030+ roadmap[1] links research on the chemistries and technologies of tomorrow with innovation and competence development. By placing it in a Swedish context, we lay the foundation for not only Europe but also Sweden to build independent supply chains and technologies in this strategically important field over time.

To take an idea from the laboratory to a product, both fundamental and applied research are needed. Research on new materials and fundamental reaction mechanisms forms the basis for new discoveries in the field, while any fundamental barriers related to material scale-up and manufacturing methods, environmental and sustainability aspects, and legislation must also be taken into account. Criteria that are important when evaluating new battery chemistries and technologies are primarily (i) low cost, (ii) circularity and recyclability, (iii) electrochemical performance, and (iv) safety aspects across different parts of the battery value chain.

A robust analysis of the above criteria should form the basis for determining whether a new battery chemistry or technology can be matched with relevant applications. Although vehicle applications have long dominated and driven development in the field, batteries are also needed in many other contexts. It is important to understand where energy-optimized or power-optimized battery cells are best suited, whether the cell concept can be used at high and low temperatures, what flexibility exists in terms of format, etc. This creates different frameworks for technical questions.

New chemistries and technologies can broadly be divided into the following categories:

- Next-generation lithium-ion batteries based on new cathode materials (e.g., LMFP, LMR, DRX (*disordered rock salt*), LMNO, among others) and/or anode materials (alloy anodes, e.g., Si). These contribute to lower costs, higher energy density, and are free of cobalt.
- Batteries based on Na, K (monovalent), Mg, Ca, Al, or Zn (multivalent) active ions. Of these, sodium-ion batteries are beginning to become commercially available, but much of the material and component development remains to be done: cathodes (oxides, polyanionic materials, and variants of Prussian blue), anodes (various carbon materials, alloys), and scale-up processes. For other active ions, more fundamental research on new materials and electrochemical processes is needed in order to potentially achieve large-scale commercialization.
- Metal batteries, which represent a further development of the lithium-ion battery, but where lithium metal is used as the anode instead of graphite in



order to increase energy density. Metal electrodes can also be applied for metals other than Li, which in many cases is likely a prerequisite for the technology to become competitive (K/Mg/Ca/Al/Zn).

- Solid-state batteries, where liquid electrolytes are replaced by a solid electrolyte, which may be based on a polymer, a glass, a ceramic, or a hybrid of these. The advantages are primarily the potential for increased energy density (if implemented with metal electrodes) and the possibility of achieving enhanced safety, as solid-state electrolytes are generally less flammable.
- Batteries based on conversion chemistries rather than intercalation, for example Li-S and Li-O_2. These offer the potential for both increased energy density and improved sustainability from a materials perspective, but the technologies are difficult to master.
- Organic electrode materials, where the active materials may be derived from biomass.
- Flow batteries, where the active materials are contained in solution rather than in solid electrodes. This makes it possible for energy and power to be scaled more independently of each other.

The new chemistries and technologies need to be developed in order to better understand their potential and shortcomings, but different timescales apply depending on the maturity level of each chemistry and technology. There are also major differences in the performance that can be expected from different types of technologies. Having an application-driven approach in fundamental research from the outset helps accelerate development towards innovation and ultimately a product. In **the short term** (<3 years), more advanced Li- and Na-based chemistries and technologies may gain traction; in **the medium term** (3–5 years), Li-metal batteries (possibly also Na- and Zn-metal batteries) as well as solid-state batteries; and in the **long term** (>5 years), multivalent metal batteries, conversion chemistries, organic batteries, flow batteries for large-scale energy storage, and so-called “anode-free” batteries, where the metal anode is created during charging.

For the next generation of battery technologies, long-term research is needed, ranging from fundamental materials science and electrochemical mechanisms to process technology, sustainability, and recycling. However, considerable benefits can be achieved if the different parts of the value chain are integrated at a relatively early stage in order to increase the potential for new materials, chemistries, and technologies to make it all the way from idea to product. Another important aspect is that “best practices” need to be developed in order to evaluate and compare results from research studies on new chemistries and concepts. This will, in turn, facilitate the use of data-driven methods.

It should be kept in mind that Sweden, as a small nation, can maintain broad expertise across all areas, but in the long term can only maintain cutting-edge expertise and world-leading status in certain areas. While Sweden should definitely maintain broad competence within the battery field and across the entire value chain, a limited number of areas also need to be identified in which Swedish research groups can make fundamental breakthroughs based on our academic excellence and decisive contributions through collaboration between academia and industry. Conditions must therefore be in place for technology-driven fundamental research across a range of battery chemistries and technologies. Knowledge of fundamental



chemical processes and materials can also be readily transferred to adjacent technology areas such as electrocatalysis, sensors, etc., which should be encouraged so that these research fields cross-fertilize each other. In this context, responsible and synergy-driven internationalization is also of great importance, where Sweden can build on existing collaborations with, for example, research groups in South Korea, Japan, and Taiwan, which are world-leading in specific technological fields.



THEME 2. ACCELERATED MATERIALS DEVELOPMENT

To create a tactical advantage in the intense international competition within the battery field, Swedish and European researchers should take advantage of the rapid developments taking place in digitalization (including AI and ML). These technologies will accelerate the development and understanding of material and battery concepts. To achieve this, we need to move from linear thinking to integrated thinking. This means that experimental battery data are used to create better algorithms and modelling tools. Based on this, five strategic research directions are proposed.

1. AI-driven multiphysics modelling at pack and system level

Develop physics-based, AI-supported digital twins that integrate electrochemistry, mechanics, and thermal behaviour, from particle to pack level. Calibrated, uncertainty-aware models will enable faster design, validation, and model-based safety analysis as a complement to physical testing.

2. Requirement-driven inverse design for strategic material selection

Start from industrial requirements regarding safety, cost, climate performance, and lifetime to derive material selections and cell architectures using multi-objective methods (e.g., Bayesian optimization). In the design of these methods, raw material availability, recyclability, and regulatory requirements should also be considered. This direction focuses on generating and comparing alternative design concepts, principle choices, and trade-offs based on a smart requirements specification.

