INTESA SANPAOLO
INNOVATION CENTER

MOST
CENTRO NAZIONALE PER LA MOBILITÀ SOSTENIBILE

SPOKE 14

INDUSTRY TRENDS REPORT

ENERGY, ENVIRONMENT & UTILITIES

EV BATTERIES

Italiadomani
PIANO NAZIONALE DI RIPRESA E RESILIENZA

Ministero dell'Università e della Ricerca

Finanziato dall'Unione europea
NextGenerationEU

INTESA SANPAOLO
INNOVATION CENTER

The majority of the data and commentary in this publication was developed and provided by Frost & Sullivan. It draws on proprietary information and a range of other sources including the companies, organizations and academics that are referenced in the text.

CONTENTS

EXECUTIVE SUMMARY

The energy and mobility sectors at the forefront of global decarbonization efforts. Here, electrification of transport is emerging as a key strategy to meet CO_2 reduction targets outlined in frameworks such as the Paris Agreement and the EU Green Deal. Traditional internal combustion engine vehicles are increasingly seen as incompatible with long-term climate goals, driving a policy and market shift toward zero-emission mobility solutions. Electric vehicles (EVs), powered by advanced battery technologies, represent a cornerstone in the transition to sustainable transport systems and renewable energy integration.

Global investments in battery innovation and EV infrastructure are not only a response to climate imperatives but also a strategic lever for economic resilience and technological leadership. Here, batteries represent the most critical and costly component of electric vehicles, directly influencing their performance, range, safety, and overall market competitiveness.

Before exploring next-generation solutions, it is essential to understand the characteristics and trade-offs of current dominant lithium-based chemistries such as LFP, NMC, NCA, and traditional Li-ion. As electric mobility accelerates, a diverse range of emerging battery technologies is being explored to overcome the limitations of conventional lithium-ion systems and meet evolving performance demands.

Here, Sodium-ion batteries are a promising alternative to lithium-ion with more abundant and less critical raw materials. Solid-state batteries promise higher energy density, enhanced safety, and extended cycle life, but face major barriers in scalability and interfacial stability. Lithium-sulphur (Li-S) batteries promise significantly higher energy densities but remain constrained by technical hurdles related to stability and limited cycle life. Redox flow batteries present a scalable option for stationary energy storage, with decoupled power and energy components that provide operational flexibility.

While lithium-based and emerging battery chemistries remain central to electric mobility, it is important to recognise that alternative zero-emission powertrains, such as hydrogen fuel cells, are also being developed in parallel. These systems further illustrate the pervasive and indispensable role of batteries within the wider landscape of electrified transport.

Battery technologies lie at the intersection of advanced scientific research and strategic industrial development, driving progress in materials science, energy systems, and global supply chains, which are all elements we will deep dive into in this report.

Battery cell manufacturing involves complex multi-step processes that include electrode preparation, cell assembly, electrolyte filling, and formation cycling, each of which significantly influences cell performance and cost. The design of battery cells comes in three major form factors, cylindrical, prismatic, and pouch, each offering distinct advantages and trade-offs.

Here, Cylindrical cells, widely adopted by Tesla (US) and other manufacturers, are favoured for their mechanical robustness and ease of automation, but face limitations in packing efficiency. Prismatic cells offer improved volumetric efficiency and are commonly used in commercial EVs and buses, although they can be more sensitive to swelling and mechanical stress. Pouch cells, while flexible and lightweight, often require complex containment and cooling systems, making them suitable for compact or high-performance applications despite their lower structural stability.

Here, gigafactories play a key role in scaling battery production and lowering costs through economies of scale, and its growth. Moreover, battery manufacturing is highly reliant on upstream supply chains involving raw materials like lithium, nickel, cobalt, and graphite, making the scalability of production closely tied to mining, refining, and logistics infrastructures.

Ensuring supply chain resilience and ethical sourcing has become a strategic priority for battery manufacturers, leading to new models of vertical integration, onshoring, and circular economy practices. Here, Redwood Materials, founded by J. B. Straubel, the co founder of Tesla (US) , embodies a vertically integrated, circular approach to EV battery supply chain resilience. Furthermore, automation, digital twins, and AI-driven quality control are increasingly being integrated into battery manufacturing to enhance scalability, reduce defects, and meet growing EV demand efficiently. As a relevant example here, BYD's (China) rapid production scale-up and in-house battery manufacturing have driven significant cost reductions, positioning the company as a global leader in affordable electric vehicles.

Furthermore, smart sensors embedded in battery packs enable real-time tracking of temperature, voltage, and location across production, transport, and deployment stages. In addition, Blockchain-backed Digital Battery Passports ensure secure, transparent records of battery origin, specifications, and usage history throughout the lifecycle. Furthermore, AI-driven analytics predict degradation patterns and optimize maintenance strategies, helping extend battery life and improve lifecycle efficiency .

Sustainable battery manufacturing begins with eco-conscious design strategies that prioritize recyclability, energy efficiency, and reduced material complexity. Furthermore, designing batteries for disassembly and end-of-life recovery simplifies recycling and minimizes resource loss in downstream processes. In this context, modern gigafactories are integrating low-emission production lines and energy-efficient systems to reduce their overall carbon footprint. Therefore, renewable energy sources such as solar, wind, and green hydrogen are increasingly being used to power battery production facilities. Moreover, the combination of sustainable design and low-carbon production is essential to reducing the embedded environmental cost of EV batteries.

Here, The Toyota (Japan) battery manufacturing in North Carolina is demonstrating clean-energy powered gigafactory model in the US. The Verkor (France) Gigafactory in Dunkerque exemplifies low-carbon EV battery manufacturing in Europe, integrating energy-efficient processes and circular economy principles to align with EU climate targets.

The battery industry continues to face critical technical risks, including fire hazards, raw material bottlenecks, and recycling limitations. Furthermore, Thermal runaway and overheating remain primary safety risks, especially under fast-charging or extreme-use conditions. Also, advancements in thermal management systems, such as liquid cooling and phase-change materials, are key to improving battery safety and stability.

The sector is under pressure to reduce dependence on critical materials like lithium, cobalt, and nickel due to supply constraints and ethical sourcing issues. Here, China's early deployment of sodium-ion batteries in grid storage and electric scooters highlights a strategic shift toward alternative chemistries that could reduce EVs' reliance on lithium and cobalt. CATL's (China) 2025 launch of its Naxtra sodium-ion battery series demonstrates rapid progress in commercializing next-gen chemistries with energy densities approaching those of mainstream lithium-ion cells.

Recycling methods must adapt to evolving battery designs and chemistries, requiring flexible and scalable systems that can process a diverse range of cell types. After their automotive lifespan, EV batteries can be repurposed for second-life applications in stationary energy storage systems. These batteries undergo testing, certification, and repackaging to ensure performance, safety, and suitability for grid or off-grid use. Second-life battery systems support renewable energy integration by balancing solar and wind fluctuations and providing backup storage.

Here, A second-life project by Enel (Italy) and Nissan (Japan) repurposed used EV batteries into a 2.1 MWh storage system at Rome's Fiumicino Airport, supporting solar energy integration and grid stability. Furthermore, repurposing used batteries reduces waste, delays recycling demand, and enhances grid stability through affordable energy storage solutions. Here, Jaguar Land Rover's (UK) partnership with Allye Energy (UK) created a mobile second-life storage unit from Range Rover PHEV batteries, offering clean, portable power as an alternative to diesel generators.

INTRODUCTION

The energy and mobility sectors at the forefront of global decarbonization efforts

Among all emitting sectors, **energy and mobility** stand out as both highly carbon-intensive and strategically pivotal, since their decarbonization unlocks systemic change across the global economy. Fossil-fuel-based electricity generation, still dominant in many economies, contributes significantly to global CO_2 levels, while the internal combustion engine (ICE) vehicle fleet remains the single largest end-use contributor to urban air pollution and oil demand. At the same time, these two sectors are also deeply **interconnected**: as electricity grids decarbonize, electric vehicles (EVs) become cleaner throughout their life cycle, reinforcing the case for transport electrification. This mutual reinforcement is why energy and mobility are often treated as a joint system in climate mitigation models.

Consequently, governments, businesses, and civil society organizations are directing unprecedented attention and resources toward transforming these sectors. From **vehicle electrification mandates** and **clean energy subsidies** to **zero-emission city targets**, policies are now being implemented with a degree of speed and ambition not previously seen. The European Union's **Fit for 55 package**, China's **New Energy Vehicle policy**, and the United States' **Inflation Reduction Act (IRA)** all reflect this emerging consensus. However, the transition is complex and multidimensional, particularly for transport, and requires scalable, safe, and affordable battery technologies as a core enabling platform.

Here, electrification of transport is emerging as a key strategy to meet CO_2 reduction targets outlined in frameworks such as the Paris Agreement and the EU Green Deal

In this global context, the **electrification of transport** has emerged as a cornerstone of climate strategy due to its potential to eliminate tailpipe emissions and leverage clean electricity. Replacing ICE vehicles with EVs powered by renewable energy sources significantly reduces **well-to-wheel emissions**, and when scaled, can lead to transformative reductions in national and regional carbon footprints. Global institutions such as the **IEA (International Energy Agency)** and **World Bank** now view electrification as not just one solution among many, but as foundational to the success of climate policies in developed and emerging economies alike.

The rationale for EV adoption goes beyond emissions. Electric drivetrains are more energy-efficient, mechanically simpler, and offer superior torque control, enabling new performance benchmarks. They also eliminate urban air pollutants such as **Nitrogen Oxides** and **Particulate Matter ≤ 2.5 micrometres**, bringing co-benefits for public health. However, these benefits depend fundamentally on the availability of high-quality, affordable, and sustainable batteries, which makes battery innovation and manufacturing capacity central to the success of transport decarbonization strategies.

