



BATTERY 2030+ ROADMAP  
SHORT POPULAR VERSION

BATTERY  
2030+

RE-INVENTING THE WAY WE INVENT SUSTAINABLE BATTERIES

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# SHORT VERSION OF THE ROADMAP

**The Battery 2030+ initiative** is a dynamic, pan-European research effort focused on achieving coordinated progress in fundamental, knowledge-driven battery science. Its mission is to advance the basic understanding of battery materials, interfaces, and processes, providing the technological groundwork needed for future innovations. Funded by the European Union's Horizon Europe Future and Emerging Technologies programme, Battery 2030+ aims to build the scientific and technological foundation that will enable industry to develop the ultra-high-performing, sustainable, safe, and affordable batteries needed to achieve the goals of the European Green Deal. These future batteries will be critical in supporting Europe's transition to a climate-neutral society, including the production of at least 200 GWh of battery capacity annually within the next five years, with a subsequent rise to the TWh range, as outlined by the World Economic Forum.

For all this to happen, it is essential to join forces in Europe. Researchers, industry stakeholders, policymakers, and the public need to move forward in a coordinated, collaborative and united approach.

## CHALLENGES

Climate change, environmental pollution, habitat loss, and decreasing biodiversity have major direct and indirect impacts on our lives, economy, and society. In

short – we are facing global challenges that require coordinated actions. The EU-27's total carbon footprint in 2019 was equal to 6.7 tons of CO<sub>2</sub> per person, according to Eurostat.<sup>35</sup> By 2030, the EU wants to reduce its greenhouse gas emissions by 55 percent or more compared with 1990 levels, aiming at zero net emissions by 2050. This goal has been formulated as part of the European Green Deal launched in December 2019.

Batteries are among the key technologies enabling a climate-neutral Europe by 2050. Since the start of Battery 2030+, the global battery landscape – including the full battery value chain from raw to battery-grade materials, cell production, system integration, use and recycling, etc. – has transformed rapidly. The US and China have started to use considerable amounts of federal funding to support battery production. China's current high volume of battery cell production creates a strong pressure for the European battery industry. However, in a recent report<sup>1</sup> from the EU commission, Mario Draghi has outlined a plan to make Europe more competitive. In this plan, batteries are seen as a battle that we should not give up on for energy security reasons, as he explained during his address at the presentation of the report in the European Parliament.

## RESEARCH CHALLENGES

What challenges do we then need to address to be innovative and ground-breaking in this field and lay the basis for disruptive innovation in Europe? There are several roadmaps, not only our own, at the European level<sup>2,3</sup> that have fed the most important needs and actions into the Strategic Research Agenda for the European Partnership BEPA.<sup>4</sup>

What sets the Battery 2030+ roadmap apart from other roadmaps? It addresses critical, specific dimensions of battery research, all with their specific challenges. Battery 2030+ explores disruptive research tools that transform battery science and support di-

verse, chemistry-agnostic breakthroughs. Advanced AI and machine learning drive rapid discovery of new materials, while multiscale modeling enables seamless insights from atomic interactions to full battery performance. A standardized battery ontology ensures that results are reproducible and comparable, integrating high-throughput, multi-modal characterization to accelerate material testing. These tools underpin each scientific theme within Battery 2030+, from studying future battery chemistries like sodium-ion and solid-state to exploring self-healing and sensor-enabled batteries, creating a cohesive research ecosystem that unites academia and industry.