3. Integrated MAP workflows (Materials Acceleration Platform)

Connect multiscale simulation, autonomous experimental synthesis, and high-throughput testing in AI-controlled closed loops. The goal should be to move from hypothesis to a validated laboratory cell in less than six months, thereby substantially shortening the path from laboratory to pilot scale.

4. Secure, layered data and model infrastructure

Develop shared data ontologies, APIs, and protocols for version management. A layered infrastructure should distinguish between open research data, confidential industrial data, and regulatory traceability data. Collaborative model training, including methods such as federated learning, should be enabled so that models can be trained across these data layers without transferring raw data and compromising data security. Advanced models should be able to be offered as secure services also to small and medium-sized enterprises.

5. Design for manufacturability, use, and circularity

Integrate manufacturability, recycled material flows, and battery data early in material, cell, and pack design and use AI-driven workflows together with advanced materials simulation models. In this way, insights from pilot studies, use, and recycling can continuously be fed back into updated design rules and requirements for subsequent design cycles.



Implementation Strategy

Initiative	*Description*
Swedish Battery Models API	Validated models and integrated workflows for multiphysics simulation, diagnostics, and uncertainty quantification provided as secure services through national and European HPC/AI infrastructures.
National MAP Alliance	An integrated workflow linking multiscale simulation, autonomous experimentation, and cell validation at testing facilities (e.g., RISE and SEEL) across Swedish nodes, with Nordic collaborations where these provide clear added value.
National Digital Twin Platform	Common data schemas, ontologies, and interfaces for simulations, experiments, and validation, demonstrated through Swedish use cases.

Three demonstrators are proposed for implementation by 2028, all of which have the potential to deliver significant international impact:

D1: An uncertainty-quantified AI-driven multiscale model for a Swedish heavy-duty vehicle use case, with validated accuracy (prediction error and domain of validity) and orders of magnitude faster than conventional simulation.

D2: An integrated MAP workflow from computation to a validated laboratory cell with no more than two manual interventions, i.e., with a very high degree of automation.

D3: A layered data and modelling platform verified together with at least one industrial partner through secure learning (enclave or federated).

Sweden has favorable conditions to be a frontrunner in this regard. There is (i) a coherent chain from materials to systems consisting of strong environments at different higher education institutions, national HPC/AI infrastructure, as well as pilot environments such as SEEL[8] and the research institute RISE; (ii) an industry-driven need represented by Swedish OEMs (e.g., Volvo Cars, Volvo Group and Scania/Traton), energy companies (e.g., ABB, Vattenfall) and recycling actors (e.g., Stena Metall), which require application-adapted solutions for packs, systems, safety, lifetime and circularity (rather than relying solely on standard cells from international suppliers); and (iii) a rich landscape of existing platforms and collaboration structures such as Battery 2030+, BASE[9], SEEL[8], Compel[10] and the Swedish Electromobility

[8] https://www.chalmers.se/en/infrastructure/swedish-electric-transport-laboratory-seel-and-fuel-cell-laboratory
[9] https://ww.batteriessweden.se/w/bs/
[10] https://www.uu.se/vetenskapsomrade/teknik-och-naturvetenskap/forskning/starka-forskningsmiljoer/compel; https://www.lth.se/forskning/profilomraaden/compel/; https://www.chalmers.se/samarbeta-med-oss/partnerskap-och-natverk/batterisatsningen-compel/



Centre[11]. These trust-based relationships between academia, research institutes and industry make shared data and testing environments practically feasible. By linking to other initiatives such as WASP and WISE, Sweden can bring together broad interdisciplinary expertise, strengthen funding and facilitate knowledge transfer between academia and industry.

[11] https://emobilitycentre.se/



THEME 3. CONTROL AND SMART SYSTEMS

Battery management is a central component in the electrification of the transport sector, the energy system, and a growing number of industrial and societally critical applications. Battery management is responsible for the safe, efficient, and cost-optimized operation of batteries through monitoring, state estimation, control, and protection. Traditionally, the field has been dominated by relatively simple model-based methods based on equivalent circuit models and limited sensor data, primarily relating to current, voltage, and temperature.

Over the past few years, however, the field has developed rapidly. Increased electrification, requirements for fast charging, longer lifetime, and higher safety have driven the development of more advanced methods based on machine learning and detailed physical models. At the same time, the application scope of the research field is expanding, from cars, buses, and trucks to, among others, battery energy storage systems (BESS), special-purpose vehicles, military applications, and vehicle-to-grid (V2G). As cost, safety, and functionality emerge as overarching drivers, smart management becomes a key tool for exploiting the full potential of batteries and managing variations in quality. In addition, these tools can enable flexibility as chemistries, technologies, cell formats, and applications change.

Vision and Objectives for the Next Decade

Within ten years, Sweden should have established an internationally leading position in intelligent, adaptive, and cost-effective battery management. The vision is battery management systems that are chemistry- and technology-neutral, learning and resilient, and that enable batteries to be safely utilized close to their limits throughout the entire life cycle, from first use to reuse and last life.

Central to this is model-based battery management that is integrated early in the development of new chemistries and technologies, such as sodium-ion batteries and solid-state batteries. BMS should therefore not be an add-on at the end of the development process, but an enabler that shapes how components, cells, modules, and systems are designed. For existing lithium-ion battery-based systems, the goal is to significantly extend lifetime, enable robust fast charging, and reduce system costs through advanced management rather than expensive hardware.

Furthermore, future battery management should be based on more detailed physics-based models that are still numerically manageable in real time. These models should form the basis for so-called soft sensing, where states such as degree of ageing, safety status, and latent faults can be estimated digitally and virtually without extensive sensor systems. The area of “state of safety” becomes central here: early identification of at-risk cells and failure mechanisms should be standard.

An important objective is to realize reconfigurable battery systems, where electrical architecture and management enable dynamic connection of cells and modules. This can ensure that weak cells no longer limit the entire system, enable the mixing of different battery and cell types, and reduce the need for external components such as converters. At the same time, this requires new methods for state estimation and control.