Traditional internal combustion engine vehicles are increasingly seen as incompatible with long-term climate goals, driving a policy and market shift toward zero-emission mobility solutions

Globally, **internal combustion engine vehicles** are being phased out through a combination of **regulatory bans, market disincentives**, and **consumer preference shifts**. Leading jurisdictions, including the EU, Canada, and several U.S. states, have announced bans on the sale of new ICE vehicles starting between 2030 and 2035. Simultaneously, automotive manufacturers are transitioning their R&D and production pipelines toward **fully electric and hybrid-electric platforms**, reflecting both consumer demand and shareholder pressure to align with net-zero targets.

ICE (Internal Combustion Engine) vehicles are no longer viewed as economically future proof. Indeed, they are increasingly vulnerable to **carbon pricing, urban access restrictions**, and **technology obsolescence**. In contrast, zero-emission vehicles (ZEVs) are receiving growing support through **subsidies, charging infrastructure investments**, and **fleet electrification mandates**.

This market evolution is not only reshaping the auto industry but also redefining upstream sectors, including materials processing, electronics, and energy infrastructure, all of which must adapt to meet the growing demands of an electrified transport system underpinned by batteries.

Electric vehicles (EVs), powered by advanced battery technologies, represent a cornerstone in the transition to sustainable transport systems and renewable energy integration

Electric vehicles are more than just replacements for fossil-fuelled cars, they are **convergent nodes** in a broader energy system transformation. Their functionality depends on the integration of advanced **battery technologies, software, thermal management**, and **power electronics**, all of which must operate in harmony to ensure safety, performance, and reliability.

Moreover, EVs increasingly interface with the **electric grid**, enabling bidirectional power flows (e.g., Vehicle-to-Grid, or V2G) that allow vehicles to act as **decentralized energy storage units**, stabilizing renewable generation and improving grid flexibility.

This expanded role transforms EVs from simple modes of transport into **strategic assets** for grid decarbonization. Batteries, therefore, serve a dual purpose: powering mobility and enabling **renewable energy integration**. Their cost, efficiency, recyclability, and environmental footprint have become metrics of systemic importance, influencing not only vehicle performance but also national energy security, infrastructure investment, and industrial competitiveness.

Global investments in battery innovation and EV infrastructure are not only a response to climate imperatives but also a strategic lever for economic resilience and technological leadership

Recognizing the critical role of batteries in both the transport and energy transitions, countries and corporations are deploying **unprecedented levels of capital** into **battery research, manufacturing, and infrastructure**. Investment in battery gigafactories alone exceeded $100 billion in 2023, with major initiatives underway in **China, Europe**, and **North America**.

Governments are aligning these investments with strategic goals: to **localize supply chains, secure critical raw materials**, and **establish industrial leadership** in what is now considered one of the most competitive and geopolitically significant sectors of clean tech.

Beyond cell production, funding is also flowing into **mining, refining, battery software, safety systems**, and **second-life solutions**. Public-private partnerships and industrial alliances, such as the **European Battery Alliance** and the **U.S. Battery Materials Initiative**, illustrate the degree of coordination required to scale a complex and rapidly evolving value chain. Batteries are no longer considered a niche technology but a **national strategic priority**, influencing everything from trade policy to labour markets and environmental regulation.

Here, batteries represent the most critical and costly component of electric vehicles, directly influencing their performance, range, safety, and overall market competitiveness

Among all EV subsystems, the **battery pack is the most defining component**, shaping the vehicle's price, range, safety profile, and carbon footprint. Battery costs, once exceeding $1,000/kWh, have fallen to ~$115/kWh (**BloombergNEF, 2024**), but still represent **the largest single cost item** in an EV.

Beyond cost, batteries influence how far a vehicle can travel, how fast it can recharge, how long it lasts, and how safely it can operate under various conditions. These variables affect not only consumer adoption but also the total cost of ownership and residual value.

Moreover, battery packs introduce **unique operational risks**, including thermal runaway, manufacturing defects, and capacity degradation, which require continuous monitoring and sophisticated **battery management systems (BMS)**. As manufacturers compete to improve energy density and performance, balancing these gains with safety, durability, and recyclability becomes a central engineering challenge. This is precisely why understanding **current battery chemistries and architectures** is a necessary prelude to discussing emerging technologies and systemic solutions.

Before exploring next-generation solutions, it is essential to understand the characteristics and trade-offs of current dominant lithium-based chemistries such as LFP, NMC, NCA, and traditional Li-ion

The modern EV market is dominated by a set of well-established **lithium-based chemistries**, including **Lithium Iron Phosphate (LFP), Nickel Manganese Cobalt (NMC), Nickel Cobalt Aluminium (NCA)**, and traditional **lithium-ion (Li-ion)**. Each chemistry brings unique advantages and trade-offs. **LFP** is lauded for its safety, cycle life, and low cost, making it ideal for entry-level EVs and commercial fleets, but its lower energy density limits range. **NMC** and **NCA** offer higher energy densities and faster charging but rely on **costly and ethically sensitive materials** like cobalt and nickel.

The choice of chemistry affects not only **vehicle performance** but also **supply chain resilience, manufacturing complexity**, and **recyclability**. As such, these systems form the **benchmark** against which emerging technologies are evaluated. They also provide the starting point for discussions in Chapter 1, which investigates **how batteries are manufactured, assembled, and optimized**, and Chapter 2, which analyses their **sustainability, lifecycle risks, and second-life applications**.

As electric mobility accelerates, a diverse range of emerging battery technologies is being explored to overcome the limitations of conventional lithium-ion systems and meet evolving performance demands

With growing demand for **faster charging, longer range, lower cost**, and **reduced reliance on critical materials**, attention is increasingly turning to **emerging chemistries** that move beyond traditional lithium-ion systems. These include **sodium-ion, lithium-sulphur (Li-S), solid-state**, and multivalent systems like magnesium and zinc. Each introduces new electrochemical architectures that seek to overcome specific limitations of conventional batteries, whether in terms of material scarcity, thermal instability, or volumetric limitations.

The development of these chemistries is motivated by both **performance requirements** and **sustainability imperatives**. However, transitioning from laboratory prototypes to industrial-scale production involves overcoming numerous challenges, including **electrode stability, cycle life, manufacturing integration**, and **supply chain readiness**. Understanding their potential, and their current limits, is essential to charting a realistic path forward for battery technology in the next decade.

… Here, Sodium-ion batteries are a promising alternative to lithium-ion with more abundant and less critical raw materials

Among the most promising alternatives is the **sodium-ion battery**, which replaces lithium with **abundant, widely distributed sodium**, offering **cost advantages, geopolitical resilience**, and **improved thermal safety**. While sodium-ion cells currently trail lithium-ion in gravimetric energy density (~140–160 Wh/kg), they are increasingly seen as viable for **short-range EVs, two- and three-wheelers**, and **stationary storage**. Importantly, they eliminate the need for cobalt and nickel, significantly reducing both cost and ESG exposure.

China has taken the global lead in **sodium-ion** deployment, with **CATL , HiNa Battery**, and other firms rolling out commercial systems as early as 2023. CATL's **Naxtra** series, launching in 2025, signals an inflection point, as its energy density approaches that of early **LFP cells**. These developments suggest sodium-ion could gain **widespread adoption in specific segments** by the end of the decade, making it a serious contender in the evolving battery landscape.

… Solid-state batteries promise higher energy density, enhanced safety, and extended cycle life, but face major barriers in scalability and interfacial stability

Solid-state batteries (SSBs) are widely regarded as a transformative evolution of lithium-based energy storage, offering the potential to significantly increase energy density while improving safety and longevity. By replacing the flammable liquid electrolyte found in conventional lithium-ion cells with a solid electrolyte, typically ceramic, polymer, or sulphide-based—SSBs eliminate the risk of leakage and thermal runaway, enhancing both mechanical stability and fire resistance. Furthermore, solid electrolytes enable the use of lithium metal anodes, which can dramatically boost specific energy beyond that of current lithium-ion chemistries.

Despite their theoretical advantages, SSBs remain largely in the development or pilot production phase. Key challenges include interfacial resistance between the solid electrolyte and electrodes, mechanical degradation during cycling, and the complexity of manufacturing processes at scale. Additionally, achieving consistent performance across varied operating temperatures and charge rates remains a technical hurdle.

Nonetheless, major automotive and battery manufacturers, such as Toyota (Japan), QuantumScape (US), and Solid Power (US), are investing heavily in commercialization efforts, aiming to deploy early-generation SSBs in EVs within the next several years. Solid-state technology thus holds the potential to redefine performance benchmarks across mobility and storage applications, provided current material and integration challenges can be overcome.

… Lithium-sulphur (Li-S) batteries promise significantly higher energy densities, but remain constrained by technical hurdles related to stability and limited cycle life

Lithium-sulphur (Li-S) batteries are attracting interest for their **theoretical energy densities exceeding 500 Wh/kg**, which could revolutionize long-range electric transport, aerospace, and defence applications. Sulphur is cheap, abundant, and non-toxic, making it an ideal cathode material from both economic and environmental perspectives. However, Li-S systems face persistent technical barriers such as the **polysulfide shuttle effect**, which leads to rapid capacity fading. Other barriers here are the poor electronic conductivity, and the **large volumetric expansion** during cycling.

To address these challenges, researchers are developing **nanostructured cathode architectures, solid-state electrolytes,** and **advanced separators** to improve stability and cycle life. While still in the R&D phase, **Li-S** holds transformative potential if its durability and manufacturing compatibility can be improved. Its development underscores the broader trend toward **function-specific chemistries**, optimized not only for range or cost, but for application context and lifecycle impact.

