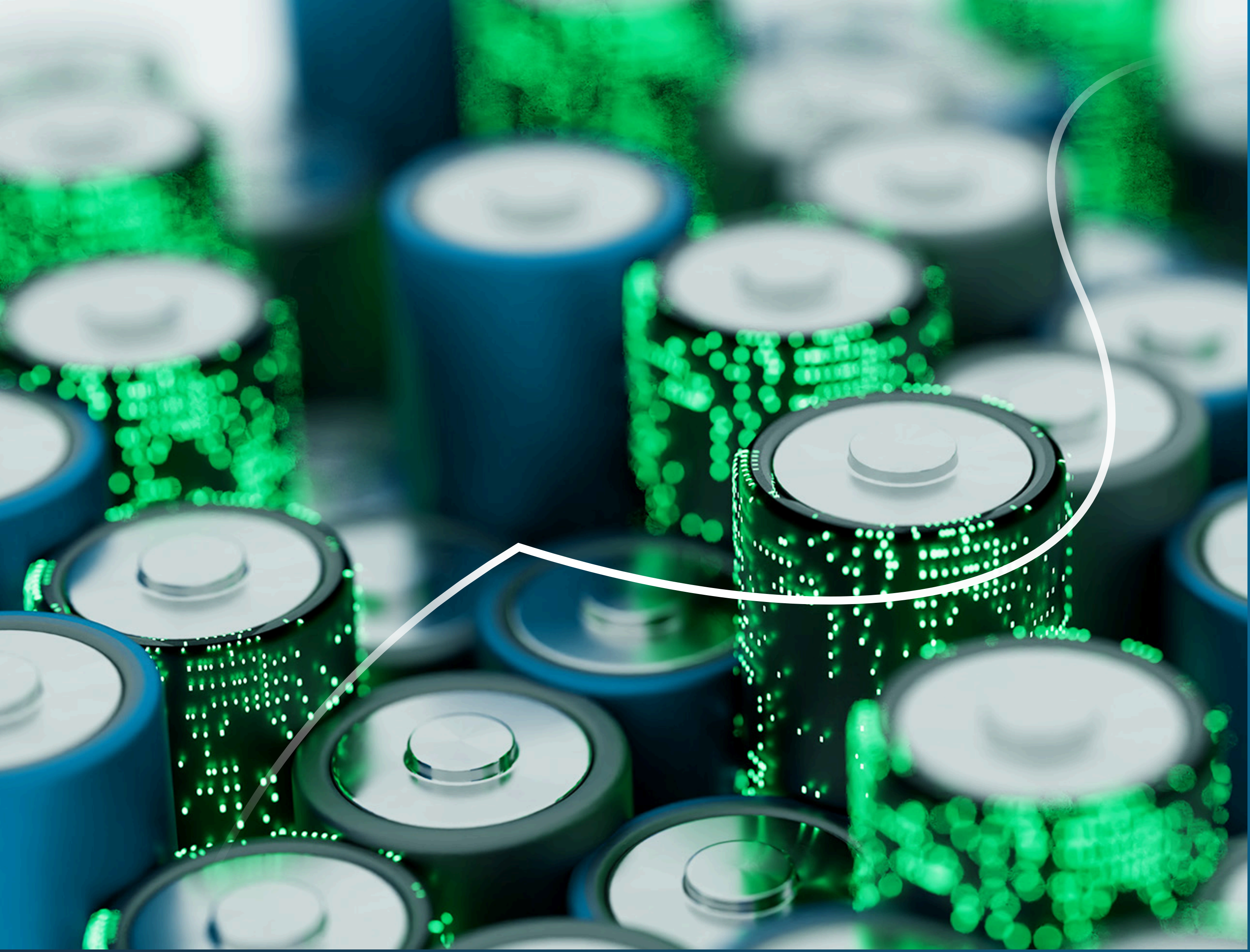

The Battery Recycler Challenge:

How to be competitive in uncertain market conditions?

Capgemini

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Executive Summary

As the global transition to electric mobility and sustainable energy accelerates, battery recycling is emerging not just as an environmental imperative, but as a strategic lever for industrial competitiveness, resource security and circular value creation. Yet, despite its critical role, the industry stands at a crossroads. While global recycling capacity is expanding rapidly, the volume and predictability of feedstock remain deeply constrained. This disconnect is creating acute economic, operational and regulatory pressures that threaten the viability of large-scale investments.

This Capgemini reports explores the multidimensional challenges and transformation opportunities facing the battery recycling ecosystem, focusing particularly on Europe's tightening regulatory landscape, the shift in battery chemistries and the urgent need for economically scalable solutions. A convergence of factors, such as slower than expected EV adoption, extended battery lifespans, delayed gigafactory ramp-ups and the rising dominance of lower-value LFP chemistries has led to a severe mismatch between installed recycling capacity and accessible materials. In this fragmented and fast-evolving market, traditional recycling models are no longer sufficient. To scale sustainably, recyclers must rethink how they operate, collaborate and invest.

To remain competitive, the industry must undergo a strategic reset across three core dimensions:

1. Reimagining Business Models and Ownership Structures: This POV evaluates emerging models (tolling, trading and licensing) alongside strategic ownership options from vertical integration to joint ventures and M&A. Each offers different pathways to secure feedstock, manage risk and build operational leverage, depending on a company's maturity and market positioning.
2. Embedding Digital and Automation Capabilities: The next frontier of recycling performance will be defined by digital innovation. Predictive diagnostics, digital twins, AI-powered supply chain control towers, IoT-enabled transport monitoring and blockchain-based traceability are no longer future concepts, they are essential levers to optimize cost, yield, safety and regulatory compliance across the value chain.
3. Forging Ecosystem-Scale Collaboration: No single player can succeed in isolation. A resilient and circular battery ecosystem requires deep coordination among OEMs, cell manufacturers, recyclers, regulators and logistics players. End-to-end data integration, shared infrastructure and harmonized regulations are critical enablers to unlock full system value.

Capgemini's unique blend of industrial expertise, digital engineering capabilities and strategic foresight enables us to support stakeholders across the battery recycling value chain. This article builds on that expertise to explore how the industry can address structural imbalances, regulatory pressures and shifting market dynamics, by adopting new business models, leveraging digital innovation and strengthening ecosystem collaboration to create long-term competitive advantage.

01.

Introduction

As global demand for electric vehicles (EVs) and battery energy storage systems (BESS) continues to grow, lithium-ion battery consumption is rising sharply, driving an increasing need for critical minerals. This is particularly true for the NMC (nickel manganese cobalt oxide) cathodes, which currently dominate the market due to their high energy density and performance advantages. These chemistries rely heavily on lithium (Li), cobalt (Co) and nickel (Ni), elements classified as critical due to their limited global production, high geopolitical concentration, and growing demand.

To mitigate these risks and diversify the supply chain, alternative cathode chemistries are gaining momentum. LFP (lithium iron phosphate) and LMFP (lithium manganese iron phosphate) eliminate the need for cobalt and nickel, relying instead on less critical and more abundant materials such as iron (Fe), phosphorus (P) and Manganese (Mn). These chemistries offer improved safety, longer cycle life and lower production costs, making them attractive for both low-cost EVs and stationary storage applications.

Despite the diversification of battery chemistries, the demand for critical materials remains substantial. By 2035, annual demand is projected to reach 435 kilotons (kt) for cobalt, 1,095 kt for lithium, and 6,179 kt for nickel (1). According to the International Energy Agency (IEA), existing and planned mining projects fall short of meeting this demand, with lithium facing the most severe supply gap.

Beyond this supply gap, the availability of these critical minerals is inherently constrained, with extraction concentrated in a few regions worldwide. This geographic limitation introduces additional risks to the supply chain, making it more vulnerable to geopolitical tensions, trade restrictions, and market disruptions. Consequently, lithium-ion battery recycling has become a global priority, not only for environmental and regulatory reasons but also for resource security. Establishing a robust domestic battery recycling ecosystem is now essential to reducing dependence on raw material imports, ensuring a stable supply of critical materials, and managing both the high scrap rates from current cell production and the slowly increasing volumes of end-of-life batteries, which together constitute the primary feedstock for recycled materials. According to the International Energy Agency, by 2035, recycling has the potential to reduce the global primary demand for cobalt, lithium and nickel by 15%, 5% and 5% respectively, and by 2050 by 40%, 25% and 25% respectively (2; 1), depending on collection efficiency and recycling yields. Moreover, this circular approach has the potential to reduce GHG emissions by at least 60% compared to primary materials produced from mining and refining (3), and battery material costs by an estimated 10% to 20% as technologies mature and economies of scale are achieved (4).

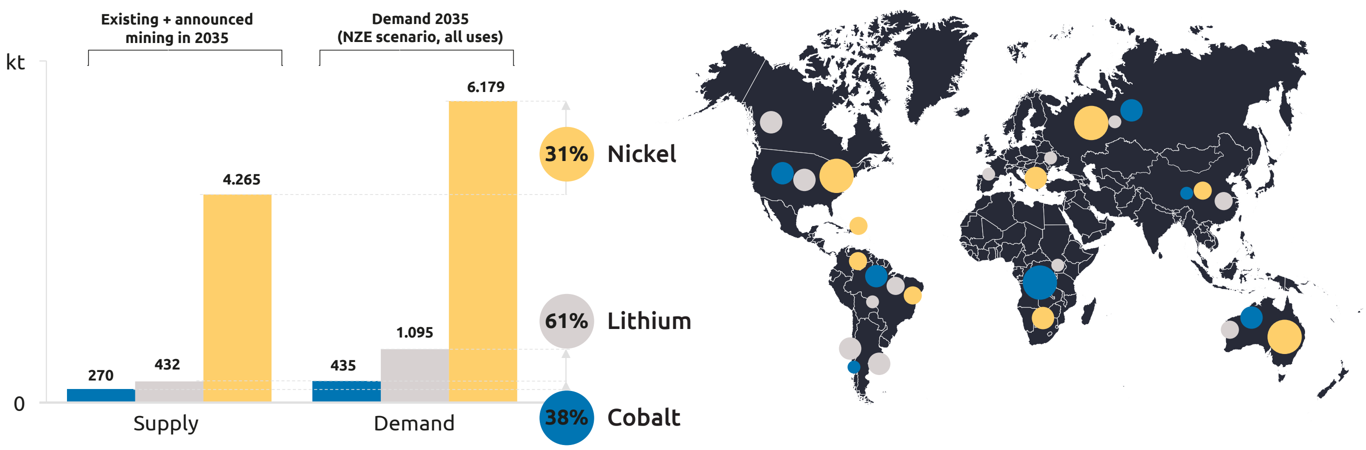


Figure 1. Global critical metals mining capacity, demand and localization towards 2035 (5)

Between 2025 and 2030, global battery recycling capacity (Fig. 2) is projected to grow significantly, reaching 12 million tons (Mt) for pre-treatment and 8.2 Mt for refining, up from 5.6 Mt and 3.8 Mt respectively. Over 70% of this capacity is expected to be located in China, with Europe and North America each accounting for about 10%, and the remaining 10% spread across the rest of the world (6; 7).

Despite this rapid capacity expansion, the forecasted global feedstock availability by 2030 is expected to be much lower, only 3 Mt for pre-treatment and 2 Mt for refining (6; 7). This mismatch highlights a significant overcapacity in the recycling sector and is driven by three main factors:

1. The adoption of electric vehicles has progressed more slowly than anticipated.
2. Batteries are lasting longer than expected due to improved durability and increasing use in second-life applications.
3. Gigafactories are ramping up more slowly than planned, with some projects delayed or cancelled altogether.