Battery management should therefore, within a ten-year period, become data-driven at multiple levels. Local, embedded BMSs should interact with cloud-based monitoring and analysis, where data streams from many units are used for continuous learning, optimization, and updating of models and algorithms. Local adaptation will be applied to accommodate both initial individual variations between cells and packs, and to counteract ageing.



Recommendations for Swedish Research and Innovation

To achieve the above vision, a number of strategic investments in Swedish research and innovation are required. Sweden should deliberately pursue two parallel research tracks. One focuses on next-generation battery chemistries and technologies, where management, modelling, and diagnostics are developed in an integrated manner and in parallel with materials and cell research. The other track focuses on today's commercial cell types that are expected to dominate over the next 5–10 years, in order to ensure that Swedish industry remains competitive in the short and medium term.

In addition, clear investments in model development and data quality are required. Research should prioritize physics-informed models that can be calibrated efficiently, combined with EIS and other advanced measurement methods, and adapted over time through adaptive and learning-based modelling. Here, Sweden has good prerequisites through strong materials research and growing expertise in data platforms and AI, as well as emerging collaboration between these areas.

Furthermore, research on functional allocation between local systems and the cloud should be strengthened. This concerns both technical issues such as real-time requirements, cybersecurity, and data management, as well as architectural choices that can reduce hardware costs and enable simpler BMS solutions for certain applications.

Particular attention should be given to the life-cycle perspective. To enable second life, reuse, and repurpose, standardized and reliable state information over time is required. Battery management is a key factor in this regard, and Swedish research can play a central role in defining which data and control strategies are required.

Finally, to maintain and strengthen Sweden's global position in the automotive industry and power electronics, and to support the Swedish ecosystem including smaller companies and new actors, testbeds and open data platforms in collaboration between industry, academia, and public stakeholders should be prioritized. Such an investment can catalyse cross-functional research and innovation in battery management and related fields, and enable Sweden to build an ecosystem where advanced battery management becomes a competitive advantage.



THEME 4. MANUFACTURING AND DIGITAL TWINS

Sweden has very favourable conditions for battery production through fossil-free electricity, competitive energy prices, and large energy storage capacities for fast-response power generation. In addition, there is a strong industrial tradition of integrated product and production development. At the same time, academic process expertise and the systematization of industrial experience are still insufficiently developed, meaning that key industrial experiences have not been fully systematized and utilised in research and education. There is a need for capacity building and revitalisation in this area, while critical steps throughout the entire production process need to be developed to create the conditions required to remain at the international forefront. The key drivers for this are cost, environmental performance, and quality.

Electrode Manufacturing

Electrode production dominates energy, cost, and quality outcomes in battery cell manufacturing, but is still often developed using recipe-based approaches. A transition to data- and simulation-driven development is crucial, where rheology, coating, drying, and calendering are treated as an integrated physical system. Multiphysics and multiscale models, from particle to process level, need to be combined with reduced-order models and ML for near real-time optimization. This is enabled by advanced inline sensing, including EIS, optical and laser-based systems, X-ray/laminography, and neuromorphic sensors, creating multimodal datasets for closed-loop control. In parallel, a transition to more sustainable process chemistry, dry coating technology, water-based processes, and compatibility with new electrolyte systems is required. Metal batteries and solid-state batteries entail changed production paradigms with new requirements for interfaces, handling, and quality assurance. To make Europe independent of base metal supply flows (e.g. through the development of LFP chemistries), integrated optimization from raw material characterization to electrode and cell performance is required, where variation in materials needed for the synthesis of electrode materials is managed through data-driven models and adaptive processes.

Battery Cell Assembly

The assembly of components into a finished battery cell requires highly automated production in controlled environments. Critical process steps such as stacking, cutting, and welding constitute bottlenecks and require micrometre precision, deep process understanding, and advanced online characterization. Variations in materials and geometry place demands on adaptive and robust production systems. Electrolyte filling is a particularly challenging process step governed by complex transport phenomena linked to pore structure, viscosity, and surface interactions in electrode materials and separators. Optimization therefore requires a combination of modelling, operando measurements, and new filling strategies. Formation and ageing are critical and energy-intensive steps, where model- and data-driven control enables adaptive charging strategies, improved quality, and early detection of deviations. Integrated into digital twins, each cell can be treated individually, increasing robustness and efficiency.

Module, Pack, and System Assembly



At the system level, electrochemical, mechanical, thermodynamic, and electronic subsystems are integrated, which requires a consistent application of integrated product and production development. Current designs are often optimized for the application rather than for production, leading to complex and difficult-to-scale assembly processes. Future systems need to be developed with production as a design parameter, where cell-to-pack and modular concepts enable a higher degree of automation. Joining technologies should balance performance, cycle time, and recyclability. BMS becomes a central node that connects operational and manufacturing data and enables traceability, predictive maintenance, and continuous feedback to design and production through digital product passports. These digital product passports enable traceability and link material content, production data, and usage history, supporting both regulatory requirements and circular business models. Consistent IT/OT integration is, in this context, a prerequisite for data-driven production and digital twins, which also affects the interaction between battery production and the surrounding energy system. This requires architectures in which data can flow between sensors, machines, and higher-level systems. Interoperability is crucial and requires standardized interfaces and semantic data models that ensure that data can be interpreted and used consistently throughout the value chain.

Infrastructure

To realize data-driven and industrially relevant battery production research, a coherent infrastructure of pilot lines and experimental environments is required, spanning from basic research to industrial scale-up. Today, there is a clear gap between laboratory experiments and full-scale production, which hinders the validation of process models, material concepts, and digital twins. Universities therefore require small- to medium-scale pilot lines, accessible nationally and within Europe, where the focus is on understanding fundamental processes and linking these to measurement data and modelling. These environments should enable research across the entire process chain, from slurry preparation to electrode and cell manufacturing, with a high degree of instrumentation and flexibility to support research and education.

In parallel, dedicated experimental setups linked to large-scale research infrastructures such as MAX IV and ESS are needed, where advanced light- and neutron-based techniques can be used to study process chemistry and physics operando. This enables unique insight into, for example, the structural evolution of materials at the atomic level, transport phenomena, and interfaces under realistic manufacturing conditions, which is crucial for the development and validation of physics-based models.