**1** [https://commission.europa.eu/topics/strengthening-european-competitiveness/eu-competitiveness-looking-ahead\\_en](https://commission.europa.eu/topics/strengthening-european-competitiveness/eu-competitiveness-looking-ahead_en) 2024-09-24

**2** Battery 2030+ roadmap [www.battery2030.eu](http://www.battery2030.eu)

**3** [https://batterieseurope.eu/wp-content/uploads/2023/09/Batteries-Europe\\_Research-and-Innovation-Roadmap-2023\\_.pdf](https://batterieseurope.eu/wp-content/uploads/2023/09/Batteries-Europe_Research-and-Innovation-Roadmap-2023_.pdf)

**4** <https://bepassociation.eu/our-work/sria/> (2023)

# THE SCIENTIFIC THEMES OF BATTERY 2030+

**The Battery 2030+ initiative** has a chemistry-neutral approach and thus is not limited to any particular battery chemistry. It covers the whole value chain for batteries, from raw materials, to material discovery and interfaces, functionalities, manufacturability and circularity in the sense of reuse and recycling of used batteries.

It is a clear ambition from the European Commission to become more independent and thus **self-supplying of the raw materials** needed for battery manufacturing. Several projects are engaged in innovative process methods for battery-grade metals and materials production with low waste, minimizing environmental impacts of downstream processing.

To secure **new sustainable materials** with high energy storage capability and high stability without unwanted degradation reactions or safety risks is essential. **Accelerated materials discovery** therefore has been and will be at the heart of the Battery 2030+ initiative. Furthermore, several projects carry out basic research to further investigate and understand the complex reactions taking place at the multitude of material interfaces within batteries.

**Sensors and self-healing capabilities** are closely connected. Embedded or external sensors allow for continuous monitoring of battery health and safety status. The sensors can be used to trigger self-healing



*Battery 2030+ explores new batteries materials and recycling concepts.*

activities at given measured parameters. The idea is to utilise passive and active components in the battery triggered by stimuli that prevent, retard, or reverse degradation processes in battery cells.

The manufacturability projects develop digital tools, such as digital twins, that can predict the impact of various manufacturing parameters which in turn reduces the need for costly and time-consuming trial and error methods. Another focus is to ensure that new materials

and methods developed within Battery 2030+ have the potential to be scaled up in production in a sustainable way.

The European battery regulation from 2023 aims for circularity and sharpens the requirements for re-use, re-manufacturing and recycling of used batteries. Battery 2030+ therefore addresses re-manufacturing and recycling concepts, including materials of low economic value, reduction of waste water and decreased carbon footprint – all complemented by a comprehensive life cycle assessment.

## **KNOWLEDGE SHARING AND STANDARDIZATION**

Large-scale battery manufacturers measure and control thousands of material and production parameters along the production process – from raw materials sourcing to final battery pack inspection. They have valuable knowledge about the effects of parameters variations, and they control critical parameters within smallest error margins to ensure high quality, safe products and low scrap rate. This is possible, because the production process is usually focused on precisely one battery chemistry and a fixed set of battery materials for which all processes are optimised. In academic research and research-oriented pilot-scale facilities, however, standard procedures are more difficult to implement. New materials and new processes require parameter adjustments or entirely new approaches, and procedures that give good results with one material combination might fail with another. For example, “simply” switching from an organic binder to an inorganic one will have a profound impact on substrate wettability during coating and on the drying dynamics, eventually resulting in electrodes with entirely different morphological and thus electrochemical proper-

ties if coating and drying processes are not adjusted accordingly.

On order to ensure that data produced during explorative battery research is reproducible, reliable and thus relevant, we must implement common ontologies, linked data, and standards along the complete research and development chain. This goes from materials synthesis at universities to cell production in pilot facilities, from basic theoretical research to electrochemical testing of full cells and batteries, and eventually to the area of recycling and re-use. In practice, this means that researchers shall be able to exchange, share and reproduce each other’s results. To address this challenge, Battery 2030+ creates a European database of battery-oriented material properties, a standardised classification of interfacial phenomena and harmonized characterization and testing protocols. Efforts towards standardization will cover manufacturing of battery components and battery assembly as well. An online knowledge base will be opened to European partners, helping to take a major leap towards FAIR principles, ensuring data is Findable, Accessible, Interoperable and Reusable. Such approaches must also include aspects of reproducibility, reliability and relevance and will integrate and connect academia and industry towards a broad implementation of standards and ontologies with a unified terminology and seamless interoperability using linked data.