Feature comparison between Lithium Ion, Sodium Ion and solid-state

Feature	Lithium Ion	Sodium Ion	Solid State
Energy Density	High	Medium	Highest
Cost	Medium	Low	High
Safety	Medium	High	Highest
Charging Speed	Medium	High	Highest
Maturity	Mature	Developing	Emerging

… Redox flow batteries present a scalable option for stationary energy storage, with decoupled power and energy components that provide operational flexibility

While unsuitable for EVs due to low energy density, **redox flow batteries (RFBs)** are becoming increasingly important for **grid-scale and long-duration energy storage**. RFBs decouple energy and power capacity by storing electrolytes in external tanks, enabling flexible scalability and **exceptional cycle life** (up to 20,000 cycles). This makes them ideal for **renewable integration, peak shaving**, and **backup power** in decentralized systems or critical infrastructure.

Vanadium-based systems dominate the current market, but alternative chemistries, including **zinc-bromine, iron-chromium**, and **organic redox couples**, are being explored to reduce cost and toxicity. RFBs may play a complementary role to lithium- and sodium-based systems by occupying a

Source: Frost & Sullivan

niche where **longevity, modularity, and safety** outweigh volumetric constraints. Their development exemplifies the growing need for **multi-technology storage portfolios** tailored to different segments of the energy landscape.

While lithium-based and emerging battery chemistries remain central to electric mobility, it is important to recognise that alternative zero-emission powertrains, such as hydrogen fuel cells, are also being developed in parallel. These systems further illustrate the pervasive and indispensable role of batteries within the wider landscape of electrified transport

Electric batteries and hydrogen mobility are closely interconnected due to the complementary roles they both play in the transition towards low-emission transport systems. Fuel Cell Electric Vehicles (FCEVs) utilise hydrogen stored on board to generate electricity through an electrochemical reaction within the fuel cell, which powers an electric motor similar to that used in Battery Electric Vehicles (BEVs).

Although hydrogen vehicles do not store energy in large rechargeable batteries, they produce electricity on board through the reaction between hydrogen and oxygen, generating only water vapour as an emission. These systems nonetheless include a battery, smaller in size compared to those used in BEVs, which performs essential functions for overall energy efficiency and power management. The battery enables the recovery and storage of energy during regenerative braking, provides auxiliary power during transient peaks (for instance, during acceleration), and stabilises the flow of electricity between the fuel cell and the electric motor.

Thus, even in hydrogen-powered vehicles, the battery remains a key component of the propulsion system, contributing to the optimisation of performance and operational efficiency. Electric batteries, on the other hand, store energy directly from the electrical grid to power the motor, offering high conversion efficiency but facing constraints related to charging times and energy density, which may limit range depending on the application.

Hydrogen mobility is particularly suitable for uses requiring long driving range, short refuelling times and reduced impact on payload – such as heavy-duty vehicles, industrial transport, and off-road applications. In these sectors, hydrogen can effectively complement battery electric mobility, which remains more appropriate for light-duty and urban transport where efficiency and infrastructure are more developed.

Overall, the transport energy system therefore positions batteries and hydrogen as synergistic technologies. Both share the common objective of powering electric motors through different energy carriers: electrochemical energy directly stored in the case of batteries, and the chemical energy of hydrogen converted into electricity via fuel cells. This complementarity enables an integrated response to the diverse requirements of range, charging time, and operational flexibility in sustainable transport systems.

Battery technologies lie at the intersection of advanced scientific research and strategic industrial development, driving progress in materials science, energy systems, and global supply chains, which are all elements we will deep dive into in this report

EVOLUTION OF EV BATTERIES

Battery cell manufacturing involves complex multi-step processes that include electrode preparation, cell assembly, electrolyte filling, and formation cycling, each of which significantly influences cell performance and cost

Battery cell manufacturing is a sophisticated, precision-driven process comprising four critical stages: **electrode preparation, cell assembly, electrolyte filling**, and **formation cycling**. Each step plays a decisive role in defining the electrochemical characteristics, durability, and safety of the final battery, and any variability across these stages can propagate defects or performance losses in downstream use.

For instance, the choice of materials and thickness uniformity during electrode preparation directly affect internal resistance and energy density, while strict environmental controls during assembly prevent particle contamination that could result in internal short circuits.

The electrolyte filling and formation cycling stages further shape the battery's stability and long-term behaviour. Electrolyte infiltration under vacuum ensures optimal wetting of porous electrodes, a critical factor for ionic conductivity and temperature resilience. Meanwhile, **formation cycling**, which establishes the solid electrolyte interphase (SEI) layer on the anode, is essential to battery lifespan and safety.

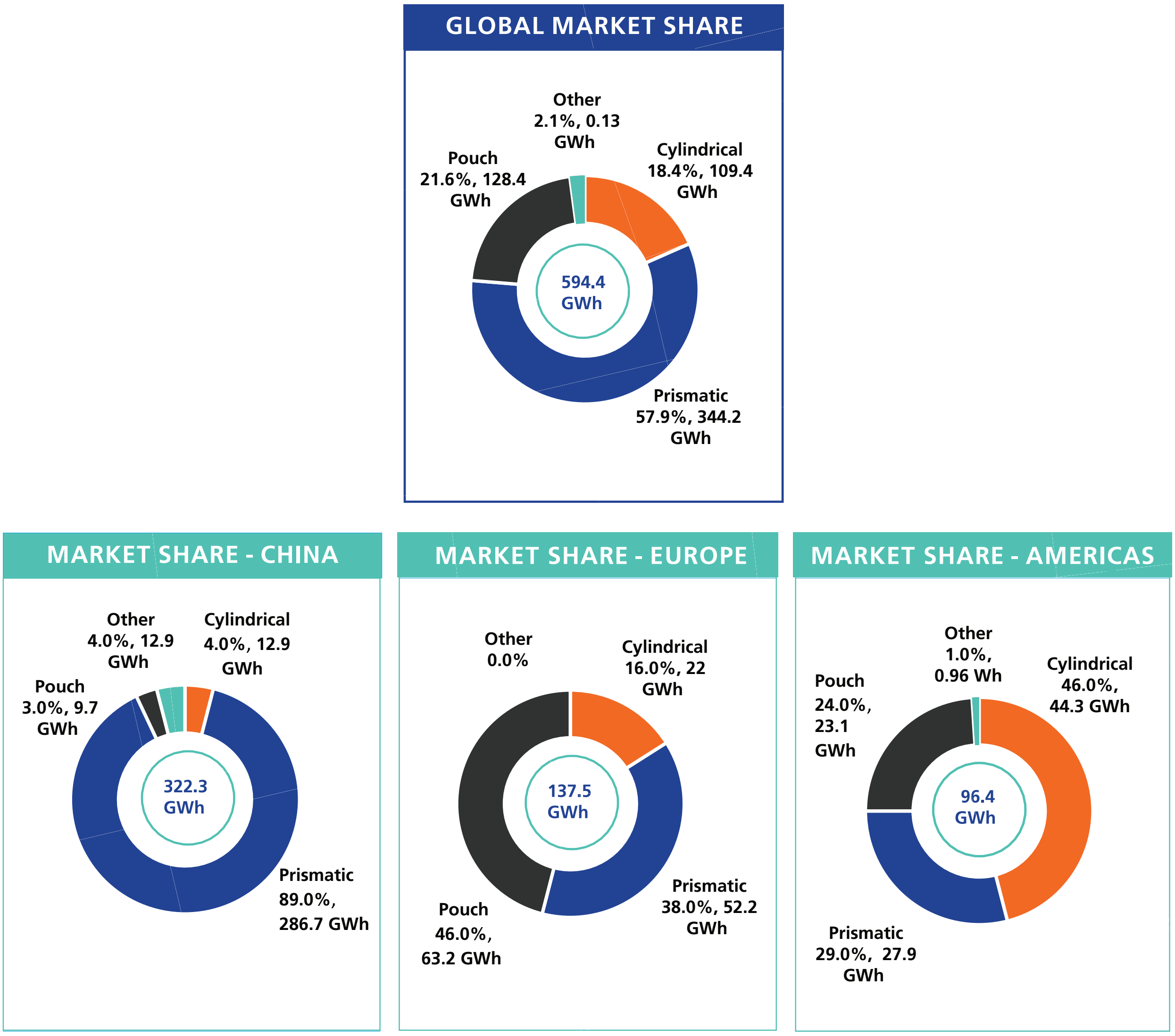
The SEI acts as a passivation barrier that allows lithium ions to pass while blocking electrolyte decomposition. However, formation is energy and time-intensive, representing a bottleneck in cell manufacturing throughput. Efforts to reduce formation time while preserving SEI quality (e.g. pulsed formation, fast charging protocols) are a current focus of process innovation, particularly as manufacturers aim to scale production while meeting tight performance tolerances.

The design of battery cells comes in three major form factors, cylindrical, prismatic, and pouch, each offering distinct advantages and trade-offs

Once the materials and processes are optimized, battery manufacturers must select an appropriate cell design, which influences the energy density, thermal behaviour, mechanical integration, and manufacturability of the pack. The three dominant cell formats, ***cylindrical, prismatic***, and ***pouch***, all house the same core electrochemistry (e.g. NMC, LFP, or solid-state) but differ in physical architecture and packaging.

These differences have profound implications on the battery system's volumetric efficiency, energy density per unit volume, ease of thermal management, and mechanical integrity during operation or under crash scenarios. The format also determines the level of automation feasible in manufacturing and impacts the total cost per kilowatt-hour (kWh) when scaled to the pack level. As such, cell geometry is not just a packaging choice but a systems-level engineering decision with cascading effects on vehicle design and performance.