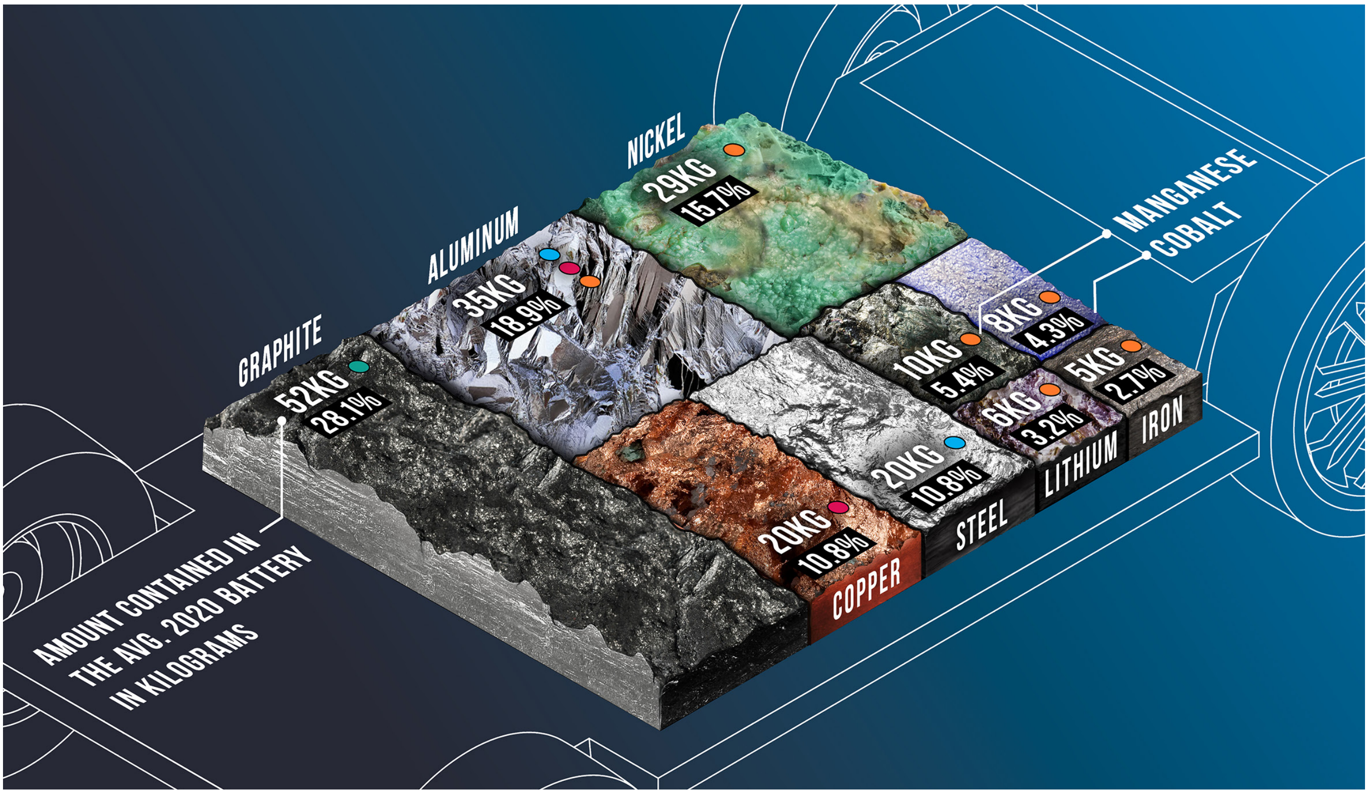
In the short to mid-term, this has made production scrap the dominant source of recycling feedstock, as many operational Gigafactories face high scrap rates and significant ramp-up challenges. In the long term, however, end-of-life batteries are expected to become the primary feedstock source as vehicle fleets mature and reach the end of their first life cycle.

In North America, the same trend of overcapacity relative to feedstock availability is evident. Projections indicate that by the mid-term, both pre-treatment and refining capacities will surpass the available feedstock. However, by 2030, feedstock availability is expected to catch up and potentially exceed the installed capacity for both stages. This suggests a temporary imbalance that may be corrected as vehicle electrification accelerates and scrap volumes grow.

Europe mirrors many of these global challenges, particularly in pre-treatment, where planned capacity already exceeds expected feedstock availability in both the mid- and long-term. For refining, mid-term overcapacity is also anticipated, but long-term projections suggest that feedstock volumes will eventually surpass installed refining capacity.

However, Europe faces an additional structural issue: a significant portion of the black mass produced in the region is currently exported to Asia for refining. This outflow reduces the availability of local feedstock and undermines Europe's efforts to build a closed-loop battery materials supply chain. In response, the European Union updated its waste classification rules in March 2025, designating waste batteries, cathode production scrap, and intermediate products like black mass as hazardous. As a result, their export to non-OECD countries is now banned, in an effort to retain valuable materials within the region and secure its strategic autonomy in battery supply chains.

> The transition to clean energy depends on how we close the loop. Scalable, digital-first battery recycling is not only good for the planet, it's a business case waiting to be unlocked."
>
> **Laurent Bromet**
> Global Head of Sustainable Engineering Services and Climate Tech



Battery recycling capacity vs feedstock availability forecast (2022-2030)

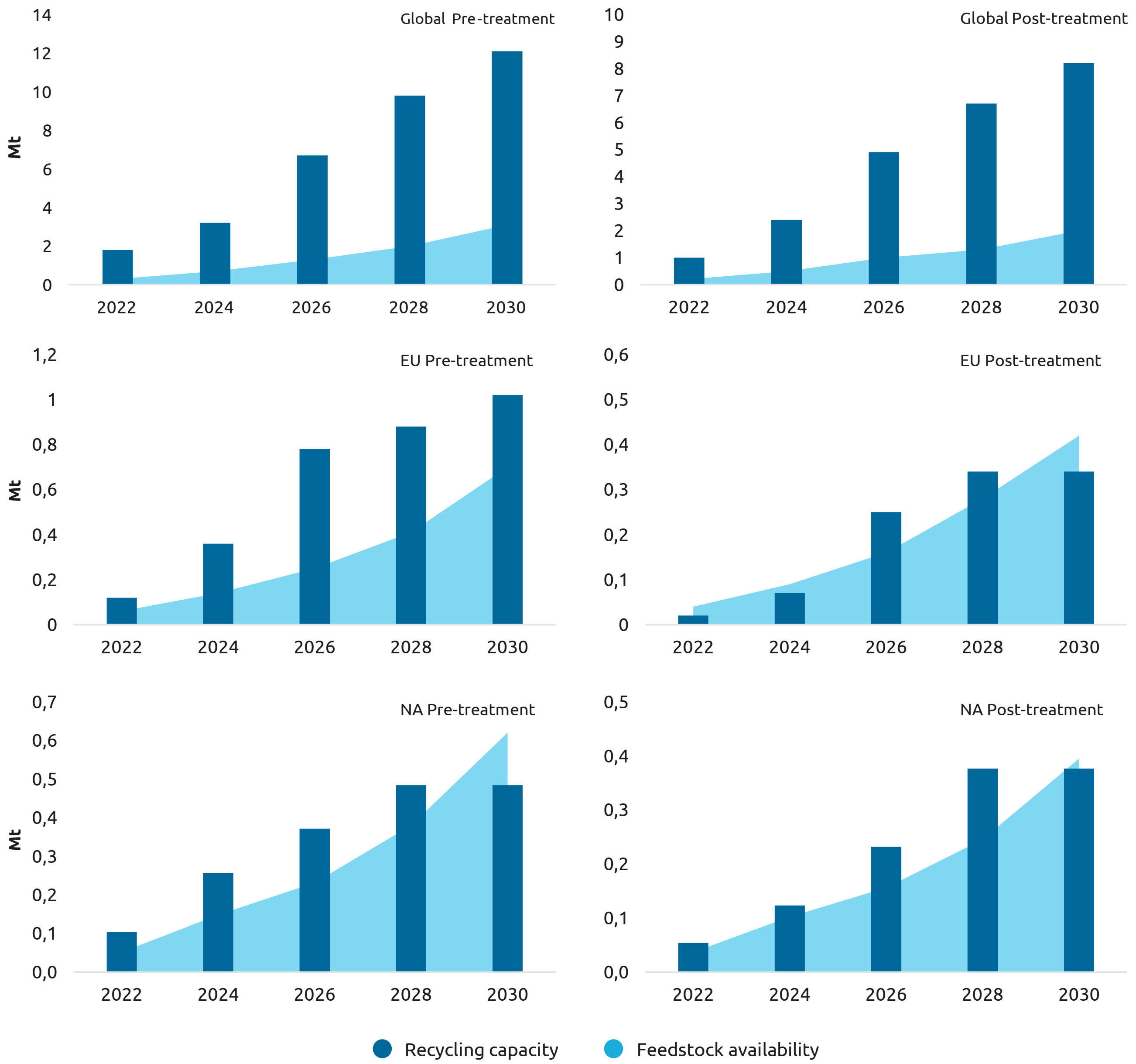


Figure 2. Battery recycling capacity vs feedstock availability forecast (2022-2030) (6)

In 2023, the European Union published a revised regulatory framework to accelerate the circularity of batteries, setting clear and specific requirements across the value chain. While the new Battery Regulation is a crucial milestone toward achieving sustainable, local, circular, and safer batteries, it also introduces added complexity to the recycling industry. Companies are still navigating the trade-off between optimizing technologies and committing to large-scale investments, in a market that currently lacks the necessary feedstock volumes to scale profitably.

This regulatory framework will, however, increase the value of recycled materials. Their incorporation into new batteries will become mandatory, and due to limited availability in the coming years, these materials are expected to become increasingly scarce, even if the precise impact on prices remains difficult to quantify.

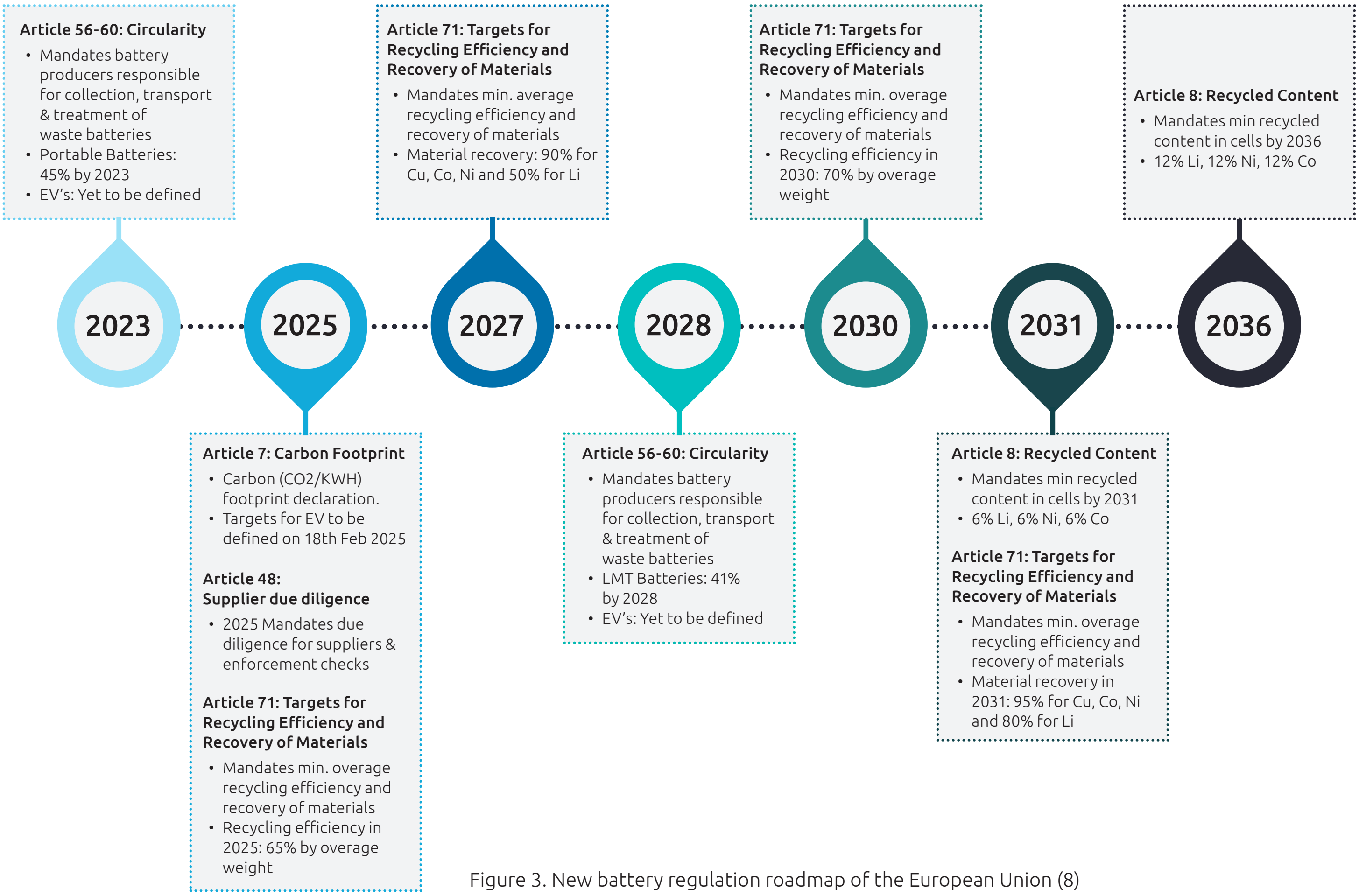


Figure 3. New battery regulation roadmap of the European Union (8)

As a leading global provider of strategy, engineering, and IT services, Capgemini's point of view dives into the most pressing challenges facing recyclers today.