## **INNOVATION UPTAKE**

The collaboration extends to common strategies and exchange of knowledge concerning IPR matters and innovation uptake. Part of this builds on earlier experiences made in the previous Battery 2030PLUS CSA and the Horizon Results Booster Service of the European Commission.

Other actions for innovation uptake will be developed in dialogue with European platforms such as BEPA, EBA250 and Batteries Europe to derive joint actions and support the Battery 2030+ projects in intellectual property rights and exploitation matters. Training programmes and workshops focusing on joint dissemination measures, capacity building and exploitation planning will also be offered.

## EDUCATION AND TRAINING

Finally, there is a need to attract the talents and build

the competences necessary to achieve the long-term scientific-technical goals and support the European industry with a skilled workforce for decades to come. Hence, the Battery 2030+ initiative is engaged in educational and outreach programmes that will make Europe a world-leading hub of battery knowledge, and create an essential basis of motivated researchers and engineers. Together, the initiative strives to realise the common, agreed vision of building the sustainable, safe, high-performing and affordable batteries of the future.



Figure 2: Battery 2030+ is a vital part of the green transition in Europe.

# BATTERY INTERFACES AND ACCELERATED MATERIAL DISCOVERY

**Advanced materials are** the foundation of nearly every clean energy innovation. Despite decades of research, the details of interfacial reactions happening in the complex electrochemical environments of batteries are not fully understood. Conventional trial-and-error based discovery of new battery materials is time-consuming and expensive. Each step of the research and development chain, from materials synthesis and processing to cell assembly, cell formation and testing, is dependent on the successful completion of the previous steps. While many steps have been automated and partially integrated, only smaller steps towards full autonomy and closed-loop discovery have been taken so far.

The interface and acceleration projects of Battery 2030+ enhance the fundamental understanding of the processes in batteries, a prerequisite to development more stable chemistries adapted for different and specific purposes. The complexity arises from multiple reactions happening simultaneously, which strongly depends on battery parameters, such as composition of the electrolyte, structures of the electrode materials, and ambient factors such as the temperature.

A fundamental understanding is necessary to control these complex and dynamic processes. The ion transport mechanisms through interfaces for instance, and the role of the electron in these interfacial reactions, must be better understood. Experimental tools

include operando Transmission Electron Microscopy (TEM), Electron Paramagnetic Resonance (EPR), operando ambient pressure photoelectron spectroscopy techniques (XPS), operando X-ray diffraction techniques, inelastic neutron scattering, ultra-fast spectroscopic methods as well as Free Electron Laser (FEL) facilities. Other synchrotron and ion-beam techniques leading to a new understanding of interfaces can also be part of the equation. Consequently, Battery 2030+ aims at the development of novel analytical techniques, supported by modelling and simulation. To handle the large quantities of heterogenous data in order to accelerate the discovery of novel materials is an ongoing effort, yet not mastered. AI will play a central role here to discover, accelerate and optimize battery materials, interfaces and cells, again relying on fully ontologised, linked data.

## MODELLING A COMPLEX MICROCOSMOS

The effects observed on cell (macroscopic) level are rooted in phenomena at the atomistic level. Machine learning techniques and other physics-guided, data-driven models can be used to identify the most important parameters, features and fingerprints. AI-based models can significantly contribute to refine these models. But the AI-based techniques are typically unaware of physical laws and may therefore violate them. The key to

overcome this is to develop hybrid models in which the predictions of the AI-models are constrained by the laws of physics and chemistry. With this in place, the next step is to inverse the design of battery interfaces, meaning you can feed the system with desired features of the battery in a computerized model and get back a battery “recipe”. This can revolutionize battery performance and life-time once it is established.