EV batteries: Cell formats' market share, global, 2023



Source: Frost & Sullivan

OEMs, cathode types, cell formats used, and their battery suppliers

OEM	Cathode Type	Format	Suppliers
Tesla	LFP, NCA, NMC	Cylindrical, Prismatic	CATL, LG Energy, Panasonic, BYD
Audi	NMC	Prismatic, Pouch	Samsung, CATL, LG Energy, Panasonic
Volkswagen	NMC	Prismatic, Pouch, Cylindrical (2025)	CATL, SK Innovation, Samsung, LG Energy, Panasonic
Hyundai-Kia	LFP, NMC	Pouch, Prismatic	SK Innovation, LG Energy, CATL, BYD
R-N-M Alliance	NMC	Pouch, Prismatic	Envision AESC, LG Energy, CATL, CALB, GS Yuasa, Farasis, Lishen
BMW	NMC	Prismatic, Cylindrical (2025)	Samsung, CATL
General Motors	LFP, NMC	Pouch, Prismatic, Cylindrical	CATL, LG Energy, CALB
Stellantis	NMC	Prismatic, Pouch	Samsung, CATL, Samsung, SVOLT, CALB, GS Yuasa, LG Energy
Mercedes-Benz	LFP, NMC	Prismatic, Pouch	Envision AESC, SK Innovation, CATL, Farasis, LG Energy, BYD, EVE Energy
Ford	LFP, NMC	Pouch, Prismatic, Cylindrical	SK Innovation, LG Energy, CATL, Panasonic, Samsung
Toyota	LFP, NMC	Prismatic	CATL, BYD, Panasonic
Volvo	NMC	Pouch, Prismatic	CATL, LG Energy
Honda	NMC	Prismatic	Panasonic, CATL, CALB
Rivian	NMC	Prismatic	Samsung
Lucid	NMC	Cylindrical	Samsung

LFP **NMC** **NCA**

... Here, Cylindrical cells, widely adopted by Tesla (US) and other manufacturers, are favoured for their mechanical robustness and ease of automation, but face limitations in packing efficiency

Cylindrical cells, popularized by consumer electronics and extensively deployed in electric vehicles (EVs) by companies such as **Tesla (US)** and **Panasonic (Japan)**, are known for their **high mechanical stability, uniform internal pressure**, and **mature automation processes**. The roll-to-roll winding of electrodes within a rigid cylindrical casing (commonly 18650 or 21700 sizes, with Tesla's 4680 format pushing recent boundaries) offers consistent manufacturing yields and excellent thermal uniformity.

These cells also exhibit superior resistance to swelling, which contributes to their safety and reliability in high-vibration environments like EVs.

Furthermore, their modularity simplifies parallel-series arrangements for pack integration and facilitates cooling system design due to the predictability of their shape and size.

However, cylindrical cells face efficiency drawbacks at the pack level. Due to their rigid round shape, gaps between cells result in lower packing density, reducing volumetric energy efficiency, a trade-off particularly critical in space-constrained platforms. According to a study by the **U.S. DOE's Vehicle Technologies Office (2022)**, cylindrical cell packs typically achieve volumetric efficiencies of **65–70%**, compared to over **80%** for prismatic formats. Thus, despite their advantages in cost, standardization, and robustness, cylindrical cells may be suboptimal for vehicle designs requiring maximum internal space utilization or custom battery integration.

… Prismatic cells offer improved volumetric efficiency and are commonly used in commercial EVs and buses, although they can be more sensitive to swelling and mechanical stress

Prismatic cells feature flat, rectangular casings, usually aluminium, that allow for tighter stacking and superior volumetric energy density compared to cylindrical formats. As a result, they are often the preferred choice for **electric buses, commercial vehicles**, and **mid- to high-range EVs** manufactured by companies such as **BMW (Germany), Volkswagen (Germany)**, and **BYD (China)**. The rigid casing offers some level of structural support within battery modules and packs, reducing the need for extensive framing materials. In terms of thermal management, prismatic designs provide large surface areas for cooling interfaces, enabling effective dissipation of heat generated during high-power charge and discharge cycles.

Nonetheless, prismatic cells also pose engineering challenges. They are more sensitive to mechanical stress and swelling, particularly under repeated cycling or elevated temperatures. Gas buildup and electrode expansion during use can deform the rigid casing, risking delamination of electrodes or internal shorts if not properly managed.

To mitigate these risks, manufacturers must implement advanced pressure-relief mechanisms, cell spacing buffers, or multi-point mechanical constraints within modules. This adds design complexity and, in some cases, limits the flexibility of vehicle integration. Additionally, although prismatic cell production is becoming more automated, it is generally slower and less efficient than cylindrical cell production in terms of manufacturing speed and yield optimization.

… Pouch cells, while flexible and lightweight, often require complex containment and cooling systems, making them suitable for compact or high-performance applications despite their lower structural stability

Pouch cells represent the most flexible and lightweight battery format, utilizing a polymer-aluminium laminate casing that offers excellent gravimetric energy density. They are especially attractive for high-performance or space-constrained applications, such as premium electric vehicles, plug-in hybrids, and aerospace systems, due to their ability to be custom-shaped, stacked, or curved within tight design envelopes. Companies like **LG Energy Solution (South Korea), SK On (South Korea), and AESC (Japan)** deploy pouch cells in applications where weight, adaptability, and compactness are paramount. Furthermore, their thin layers and wide surface area promote effective thermal contact, supporting aggressive fast-charging profiles when paired with adequate cooling systems.

However, the lack of a rigid external shell makes pouch cells structurally unstable under mechanical stress. They are particularly vulnerable to swelling, punctures, and deformation due to internal gas evolution or external compression. As such, pouch-based battery packs require complex containment systems, such as reinforced casings, compression plates, and advanced cooling solutions, all of which increase integration complexity and add to the system's cost.

Moreover, swelling tolerance and cell expansion must be tightly controlled through precise formation and aging protocols. These requirements complicate their use in mass-market EVs where cost per kWh and mechanical ruggedness major design constraints are, though ongoing material science advances may help overcome these barriers.

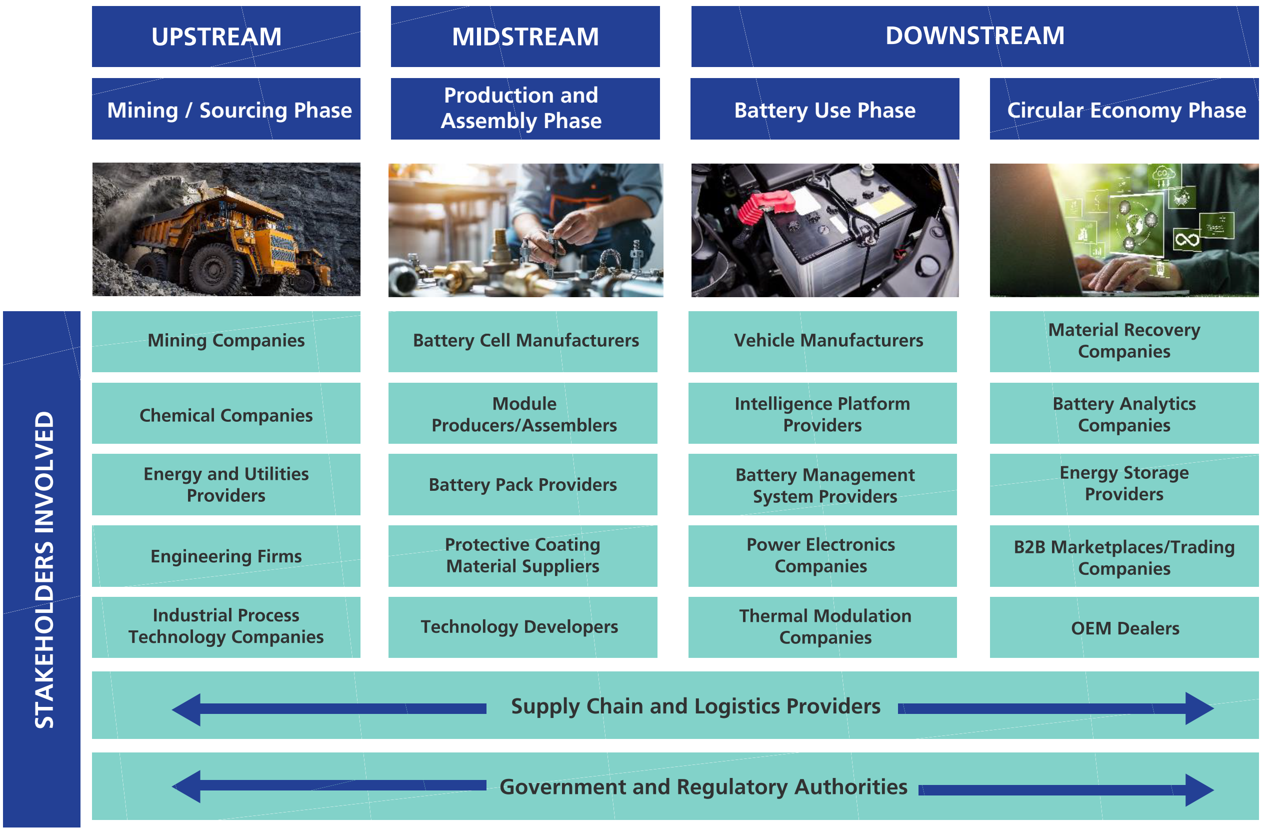
Here, gigafactories play a key role in scaling battery production and lowering costs through economies of scale, and its growth

The rise of gigafactories, large-scale battery production facilities typically exceeding 10 GWh of annual output, has become central to the global effort to accelerate the electrification of transport while reducing battery costs. By consolidating electrode preparation, cell assembly, and module integration under one roof, these facilities capitalize on **economies of scale**, lowering the cost per kilowatt-hour (kWh) through automation, continuous process optimization, and vertical integration. As per **BloombergNEF (2024)**, battery pack costs have dropped from over **$1,100/kWh** in 2010 to under **$115/kWh** today, driven in large part by manufacturing scale-ups and process learning in such facilities. Companies like **Tesla (in Nevada, Berlin, Texas), CATL (in China, Hungary, Indonesia)**, have established vertically integrated gigafactories that tightly couple manufacturing with R&D, logistics, and recycling capabilities.