In the first part of the document, we examine the strategic challenges facing the European battery recycling industry, including feedstock supply uncertainty, regulatory complexities, and investment risks. We explore different business models, analysing their advantages and challenges in securing feedstock and ensuring profitability. Additionally, we discuss various ownership models, highlighting their impact on scalability, financial viability, and technological advancement. Finally, we emphasize the importance of collaboration across the battery recycling value chain to enhance collection efficiency, stabilize supply chains, and drive industry-wide innovation.

In the second part of the document, we explore practical use cases on how digitalization, automation, data-driven models, and simulation can empower our clients to tackle operational and technological challenges, driving down costs and boosting efficiency throughout the industrialization and operational phases of lithium-ion battery recycling projects.

> Battery recycling is the cornerstone of a truly circular energy economy.
> At Capgemini, we believe sustainability is not a trade-off, it's a technology-enabled accelerator of long-term competitiveness and resilience."

Florent Andrillon
Global Head Climate Tech

Strategical Challenges

The European battery industry's uncertain market conditions, such as low recycling feedstock volumes, high export of black mass to Asia for refining (9), and dynamic regulatory landscape, pose significant strategic challenges in terms of supply chain security, investment viability, and regulatory compliance.

Securing a stable and cost-effective supply of feedstock, whether from end-of-life batteries, production scrap, or black mass, is essential for planning, scaling, and sustaining recycling operations. However, ongoing market uncertainties pose significant risks to large-scale projects, leading many recyclers to delay investments and strategic decisions. With feedstock volumes both uncertain and insufficient, recyclers and investors face considerable challenges in building a solid business case for large-scale infrastructure development.

Additionally, the variability of the incoming recycling feedstock in terms of cell chemistry and design has a direct impact on the operational model and scaling-up strategy of recyclers. This variability is not only technical but also strategic, as many OEMs and cell manufacturers are currently reconsidering their product roadmaps and transitioning toward alternative chemistries, particularly lithium iron phosphate (LFP). This shift is gaining momentum, especially for stationary storage and entry- and mid-range electric vehicles, due to LFP's lower cost, improved safety profile and longer cycle life.

However, for recyclers, this transition presents a significant challenge. LFP batteries contain no nickel or cobalt, two of the most valuable metals recovered in NMC chemistries. As a result, the intrinsic material value of LFP batteries is substantially lower. For example, even though the recoverable material value of batteries can strongly fluctuate depending on market prices, for an NMC battery, it can exceed 40 EUR/kWh, while the corresponding value for an LFP battery is typically below 20 EUR/kWh (10; 11; 12). This economic disparity should be considered a critical factor in any scaling-up or investment strategy, as it impacts the business case for recycling infrastructure and may delay or reduce investments.

To successfully address these challenges, recyclers need to develop robust and competitive business and ownership models, combined with strong partnership ecosystems and long-term collaboration frameworks across the value chain. This will enable them to secure a reliable and steady flow of feedstock, minimize material variability entering the reverse supply chain, scale their operations rapidly, and still maintain the flexibility needed to adapt to evolving technologies, regulations, and market dynamics.

In the next section, we will explore strategies that recyclers can implement to address these pressing challenges and secure a stable and scalable business.

> In a landscape shaped by shifting regulations and volatile raw material markets, strategic competitiveness relies on dynamic scenario modelling and agile business model adaptation across the battery recycling lifecycle."

Pierre Bagnon
Global Head of Intelligent Industry Accelerator

Battery Recycling Business Models

Given the complexity and capital-intensive nature (Fig. 4) of recycling, building the right business model is crucial for securing feedstock, maximizing battery value, and increasing supply chain security. Three of the most common business models for recyclers include the trading model, tolling model, and licensing model.

CAPEX & OPEX of recycling facilities

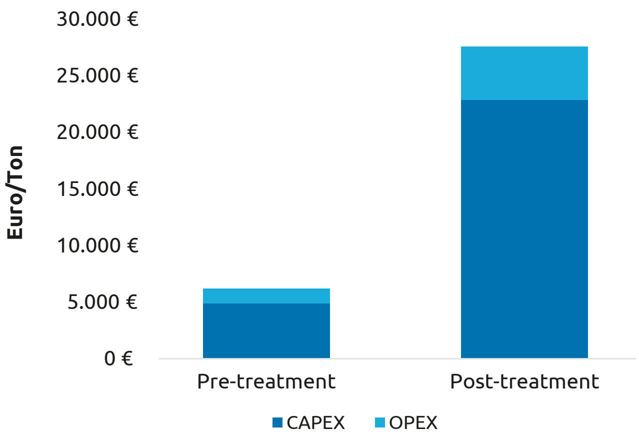


Figure 4. Exemplary CAPEX and OPEX for pre-treatment and post-treatment facilities (11; 13; 14)

Business model	Impact to recycler	Impact to OEM
Tolling model	• OEM pays a fixed fee to the recycler per battery processed • Revenues are less susceptible to fluctuating commodity prices • Requires capabilities to produce battery materials	• Ownership of batteries remains with the OEM • OEM pays a fee to the recycler per battery processed
Trading model	• Recyclers take ownership of recycling feedstock • Higher exposure to price and feedstock availability fluctuations • Higher feedstock variability, requiring higher flexibility in the operations	• Additional revenue stream by selling EOL batteries in the open market • Battery materials must be sourced from an additional source, being exposed to price and availability fluctuation
Licensing model	• Enables scalability without the need for direct investment in facilities • Risk related to intellectual property protection • High investment in R&D required	• Cost and time effective access to innovation to the OEM • Reduced risk associated with new process development • Limited control over the technology development

Table 1. Summary of business models and their impact on recyclers and OEMs

In the trading model, recyclers take ownership of end-of-life batteries or production scrap by purchasing them directly from the producers or brokers. After recovering the valuable materials, these are sold in the open market. While this model can yield substantial profits during periods of high commodity prices, it also exposes recyclers to significant risks, particularly during price downturns. Additionally, as consequence of the diversity of sources, feedstocks can have higher variability in terms of chemistry, quality and volume, requiring higher flexibility in the operations and increased storage capabilities, as recyclers must maintain optimal conditions for materials until they are sold.

Conversely, in the tolling model, ownership of the batteries and production scrap remains with the OEM or battery producer, while recyclers provide recycling services and return the recovered materials. This model allows recyclers to charge a fee per battery processed, making revenues less susceptible to fluctuating commodity prices. This predictability reduces risk, but profitability hinges on achieving high recycling volumes and minimizing costs. Additionally, this business model requires, either through vertical integration or partnerships, the capability to produce active battery materials that can be directly incorporated into the cell manufacturing process.

The licensing model allows recyclers with proprietary technologies to license their processes to other recyclers, battery manufacturers, or OEMs. This approach enables them to scale their technology across various markets without the need for direct investment in recycling facilities. Although this model generates a steady revenue stream and reduces overhead, it faces challenges related to intellectual property protection and requires substantial investment in research and development to keep pace with the rapid industry innovation.

Traditionally, the “trading” model, where recyclers buy and fully own recycling feedstock, has been the predominant business model in battery recycling. However, as OEMs prefer to retain ownership of the valuable materials, there has been a shift toward the “tolling” model in recent years (15; 16). Still requiring accelerating and strengthening the long-term close collaboration between producers and recyclers.

> Emerging ownership models, such as recycling-as-a-service and OEM-led closed-loop systems, are reshaping value capture and risk distribution across the battery materials supply chain.”
>
> **Richard Biagioni**
> Vice President, Climate Tech

Battery Recycling Ownership Models

In addition to the different business models seen in the battery recycling industry, companies must also decide how to structure the ownership and capital investment behind their recycling operations. Several ownership models exist, each offering different advantages and risks depending on a company's financial strength, technological capabilities, strategic ambitions, and risk appetite.

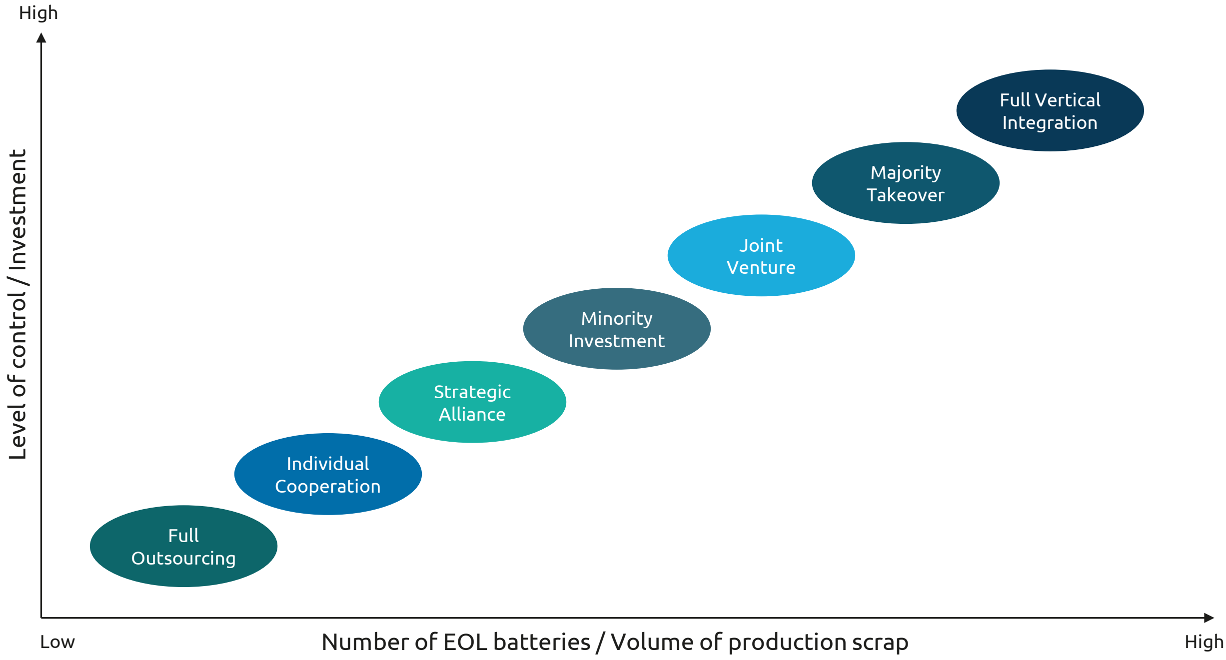


Figure 5. Potential ownership models as function of desired level of control/investment and volume of recycling feedstock

One option is vertical integration, where companies invest heavily to own and operate multiple steps along the recycling value chain, from collection and pre-treatment to refining. An example of this model is Umicore, who is building an integrated battery recycling value chain combining their proprietary pyro- and hydrometallurgical processes (17). This capital-intensive approach provides full control over processes, quality, and innovation, while enabling direct capture of value at every stage. However, it also comes with high upfront investment requirements and operational complexity, making it particularly challenging in an uncertain and rapidly evolving market.

An alternative approach is developing strategic partnership or Joint Ventures (JV), where recyclers form strategic collaborations with specialized players across the value chain. In this model, companies can focus on their core competencies and leverage other's expertise without incurring substantial capital costs. An example of this model is the strategic partnership closed between Glencore and Li-Cycle, where Glencore will acquire the Lithium Carbonate and Mixed-Metal Hydroxide produced by Li-Cycle to further process it into battery materials (18). This significantly reduces the need for upfront capital and accelerates market entry, while providing access to external expertise and established capabilities. However, it also means relinquishing some degree of control over quality, process optimization, and innovation. Moreover, recyclers become dependent on the performance and reliability of their partners, and potential misalignment of long-term strategic goals can create further challenges. An example of this is the Joint Venture Hydrovolt that Norsk Hydro and Northvolt created in 2020 (19) and was recently fully acquired by Norsk Hydro due to the financial setbacks faced by Northvolt in recent times (20).