Finally, structured and funded access for academia and research institutes to (pre-)industrial pilot and production lines is required. These environments enable validation at a relevant scale, where process robustness, variation, and integration with real production systems can be studied. This does not primarily constitute a supporting function, but a strategic core capability. It is only through these integrated environments that Europe can accelerate development, reduce risks in the scale-up phase, and establish a truly competitive and knowledge-driven battery industry. By combining these levels, from university environments to advanced research infrastructure and industrial lines, a coherent development chain can be established, in which knowledge, data, and models are continuously transferred and refined.



THEME 5. A CIRCULAR AND SUSTAINABLE VALUE CHAIN

Sweden is one of the EU's leading nations in mineral exploration and mining and is also well positioned in research related to mineral extraction. Active mining operations are conducted for iron ore as well as base and precious metals, and there is a confirmed geological potential for battery raw materials such as graphite and lithium. Sweden was an early adopter of regulated waste management and has prioritized recycling due to progressively stricter environmental legislation. There are also pioneers in life cycle assessment (LCA) and other environmental assessment methodologies. Academic research focused on batteries is growing in these fields, and the potential to further strengthen Sweden's position is strong. At the same time, rapid geopolitical shifts are changing international resource flows and creating or eliminating bottlenecks, reinforcing the need for flexibility along the battery value chain.

The European roadmap for Battery 2030+ emphasizes the role of batteries in sustainable mobility as well as clean and secure energy and is based on the life-cycle perspective and a circular economy. Recycling of battery materials such as lithium, cobalt, and nickel is described as having a key role, while primary raw materials receive limited attention. Cell production based largely on recycled material can be expected to occur only when a significant share of electric vehicles is scrapped and when battery storage systems in the electricity grid are replaced by a new generation, which can be expected to happen more rapidly towards the end of the 2030s. At the same time, measures to achieve circularity in other ways, for example through the reuse of cells, may delay the point at which recycling becomes relevant.

Environmental assessment studies within the battery field have shown that greenhouse gas emissions from cell manufacturing have decreased substantially over the past decade thanks to large-scale efficient manufacturing. At the same time, data gaps and knowledge gaps regarding processes further upstream in the supply chain have been identified.

Challenges and Actions

- The national mineral strategy, which emphasizes sustainable resource development, strengthened competitiveness, and increased knowledge building, is currently being revised to better address critical raw materials. To utilize new deposits, efficient processing methods adapted to the specific ore are also required, extending to finished feedstock materials for use in cell manufacturing.
- Efficient recycling to supply cell production with materials is important for reducing costs and energy consumption, as well as achieving low emissions. Given that a large share of global battery recycling takes place in China, creating a geopolitical dependency, European and Swedish recycling is essential for the supply of certain critical metals.
- For some materials, technical processes for cost-effective recycling are lacking, for example lithium and graphite, and specifically the recycling of LFP batteries.



- There are knowledge gaps regarding the automated disassembly and discharge of battery packs, which is important both for broader industrialization of a circular economy for batteries and for efficient recycling.
- Important challenges requiring action include increasing knowledge of global supply chains and flows of critical raw materials in society, including larger material streams that could constitute future secondary raw material flows for batteries. This is crucial for clarifying how the environmental effects and social impacts of batteries can be reduced, and for ensuring the right incentive structures within the system.
- The environmental impacts of supply chains beyond greenhouse gas emissions, such as water use and water pollution, as well as global and local availability of limited resources, are significantly less explored by LCA than climate impacts.
- Transparent data sharing regarding battery health, as well as efficient return and circular logistics, are needed to enable the reuse and remanufacturing of cells, modules, and packs, and to create the conditions for cost-effective material recycling.
- Limited access to primary data from battery manufacturers also means that LCA studies must partly be based on proxy data. This applies in particular to chemistries and technologies other than lithium-ion batteries. Upcoming digital product passports may partly alleviate this but may at the same time create uncertainty regarding how several different EU regulations will interact and affect the establishment of circular systems.
- The fact that certain circular measures may delay the availability of recycled materials constitutes a paradox. Maximizing the availability of secondary raw materials and minimizing climate impact do not necessarily go hand in hand.

Research aimed at strengthening European and Swedish capacity in the production of primary battery raw materials should prioritize improved exploration and geological mapping, as well as the development of efficient extraction processes where such processes are lacking. **In the short term**, the challenge is to increase extraction from existing mines. System analyses and assessments are important for mapping how demand for specific battery technologies may develop, and in which applications these will be used. This is needed to answer how batteries can contribute the greatest possible societal benefit. It is also important to develop a basis for how dependence on critical and strategic raw materials (e.g. Cu, Ni, Co, Li) can be reduced through mapping of alternative European supply routes, but also through changed design at the system level or direct substitution of cell chemistries. **In the long term**, research should focus on new deposits and materials, based on what other research indicates regarding expected future demand. Lithium extraction has good potential in Europe, while bio-based materials may become a unique competitive advantage for Sweden. Recycling technology should, as far as possible, be integrated with the cell manufacturing capacity being established nationally. Recirculation of complete components or active materials should be continuously balanced against the production of more generic precursor materials, such as cobalt or lithium salts, which are not locked into a specific cell design.

- The potential for producing battery materials from material streams in other sectors needs to be explored, for example waste from industrial processes, forest-based raw materials, and phosphorus in sewage sludge. However, high



purity requirements make it challenging to use raw materials containing large amounts of impurities.

- Environmental systems analysis and LCA need to be given a clearer independent role within battery research. In large EU projects, LCA is often required, but it is generally addressed without the rigor and methodological development that characterize robust research.
- There are knowledge gaps regarding the environmental impacts of mining and raw material processing in the different parts of the world that supply Sweden and the EU with battery materials.
- Prospective and scenario-based LCA makes it possible to evaluate new technologies at an early stage, before large-scale production, and is essential for studies of vehicles and BESS. Robust life cycle-based knowledge is also a prerequisite for ensuring that EU policy instruments related to batteries promote sustainability.
- Interdisciplinary research and collaboration between technology development and systems analysis are prioritized. The conditions for manufacturing, recycling, and other circular measures should be more closely linked to cell and pack design.