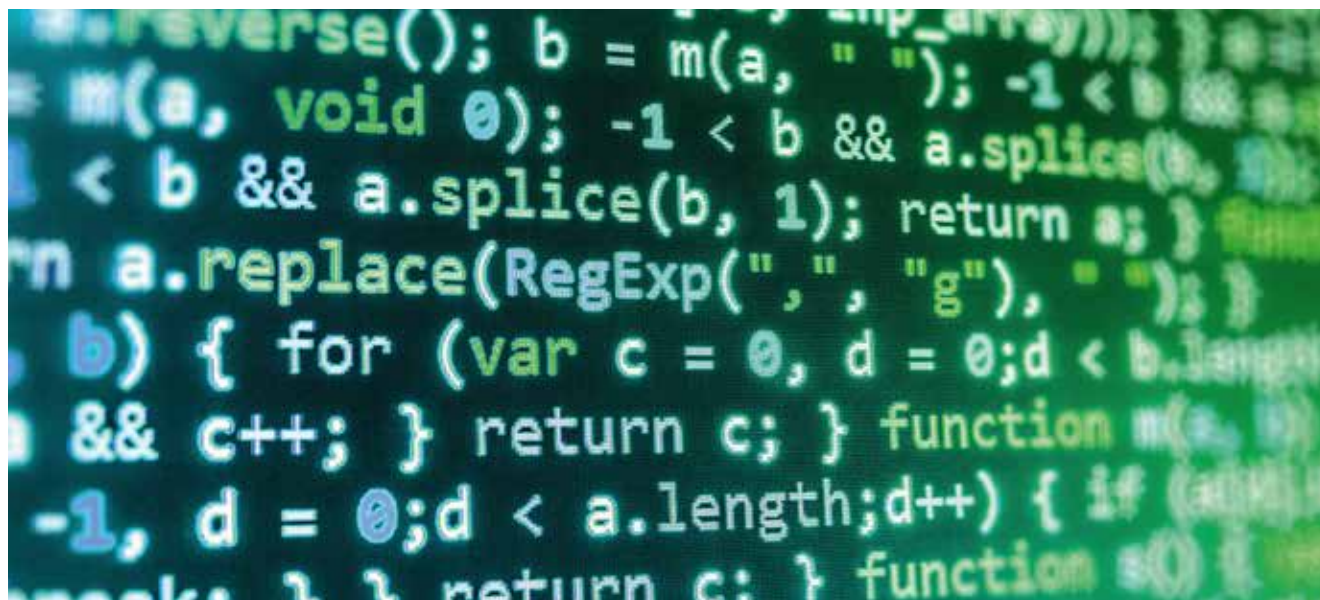
### NATURAL LAWS AND AI-MODELS

AI has the potential to become a powerful tool for autonomous discovery of new materials and offers great prospects to solve many problems outlined above. With the help of AI, combined with powerful approaches from high-throughput automated synthesis and cha-

racterisation as well as advanced multiscale modelling, an autonomous, “self-driving” laboratory to accelerate the discovery and optimization of battery materials can be created.

However, existing methods cannot handle the complexity and interfaces at a precise scale. Single scale models are not enough, they must be multiscale, combining insights from density functional theory, molecular dynamics and kinetics with larger-scale effects such as charge transport and mechanical stresses up to full-cell level. Therefore, a proper choice of computational algorithms is needed as well as it is necessary to understand when additional data is required.

The massive amounts of raw data generated by large-scale research facilities, need to be stored in machi-



*Figure 3: Large amounts of data are generated in the quest for fundamental understanding of the processes in a battery under operation.*

ne learning readable language to permit automatic queries, to share and to be analysed across European labs. Already successful examples can be found in organic chemistry and pharmaceutical research where

highly automated syntheses are state of the art. Examples are also emerging in the development of solids and thin-film materials.