Beyond these two main approaches, other ownership and capital structures like minority investments or Mergers & Acquisitions (M&A) are also gaining relevance. Minority investments, for instance, allow companies to acquire small equity stakes in innovative technology providers, rather than building capacity from scratch or pursuing full acquisitions. Such is the case of Ford's investment in Redwood Materials to support the expansion of Redwood's footprint (21).

On the other hand, Mergers & Acquisitions (M&A) can be particularly interesting for established players seeking rapid scale-up or consolidation. A well-known example of this model is the acquisition of Redux Recycling by Redwood Materials to expand its footprint in Europe (22). By acquiring or merging with existing recyclers or adjacent players, they can rapidly gain capabilities, technology, market share, or geographical presence. While this approach offers fast-track access to critical assets and potential operational synergies, it also comes with high transaction costs and integration risks.

In practice, many players in the battery recycling industry use hybrid strategies that combine different ownership models to find the right balance between control, flexibility, and capital efficiency. For instance, a recycler may choose to vertically integrate pre-treatment and refining to ensure feedstock quality and maintain control over the core recycling process. While partnering with logistics providers to minimize capital investment and collaborating with other recyclers to consolidate volumes, reducing transportation costs. At the same time, they may pursue minority investments to secure technological breakthroughs that could shape the industry's future. As the battery recycling industry matures and feedstock dynamics, regulations, and technologies evolve, companies will likely continue to adjust and combine these ownership models to navigate uncertainty while positioning themselves for long-term success.

Collaboration Across the Battery Recycling Value Chain

Building an efficient, resilient, and economically viable battery recycling industry is not the responsibility of a single player but rather the result of coordinated collaboration across the entire battery ecosystem. This includes end users, OEMs, battery manufacturers, logistics service providers, dismantlers, and recyclers. Establishing transparent partnerships, aligned incentives, and seamless data exchange across these stakeholders is crucial to improving collection rates, optimizing logistics, and ensuring stable feedstock supply.

Additionally, mechanisms such as consumer incentive programs for battery returns, regulatory frameworks that set ambitious but realistic, clear and harmonized guidelines for material classification, collection targets and recycling efficiencies, and investment and funding mechanisms that support technology development, infrastructure expansion, and the scaling of innovative recycling processes will be critical.

In a rapidly growing and evolving industry, achieving circularity and economic sustainability at scale requires collaboration across the entire ecosystem. This includes active participation from consumers, regulators, and investors, working together with OEMs, recyclers, and logistics providers.

Operational and Technological Challenges

The operational and technical challenges in the end-of-life (EOL) batteries are significantly influenced by the diversity in battery chemistry, formats, conditions, and geographic distribution (23; 24; 25). This variety complicates each stage of the recycling process, from reverse logistics to diagnosis, disassembly, and material recovery.

Reverse Logistics:

The collection and transport of EOL batteries are hindered by the scattered origins and varying conditions of the batteries, making it difficult to predict volumes and optimize logistics. Moreover, the diversity of chemistries and formats, along with the varying conditions of the returning batteries require different handling and packaging solutions, further complicating compliance with safety regulations and increasing costs. The inconsistent classification of waste batteries across regions further adds to the complexity to the logistics process (26).

Diagnosis, Discharge & Disassembly:

Diagnosis, discharge and disassembly are also affected by the variability in battery designs and conditions. Different chemistries, formats and conditions require tailored diagnostic methods to accurately assess the state of health (SOH) and determine the appropriate end-of-life pathway (27; 28; 29). Similarly, discharge protocols should be adapted to the condition of the battery for safe and efficient discharge (30; 31). Finally, the diversity of battery designs and manufacturing methods, require specific disassembly operations for each design (32). The need for specialized equipment and skilled labour underscores the operational challenges.

Material Recovery:

Extracting valuable materials from diverse battery types involves mechanical, thermal and chemical separation processes. The economics and the efficiency of these processes are highly sensitive to the characteristics of the input material like share of valuable materials and level of impurities. These processes must be accurately adjusted to the unique chemical and physical properties of each battery type to maximize purity and yield. Achieving optimal recovery while minimizing energy consumption, toxic emissions, and unwanted by-products requires continuous technological innovation and process optimization (33; 34; 35; 36).

In the next section, we will explore how data-driven and digital technologies can enhance the flexibility and resilience of operations and processes throughout the battery recycling value chain, especially under such variable conditions.

> The next frontier in battery recycling is not just physical, it's digital. Unified data convergence across the value chain enables predictive traceability, regulatory compliance, and circularity at scale ."

Rajendra Negi
Senior Manager & Lead of Battery Materials

Leveraging Digitalization and Automation to Overcome Operational and Technological Challenges

There are many challenges that recyclers face throughout the battery recycling value chain. These challenges can range from data security issues to high storage costs and inefficient recovery of critical materials. To tackle these problems, various technologies and digital tools come into play. By integrating automation, operational technology (OT), and advanced data analytics, companies can dramatically enhance process efficiency, safety, and scalability, transforming recycling operations into a smarter, more sustainable, and cost-effective ecosystem.

This chapter will explore different use cases, each presenting specific challenges and the technologies or tools that can help address them. The table below summarizes these use cases, highlighting the importance of technology in making battery recycling more efficient and effective. In the following sections, we will delve into these use cases, showcasing how technology is crucial in overcoming the obstacles faced by battery recyclers.

		Challenges	Use Cases of Digitalization & Automation	Key Technologies/Tools
End-to-End Perspective		• Large amount of data generated • Inefficient data collection • Data loss across stakeholders • Lack of data security • Non-standardized data protocols	• Unified Data Convergence System for the Battery Recycling Value Chain	• Cloud + Edge Computing • Industrial IoT • Machine Connectivity • PLM/ERP/MES/QMS/WMS • Blockchain • SaaS
Reverse Logistics	Collection	• Scattered material origin • Uncertain volumes • Variable condition of EOL batteries • New codes for battery waste classification • Handling of hazardous materials • Risks of fire, thermal runaway, or toxic leakage • Certified packaging, transport and storage facilities for hazardous materials • Complex regulatory processes for cross-border transport	• Simulation-Based Approach for Reverse Logistics Network Design	• NP-Hard Problem-Solving Algorithms • Agent-Based Modelling (ABM) • Discrete Event Simulation (DES) • GenAI-Driven Data Mining and Analytics • Supply Chain Digital Twin
	Storage		• AI -Powered Supply Chain Optimization for Battery Recycling	
			• Digital Simplification and Acceleration of Cross-Border Battery Clearance	• Cloud Computing • Robotic Process Automation (RPA) • Machine Learning • Software as a Service (SaaS)
	Transport		• IoT Monitoring of Battery Condition During Transport and Storage	• Edge Computing • Smart Sensors • IoT • Computer Vision • 4G&5G
Preparation	Diagnose	• SoH cannot be directly measured • Different degradation patterns at cell level • Time-consuming charge/discharge test	• Optimized Off-Line Battery Diagnose Techniques	• Advance Battery Characterization Methods • Machine Learning
	Discharge	• No industry standard for deep-discharging batteries • Time-consuming deep discharge • No recovery of residual energy • Generation of large amounts of wastewater • Voltage recovery at high discharge C-rates	• Fast and Safe Deep Discharge	• IoT • Machine Learning
	Disassembly	• High variability of battery designs and assembly methods • Heavily reliant on manual labour • Time-consuming manual disassembly • Electrical, chemical, flammable, and heavy load hazards	• Automated Battery Disassembly	• Computer Vision • Machine Learning + Data Mining • Robotics • Augmented / Mixed Reality (AR/MR) • Battery Passport
CFD Material Recovery	Pre-treatment	• High variability of recycling feedstock material (EoL batteries, production scrap and black mass) • High recycling efficiency and material recovery targets • Complex physico-chemical interactions in the process • Complex interdependencies of parameters and processes • High utilities and reactants consumption • Large amounts of undesired bi-products (e.g. Sodium Sulfate) • Extended timelines for plant design and commissioning	• Plant Simulation and Virtual Commissioning	• PLC/DCS Virtual Commissioning • Robot Simulation • SCADA/HMI Virtual Testing • Mechanistic models for the process • CFD and Process Simulation • Digital Twin for Factory Collaboration and Process Simulation in Battery Recycling
	Hydrometallurgy		• Digital Twin for Hydrometallurgical Process Optimization	• Digital Twin • Computational Fluid Dynamics (CFD) • Industrial IoT • Mechanistic Models of the Process • Model Predictive Control (MPC) • Advanced Process Control (APC) • Real-Time Optimisation (RTO) • GenAI Driven Data Mining and Optimization

Table 2. Summary of use cases of digitalization and automation in battery recycling and enabling technologies

05.

Use Cases of Digitalization and Automation in Battery Recycling

End-to End Perspective

Unified Data Convergence System for the Battery Recycling Value Chain

As it will be extensively described in the following sections, the battery recycling value chain involves multiple stages, from collection to material recovery. With the increasing regulatory requirements and economic pressure to maximize material recovery, greater digitalization is becoming necessary, leading to large volumes of data being generated at each stage of the battery recycling value chain.

For example, with increasing EOL battery volumes, predictive analytics and real-time tracking of material flows will help recyclers to anticipate fluctuations in battery feedstock volumes and geographies (37). Battery passports with information on battery composition, state-of-health, and dismantling instructions will improve disassembly efficiency (38). AI-driven robotics and vision-based automation will enable safer and more precise handling of used and waste batteries. In material processing, IoT monitoring and AI-based process control will enhance recovery rates by adjusting process parameters based on real-time feedstock composition data (39). While digital twins will reduce the risk, time and cost of implementing new recycling technologies (40; 41).

However, as more digital tools are embedded across the value chain, the increasing volume of generated data remains largely fragmented, limiting process optimization and traceability. Standardized data sharing between recyclers, logistics providers, automation suppliers, and regulatory bodies is still lacking, leading to inefficiencies, high integration costs, and challenges in ensuring material circularity.

To overcome these barriers, a unified digital platform that consolidates data from various sources and enables seamless collaboration across stakeholders is needed. This platform should leverage cloud computing for scalability and edge computing for localized processing, integrating real-time tracking, AI-driven analytics, and blockchain-based traceability to address key challenges such as real-time data collection at various lifecycle stages, structured data governance and integration, and enhanced data security for traceability and compliance.

These foundational technologies will establish a consistent and accurate data infrastructure, ensuring seamless integration across the battery value chain. This not only reduces data management and application costs but also provides a solid foundation for various use cases, enabling efficient, secure, and scalable battery lifecycle management.

> Data silos kill efficiency. A unified data system connects every step, from collection to recovery, for smarter decisions."
>
> **Le Wang**
> Digitalization Expert

Reverse Logistics

Simulation-Based Approach for Reverse Logistics Network Design

Reverse logistics in the battery recycling industry is a complex, multi-stage process that starts with the collection of recycling feedstock, in the form of battery packs, modules, cells, production scrap or black mass, and ends with material processing at recycling facilities. As EOL battery volumes are expected to rise significantly by the end of the decade, designing a well-structured reverse logistics network is crucial for ensuring cost efficiency, scalability, and regulatory compliance. However, the fragmented market distribution, uncertain volumes, and inconsistent collection rates of recycling feedstock make it challenging for recyclers to plan an efficient reverse logistics infrastructure (42; 43; 44).

> Reverse logistics is the backbone of a sustainable battery lifecycle - By combining simulation-based design with AI-powered control towers, reverse logistics becomes a digitally optimized engine for efficient and compliant battery recycling."
>
> **Stephanie Epple**
> Manager, Supply Chain Transformation

A robust reverse logistics network encompasses collection points, storage facilities, transportation routes, intermediate processing facilities and recycling plants. The key challenge lies in optimizing this infrastructure while balancing cost, operational flexibility, and sustainability. Two common network design approaches are centralized and decentralized configurations.