THEME 6. SCIENCE AND SOCIETY

Battery research and innovation are matters of concern for society as a whole and include aspects such as standards, regulations, education, and lifelong learning. These strengthen the necessary research environments and skills supply within the Swedish battery value chain.

The EU has created several regulations that affect the battery sector: the *Critical Raw Materials Act*[12], the Battery Regulation (which regulates, among other things, recycling)[13], and the chemicals regulations REACH[14] and CLP[15] are some examples that can both hinder and/or strengthen the development of the battery value chain in Europe. Sweden has the opportunity to influence the EU's regulatory and standardization work, which is important because these establish the framework for national legislation. The public and decisionmakers need to be provided with objective and balanced information in order to increase understanding and acceptance of the broader societal changes resulting from the technological transition and electrification.

Skills supply is a bottleneck, and higher education institutions need to be adaptive and scale education and research in line with society's needs. The need for continuing professional development and further education is also increasing as technological development accelerates and working lives become longer. To create internationally leading expertise, strategic investments are needed in excellent research environments that are clearly linked to education, which is crucial for education of world-class quality.

Political Clarity. A joint organisation of academia, industry, authorities, and decisionmakers is required to optimize the resources that already exist, but long-term resources for future research and innovations will require additional capital. Many efforts have been made, but more will be needed. It is important that this approach is based on expert knowledge and broadly anchored.

Research Focus. Battery technology is central to several different industrial sectors, but the choice of cell chemistry, performance optimization, and system engineering solutions varies considerably. Sweden should make use of this roadmap to establish a common vision and strategy, while also ensuring breadth in research. The strong battery research expertise that exists within both the Swedish automotive industry and academia should be utilized. Central to this is the creation of environments for collaboration between the very best researchers across higher education institutions in order to accelerate and contribute to competence building, innovation capacity, and market establishment in strategic areas without violating competition law. Already established platforms such as Swedish Electromobility Center (SEC) and Batteries Sweden (BASE) play important roles, but with alternative funding models

[12] https://single-market-economy.ec.europa.eu/sectors/raw-materials/areas-specific-interest/critical-raw-materials/critical-raw-materials-act_en
[13] https://www.kemi.se/lagar-och-regler/lagstiftningar-inom-kemikalieomradet/eu-gemensam-lagstiftning/batterier/kort-om-batteriforordningen
[14] https://environment.ec.europa.eu/topics/chemicals/reach-regulation_en
[15] https://www.kemi.se/lagar-och-regler/lagstiftningar-inom-kemikalieomradet/eu-gemensam-lagstiftning/clp-forordningen



without strict co-financing requirements, they could create better conditions for joint cutting-edge research with a more focused approach.

New Approaches for Government Agencies and Research Funders in Collaboration with Academia and Industry. Authorities, academia, and industry should find new ways of addressing larger and more comprehensive questions from the micro (materials) to the macro (battery systems) level using a portfolio perspective. The current call-driven system has advantages in terms of healthy competition but often creates long processes before new projects can be launched. Internal competition is not necessarily the best way to sharpen Sweden's position in the international battery research landscape, where technology focus is highlighted as a decisive success factor. To create funding instruments that enable holistic approaches, cooperation between responsible authorities and research funding organizations is required. In this context, Sweden can learn from other countries, such as China and South Korea, regarding risk-taking culture, rapid iterations, and industrial experimentation.

Mobility Between Academia and Industry. Another key factor is a system that facilitates and promotes continuous mobility within and between academia and industry, in order to capture and capitalize on collective knowledge in the form of innovation, productization, and industrialization.

European Commission targeted support. To ensure that Sweden can secure a larger share of targeted support for the battery sector at the European level in the future, a proactive and strong voice for Swedish interests in the EU is needed, promoting evidence- and fact-based regulations and standards in support of electrification.

Skills Supply. The challenges related to skills supply concern attracting key international expertise to the country, retaining the competence that exists, and the ability of the education system to attract young people to pursue STEM professions. The existing workforce must be utilized more effectively through recurring continuing professional development and further education throughout working life so that knowledge remains up to date in line with technological developments. Skills shortages exist throughout the entire battery value chain but are particularly noticeable in systems thinking, data analysis competence, manufacturability, and understanding of integrated manufacturing processes.

Vision and Objectives for the Next Ten Years

Within ten years, Sweden shall have a vibrant, diversified, and internationally competitive battery sector. Sweden shall be a leading nation in battery research and innovation, where academia, industry, and policymakers jointly create scalable research environments that are close to both fundamental research and production. Attractive and stable career paths shall be established to encourage young academics to pursue research careers and to enable Sweden to attract international top talent within the highly competitive battery field. This will ensure a long-term supply of skills and expertise.

Proposed Actions to Achieve the Vision



There is a need to establish a national coordination group/platform with representatives from leading research environments, industrial R&D, and authorities. Such a platform should support a strategic direction of research funding, shorter project start-up times, fewer but more powerful initiatives, and better conditions for applied and industry-driven research to access EU funding from Horizon Europe and the Competitiveness Fund.



8. THREE CENTRAL FOCUS AREAS

Three central focus areas are presented here as support for all thematic areas.

1: COLLABORATION: A STRATEGIC BATTERY RESEARCH AND INNOVATION ARENA

Coordination and collaboration are crucial for enabling us to capitalize on and further develop the excellence and shared expertise that exist within the country. By establishing a geographically distributed but nationally and organizationally coherent arena for research and innovation in the battery field, conditions are created for a visionary and forward-looking approach. This can advantageously build on established platforms within the Swedish battery ecosystem, such as Compel and BASE. The arena is intended to encompass the entire battery value chain, bring together all relevant actors in research and innovation (including authorities and funders), and contribute to the basis for strategically important decisions that strengthen Sweden's position in the field.