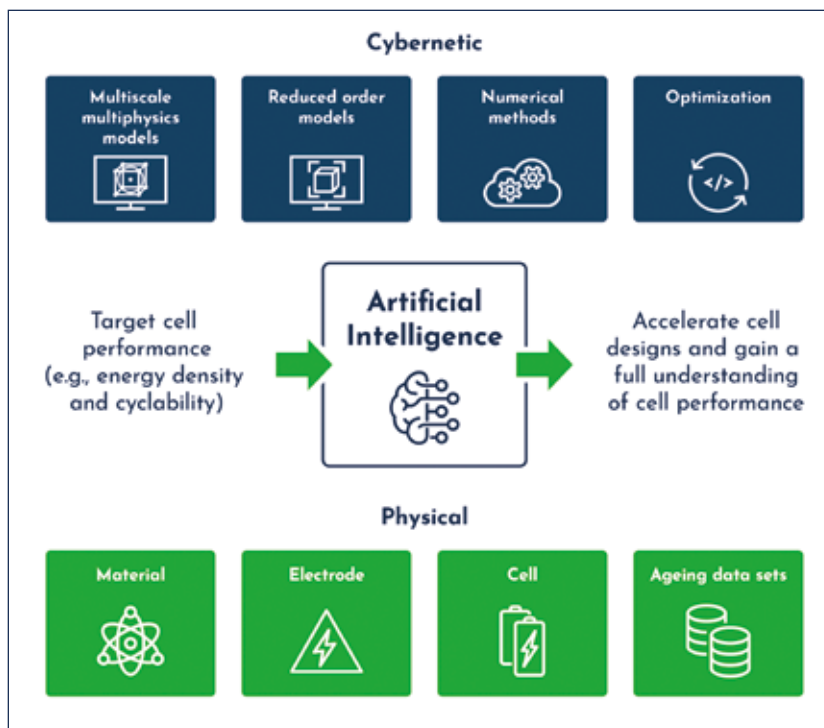


Figure 4: Key components of establishing a more fundamental understanding and acceleration of battery cells research.

# BATTERY FUNCTIONALITY

**Sensors (mainly embedded)** and self-healing properties are becoming a central part of the design of future battery cells. Sensors provide a good understanding of what is taking place inside the battery during operation and can help gather information about the aging mechanisms and degradation processes during charging and recharging. Despite these obvious advantages, adding sensors still has drawbacks like problems with chemical stability of the sensor elements, poor spatial resolution (e.g., temperature mapping), susceptibility to background noise and handling of massive amounts of data generated by the sensors. Lastly, the most important requirement for using sensors in batteries is their non-interference with battery operation and performance. Presently this hinders their industrial introduction.

Sensors by themselves are of no use - they must communicate with the surrounding, in this case the battery management system. Hence, the communication interface should be viewed as an integral part of the sensing system, and standardised protocols need to be in place to report, interpret and act on the data collected from the various sensors. It is particularly the detection of critical degrading electrochemical processes and chemical ageing one strives to measure. The internal conditions one needs to measure include properties such as cell temperature, pressure, strain,

electrolyte composition and alike. The sensors must also be capable of continuous, long-term operation. Furthermore, aspects of ease to manufacture and reuse/recycling must be considered.

## TO MEASURE IN REAL TIME

Battery cells expand and contract during charging and re-charging and the volume change can be as great as ten percent and even higher locally. This might lead to potential cracking inside the cell components. The performance of batteries relies on chemical reactions that can become unpredictable and hard to control if certain critical functional status is reached. The shift towards monitoring the battery's full functional status in real time is only partly met today. The BMS of a lithium-ion battery in a modern EV can monitor and control the current and voltage at each individual cell to avoid overcharging or deep discharge. However, other parameters such as temperature are only monitored globally or at a few selected points in the battery.

To integrate sensor technology with an efficient battery management system (BMS) having an active connection to self-healing functions, is a main objective in the Battery 2030+ initiative. We believe that within a ten-year horizon, the development of new sensors with high sensitivity, high accuracy, and low cost will offer the possibility of fully operational smart batteries.