Gigafactories are also hubs of technological innovation and process iteration, enabling manufacturers to test and rapidly deploy advancements such as dry-electrode coating, solid-state electrolytes, and AI-driven quality control systems. However, scaling production is not merely a matter of building larger factories. These facilities demand massive capital investments (often >$2–5 billion per site), long lead times (2–4 years), and secure access to both skilled labour and clean energy.

Moreover, battery manufacturing is highly reliant on upstream supply chains involving raw materials like lithium, nickel, cobalt, and graphite, making the scalability of production closely tied to mining, refining, and logistics infrastructures

EV battery supply chain: Ecosystem and key stakeholders



Source: Frost & Sullivan

Despite the progress in scaling manufacturing, battery production remains deeply dependent on upstream supply chains, particularly the availability and refinement of key materials such as **lithium, nickel, cobalt**, and **graphite**. These materials constitute the core of current-generation lithium-ion chemistries (e.g., NMC, NCA, LFP), and their quality, purity, and sourcing pathway significantly influence both battery performance and environmental footprint. For example, battery-grade lithium hydroxide used in high-nickel cathodes must meet strict impurity thresholds, requiring complex refining processes not readily available in all mining regions. This creates a tight coupling between **battery scalability** and the **capacity of mining, refining, and logistics infrastructures**, especially in countries with concentrated reserves.

Geopolitical concentration exacerbates this fragility. Over 70% of global cobalt supply originates from the **Democratic Republic of Congo**. Similarly, **China dominates refining capacity** for lithium, cobalt, and graphite, processing over 60–80% of global output despite producing a smaller share of the raw ores themselves. This imbalance exposes global battery supply chains to **geopolitical risks**, export restrictions, and price volatility.

For instance, during the **2022–2023 supply squeeze**, lithium prices surged by over **400%**, temporarily stalling investment in new battery production lines. As such, even the most advanced gigafactory cannot operate at full capacity if constrained by upstream bottlenecks. This reality is now pushing automakers and battery producers toward **vertical integration, strategic resource partnerships**, and **regional diversification** of critical material supply chains, all of which will be vital for long-term production resilience.

Ensuring supply chain resilience and ethical sourcing has become a strategic priority for battery manufacturers, leading to new models of vertical integration, onshoring, and circular economy practices

Considering mounting geopolitical, environmental, and social pressures, ensuring **supply chain resilience and ethical sourcing** has become a strategic imperative for battery manufacturers. The historically linear model, dependent on long-distance raw material extraction, centralized refining (often in China), and just-in-time logistics, is now evolving toward **vertically integrated, localized, and circular value chains**.

This transition is driven not only by supply risk and cost volatility, but also by increasing regulatory scrutiny and ESG expectations from investors and governments. **The European Union's Battery Regulation (2023)**, for example, mandates traceability and due diligence for critical raw materials and requires a minimum percentage of recycled content in new batteries by 2030. In response, industry leaders are adopting new models that emphasize **onshoring of key refining operations, direct sourcing agreements with mines**, and **closed-loop recycling systems** that reduce dependence on virgin material extraction.

Vertical integration, where a single company controls multiple steps in the value chain, is a powerful approach to mitigate risk while capturing margin. Companies like **Tesla (US)** and **BYD (China)** have aggressively pursued this model by securing lithium and nickel supply contracts, building their own cathode and anode processing plants, and internalizing battery cell and pack manufacturing.

At the same time, ethical sourcing initiatives are gaining prominence, with traceability tools like blockchain and third-party auditing systems being deployed to certify responsible mining, particularly for cobalt and artisanal-sourced materials. Ultimately, this shift toward resilient and responsible sourcing strategies not only safeguards manufacturing continuity but also aligns the battery industry with the principles of sustainable development.

Here, Redwood Materials, founded by J. B. Straubel, the co founder of Tesla (US) , embodies a vertically integrated, circular approach to EV battery supply chain resilience

A compelling example of this next-generation supply chain architecture is **Redwood Materials**, a **U.S.-based** startup founded by JB Straubel, Tesla's former CTO. Redwood embodies a fully circular and vertically integrated approach to battery supply chain resilience, aiming to reduce dependency on raw material imports by closing the loop through recycling, refining, and remanufacturing.

The company collects used consumer electronics, end-of-life EV packs, and production scrap from gigafactories, then extracts high-purity lithium, nickel, cobalt, and copper using advanced hydrometallurgical and pyrometallurgical processes. These materials are subsequently reintroduced into battery-grade precursor materials, anode foils, and cathode active materials, all of which can be directly supplied back to U.S.-based battery manufacturers.

Redwood's model illustrates how local circularity can mitigate both environmental impact and geopolitical exposure. Unlike traditional recyclers that only focus on metal recovery, Redwood integrates downstream refining and materials production, essentially bypassing overseas processing bottlenecks. By the end of 2025, the company aims to produce enough cathode and anode materials to support over **1 million EVs** annually.

This localized, full-stack model is particularly attractive to automakers like Ford and Panasonic, which have signed strategic partnerships with Redwood (US) to de-risk their North American battery supply chains. Beyond economics, the environmental benefit is substantial: **Redwood's (US)** processes claim to reduce lifecycle CO_2 emissions of cathode materials by over 40% compared to virgin supply chains. As such, **Redwood (US)** stands as a blueprint for circular industrial ecosystems that enhance battery scalability, reduce environmental impact, and strengthen regional autonomy.

Furthermore, automation, digital twins, and AI-driven quality control are increasingly being integrated into battery manufacturing to enhance scalability, reduce defects, and meet growing EV demand efficiently

To meet the dual challenge of increasing global EV demand and maintaining stringent performance and quality standards, ***battery manufacturers are increasingly integrating advanced technologies such as automation, AI-driven defect detection, and digital twins***. These tools not only improve throughput and consistency but also reduce defect rates and operational costs in a high-precision environment. Automation plays a key role in electrode coating, cell stacking, electrolyte filling, and sealing, processes where micron-scale tolerances and contamination control are vital. The latest gigafactories deploy robotic systems with machine vision to ensure alignment accuracy, defect detection, and seamless transition between process steps, often operating in ISO Class 5–7 cleanroom conditions.

AI and machine learning algorithms further enhance quality control by enabling real-time anomaly detection and predictive maintenance. For instance, by analysing sensor data from roll presses, winding machines, or electrolyte vacuum chambers, AI systems can flag deviations from normal behaviour, reducing scrap rates and unplanned downtime.

Meanwhile, digital twins, virtual replicas of the production line or individual battery cells, allow manufacturers to simulate process parameters, anticipate failures, and optimize energy usage. Companies like Siemens and ABB are actively promoting digital twin platforms for battery manufacturing, offering integrated control, simulation, and analytics. These technologies mark a transition toward Industry 4.0 in the battery sector, where cyber-physical systems and data-driven decision-making underpin scalable, high-yield production environments.

As a relevant example here, BYD's (China) rapid production scale-up and in-house battery manufacturing have driven significant cost reductions, positioning the company as a global leader in affordable electric vehicles

BYD (China) offers a powerful case study of how in-house battery production and tight value chain control can deliver both scale and affordability. As one of the few EV manufacturers that designs, manufactures, and integrates its own battery cells, primarily LFP chemistry in blade cell format, **BYD (China)** has achieved a cost advantage that underpins its rapid global expansion. Unlike many Western automakers reliant on external suppliers, **BYD (China)** leverages its vertical integration across battery materials, cell production, powertrain systems, and vehicle platforms. This allows for synchronized product development and shorter design-to-production timelines, enabling the company to iterate quickly and optimize cost structures.

In 2023–2024, **BYD (China)** became the world's top EV seller (surpassing **Tesla (US)** in some quarters), largely due to its ability to produce affordable mass-market EVs without compromising on performance or safety. The company's proprietary Blade Battery offers enhanced thermal stability, space efficiency, and high cycle life, key advantages for compact vehicles. Moreover, **BYD's (China)** automation-driven gigafactories in China boast some of the highest throughput rates in the industry, supported by AI-enabled diagnostics and automated material handling systems. As a result, **BYD (China)** is not only a leader in battery innovation but also an exemplar of how strategic vertical integration and advanced manufacturing can coexist to deliver both scale and cost competitiveness in the global EV landscape.

Furthermore, smart sensors embedded in battery packs enable real-time tracking of temperature, voltage, and location across production, transport, and deployment stages

The integration of smart sensors into EV battery packs has emerged as a crucial enabler of real-time monitoring, safety assurance, and performance optimization across all phases of the battery lifecycle, from production to operation and eventual recycling. These sensors continuously track key parameters such as temperature gradients, voltage across individual cells, current flow, internal pressure, and geolocation, enabling manufacturers and fleet operators to assess the operational health and safety of each battery pack. During manufacturing and transportation, sensors can detect abnormal heating or voltage deviations that may indicate early-stage defects or handling-induced damage. Once deployed in vehicles, the data collected enables dynamic thermal management and helps prevent thermal runaway events, especially under fast-charging or high-load conditions.

In addition, sensor data provides the foundation for battery management systems (BMS) to make real-time decisions regarding charge/discharge rates, load balancing, and fault detection. Advanced BMS now leverage multi-sensor arrays to construct granular internal state models (e.g., cell impedance, State of Charge (SoC), State of Health (SoH)) with high temporal resolution. This sensor-enabled architecture is particularly valuable for second-life applications, where accurate knowledge of each cell's historical stress and degradation allows for more precise sorting, repurposing, or recycling. As EV adoption expands globally, these smart sensing systems are becoming standard in premium and commercial EVs and are increasingly regulated under evolving safety and diagnostic standards, such as UNECE R100 and ISO 26262.

In addition, Blockchain-backed Digital Battery Passports ensure secure, transparent records of battery origin, specifications, and usage history throughout the lifecycle

Digital Battery Passport: Ensuring transparency and sustainability along the whole value chain

The Digital Battery Passport is a tool and more comprehensively an initiative that aims to make all information related to a battery's lifespan traceable and transparent, from production to recycling. This system is designed to provide comprehensive data on materials and their provenance, on battery's performance, and the environmental and social impacts of battery production and management.