Centralized networks focus on the consolidation of the batteries in one or a few high-capacity facilities, allowing them to achieve greater consistency in the operations and reduce the recycling costs per unit due to economies of scale. However, long-distance transportation of batteries from collection points to central hubs increases total costs, particularly given the hazardous nature of the materials. Additionally, centralized hubs may face capacity constraints, leading to operational bottlenecks (45; 46).

On the other hand, a decentralized network consists of multiple smaller and regionally distributed facilities that are closer to battery collection sources. These facilities can handle pre-treatment tasks, such as sorting, discharging, dismantling, shredding and thermo-mechanical separation of batteries, before transporting pre-processed materials to larger hubs for final material recovery. With these facilities located closer to the collection points, transportation costs can be reduced. Additionally, its modular configuration offers flexibility and easier scalability. However, multiple smaller facilities usually result in higher capital and operational expenditures (47; 45; 48).

To determine the optimal network configuration, advanced modelling and simulation tools enable recyclers to analyse various logistics scenarios and make data-driven infrastructure decisions. These tools incorporate mathematical optimization, discrete event simulation (DES), and agent-based modelling (ABM) to evaluate facility placement, capacity planning, transportation flows, and process allocation (49; 50). By integrating real-world data, such as battery return rates, geographic distribution, transportation constraints, and processing capacities, these platforms allow recyclers to simulate multiple scenarios, test infrastructure setups, and optimize transport routes before implementation.

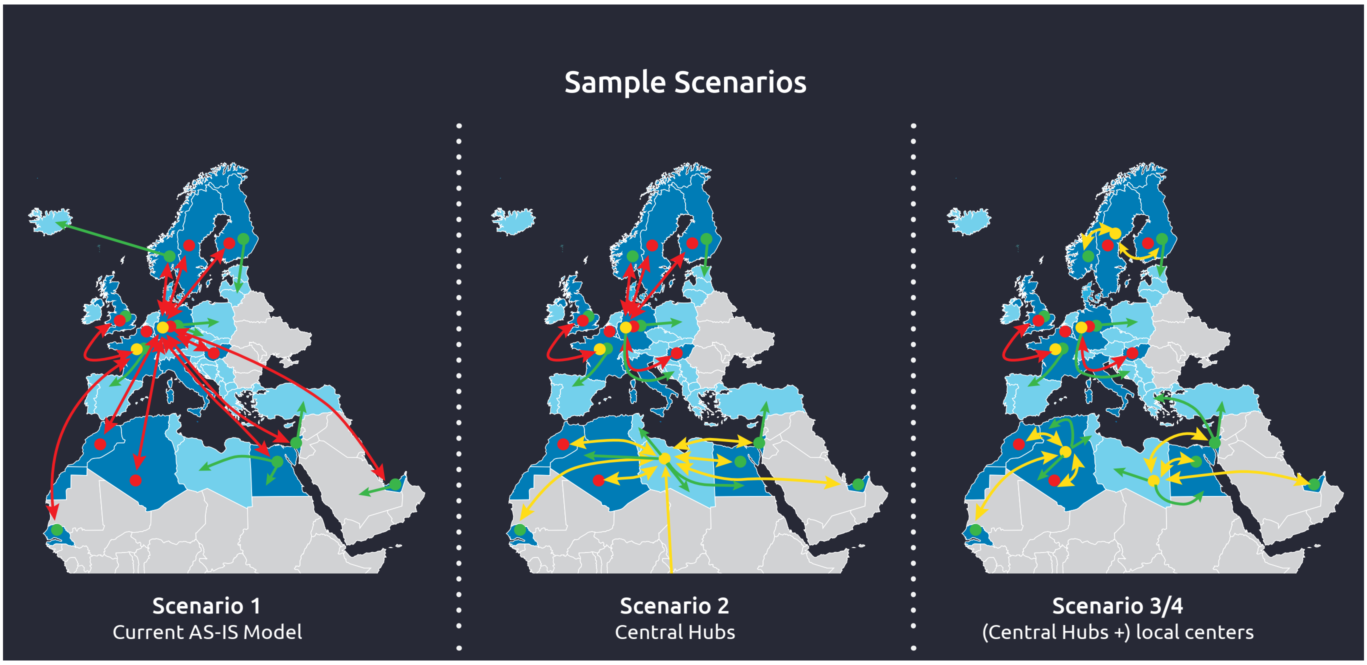


Figure 6. Sample scenarios for network optimization modelling

Mathematical solvers apply linear and mixed-integer programming (MIP) to optimize network design, while supply chain simulation platforms use digital twins to model dynamic logistics flows, anticipate bottlenecks, and test operational strategies under varying conditions (51). This simulation-based planning approach minimizes costly redesigns, reduces operational risk, and ensures scalability while aligning logistics networks with long-term market demand, cost efficiency, service levels, and regulatory requirements and sustainability goals.

AI-Powered Supply Chain Optimization for Battery Recycling

One of the persistent challenges in battery recycling is achieving full traceability of materials throughout the entire reverse supply chain. Visibility into the volumes, locations, chemistries, formats, and conditions of incoming end-of-life (EoL) batteries is crucial, not only for operational planning but also for ensuring compliance with regulatory requirements, such as storage limits for hazardous materials at certified facilities (52; 8), and for enabling the efficient tracking and reuse of packaging for hazardous materials (53).

To address these challenges, AI-powered Supply Chain Control Towers provide a centralized platform that consolidates real-time data from multiple stakeholders, allowing for end-to-end monitoring and intelligent coordination of material flows (54; 55; 56). At their core, these systems employ AI-driven data mining techniques and optimization algorithms designed to solve NP-hard logistical challenges (57), enabling the development of predictive and prescriptive tools, such as predictive planning modules for forecasting battery returns, transport and storage capacity allocation, and transport optimization tools that leverage smart routing, real-time risk management, and automated alerts for proactive decision-making. As a result, critical resources, including ADR-certified vehicles, specialized handling equipment, and certified storage facilities, are allocated efficiently while ensuring regulatory compliance and the highest safety standards.

A Supply Chain Control Tower not only enables real-time coordination of reverse logistics, but it can also play a crucial role in optimizing downstream recycling processes by supporting the standardization of black mass composition. One of the main challenges in battery recycling is the variability of black mass, which impacts the stability and efficiency of hydrometallurgical refining. By gaining early visibility into the chemistry, format, and volume of the recycling feedstock entering the supply chain, recyclers can strategically plan pre-treatment operations to achieve a more consistent black mass composition. This proactive approach reduces the need for frequent major recalibrations at hydrometallurgical recycling plants, enhancing process stability, maximizing the utilization of installed capacity, improving recovery yields, and ultimately enhancing the economic viability of battery recycling.

To fully leverage this capability, the Control Tower should be seamlessly integrated with enterprise and operations management systems, such as ERP, WMS, and MES, ensuring that financial planning, warehouse operations, and recycling execution remain synchronized.

By integrating real-time tracking, predictive analytics, automation, and enterprise systems, recyclers can shift from reactive material handling to proactive and AI-driven process optimization, enhancing economic performance, minimizing operational risks, and maximizing material recovery from increasingly complex battery waste streams.

> What gets overlooked is that industrial recycling is a logistics and systems challenge as much as a chemical one, success depends on mastering both."

Julian Fronza
Head of Battery Industrialization, Launch & Ramp-Up

Digital Simplification and Acceleration of Cross-Border Battery Clearance

Transporting hazardous materials, especially across borders, has an extra layer of complexity. As there were no specific waste codes defined for end-of-life batteries, black mass and production scrap in the European List of Waste, the classification as either non-hazardous or hazardous could differ from shipment to shipment. To harmonize this, the EU Commission has released in March 2025 a reviewed list of European Waste Codes (EWC), where waste batteries, production scrap and black mass are classified as hazardous (58). This allows to retain these valuable materials within the areas of economic cooperation, prohibiting their export to non-OECD countries. However, the adoption of these new codes increases the traceability requirements for cross-border transports, representing an additional challenge for recyclers.

In addition to the strict measures that must be implemented to ensure safety during handling, storage and transport according to the classification of the waste, recyclers must meet regulatory requirements such as the cross-border notification and consent procedure (59). This means that a recycler planning to ship waste within the EU and OECD countries needs the authorization of the authorities of all the involved countries (origin, transit and destination) before the waste material can be shipped. Currently, this process it not fully digitalized, leading to processing times of 6 months on average and representing a high risk of becoming a bottle neck when the volumes of recycling feedstock increase (60).

Leveraging a cloud-native traceability platform, all necessary data and documentation required for cross-border transport applications can be automatically generated in compliance with national and global standards. The system allows to organize and manage the data directly from the platform to avoid redundancy and data quality issues. Additionally, Application Programming Interfaces (APIs) enable seamless processing data among systems, minimizing manual intervention.

This approach facilitates seamless data transfer between the applicant party and the reviewing authority by enabling a fully automated and paperless workflow. This not only enhances the efficiency of permitting processes but also reduces transport and storage times and costs.

IoT Monitoring of Battery Condition During Transport and Storage

Transporting end-of-life batteries is expensive and complex due to the risks of fire, thermal runaway, or toxic leakage (61). One single incident can disrupt the entire logistics chain. Therefore, handling these materials requires skilled labour and appropriate equipment, certifications and strict adherence to dangerous and hazardous regulations for transportation, including specific packaging, labelling, and documentation requirements (61; 62; 63; 64; 65).

Effective packaging is critical to ensuring the safe transport and storage of end-of-life (EOL) batteries. It must be lightweight yet fire-resistant, capable of filtering toxic emissions, reusable, non-explosive, customizable, and UN-certified to prevent hazards during transit (63). However, sourcing compliant packaging solutions adds significant complexity and cost to the logistics process. Given the inherent risks, the development and widespread adoption of standardized, high-performance packaging solutions are essential to ensure safety during storage and transport of EOL batteries.

To mitigate the risks during transportation and storage advanced Internet of Things (IoT) based monitoring systems, leveraging 4G/5G connectivity can be deployed. These systems integrate smart sensors to continuously track critical parameters such as temperature, pressure and off-gassing levels in real time. Additionally, edge-computing-powered computer vision cameras can detect early signs of fire hazards, gas leaks, or structural damage (67).

By enabling automated risk detection and real-time alerts, this system empowers drivers and logistics control centres to take immediate preventive actions. Centralized dashboards can be implemented within the IoT system allowing control centres to inspect, review and take action on alerts. These alerts can also be sent to other key systems such as the MES or ERP to enable users to take actions. Automated risk detection and real-time alerts will minimize the impact of thermal runaway, fires and environmental hazards. Implementing such proactive monitoring not only strengthens supply chain resilience but also enhances safety and reduces operational disruptions in battery logistics.

Battery Diagnosis

Optimized Off-Line Battery Diagnose Techniques

Accurate diagnosis of end-of-life (EOL) Li-ion batteries is crucial for determining their condition to be transported and their state of health (SOH). The diagnostic process involves assessing key parameters such as remaining capacity, internal resistance, voltage stability, and physical integrity (64). Implementing advanced diagnostic methods lays the foundation for improved resource efficiency by identifying the most suitable pathway for each battery, whether it can be reused, repurposed for secondary applications or recycled to recover valuable materials.

EV battery packs consist of multiple interconnected cells and modules, each of which can have different performance characteristics and degradation patterns. This makes it difficult to diagnose the health of the whole battery pack without a detailed cell or module-level analysis. As SoH cannot be directly measured, it is traditionally estimated by measuring the capacity in a slow charge/discharge test, but this method is time-consuming (68; 69; 29; 27).

Leading electric vehicle (EV) manufacturers are investing in the development of model-based and data-driven methods to estimate the SoH of batteries. These cutting-edge methods can provide the dynamic data required for the forthcoming battery passport, streamlining the SoH assessment of EoL batteries. However, the majority of batteries equipped with a battery passport won't be ready for recycling for another 15 years. Furthermore, the diversity of battery packs, the multitude of variables, and the extensive data needed to train these models mean that these methods are best suited for in-line SoH estimation. This underscores the importance of developing and implementing alternative fast off-line diagnostic techniques.

A combination of methods like partial charge (PC), intermittent current interruption (ICI), pulse test technique (PTT) and electrochemical impedance spectroscopy (EIS) are potential fast estimation solutions that could be suitable for assessing spent batteries. These methods do not only rely on measurements of the specific charging/discharging curve and can estimate the SoH and internal resistance at a given test point without considering the historical information of the battery.