So far, self-healing activities have mainly targeted the auto-repair of electrodes to restore conductivity and functionalising membranes to regulate ion-transport or minimise parasitic reactions. The self-healing properties can be a thermally activated polymer network that support the re-binding of silicon nanoparticles. In the case where Mn is part of the cathode, it will be embedded with heat-activated scavenging parts removing Mn ions that else would degrade the cell. Precise measurements of temperature difference between core and surface of the cell can enable improved battery management system at high charging and discharging rates. Early detection of the hydrogen formation can prevent thermal runaway, one of the main obstacles for wider use of Li-ion battery technology. Many of the reported auto-repair demonstrations are elegant and appealing, but still not fit for industrial use. This gap must be closed for innovative research and technological development.

## INSPIRATION FROM NATURE

Researchers also look at nature – can we mimic natural healing mechanisms to fabricate smart and long-life batteries? Biomimetic and „self-healing“ materials have been around for decades; now the time have come to batteries. Natural polymers can control the transport of cations, maintenance of electrode integrity, and can capture degradation products by using scavengers or chelating molecules. For batteries, the main strategy for copying nature is dynamic supramolecular assemblies, such as hydrogen bonding, electrostatic crosslinking, and distance dependent interactions on the molecular level (van der Waals force). The design often aims at regulating ion transport to minimize parasitic reactions. One interesting method is inspired by a process occurring within blood vessels. In batteries, this



*Figure 5: Mimicking nature can give valuable clues to equip batteries with self-healing properties.*

can be translated to solubilising solid lithium-sulphide, thus enabling its subsequent participation in electrochemical cycling.

## STRONGER MUST BE SAFER

In line with this is also to develop safer materials for high-performing cells by targeted modification in cell components like the cathode, anode, separator and electrolyte. The higher the energy density of a battery cell, the more energy will be released in a failure. New cathode materials aimed to eliminate decomposition/reactions and reduced risk for gas evolution are tested. Strategies can be to apply more robust surface coating materials, to design high-capacity, high-voltage cathodes materials based on safer chemistries, or innovative approaches of cathode structuring that mitigate heat generation. For the anodes and cathodes the quest is to develop new, stable, non-swelling materials with

high resistance to metal-dendrite formation resulting in increased cell lifetime and no decomposition or ex-foliation inside the battery. New electrolyte formulations with flame retardant properties, and high ionic conductivity is also part of building a broad electrochemical stability.

## INDUSTRIAL IMPLEMENTATION

The integration of sensors in the production of battery cells has to overcome a number of challenges in order to meet the requirements of commercial applications.

Among these are

- cost-efficient solutions
- size of sensor elements down to a few microns
- easy to integrate in the cell manufacturing process
- materials showing extremely high chemical and thermal stability
- data transmission concepts to bypass connectivity issues
- standardisation in terms of data handling and protocols
- designed with recycling in mind.



Figure 6: Industrial implementation is central in the European efforts.

# MANUFACTURABILITY

**Battery production consists** of diverse multi-disciplinary steps with numerous influencing factors and interdependencies. Current manufacturing processes still face numerous challenges to meet the ever-growing demands regarding high standards in quality, low environmental impact, and economic competitiveness. Despite highly specialised production lines in the so-called gigafactories, significant quantities of materials and cells are discarded due to specification mismatches. To address this issue, advanced tools at the technological forefront will certainly play an important role. Digital twins, as a core element of the accelerating digitisation in manufacturing, bear the potential to improve planning and operation of current and future battery production system for today's LIBs as well as for other chemistries and technologies of the future.

The battery cell is the smallest and most fundamental functional element in the battery value chain that gathers the essential materials, components, and features of a given battery technology. Modules and battery systems basically comprise the engineering solutions to make such cells work in a practical environment. The Battery 2030+ roadmap focuses mainly on the cell level.