The purpose is to work towards:

- National battery-related projects and other infrastructure investments, such as instruments for advanced characterization and pilot lines, being coordinated and aligned,
- Research, development, and innovation investments, including new and existing infrastructures, being fit for purpose and administratively cost-efficient,
- Investments being made in a diversity of battery chemistries and technologies, both current ones (Li-ion and Na-ion) and future ones (next-generation batteries),
- Future projects consisting of both fundamental research and application-inspired and applied research for a broad range of applications,
- Increasing the number of strategic international collaborations,
- Sustainable development and circularity permeating Swedish strategic battery R&I in a positive and open, non-restrictive manner. Aspects, methodologies, and materials to monitor include CRMs, PFAS, SSbD, LCA and pLCA, MSA, the role of recycled materials in process and production, material criticality, and YIMBY (e.g. socially accepted exploration and mining),
- Ensuring that different aspects of AI and data-driven approaches and tools (for example generative AI, APIs, data formats/transfer/storage, cybersecurity, and digital twins) are integrated responsibly but effectively across academia, research institutes, and industry.



The arena's role as a strategic dialogue partner

- Be the natural dialogue partner for the surrounding society and corresponding international initiatives.
- Work to ensure that Swedish battery research and innovation gain a stronger role within the EU.
- Strengthen the conditions for small and medium-sized enterprises within the ecosystem and work towards a future self-financed national network of SMEs.
- Work nationally and internationally with standardization and regulation, for example "battery passport", ontologies, "best practices", policy, and techno-economic assessments, evaluations, scouting, and mapping.
- Manage IP development/strategy/policy.

Evaluation and Follow-Up

- Develop and monitor KPIs adapted to Swedish conditions, industrial criteria, and end-user requirements.



2: Accelerated Research, Development and Scale-Up Through Large-Scale Research Infrastructures and Other Technology Infrastructures

Battery research and development require access to advanced, specialized, and experimental equipment and the integration of this with broad use of national (dedicated) computing capacity, not least to enable accelerated materials development that utilizes different forms of AI and digital twins.

To increase the relevance of academic research, shorten the time from discovery to innovation and application, and strengthen Sweden's competitiveness, several types of technology infrastructure (e.g. pilot lines) need to be implemented at universities and institutes, in collaboration with industry.

Purposes and objectives:

- Establish and expand battery research environments at MAX IV and ESS with advanced cell development for realistic operando/real-time studies of materials and processes.
- Develop, integrate, and utilize digital infrastructure and computational resources for multiphysics modelling from particle to pack level, enabling automated laboratories to perform high-throughput testing linked to AI/ML management.
- Further develop BMS with smart control, algorithms, data-driven systems, sensors, requirements and functionality, cell-pack levels, and physical models.
- Data generated at all levels of the value chain shall be manageable in real time, enabling further integration with AI/HPC.
- Collaborate with local, regional, and national infrastructures to provide secure storage resources for data management. Promote open, confidential, and traceable data.
- Establish pilot lines at research institutes and industry, designed for production and serving as entry points and educational platforms for academia. These should be flexible with respect to different chemistries and technologies to meet varying needs depending on maturity level and methodology, including the ability to handle the introduction of recycled materials with purity considerations, alternative material streams, and circularity principles. The use of the pilot lines should reflect production requirements, manufacturability, and material-cell-pack-system design issues, but costs should be scaled to current and future R&I needs and, therefore, the majority should be small and modular.
- Integrate digital twins and in-line sensors and link these to calibrated models, design, validation, and safety testing, enabling inverse design.



3: Education and Skills Supply

To strengthen Sweden's position in battery research and innovation, considerably more trained individuals are needed. There is therefore a need for educational initiatives at all levels. Interest in the field needs to be created already in primary and secondary school through good educational materials, continuing education for teachers, and public education initiatives. Vocational education and training in process engineering and production, as well as opportunities for those active in industry to pursue further education (lifelong learning), are also important. University education is needed at both undergraduate and advanced levels, including a dedicated national graduate school covering the entire battery value chain. Individuals in leadership positions in different organizations throughout society also need battery-related competence.

The educational initiatives will further strengthen and expand the Swedish battery ecosystem by:

- Attract international top-level expertise,
- Build on the diversity of experience from academia and industry that exists in order to create an understanding of the different requirements and conditions that exist in different parts of the system (academia-industry and the different parts of the value chain). Mobility initiatives may, for example, be relevant.
- Stimulate entrepreneurship and mobility throughout the entire value chain.

Purposes and objectives:

- Create a national graduate school that is broad and cutting-edge, focused and flexible, integrating battery production and processes with the use phase and advanced control, together with the fundamentals of chemistry, physics, materials science, mechanics, and electronics, and across the raw material-material-component-cell-pack-system chain. The graduate school shall be connected to large-scale research facilities such as pilot lines.
- Increase educational capacity at universities in order to capitalize on academic excellence as well as industrial experience and needs earlier and more clearly. Emphasize specific characteristics, differences in maturity, fundamental knowledge, and science for both LIBs and next-generation batteries, and broaden the dissemination of industry technological know-how based on actual needs and a critical approach in order to both evaluate and stimulate science, development, and innovation.
- Work to increase competence throughout the entire value chain, including beyond STEM: resources, raw materials, exploration, geology, material flows, law, circular economy, conflict management,



etc. The initiatives should clearly address different time horizons and complex dependencies and allow AI and other generic tools to permeate the educational programmes.

- Deepen and broaden current educational initiatives and ensure that up-to-date and current information materials and teaching resources are available, covering practical aspects (e.g. battery disassembly and discharge), regulations, legislation, systems perspectives, social impacts, and societal benefits. Work with public education and lifelong learning through different channels (social media, influencers, etc.) to reach new groups.
- Stimulate mobility between academia and industry to increase understanding of realities, requirements, and needs through feedback and the dissemination of lessons learned.
- Utilize international contacts and networks for top-level recruitment and exchanges at all levels within the ecosystem.
- Stimulate the formation of spin-offs and spin-outs through education in entrepreneurship and exposure to different support organizations for commercialization.