> Battery recycling faces growing complexity due to rapidly evolving chemistries, diverse and numerous cell types, and the urgent need for fast, reliable, and cost-effective diagnostic tools to enable optimized, individualized reuse strategies."

Leander Peis
Battery Characterization Expert

Characterization Method	Application Level	Application Mode	Indicator
Partial Charge (PC)	Cell, module and pack	In-line and off-line	Charging data
Intermittent Current Interruption (ICI)	Cell, module and pack	In-line and off-line	Internal resistance
Pulse Test Technique (PTT)	Cell, module and pack	Offline	Internal resistance
Electrochemical Impedance Spectroscopy (EIS)	Cell, module and pack	Offline	Impedance

Table 3. Overview of alternative off-line state of health characterization methods (69)

For instance, implementing Partial Charge (PC) analysis allows a reduction in measurement time required to estimate the usable capacity by focusing on a narrowed voltage region. This approach enables the efficient extraction of sufficient data to quickly determine the usable capacity and provide insights into the anode's capacity, which is one of the most dominant aging factors of batteries.

The Partial Charge (PC) analysis can be further optimized by incorporating Intermittent Current Interruption (ICI) protocols, which consists of small, regular current interruptions during the charging and discharging cycles. Each of these interruptions provides valuable insights into the resistive behaviour of the battery, offering a clearer understanding of the battery's characteristics, including the magnitude and State of Charge (SoC) dependence of the resistance.

By integrating these methods, not only the speed to determine the SoH can be reduced but also a more comprehensive analysis of the battery's performance and longevity can be achieved, increasing the potential for data-driven approaches in clustering and predicting further aging behaviour.

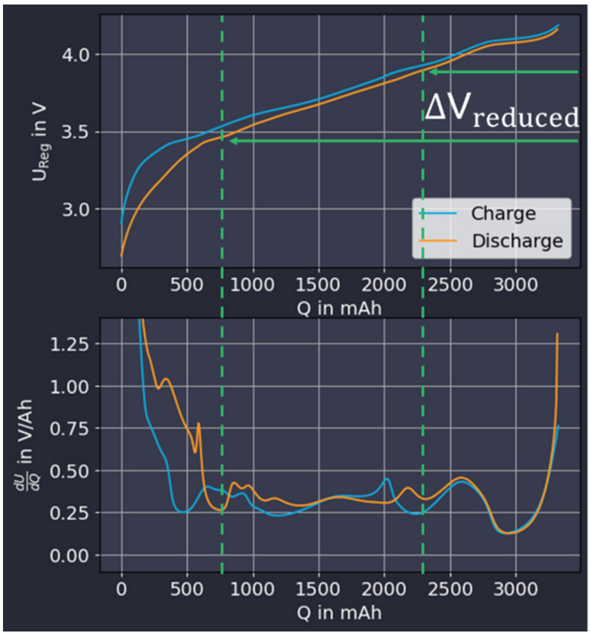


Figure 7.
Exemplary voltage window for a Partial Charge analysis of an NCA/Si-C battery

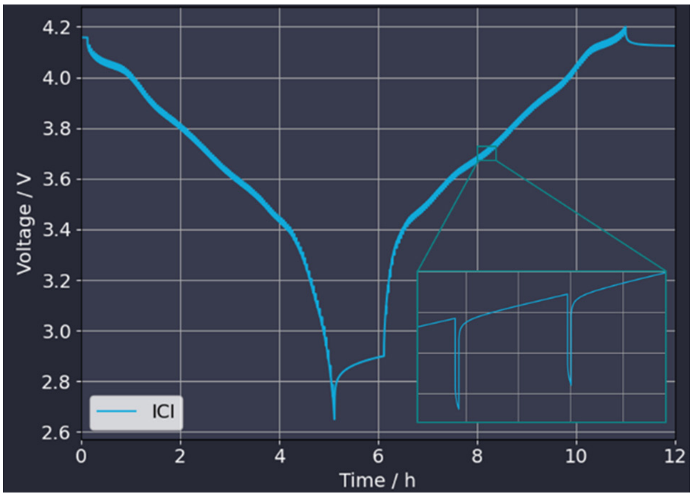


Figure 8.
Intermittent Current Interruption (ICI) Test for SoH diagnostic of an NCA/Si-C battery

Battery Discharge

Fast and Safe Deep Discharge

Before Li-ion batteries can be safely disassembled, they must undergo a deep discharge process, to decrease the voltage below 0.5V for preventing safety risks such as thermal runaway, short-circuiting, or accidental electrocution (67). There is no industry standard for discharging electric vehicle batteries. In some cases, batteries are deactivated thermally or are submerged for up to 24 hours in a saline solution that induces a short circuit. However, these methods don't allow the recovery of the residual energy and generate large amounts of wastewater (70; 71; 72; 73; 74; 75).

Other deep discharge methods involve discharging batteries over long periods, often using resistive loads. Some of them incorporate energy recovery technologies that consist of bidirectional power converters, to make use of the residual energy stored in the battery to power other systems or feed back to the grid rather than being wasted as heat (69). This not only improves the overall efficiency of the process but also offers potential cost savings. However, fully discharging certain batteries, like high-capacity EV batteries, can take several hours. Additionally, accelerating the discharge process can sometimes lead to voltage recovery, where the battery's voltage rises after a few minutes or hours, becoming a safety risk for the operators (76; 77; 70; 78).

For safe and efficient deep discharge, it is critical to determine the optimal C-rate that allows fast discharge without overheating the battery (<60°C). At medium State of Charge (SoC) values, a battery can be discharged at a C-Rate of 1 or higher. However, at lower SoC, the internal resistance tends to increase, resulting in a faster temperature increase. Therefore, the discharge current must be dynamically adjusted to maintain the temperature within the safety boundaries.

One way of controlling the discharge temperature of the battery, is by implementing a step function coupled with a thermal monitoring system to create a feedback loop where the current is adjusted in response to the real-time temperature of the battery. If the battery temperature approaches a critical threshold, the step function can reduce or stop the discharge rate temporarily, giving the battery time to cool down.

However, as EoL batteries vary significantly in their residual charge, state of health and condition, it is required to perform an individual assessment to determine the appropriate discharge procedure for each of them. To significantly reduce the time and complexity of the process, machine learning algorithms can be trained to predict the optimal discharge profile and develop standardize discharge protocols based on the battery's age, chemistry, usage history, residual charge and conditions.

> Battery recycling is no longer a downstream afterthought. With the right use of AI, automation, and virtual process design, we're turning complexity into opportunity across the entire battery value chain."

Marcus Fiege
Head of Center of Excellence Battery

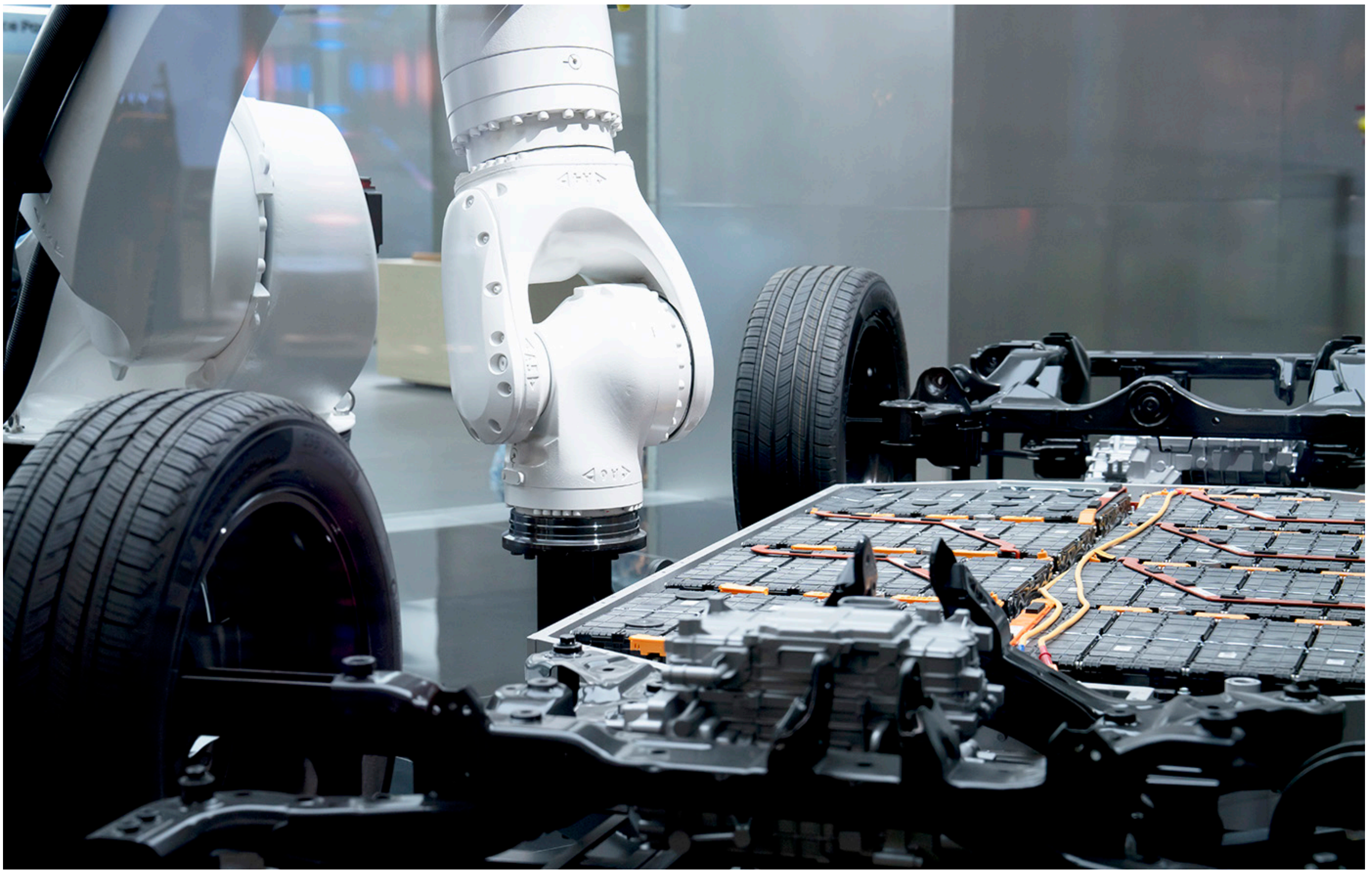
Battery Disassembly

Automated Battery Disassembly

Once batteries have been thoroughly diagnosed and safely discharged, they can be disassembled down to module or cell level, which serve as the primary input materials for subsequent mechanical or pyrometallurgical pre-treatment processes. In the case of direct recycling, a deeper level of disassem-bly may be necessary, sometimes requiring the delamination of the electrode coating from the current collectors (79; 80).

Disassembly not only enables the recovery of valuable materials, such as electronic and electrical components, but also allows the removal of various elements such as resins, insulating fibres, metallic and plastic fasteners, etc. Removing these components at this stage is significantly more cost-effective and less labour-intensive than if they were to be extracted later in the recycling process (81).

The complexity of disassembly can vary greatly depending on the design of the battery pack. In some cases, disassembling a battery down to the cell level may involve over 50 main steps, including the removal of fasteners, battery pack covers, low and high-voltage wire harnesses, busbars, insulating pads, cooling plates, modules and cells (82; 83; 84; 85).



Currently, the disassembly of batteries relies heavily in manual labour due to the diverse handling requirements associated with various cell chemistries, formats, module designs, and the specific conditions of end-of-life (EoL) batteries. However, the expected rise in the volume of end-of-life (EoL) batteries, combined with the inherent risks of electrical, chemical, flammable, and heavy load hazards, emphasizes the need for automation solutions in this step. These solutions can range from semi-automated to AI supported full-automated solutions depending on the specific level of automation and flexibility required for the materials handled (86; 87).

When it comes to guiding automated systems for the disassembly of EV batteries, two primary approaches stand out. The first makes use of manufacturer's documentation and the second utilizes vision systems, advanced sensors and AI-driven decision-making models to define disassembly sequences.