## THE MAKING OF A BATTERY

The manufacturing process of battery cells can be divi-

ded in four stages: materials sourcing and processing, electrode production, cell assembly and cell finishing. Once all materials are processed and their quality is assured, electrodes are typically manufactured by roll-to-roll casting of the slurry onto a metallic current collector, followed by drying and compressing the electrodes to desired thickness and final microstructure. It is followed by the cell assembly with steps for stacking and electrolyte filling and finally cell finishing which includes formation and degassing.

In order for the digital models to be robust they must incorporate multi-physics, data-driven models and hybrid modelling, and be able to handle different kinds of battery chemistries, new disruptive materials as well as new manufacturing processes. Advanced digital models can autonomously control steps of battery production and support process chains. The first applications can already be found in research and partly in industrial practice – although they still tend to cover just selected aspects of digital twins-models. They are rarely transferable between production stages and between different battery configurations. The development of digital twins of battery cell manufacturing directed to routes that incorporate a connection to real manufacturing plants can accelerate and optimize the manufacturability of new cell architectures, novel materials as well as integration of new self-healing,

and sensorisation functionalities. The power of computational modelling and of AI in particular, will be exploited to deliver digital twins both for innovative, breakthrough cell geometries and for both current and advanced manufacturing routes, avoiding or substantially minimising classical trial-and-error approaches.

The current focus is on establishing connections between the different digital parameters of models and the controllable parameters in the manufacturing process. This linkage is crucial in enabling practical optimization workflows to optimize the manufacturing process and achieve desired outcomes. Furthermore, 4D-resolved finite element method models using electrode microstructures arising from manufacturing simulations have been also reported linking the hete-

rogenities of lithiation/delithiation upon cycling as a function of the manufacturing parameters. Although these models are not yet connected to real-time cell operation, they hold potential as key components for future developments of digital twins of cells.

The new concepts will lead to new designs that:

- minimise scrap, reduce primary energy use and emissions
- speed up processing by smart prototyping and manufacturing techniques
- improve quality and generate cost reduction strategies
- improve the homogeneity of the manufactured cells.

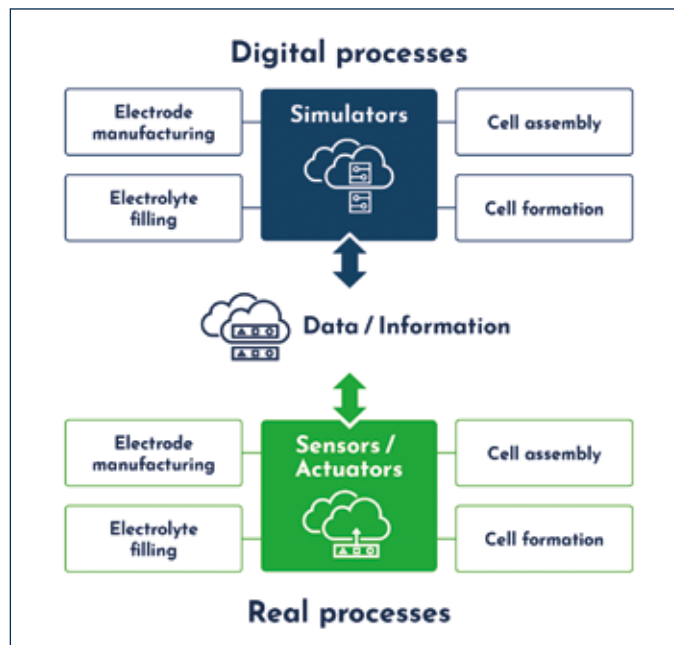


Figure 7: Digital twin of cell manufacturing processes.