APPENDIX 1 WORKING GROUPS AND WORKSHOP PARTICIPANTS

A number of experts served as leaders of the thematic areas covered by the roadmap. In this role, they were responsible for structuring and advancing the work, including preparing background material, identifying research and innovation needs, and formulating priorities within their respective areas.

The following experts were responsible for each thematic area:

1. Aleksandar Matic (Chalmers University of Technology), supported by Annika Kauppi (Altris) – New Chemistries and Technologies (Materials)
2. Peter Broqvist (Uppsala University), supported by Artem Kulachenko (KTH Royal Institute of Technology) – Accelerated Materials Development (Modeling, AI, and Data)
3. Verena Löfqvist Klass (Scania/Traton), supported by Torsten Wik (Chalmers University of Technology) – Control and Smart Systems
4. Martin Karlsson (Luleå University of Technology), supported by Maciej Wysocki (RISE) – Manufacturing and Digital Twins (Including Next-Generation Batteries)
5. Anders Nordelöf (Swedish National Road and Transport Research Institute (VTI) and Chalmers University of Technology), supported by Kerstin Forsberg (KTH Royal Institute of Technology) – A Circular and Sustainable Value Chain (Life Cycle Assessment, Raw Materials, and Recycling)
6. Annika Ahlberg Tidblad (Volvo Cars), supported by Guiomar Hernández (Uppsala University) – Science and Society (Standards, Regulations, Education, and Lifelong Learning)

As a central part of the assignment, the thematic leaders actively engaged and collaborated with relevant stakeholders from academia, industry, and research institutes to ensure that the content was well anchored and reflected scientific advances, industrial needs, and broader societal perspectives. This was accomplished through targeted dialogues, consultations, and the collection of input from key experts within each thematic area.

This approach has been used to create broad and cross-sectoral anchoring, with the aim of strengthening the quality and relevance of the recommendations developed.

Representatives from the following organizations have had the opportunity to provide comments on the content:

- Altris
- Batixt
- Business Sweden
- Chalmers University of Technology
- Echandia
- Husqvarna
- InnoEnergy
- KTH Royal Institute of Technology
- Libergreen



- Linköping University
- Luleå University of Technology
- Lund University
- Lyten AB
- Micropower Group AB
- Mid Sweden University
- Mälardalen University
- Phinia
- Polestar
- RISE Research Institutes of Sweden
- Scania/Traton
- SEEL – Swedish Electric Transport Laboratory
- Stockholm University
- Stora Enso AB
- Svemin
- Swedish Defence Research Agency (FOI)
- Swedish Energy Agency
- Swedish Environmental Protection Agency
- Swedish Foundation for Strategic Research (SSF)
- Swedish National Road and Transport Research Institute (VTI)
- Swedish Research Council
- Uppsala University
- Vinnova (Sweden's Innovation Agency)
- Volvo Cars
- Volvo Group

APPENDIX 2 THE BATTERY VALUE CHAIN

The battery value chain can be described in both a linear and a circular form. The classical illustration developed at the EU level within the SET Plan work and interpreted by EBA250[16] is shown in Figure 1. This circle is sometimes presented with the raw materials located outside the circle to indicate that raw materials from mining must be continuously replenished, since it is doubtful that recycled metals alone will be sufficient to meet future battery demand. A stage is also sometimes shown between active materials and cell manufacturing, indicating that the materials must be balanced and optimized within a typical cell chemistry.

The weakest link in this chain from a research perspective, both in Europe and in Sweden, is considered to be knowledge of how battery cells are manufactured.



Figure 1. Battery Value Chain According to the SET Plan and EBA250

[16] EBA250 https://www.eba250.com/



APPENDIX 3 SHORT- AND LONG-TERM ACTIONS – CONCLUSIONS

All six themes highlight a need for long-term research covering all parts of the battery value chain, combined with time-limited initiatives to promote innovation and strong collaboration between academia and industry. Within ten years, Sweden shall have a vibrant, diversified, and internationally competitive battery sector. Sweden shall be a leading nation in battery research and innovation, where academia, industry, and policymakers jointly create scalable research environments that are close to both fundamental research and production. This requires both short-term and long-term efforts. These are described in different ways within the various themes and are summarized below.

THEME 1

Short term

Long-Term Research Priorities:

- Next-generation Li- and Na-based chemistries, such as LMFP, LMR, DRX (disordered rock salt), LMNO, and alloy anodes (Si, Sn).
- Lithium-metal batteries (potentially also Na and Zn).
- Solid-state batteries: ceramics/polymers/hybrids.

Additional Actions

- Resources for a critical mass of research groups and research topics across the entire battery value chain to ensure long-term support for innovation.
- An established platform for dialogue that enables manufacturing, recycling, and sustainability aspects to be incorporated at an early stage, ensuring that resources are invested in battery concepts with future potential.

Long term

Research efforts regarding:

- Multivalent batteries (Ca, Mg, Al)
- Conversion chemistries (O, S, etc.)
- Organic batteries/biomass for energy storage
- Flow batteries

Additional Actions

- A responsible internationalization strategy to create collaborations that generate synergies.
- New battery chemistries and technologies should be based on strong fundamental research in materials, processes, and cell concepts.
- Access to advanced analytical methods at universities and large-scale research facilities to study materials and chemical processes under conditions that are as realistic as possible, through ex situ, in situ, and operando experiments on components and cells.



THEME 2

Short term

- A stepwise establishment of a Materials Acceleration Platform (MAP), where modelling from the atomic level to the system level is bridged with new algorithms based on experimental data, AI, and ML.
- Development of a platform for uniform reporting of results and access to data for different stakeholders.
- Collaborative model training should be developed so that models can be trained across different data layers without the need to move raw data.

Long term

- A tenfold reduction in development time from fundamental research to product compared with today. A MAP implemented for both academia and industry.
- Developed common data ontologies, APIs, and version control. A layered storage infrastructure that distinguishes between open research data, confidential industrial data, and regulatory traceability data, as well as a layered model infrastructure with advanced models that can provide secure services also to small and medium-sized enterprises.
- Strong environments in modelling and AI development that accelerate the development of new chemistries.