Production of battery raw materials is set to rise steeply in the years ahead: demand for the three most used materials is projected to grow by 20 (nickel), 19 (graphite) and 14 times (lithium) from 2020 levels[1]. In general, battery demand is forecast to grow from 937 gigawatt-hours in 2023 to 7.4 terawatt hours in 2040, requiring a global investment of US$ 1.6 trillion[2]. As the global demand for batteries is expected raising rapidly – a 14-fold growth is estimated by 2030 - and the EU could account for 17% of that demand[3], it is essential to find effective solutions to the lack of raw materials also promoting reuse and recycling.

After many years of gestation, the new EU Batteries Regulation has been in force since February 18, 2024, with the exception of some specific provisions, and aims to minimise the environmental impact of this exponential growth considering new socioeconomic conditions, technological developments, markets, and battery usages.

This new law brings forward the circular economy and zero pollution ambitions of the EU and strengthens the EU's strategic autonomy from critical materials and foreign supply chains while improving competitiveness and sustainability.

Among the most interesting aspects of the new regulation, based on the frameworks for eco-design and batteries end-of-life, the introduction of the Digital Battery Passport (DBP) is by far the most innovative. In general, the Digital Product Passport (DPP) supports the collection and sharing of product-related data, addressing existing information gaps for products and components throughout global supply chains, and using new digital technologies. Thanks to the progress in blockchain and other distributed ledger technologies, DPPs make it possible to store this information in a secure and distributed way, while still making it easy for users to access the exact details they need, free of charge based on access rights.

Though a growing number of initiatives within the evolving EU DPP landscape are developing proof of concepts or pilot cases, only the battery passport has been included in a mandatory regulation so far. In addition to batteries for which the passport will be a legal requirement as of 2027, these initiatives will involve many other sectors including textiles, construction and electronics, potentially creating cross sector synergies.

For this reason, it is essential to ensure coordination and compatibility between the various DPP initiatives, considering that these efforts can also promote collaboration among multiple stakeholders and offer valuable insights and guidance for other product categories beyond just batteries. Regarding technical design and operation, Battery passport should be fully interoperable with other EU DPPs.

---

[1] Raw Materials Information System. (n.d.). Lithium-based batteries supply chain challenges. Retrieved from: https://rmis.jrc.ec.europa.eu/analysis-of-supply-chain-challenges-49b749
[2] Benchmark Minerals. (2024, August 14). $1.6 trillion investment needed in battery industry by 2040. Retrieved from: https://source.benchmarkminerals.com/article/1-6-trillion-investment-needed-in-battery-industry-by-2040
[3] https://environment.ec.europa.eu

I. The European Regulation on Batteries and Battery Waste

The regulation approved by the European Parliament on 12 July 2023 (EU Regulation 2023/1542), replaced the previous directive on batteries (Directive 2006/66/EC). The new Regulation establishes several compulsory measures regarding battery design and end-of-life (EoL) management, with the goal of improving battery sustainability, circularity, and safety.

Mandatory requirements apply to:

- All economic operators (all manufacturers, producers, importers and distributors) of any type of battery placed on the EU market.
- All batteries in the EU, regardless of the origin of the battery or its materials, including portable batteries, for smartphones and other electronic devices, batteries for electric vehicles and LMT (light transport vehicles) batteries.

The regulation defines many objectives, including establishing more stringent requirements in terms of sustainability, recycling and producer responsibility, with a special focus on electric vehicle batteries and other key technologies. Regarding sustainability and safety standards, various issues, including limits on hazardous substances and documentation requirements related to carbon footprint and recycled material content, are addressed. Specific recycling targets are defined for materials used in industrial batteries, SLI batteries, and electric vehicle batteries (EVBs).

The new Commission Delegated Regulation (EU) 2025/606 of 21 March 2025[4] states that the material recovery targets to be achieved by 31 December 2027 are 90% for cobalt, copper, lead, and nickel and 50% for lithium. These will be increased by 31 December 2031 to 95% for cobalt, copper, lead, and nickel and 80% for lithium.

The regulation also sets electrochemical performance and durability standards for different battery types, including criteria like battery capacity and discharge duration. Furthermore, portable batteries must be easy for end users to remove and replace, and specific safety standards are outlined for stationary battery energy storage systems[5].

Other significant objectives are:

- Improving collection rates and the circularity of the life cycle of batteries.
- Paying particular attention to the use of critical raw materials and the objective of reducing environmental impact.
- Introducing a digital passport for batteries, providing information on the composition and life cycle of batteries.

[4] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=OJ:L_202500606

[5] https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32023R1542

II. Distinctive features of Battery passport

EU Regulation 2023/1542 (Chapter IX "Digital battery passport") establishes that, from 18 February 2027, all batteries for light transport vehicles, industrial batteries with a capacity exceeding 2 kWh and batteries for electric vehicles placed on the market or put into service, are registered in electronic format ('battery passport'). The battery passport will contain detailed information on the battery life cycle, from production to recycling, and on its durability, capacity and resistance over time.

The European Commission's proposal for a new Eco-design for Sustainable Products Regulation (ESPR)[6] considers the DPP as a tool that will "electronically register, process and share product-related information amongst supply chain businesses, authorities". This information "should be easily accessible by scanning a data carrier, such as a watermark or a quick response (QR) code". In general, the aim of DPPs is to collect information about a product, its production process and the supply chain that feeds the product.

In short, the DPP can be described as an individual digital system that provides detailed information about a battery, accessible via a simple QR code.

The digital battery passport will be useful for monitoring environmental impact, facilitating battery recycling and reuse, and improving transparency along the value chain. All the producers, and in particular car manufacturers will need to implement new technologies and information management systems to provide and manage this data.

The most significant objectives are connected to improving:

- Sustainability by tracing the materials used
- Transparency by facilitating regulatory compliance and promoting sustainable practices
- Recycling and reuse by facilitating the battery recycling process
- Value for consumers by ensuring reliable information

Contents:

- The carbon intensity of their manufacturing processes
- The origin of the materials used and whether renewable or recycled materials are used
- The composition of the batteries, including raw materials and hazardous chemicals, operations, and options for repair, reuse, and dismantling
- The treatment, recycling, and recovery processes to which the batteries may be subjected at the end of their life cycle

[6] European Commission (2022), Proposal for a Regulation of the European Parliament and of the Council establishing a framework for setting ecodesign requirements for sustainable products and repealing Directive 2009/125/EC, COM (2022) 142 final; p.9, p.26

III. Battery Passport: advantages and critical issues

As often happens with the introduction of innovative tools and policies, the battery passport also highlights many positive aspects, some of which have already been indicated in the previous paragraphs, as well as many critical issues.

Regarding supply chains, it helps reduce inefficiencies in current value chains through more transparent information exchange between stakeholders (producers, suppliers, and consumers), creating entirely new revenue streams based on the intelligent use of embedded information. Moreover, it could improve supply chain management with accurate, real-time data across all stages of production, from material sourcing to final product delivery. This helps to react quickly to quality or supply issues, reduce risks related to human rights violations (child labour), identify bottlenecks. Also, consumers could be advantaged by a guarantee of quality and transparency, allowing them to easily verify critical information such as the origin of materials, battery performance, environmental impact, and emissions associated with production. This increases consumer confidence in the products they purchase.

Moreover, it promotes innovation, pushing battery manufacturers to continuously improve their processes and products to develop longer-lasting batteries with a lower environmental impact. This meets growing sustainability demands from governments and consumers, improving the competitiveness of companies with green production.

On the other side, many companies are reluctant to share personal and corporate data (production, traceability, performance, compliance data) for fear of privacy and data security breaches. The perceived risks concern:

- Potential vulnerability to cyber-attacks and data theft, especially if the information is not adequately protected.
- difficulty ensuring compliance with privacy regulations in various jurisdictions (such as the GDPR in Europe).
- data sovereignty issues: Who owns the data? where is it stored? and how is it managed.

Another major obstacle is the difficulty in collecting accurate and complete data throughout the supply chain, particularly regarding the origin of raw materials, and the lack of uniform standards. Some supply chain stakeholders may resist providing data, due to negligence or fraud, or may provide inaccurate data.

Smooth operation is needed between different supply chain stakeholders, including manufacturers, material suppliers, recyclers, and governments. However, currently there is a lack of universally accepted, shared, and interoperable standards. In the absence of common due diligence resources and framework for showcasing sustainability performance to stakeholders, it is difficult to harmonize technology standards across countries or sectors and also fix compatibility issues between different digital platforms and existing traceability tools.

The risks of large companies imposing their own standards, creating technological monopolies without inclusive participation should not be underestimated. On the other hand, in the absence of a harmonised framework for incorporating sustainability data and analytics into battery passport products, technology companies may find it challenging to convince customers that sustainability indicators they develop individually are credible, trustable and normative.

A complex and costly technological infrastructure will be required, including energy consumption, which may not be easily accessible to all companies, especially SMEs or manufacturers in emerging markets. High initial costs for integrating the necessary technologies (blockchain, IoT, management software) are envisaged, as well as difficulty in making the system economically viable in the short term and sustainable in terms of energy and resources used to operate, with benefits that may only be visible in the long term.

Another issue is connected to the difficulty in properly managing expired or non-operational batteries, especially in less developed geographical areas. Traceability does not automatically guarantee that the recycling process is efficient or problem-free and the risk that some batteries will never be returned for recycling, undermines the Digital Battery Passport efforts.

Finally, in the absence of a credible, harmonised system for sustainability assurance, the due diligence burden for companies would be significantly more onerous, and purchasers of batteries and electric vehicles would be severely limited in their ability to make informed green choices.

IV. Concrete initiatives and pilot projects

Waiting for the obligation to become binding, several European and global initiatives are working to develop and implement the Digital Battery Passport.