The first approach relies heavily on detailed documentation provided by battery manufacturers, which might be accessible through the forthcoming battery passport. This documentation includes comprehensive information about the battery design, materials used, and specific assembly and disassembly sequences. This information can be further utilized to guide operators or robots to ensure that each step is executed according to the manufacturer's specifications. For example, some companies, like Bosch Rexroth, are developing semi-automated solutions where robots perform initial disassembly steps, such as removing the battery pack cover, while Augmented Reality-guided operators complete the subsequent steps based on the manufacturer's data (88).

> Advanced robotics, machine vision, and modular automation platforms are enabling scalable, safe, and economically viable disassembly and material recovery processes, even for heterogeneous battery formats."
>
> **Carlos Naranjo**
> Manager & Lead of Battery Recycling

The second approach introduces a more adaptive and intelligent method by integrating vision systems, sensors, and AI. These technologies provide real-time insights into the battery's condition, identifying variations or damages that may not be accounted for in the original documentation. AI-driven models analyse this data to make informed decisions, adjusting the disassembly process as needed. This enables greater flexibility and allows for handling a diverse range of battery designs and conditions, making it particularly valuable for batteries that have undergone different usage patterns or varying degrees of wear and tear (89; 90; 91).

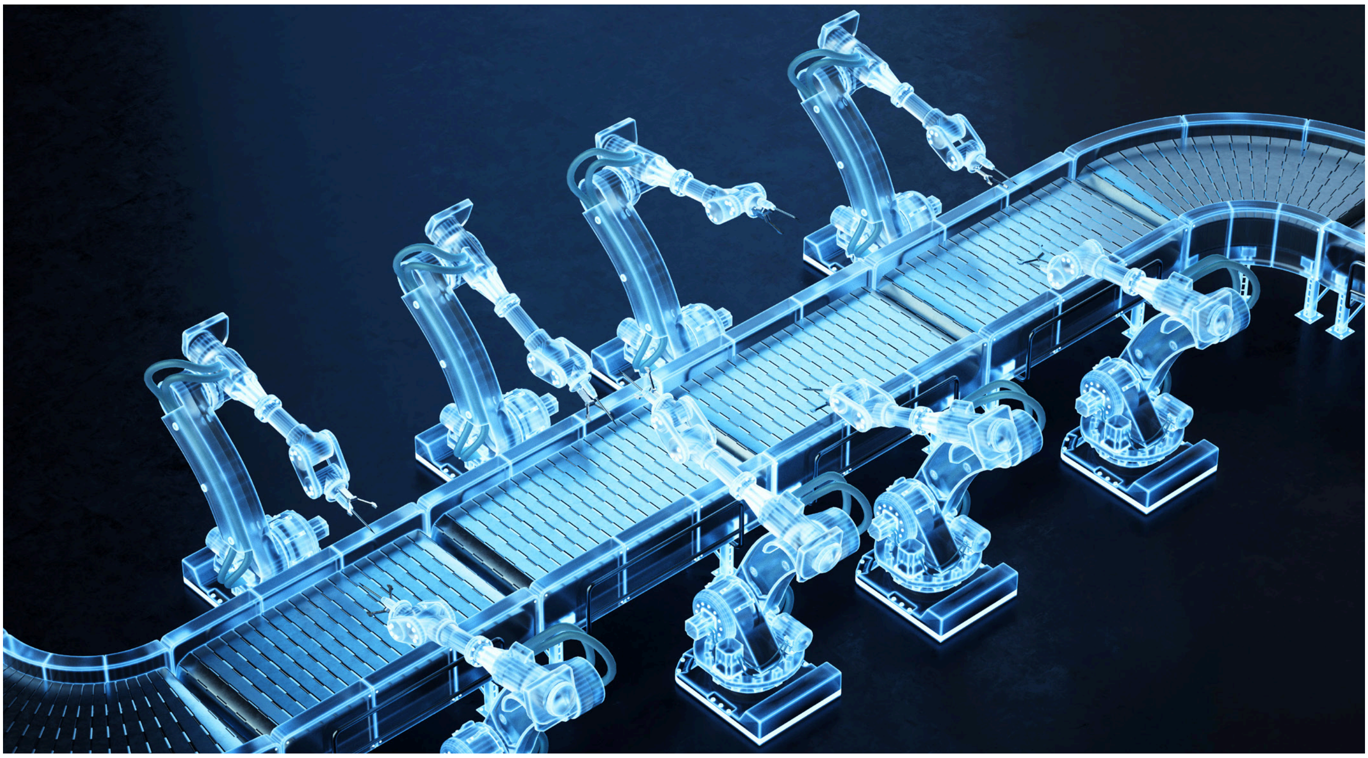
While AI and vision-based approaches enhance adaptability, manufacturer-provided data remains a critical enabler for efficient disassembly. A well-structured combination of both approaches can lead to safer, more precise, and cost-effective processes. However, achieving true efficiency in battery disassembly requires strong collaboration between manufacturers, recyclers, automation and digitalization providers to improve disassembly strategies and ensure compatibility within systems. Additionally, integrating principles of design for circularity like standardized battery designs, modular construction, and accessible disassembly information will play a crucial role in gnificantly enhancing disassembly efficiency and material recovery (92; 93; 94).

Material Recovery

Plant Simulation and Virtual Commissioning

Scaling battery recycling operations presents significant challenges in factory planning, commissioning, and ramp-up. One of the main hurdles is optimizing facility layout and material flow. Poorly planned equipment placement and suboptimal intralogistics can create bottlenecks, increase handling requirements, and limit space utilization, ultimately delaying production and driving up operational costs. Additionally, if key production equipment such as crushers, dryers, or leaching reactors are not properly dimensioned, the system may suffer from capacity imbalances, either underutilizing assets or overloading critical process steps. This lack of coordination between material flow and equipment sizing can lead to frequent disruptions and unplanned stoppages (95).

Traditional means of validation for automation and control systems, such as PLC/DCS logic, HMI, interfaces, and process control loops have limitations, which may generate complications during the commissioning, causing operational instability and requiring extensive debugging and adjustments under extreme time pressure, ultimately delaying ramping up and extending the commissioning phase.



Additionally, lack of workforce training on innovative processes and new automation interfaces can result in slow adoption, compromising process efficiency (96).

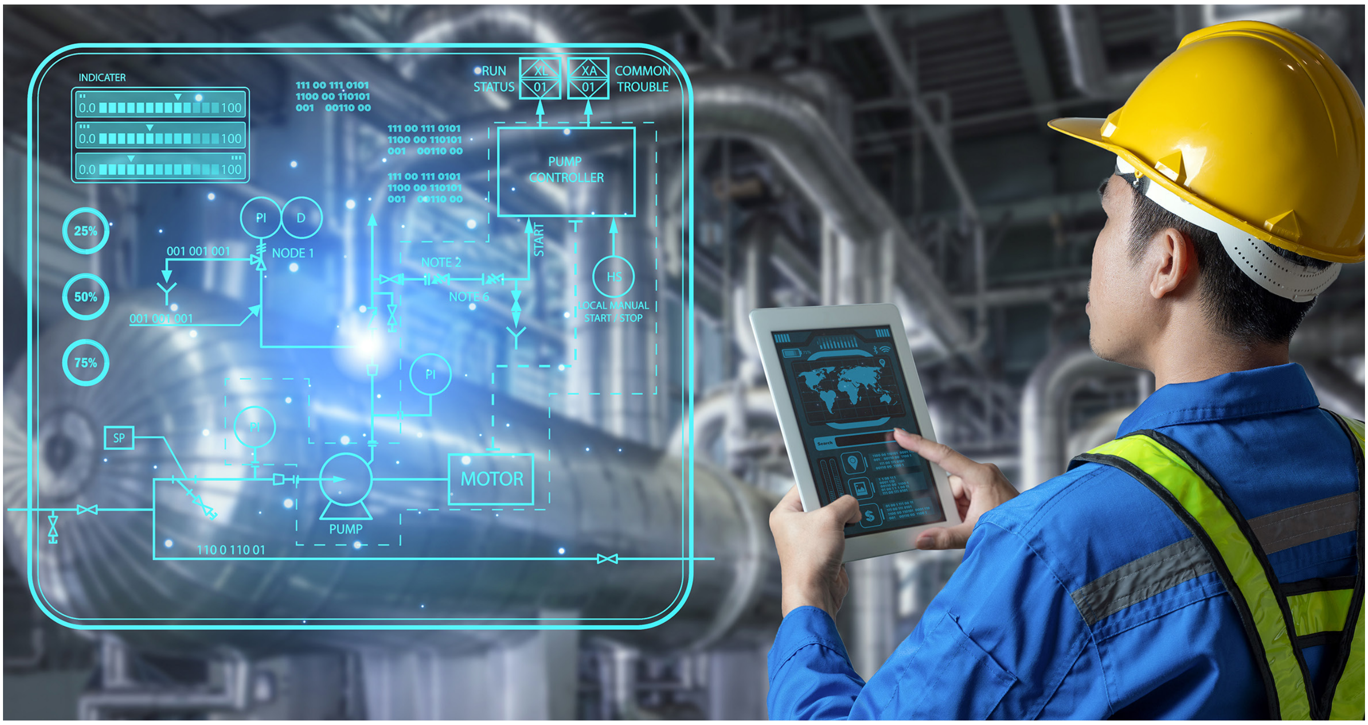
Energy consumption is another critical factor in battery recycling operations, as many processes require substantial power input. Crushing, drying, and mechanical separation demand high energy loads, while hydrometallurgical processes heavily rely on heating, agitation, and in some cases electrochemical recovery, all of which contribute to significant operational costs. Achieving energy efficiency without compromising process quality is challenging, often requiring extended trial-and-error periods.

To address these issues, digital twins provide a risk-free environment to simulate and optimize the production environment on plant, equipment and process level before implementation. Process and equipment validation can be significantly benefited from plant simulation and virtual commissioning, as it allows to simulate different scenarios for equipment placement, intralogistics, and process sequences, ensuring an efficient material flow and preventing bottlenecks or costly layout adjustments during construction phase. To further optimize the system, virtual commissioning can validate equipment sizing, dimensions, and throughput by simulating different configurations and operational scenarios. By analysing these variables virtually, potential issues such as under- or over-sized equipment, inefficiencies in space usage, and throughput imbalances can be addressed before physical implementation. Furthermore, by integrating process simulation models, process parameters such as separation efficiency and reagent dosing strategies can be fine-tuned in the virtual model, improving metal recovery rates and reducing operational waste.

Validation of automation systems can be also improved with virtual commissioning. PLC/DCS programs, interlocks, and HMI interfaces can be tested and debugged in a virtual environment, minimizing delays and ensuring right-first-time implementation. This approach ensures that automation systems are functional and optimized before physical deployment, cutting down commissioning time by up to 25%. This virtual environment also allows operators to familiarize themselves with system behaviour before startup, reducing skill gaps and accelerating the learning curve.

> Digital twin architectures, AI-driven process control, and predictive analytics are no longer aspirational, they are foundational to achieving throughput optimization and cost efficiency in battery recycling operations."

Michael Müller
Head of Climate Tech & Sustainability



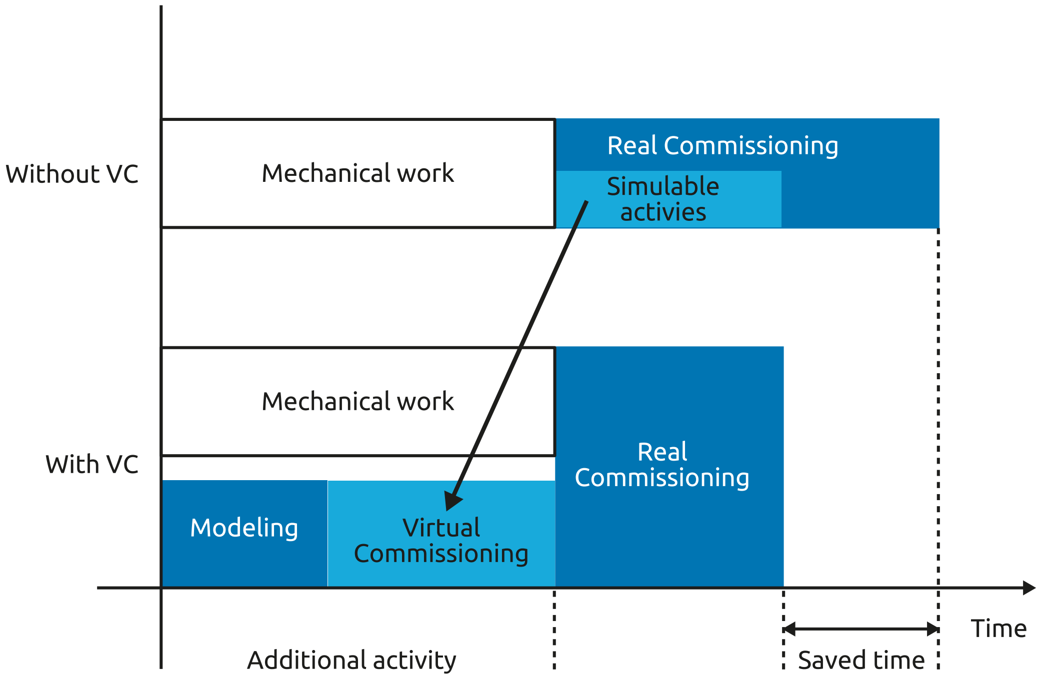


Figure 11. Time saving potential of integrating virtual commissioning in parallel to factory set-up (97).