# RAW MATERIALS & RECYCLING

**Mining in Europe** and extensive recycling will be inevitable if Europe is to be more self-sufficient in battery minerals. During 2023, the EC published the Critical Raw Materials Act targeting domestic processing and refining for strategic raw materials; among them are Ni, Co and Mn with the goal of 40 percent “in house” in Europe. Securing a steady supply of battery grade metals and materials requires sophisticated technology for production, refining and recycling with

efficient and stable reagent circulation, targeting minimized use of chemicals and reducing environmental impacts from such processes while improving recovery rate and yield. Disposal methodologies for those materials that cannot be recycled must also be included.

The projects in Battery 2030+ for raw materials comprise research and innovation activities focusing on improved battery metal and material production. This calls for an efficient technology for the extrac-



*Figure 8: Environmental aspects give rise to new legislation requiring higher degree of recycling of batteries.*

tion of lithium from poor or complex ores of underutilised lithium deposits in Europe. These deposits can be found from Finland in the North, through Germany, Austria and Czech Republic in Central Europe, to Spain and Portugal in the South-West.

Flexible technology and pilot scale solutions for sustainable production of battery-grade precursors and their anode and cathode materials, applied to materials from primary and secondary sources are also part of the efforts.

## **CIRCULARITY AND RECYCLING**

In the EU Battery Directive effective during 2023, lithium has to be recycled to at least 70 percent by weight, as compared to today's 50 percent. New batteries produced in Europe must also include recycled materials. As mentioned earlier a high degree of recycling is furthermore important since it decreases EU's dependency of imported metals. To significantly improve the recovery rate of critical raw materials is the goal for the projects within recycling in B 2030+. This includes prediction and modelling tools for the reuse of materials in secondary applications.

A major challenge for dismantling and recycling is the complexity of batteries incorporating micro-components, embedded electronics, active and inactive material, binding material and alike. Hence, today's recycling is a multi-step recovery process and there are presently no available methods for efficient component separation. This causes high recycling costs. After dismantling and sorting into categories according to the battery chemistries, the battery parts are fed into the recycling process or further fragmented by physical means. Several steps follow, involving physical, mechanical and/or chemical transformations. Currently, pyrometallurgy is the most commonly used

process for recovery of the metals. The ultimate goal is a novel approach to directly recover the active materials in a single step process.

## **INDUSTRIAL PROFITABILITY**

To attract the industry there must be a business case. As of today, the value of the active materials of lithium batteries is lower than the cost of recycling them. On top of this, the number of battery chemistries increases all the time. New battery technologies, such as lithium-sulphur, sodium-ion, or redox flow batteries are entering the market. Multiple Li-ion chemistries make recycling even more complex and sorting will be a major challenge. Furthermore, the introduction of Li-metal in highly efficient batteries requires strict safety cautions also in the recycling step. To cut the costs it is necessary to label the batteries and automate the sorting of mixed battery types, which in turn calls for standards and protocols. This is addressed as part of the EU regulatory framework for eco-design and batteries with the digital product passport (DPP) that supports the collection and sharing of product-related data among supply chain actors. The same goes for the transition to aqueous processing of electrodes on a large scale, and for the recycling and recovery processes of electrodes. Another aspect is that obsolete binders and additives have to be removed in advance to further enhance recovery steps of active materials. In particular, EV automotive battery systems, designed for high safety, are hard to efficiently dismantle – it is still a manual process.

## **CLOSED LOOP**

A circular economy requires a closed loop, meaning no waste after production, use and recycling of batteries. This becomes increasingly important when very

large volumes of automotive batteries are expected to “retire” shortly after 2030. New business cases like the reuse of battery modules or cells for a second life will emerge. However, the batteries will eventually come to final recycling, often in a more mixed condition, some more degraded than others.

Well-structured and standardised data from embedded sensors, digital battery passports, and sophis-

ticated battery management systems can improve the contribution from the battery recycling industry to the circular economy. Apart from providing valuable input for different second-life applications and give degradation status, it can also tell when to exchange individual battery cells in a battery pack.





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# BATTERY 2030+

<https://battery2030.eu>