The Global Battery Alliance (GBA) is a partnership of over 170 companies (175 in 2024), governments, academics, international organizations, and non-governmental organizations, which aims to ensure that battery production not only supports green energy but also protects human rights and promotes health and environmental sustainability. The GBA Battery Passport Program, a prototype of which was presented at the 2023 World Economic Forum, was created as a digital twin of the battery and also involves Umicore (Belgium), Glencore (Switzerland), Audi (Germany), Tesla (US), and BASF (Germany).

To design a fully scalable and global battery passport infrastructure an ecosystem approach connecting and engaging businesses, IT solution providers, regulators, auditors, public, and international and non-governmental organizations are necessary.

The GBA Battery Passport has the ambition to enable the benchmarking and comparison of supply chain sustainability performance, at the level of individual batteries. This will contribute to a marketplace where products can compete on independently validated and verifiable sustainability performance, and companies can differentiate themselves to customers, investors and end consumers with robust and trustable green claims. Ultimately, this scoring system will incentivise improved sustainability performance throughout the battery supply chain[7].

GBA has developed tailored value propositions for the principal constituencies of the Association, which contain specific objectives and benefits, based on a detailed framework.

[7] https://www.globalbattery.org/media/publications/gba-batterypassport-2024-v1-web.pdf

GBA Battery Passport indicator framework

Environmental	Social & Economic	Governance
Energy and GHG 2. EGE emissions 3. Energy efficiency **Environmental Degradation** 4. Pollution (air including GHG emissions, water, soil, hazardous substances, noise and vibration, plant safety 5. Biodiversity loss 6. Water management (usage, recycling, depletion) 7. Waste management (generation, recycling/reuse) **Circularity** 8. Material consumption/usage 9. Circular design	**Human Rights** 10. Child labor 11. Forced labor **Workers' Rights** 12. Freedom of association and collective bargaining 13. Worker health and safety **Community Impacts and Rights** 14. Respect for Indigenous Peoples' rights 15. Community life 16. Diversity **Local Economy** 17. Contribution to local economic development (payments to governments and local supplies and employment 18. Engagement with artisanal and small-scale miners **Product Cost** 19. Total cost of ownershipp	**Compliance & Good Governance** 20. Product quality and safety 21. Data security and privacy 22. Occurance of corruption and bribery **Legend:** ■ ESG issues corresponding to the risk categories of the EU Battery Regulation ■ Additional salient ESG issues

The GBA Battery Passport will make it possible to assess and compare the sustainability performance of battery supply chains on a battery-by-battery basis. This will support the creation of a market where products compete based on independently verified and credible sustainability standards. It also allows companies to stand out to consumers, investors, and customers with reliable environmental claims. In the long run, this rating system aims to motivate better sustainability practices across the entire battery supply chain.

For example, electrifying vehicle fleets worldwide is a key part of the shift to clean energy. The Battery Passport helps ensure that this transition is fair and inclusive for all people involved in or affected by the battery supply chain.

Case Study

In 2023, the **Global Battery Alliance** demonstrated the Battery Passport proof-of-concept through the involvement of **Tesla (US)** and **Audi (Germany)**, two of the EV manufacturers which participates in the Alliance. The initiative's goal is to make battery materials fully traceable, thus verifying their sustainability along the entire value chain.

Essentially, GBA's goal is to be able to monitor the entire process involved in an EV battery, from material extraction to the production of the finished pack. The aim is to make module production completely sustainable, effectively reducing their environmental impact to zero.

Source: Frost & Sullivan

To achieve this goal, 100% of the materials that make up a battery must be fully traceable, and this traceability must be easily accessible.

In this first concrete example of a digital passport, **Tesla** (US) has only published data relating to the cobalt used in the battery of the Long-Range trim of one of its models. This represents just 1% of all materials in the battery in question.

Conversely, for **Audi (Germany)** traceability also covered lithium, reaching up to 13.6% of the materials for one of the two batteries examined. It should be noted, however, that this is still a preliminary phase, which offers a first glimpse of a very interesting project.

Battery Passport of one of the Audi (Germany) batteries

Essentially, the GBA's goal is to be able to verify the entire process involved in an EV battery, from material extraction to the production of the finished battery pack. This way, the goal is to make module production completely sustainable, effectively reducing their environmental impact to zero.

To achieve this goal, 100% of battery materials must be fully traceable, and this traceability must be easily accessible. The Battery Passport is essentially a database that collects all the information from the origin of the materials to the packaging.

Data exchange frameworks initiatives

Several other initiatives are currently developing data exchange frameworks, to ensure that information on battery supply chain sustainability performance (and other battery data) can be passed through the supply chain securely and accurately by digital battery passport solution providers. These initiatives include the UN Transparency Protocol, Catena X, and JTC24 in the European Union.

The UN Transparency Protocol, developed under the auspices of the Global Battery Alliance, establishes an internationally recognized framework to enhance traceability, sustainability, and accountability across global battery value chains. Central to this initiative is the Battery Passport.

The Transparency Protocol outlines the technical standards and governance structures required to ensure that the information provided is accurate, secure, and accessible to relevant stakeholders, including regulators, consumers, investors, and manufacturers. By promoting transparency and comparability, the protocol aims to incentivize improved practices throughout the battery supply chain.

Moreover, the Battery Passport supports the broader objectives of the clean energy transition by ensuring that the shift to electric mobility is not only environmentally beneficial but also socially equitable. It provides a mechanism to monitor and address human rights impacts and environmental risks associated with the sourcing and production of battery materials.

Catena-X is the first open and collaborative data ecosystem designed specifically for the automotive industry

It enables sovereign, standardized, and secure data exchange across the entire value chain, from OEMs and suppliers to mid-sized companies. The goal of Catena-X is to sustainably enhance transparency, efficiency, and resilience across the industry through shared standards, assuring that all participants retain full control over their data at all times.

Driven by industry needs, Catena-X has evolved into a global network with strong support from regional partners and a specific focus on sustainability. In this perspective it is developing a standardized rulebook for calculating the Product Carbon Footprint (PCF), with the aim to use this framework to enable accurate, comparable collection of real CO_2 emissions data across the entire value chain.

Another key focus area is promoting digital solutions for tracking and documenting materials and components. One example is the Battery Passport, which records data across the entire lifecycle of a battery – supporting effective reuse and recycling efforts. Catena-X offers companies a standardized digital infrastructure for capturing and leveraging sustainability-related data. This helps meet regulatory obligations and enhances the efficiency of business processes across the supply chain.

JTC24, also known as CEN/CENELEC JTC 24, is a joint technical committee focused on developing the framework and system for a Digital Product Passport (DPP)

This initiative, started in 2023 and is planned to end in 2028. It is driven by the European Union's Eco-design for Sustainable Products Regulation (ESPR) and other relevant regulations like the Battery Regulation, with the aim to fulfil the standardization request to define harmonized standards for the DPP System. Other main objectives are:

- Achieving a common architectural and applicative framework for DPP based on existing standardization achievements
- Working on common interoperability principles (e.g. European Interoperability Framework)
- Enabling simplicity and modularity
- Identifying the most generic required interoperability components in order to promote collaboration as much as possible

Organisation Scope

Counterparties potentially interested into JTC24 are:

- European Commission and National Authorities
- Economic Operators, brings products on the market (e.g. manufacturers, importers)
- DPP System and Service Providers (e.g. for operating services, backup services)
- DPP System Component Suppliers (e.g. for Data Carrier)
- Partners in the value chain (e.g. supplier, dealer, recycler) to know how data has to be provided, how to get access
- Standardisation Bodies (e.g. for sector specific data standardisation)
- Consumer Organisations to ensure applicability of DP

AI-driven analytics predict degradation patterns and optimize maintenance strategies, helping extend battery life and improve lifecycle efficiency

As EV batteries become more sophisticated and embedded with real-time sensors and digital records, the role of AI-driven analytics in managing battery health and lifecycle performance is expanding rapidly. Machine learning algorithms, trained on large datasets of historical battery usage and degradation patterns, can predict future performance, identify failure risks, and optimize maintenance strategies. This predictive capability is essential for fleet operators, utilities, and OEMs seeking to extend battery life, maximize uptime, and reduce total cost of ownership (TCO). By anticipating when and where degradation will occur, AI systems allow for condition-based maintenance rather than fixed replacement intervals, significantly improving lifecycle efficiency.

Moreover, AI tools are being integrated into battery management systems (BMS) and cloud-based platforms to provide real-time recommendations on optimal charging patterns, thermal management strategies, and usage cycles. For instance, adaptive charging algorithms can minimize lithium plating and thermal hotspots by adjusting charge rates based on SoH and ambient conditions. In second-life contexts, such as grid storage or electric buses, predictive models help identify which cells can be reused safely and efficiently, reducing waste and increasing return on investment.

Companies like **Nuvation Energy (Canada), Twaice (Germany)**, and **Volytica Diagnostics (Germany)** are already commercializing AI-based battery analytics platforms, and major OEMs like **Volkswagen (Germany)** and **GM (US)** are investing in in-house AI teams for battery intelligence. As data ecosystems grow and vehicle connectivity deepens, AI-driven lifecycle optimization will be a cornerstone of economically and environmentally sustainable battery usage.

Automation and AI are also being introduced in battery disassembly lines to enhance safety, precision, and scalability in recycling operations. As EV batteries vary widely in chemistry, architecture, and aging state, **disassembly remains one of the most hazardous and costly steps** in battery recycling. Manual labour is often dangerous due to residual high voltages and risks of thermal runaway. Furthermore, inconsistent pack designs and embedded adhesives complicate safe and efficient separation of modules, cells, and components. In response, the industry is moving toward **automation and AI-enhanced disassembly lines** that combine **robotic systems, machine vision**, and **sensor data** to identify battery formats, locate attachment points, and perform high-precision extraction.