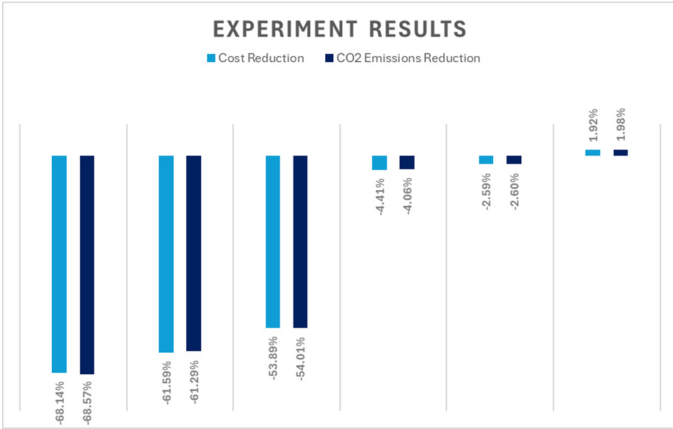
Finally, virtual commissioning allows recyclers optimize energy consumption by testing control strategies, refining equipment settings, and simulating power demand under various conditions. By adjusting parameters such as heating cycles or agitation speeds in a digital environment, it can be identified the optimal process parameters that minimize energy waste while ensuring optimal material recovery, reducing costs and improving overall sustainability.

Without virtual commissioning, issues are often discovered at later phases of the project, leading to costly rework, delays, and inefficient operations. Developing a virtual model alongside facility design allows for early detection and resolution of potential risks, preventing misalignments before implementation. This approach ensures that the system is fully optimized before startup, allowing plants to begin operations with balanced, efficient processes from day one. By reducing process instability and debugging efforts, virtual commissioning helps achieve a smoother and faster production ramp-up, making it a critical tool for scaling cost-effective, high-performance recycling plants.

> Digital technologies such as Virtual Commissioning help companies to secure the Entry-In-Service of battery recycling facilities and accelerate the scale-up of operations efficiently, responsibly, and sustainably through simulation."

David Garcia Luna
Technical Expert & Lead, Digital Manufacturing & Virtual Commissioning

SETUP	Consumption (kWh/Year)	Energy Cost* (EUR/Year)	CO2Emissions** (Ton/Year)
Experiment 1 (Kp=2.5; Ti=1)	387,544.71	46,427.86 EUR	162
Experiment 2 (Kp=2.5; Ti=2.5)	372,447.94	44,619,26 EUR	155
Experiment 3 (Kp=2.5;Ti=5	354,703.82	42,493.52 EUR	148
Experiment 4 (Kp=2.5; Ti=10)	240,666.25	28,831.82 EUR	100
Experiment 5 (Kp=2.5; Ti=20)	236,464.93	28,328.50 EUR	98.6
Experiment 6 (Kp=2.5; Ti=25)	**230,495.56**	**27,613.37 EUR**	**96.1**
Experiment 7 (Kp=2.5; Ti=50)	226,062.75	27,082.32 EUR	94.2



Estimation with costs from 09.10.2024. Continuous yearly operation is assumed (e.g. no maintenance stop)

*** Emissions estimated using online tool: https://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator*

Figure 12. Example of energy and CO2 optimization using virtual commissioning

Digital Twin for Hydrometallurgical Process Optimization

The final and most critical step in achieving true circularity in battery recycling is the efficient recovery of valuable metals such as lithium (Li), cobalt (Co), nickel (Ni) and manganese (Mn) from black mass through a multistep hydrometallurgical process. This typically includes thermal pre-treatment, leaching, precipitation, solvent extraction, stripping, and crystallization. Each stage involves tightly interdependent physical and chemical parameters, making optimization a highly complex challenge, particularly when considering the inherent variability of black mass due to diverse battery chemistries and diverse black mass production methods (99; 100; 101).

To face this complexity, digital twins are becoming a central tool in process control, R&D acceleration and scale-up risk reduction. In the context of hydrometallurgical battery recycling, a digital twin is a high-fidelity virtual replica of the physical recycling system that integrates data from real-time sensors, historical operational data and physics-based models and enables simulation, prediction and optimization of process performance under varying conditions (102; 25; 41).

These capabilities are particularly relevant in the battery recycling industry, as recyclers must not design plants solely for the chemistries present in today's black mass, which typically reflect battery designs from 5 to 10 years ago, but also for the chemistries entering the market now and in the near future. While today's recycling feedstock may still be rich in NMC111, the horizon includes high-nickel NMCs, LFP, silicon-dominant anodes and increasingly complex materials with dopants, surface coatings, functional additives and novel electrolytes.

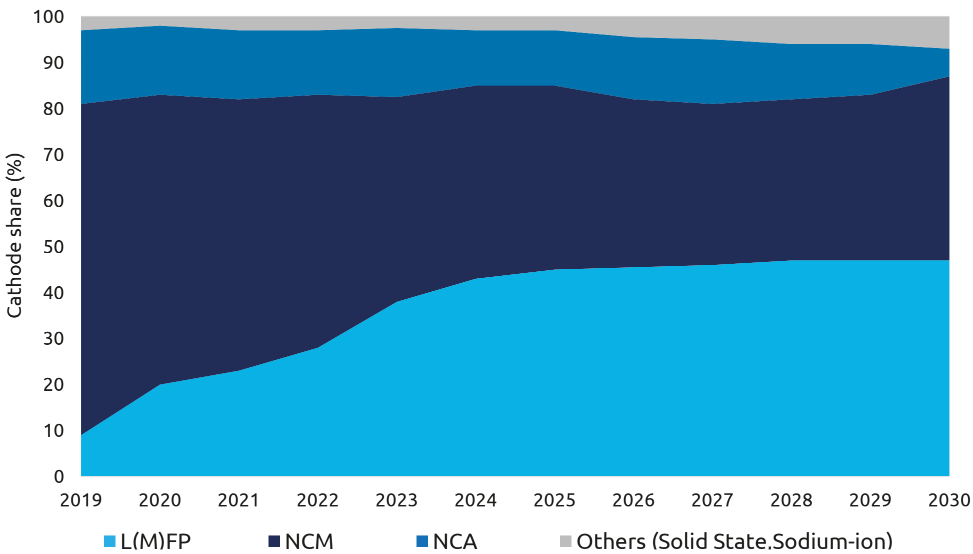


Figure 13. Global cathode chemistry forecast towards 2030 (103)

In hydrometallurgical systems, dozens of process variables, such as equipment geometry, pH, temperature, reagent flow rates, metal concentrations and S/L ratios interact in non-linear ways. The traditional Design of Experiments (DoE) approach to equipment and process optimization is hardly scalable or reliable, especially at industrial scale where small fluctuations can lead to major performance or safety issues. Therefore, digital twins serve as a risk mitigation tool, as it enables rapid hypothesis testing, reduces pilot campaign durations and supports early identification of critical process parameters, reducing the testing scope to a few strategically selected conditions, thus saving time and resources (104).

Digital twins often incorporate Computational Fluid Dynamics (CFD) models to provides critical insights into the physical behaviour of fluids and reactions within process equipment. In hydrometallurgy, many processes involve liquid or semi-liquid phases and exothermic reactions where flow distribution, mixing zones and heat transfer become difficult to analyse through laboratory trials alone.

CFD models allow to simulate internal flow dynamics, heat exchange and even localized chemical reaction rates within leaching reactors, solvent extraction columns and crystallizers. For instance, CFD can reveal "dead zones" in a leaching tank where solid suspension is poor or regions of temperature gradient that lead to uneven reaction kinetics (105; 106; 107; 108; 109; 110). These insights can guide equipment redesign or operating parameter tuning, such as impeller speed, inlet geometry or temperature profile to improve efficiency and yield.

Similarly, digital twins often incorporate machine learning (ML) models trained on historical and real-time process data to uncover hidden relationships between operating conditions and key performance indicators (KPIs). For implementing such approach, it is first needed to understand the process behaviour under varying conditions by continuous collection of real-time data from sensors (pH, temperature, metal ion concentrations, reagent flows). Building on this, predictive models can be trained to recommend optimal process conditions for each new batch of black mass, taking into account its composition and historical processing data (111; 112; 113). For example, a machine learning model could predict optimal process setpoints based on the composition of incoming black mass, including subtle variations in Li:Ni:Co:Mn ratios or presence of problematic elements like Zn or Si.

Finally, the digital twin can be extended into live process control by deploying real-time feedback loops. During each process phase, the data-driven models would continuously evaluate sensor data and provide adjustment recommendations. For this to succeed, a "process health score" must be developed to guide the models in distinguishing optimal from suboptimal conditions based on historical best-performing processes (114; 115).

As battery technologies evolve, the integrated use of digital twins becomes a key enabler for building recycling systems that are not only efficient today but also adaptable to future feedstocks. By combining simulation, data-driven modelling and real-time process control, digital twins support more stable, efficient and selective recovery operations. This makes them a central element in ensuring that hydrometallurgical recycling processes remain robust and economically viable, even as battery chemistries and black mass compositions become more complex over time.

> The 20th-century industrial economy was revolutionized by the implementation of standardized processes and assembly lines. As we move deeper into the 21st century, digital tools and AI are driving a new transformation, streamlining lean manufacturing and supporting a more efficient, sustainable energy transition."

Eleonora Casalese
Process Development Engineer

Conclusions

The battery recycling industry is at a crossroads, shaped by evolving regulations, market development, rapid technological advancements, and an urgent need for scalable solutions. To thrive in this dynamic environment, recyclers must make strategic decisions that balance compliance, long-term business viability and technological innovation.

Capgemini's deep industry expertise and technological leadership empower recyclers to navigate these complexities with confidence. Our comprehensive approach helps recyclers stay ahead of regulatory shifts and refine their business strategies and business plans. And our insights into emerging technologies support recyclers to adopt cutting-edge technologies to drive efficiency, safety, and material recovery, ensuring recyclers to remain competitive in a rapidly advancing market.

Capgemini fosters collaboration across the entire value chain, linking manufacturers, recyclers, and end-users to build a truly circular economy. By maximizing resource utilization and minimizing environmental impact, we help recyclers establish their critical role in a sustainable future. Together, we are driving the transition to a resilient, profitable, and environmentally responsible battery recycling ecosystem.

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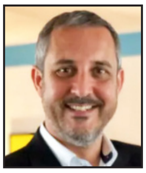

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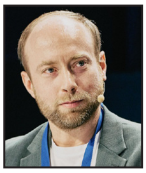

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Capgemini is a global business and technology transformation partner, helping organizations to accelerate their dual transition to a digital and sustainable world, while creating tangible impact for enterprises and society. It is a responsible and diverse group of 340,000 team members in more than 50 countries. With its strong over 55-year heritage, Capgemini is trusted by its clients to unlock the value of technology to address the entire breadth of their business needs. It delivers end-to-end services and solutions leveraging strengths from strategy and design to engineering, all fueled by its market leading capabilities in AI, generative AI, cloud and data, combined with its deep industry expertise and partner ecosystem. The Group reported 2024 global revenues of €22.1 billion.

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