THEME 3

Short term

- Optimize today's commercial battery systems through advanced BMS: extended lifetime, robust fast charging, and reduced system costs.
- Invest in research on functional allocation between local systems and the cloud (architectural choices, real-time requirements, cybersecurity, and data management).
- Strengthen the life-cycle perspective to enable second life, reuse, and repurposing. This requires standardized and reliable state information over time through high-quality data, adaptive physics-informed models, and advanced measurement methods such as EIS.
- Establish testbeds and open data platforms in collaboration between industry, academia, and public stakeholders to accelerate innovation of new BMS solutions.



Long term

- Develop learning, chemistry-neutral, and cost-effective battery management that enables batteries to be utilized efficiently throughout the entire life cycle, from first use to reuse and last life, in a safe manner.
- Integrate the BMS perspective early in the development of next-generation battery chemistries and technologies.
- Invest in the development of smart management of reconfigurable battery systems.

THEME 4

Short term

- Establishment of entry-level environments and pilot lines on a small to medium scale at universities, accessible nationally and across Europe, where the focus is on understanding fundamental processes and linking these to measurement data and modelling.
- Support research and education by enabling these environments to conduct controlled experiments throughout the entire process chain, from slurry preparation to electrode and cell manufacturing, with a high degree of flexibility.
- Dedicated experimental setups linked to large-scale research infrastructures such as MAX IV and ESS, where advanced light- and neutron-based techniques can be used to study process physics operando, shall be provided.

Long term

- Create industrial pilot and production lines with structured access for academia and research institutes, enabling validation at a relevant scale, where process robustness, variation, and integration with real production systems can be studied.
- Combine these levels, from university environments to advanced research infrastructure and industrial lines, into a coherent development chain where knowledge, data, and models are continuously transferred and refined.
- Create strategic core capability at the European level through pilot lines, where integrated environments can accelerate development, reduce scale-up risk, and establish a truly competitive and knowledge-driven battery industry.



THEME 5

Short term

- Increase the extraction of battery materials from existing mines and establish new mines. Research should focus on new deposits and materials, based on expected future demand.
- Recycling technology should be integrated with the cell manufacturing capacity being established nationally.
- Recirculation of complete components or active materials, i.e. the shortest possible recycling loops, should be continuously balanced against the production of precursor materials, such as cobalt or lithium salts.
- A more dedicated role for environmental systems analysis and LCA within battery research, and greater emphasis on LCA studies of how batteries are used in different applications, in particular electric vehicles and stationary energy storage.
- The environmental impacts of mining and raw material processing in the different parts of the world that supply Sweden and the EU with battery materials should be explored.
- Prospective scenario-based LCA should be implemented to evaluate new technologies at an early stage, before large-scale production.

Long term

- Production of battery materials from material streams in other sectors, such as waste from industrial processes, forest-based raw materials, and phosphorus in sewage sludge.
- Research focused on new deposits and materials, based on expected future demand.
- More thoroughly establish interdisciplinary research and collaboration between technology development and systems analysis.
- Establishment of a platform for manufacturing, recycling, and other circular measures, which are linked more closely to cell and pack design.
- Development of methods to reduce dependence on critical and strategic raw materials (e.g. Cu, Ni, Co, Li) through changes in system-level design or direct substitution of cell chemistries.

THEME 6

Short term

- Establishment of a national interdisciplinary graduate school covering the entire battery value chain.
- Develop a policy framework for open but protected management of battery data and IP, including protection against international data collection.
- Inventory competence needs along the battery value chain, as well as across the entire spectrum from operator to specialist.
- Develop a Swedish policy framework to facilitate mobility between and within academia and industry, for example through adjunct appointments and affiliations of researchers, as well as exchange of teachers.



Long term

- Creation of strong, flexible systems for lifelong learning in line with the advancing frontiers of knowledge.
- Broad dissemination of knowledge about batteries in society through accessible and up-to-date information that can be used in primary and secondary education as well as by an interested public.
- Development of battery competence within relevant higher education programmes, including beyond traditional STEM disciplines.



APPENDIX 4 ABBREVIATIONS

- **AI –** Artificial Intelligence
- **API** – Application Programming Interface
- **BASE** – Batteries Sweden (Competence Centre)
- **BESS** – Battery Energy Storage System
- **BMS** – Battery Management System
- **CLP** – Classification, Labelling and Packaging
- **CRMs** – Critical Raw Materials
- **DRX** – Disordered Rock Salt
- **EIS** – Electrochemical Impedance Spectroscopy
- **EU** – European Union
- **HPC** – High-Performance Computing
- **HTS** – High-Throughput Screening
- **IP** – Intellectual Property
- **IT** – Information Technology
- **LCA** – Life Cycle Assessment
- **LFP** – Lithium Iron Phosphate
- **LIB** – Lithium-Ion Battery
- **LMFP** – Lithium Manganese Iron Phosphate
- **LMNO** – Lithium Manganese Nickel Oxide
- **LMR** – Lithium Manganese-Rich
- **MAP** – Materials Acceleration Platform
- **ML** – Machine Learning
- **MSA** – Material System Analysis
- **NAISS** – National Academic Infrastructure for Supercomputing in Sweden
- **NGB** – Next Generation Batteries
- **NMC** – Nickel Manganese Cobalt
- **OEM** – Original Equipment Manufacturer
- **OT** – Operational Technology
- **PFAS** – Per- and Polyfluoroalkyl Substances
- **R&D** – Research and Development
- **RISE** – Research Institutes of Sweden
- **SDL** – Self-Driving Laboratory
- **SEC** – Swedish Electromobility Centre
- **SEEL** – Swedish Electric Transport Laboratory
- **SGU** – Geological Survey of Sweden
- **SIB** – Sodium-Ion Battery
- **SMEs** – Small and Medium-Sized Enterprises
- **SRA** – Strategic Research Agenda
- **SSbD** – Safe and Sustainable by Design
- **STEM** – Science, Technology, Engineering, and Mathematics
- **TRL** – Technology Readiness Level
- **pLCA** – Prospective Life Cycle Assessment
- **V2G** – Vehicle-to-Grid