Projects such as **ReLIB (UK)** and pilot initiatives under the **U.S. Department of Energy** have demonstrated AI-guided robotic disassembly capable of adjusting procedures in real time based on battery state and geometry. These systems can also integrate battery passport data and onboard sensor histories to assess **state-of-health (SoH)** and determine the most suitable downstream pathway, reuse, repurposing, or recycling. As regulatory frameworks begin to require disassembly standardization and traceability, such intelligent systems will be essential for achieving **safe, cost-effective, and scalable battery circularity.** They also serve as a foundational element for integrating circularity into gigafactory ecosystems.

LINOVA ENERGY

COMPANY OVERVIEW

Industry Segment:
Evolution of EV batteries

Brief Description:
LiNova Energy is developing high-energy density batteries leveraging polymer cathode.

Maturity:
Under development

Website:
https://www.linovaenergy.com

Multimedia:
https://www.youtube.com/watch?v=HlEciQ4_tXQ

COMPANY STRUCTURE

FOUNDED: **2022**

COUNTRY: **USA**

OF EMPLOYEES: **11 - 50**

TOTAL FUNDING: **$15,8 M**

PRODUCT OVERVIEW

Technology Focus

- LiNova Energy develops batteries based on polymer cathode technology for the electric vehicle, aerospace and energy storage industries.
- The solution leverages a metal-free battery design that eliminates nickel and cobalt, employing materials that ensure high energy density, sustainability and cost efficiency.
- LiNova is developing cathode technology that can be integrated into existing lithium-ion battery production lines with an active material content of over 90% and solvent-free coating processes, leveraging water-based binders and dry techniques.

Main Competitive Advantage

LiNova is developing high-energy polymer battery technology designed to replace conventional cathodes containing cobalt, nickel and other critical materials. The solution leverages abundant, readily available and low-impact materials, ensuring a stable and sustainable supply chain while reducing environmental footprint. The technology allows for lower costs over the lithium iron phosphate and Li-Ion Nickel Manganese Cobalt cathode competitors. The solution is designed to offer great energy density, ensuring safety, lightness and convenience for the battery market in automotive, aerospace and energy storage industries.

Value Proposition

- LiNova Energy is on a mission to ensure progress in battery technology by offering a high energy density solution powered by a polymer cathode.
- The company is committed to offering a sustainable and affordable energy solution without the use of nickel and cobalt, ensuring a stable supply chain.

ELEVENES

COMPANY OVERVIEW

Industry Segment:
Evolution of EV batteries

Brief Description:
ElevenEs is developing Lithium Iron Phosphate - LFP cathode battery technology to ensure fast charging, long life and high battery performance.

Maturity:
Under development

Website:
https://elevenes.com

Multimedia:
https://www.youtube.com/watch?v=OrifCeBALKI

COMPANY STRUCTURE

FOUNDED: **2019**

COUNTRY: **SERBIA**

OF EMPLOYEES: **50 – 100**

TOTAL FUNDING: **N.A.**

PRODUCT OVERVIEW

Technology Focus

- ElevenEs is developing cobalt and nickel free battery cells leveraging Lithium Iron Phosphate – LFP technology. The cell-to-pack/cell-to-body solution reduces cost per cycle and increases energy density at the battery pack level, powering electric vehicles, buses, trucks and home energy storage systems.
- The lithium iron phosphate cell Edge574 offers a maximum charging power of 1MW for a battery pack of 210 cells. The company optimizes design, materials and safety solutions to reduce internal strength and ensure high performance.
- The cell is designed to support fast charging over a wide temperature range, with discharge capacities from -30°C to 60°C, enabling consistent performance under different environmental conditions.

Main Competitive Advantage

ElevenEs develops battery cells based on Lithium Iron Phosphate – LFP technology, suitable for several applications including electric vehicles. The Edge574 is capable of charging from 10% to 80% in about 12 minutes delivering up to 1.1km of range per second of charging. The cell supports a life cycle equivalent to at least 500.000 km, three times longer than many competing technologies. The company produces safe and more sustainable batteries thanks to LFP technology that eliminates the need for nickel and cobalt. Edge cells offer higher energy density at the pack level compared to other LFP-based solutions, enhancing the overall efficiency of electric vehicles.

Value Proposition

- ElevenEs aims to spread the adoption of electric vehicles in Europe by developing Lithium Iron Phosphate - LFP batteries.
- The company is committed to delivering high-performance, reliable and cost-effective battery solutions that accelerate the global transition to clean energy.

ECHION TECHNOLOGIES

COMPANY OVERVIEW

Industry Segment:
Evolution of EV batteries

Brief Description:
Echion Technologies provides a niobium-based anode material for manufacturers of lithium-ion battery cells.

Maturity:
On the market

Website:
https://www.echiontech.com

Multimedia:
https://www.youtube.com/watch?v=vX8jHzsnbjE

COMPANY STRUCTURE

FOUNDED: **2017**

COUNTRY: **UNITED KINGDOM**

OF EMPLOYEES: **50 – 100**

TOTAL FUNDING: **£52,1M**

PRODUCT OVERVIEW

Technology Focus

- Echion Technologies develops niobium-based active anode materials designed to ensure safety, fast charging and long life in lithium-ion batteries, meeting the needs of the heavy transportation and industrial applications sectors.
- The anode material developed is based on proprietary mixed niobium oxide compositions and microparticle designs protected by international patents.
- The materials are moisture-stable micrometric particles, integrable with existing industrial battery manufacturing processes. They are compatible with standard materials such as collectors, binders, electrolytes and cathodes. The company offers technical support to cell manufacturers, helping at all stages of development.

Main Competitive Advantage

Echion Technologies develops niobium-based active anode materials as an alternative to conventional anodes such as graphite, silicon or lithium-titanate in lithium-ion batteries. The solution enables ultra-fast charging in under 10 minutes, high energy density even at low temperatures and long cycle life exceeding 10.000 cycles. The technology offers up to twice the energy density of lithium titanate anode cells, while ensuring a reduced environmental impact. The combination of solution features makes the technology suitable for heavy-duty and high-speed industrial transportation applications.

Value Proposition

- Echion Technologies is committed to enabling the efficient electrification of heavy-duty vehicles by providing advanced niobium-based anode materials for lithium-ion batteries.
- The company aims to overcome the limitations of existing battery technologies by delivering a solution that combines ultra-fast charging, high energy density and enhanced safety.

NYOBOLT

COMPANY OVERVIEW

Industry Segment:
Evolution of EV batteries

Brief Description:
Nyobolt is developing lithium-ion batteries for electric vehicles, designed to deliver ultrafast charging, high power output and extended cycle life.

Maturity:
Under development

Website:
https://nyobolt.com

Multimedia:
https://www.youtube.com/watch?v=4XiZ5BM3nP4

COMPANY STRUCTURE

FOUNDED: **2020**

COUNTRY: **UNITED KINGDOM**

OF EMPLOYEES: **100 – 150**

TOTAL FUNDING: **$113,6M**

PRODUCT OVERVIEW

Technology Focus

- Nyobolt is developing high-power-density battery and charging systems, integrating proprietary carbon and metal oxide anode materials, low-impedance cell design, power electronics and software controls.
- Low impedance cells reduce heat generation during charging, improving thermal management and enabling fast charging cycles without compromising battery life. The technology is designed to address the electrification needs of electric vehicles, heavy-duty off-road trucks, robotics and consumer devices.
- Lithium-ion batteries for electric vehicles can achieve over 4.000 fast charging cycles while maintaining 80% capacity and working at temperatures lower than 60 degrees thanks to a patented cooling system.

Main Competitive Advantage

Nyobolt is developing high-performance batteries for electric vehicles, integrating innovative materials, optimized design and advanced software. The technology enables ultra-fast charging of 10% to 80% in less than 5 minutes leveraging 350 kW chargers, providing a range of up to 250 km. The batteries achieve over 4.000 fast charging cycles for over 1 million km, demonstrating greater longevity and reliability than electric vehicle batteries on the market. The company is developing Bolt-ee, an ultra-fast mobile charging system that provides up to 160 km of range in less than 10 minutes.

Value Proposition

- Nyobolt is on a mission to provide advanced fast-charging electric vehicle lithium-ion batteries based on proprietary materials, low-impedance cell design and integrated power electronics.
- The company aims to overcome the limitations of conventional battery technologies by enabling ultra-fast charging speeds and high endurance.

TWAICE

COMPANY OVERVIEW

Industry Segment:
Evolution of EV batteries

Brief Description:
TWAICE provides predictive battery analytics using digital twins to optimize performance, safety and lifespan of energy storage systems.

Maturity:
On the market

Website:
https://twaice.com

Multimedia:
https://www.youtube.com/watch?v=eSvPDrJKmal

COMPANY STRUCTURE

FOUNDED: **2018**

COUNTRY: **GERMANY**

OF EMPLOYEES: **100 – 150**

TOTAL FUNDING: **$71.5M**

PRODUCT OVERVIEW

Technology Focus

- TWAICE has developed a cloud-based platform for predictive analysis of battery lifecycle. The solution relies on digital twins that enable real-time monitoring of State of Health – SoH, performance and degradation factors of energy storage systems.
- The digital models replicate the electrochemical and thermal behavior of battery cells in real time, allowing for simulation of aging and wear under various operational conditions.
- The model architecture combines real-world data with Machine Learning – ML techniques to refine parameters and generate insights. Functionalities include automatic alerts on critical behaviors and suggestions for targeted maintenance actions.

Main Competitive Advantage

TWAICE has developed a cloud-based platform for the optimization of performance, safety and lifecycle of batteries. The solution is used in both electric vehicles and stationary energy storage systems, with the aim of optimizing their utilization and extending their operational lifespan. TWAICE has introduced an insurance-backed guarantee on the accuracy of its models, making the platform one of the few predictive technologies with coverage based on diagnostic parameters. The solution is scalable, designed to operate on individual battery packs as well as entire fleets. The software modules can be tailored according to the customer’s profile.

Value Proposition

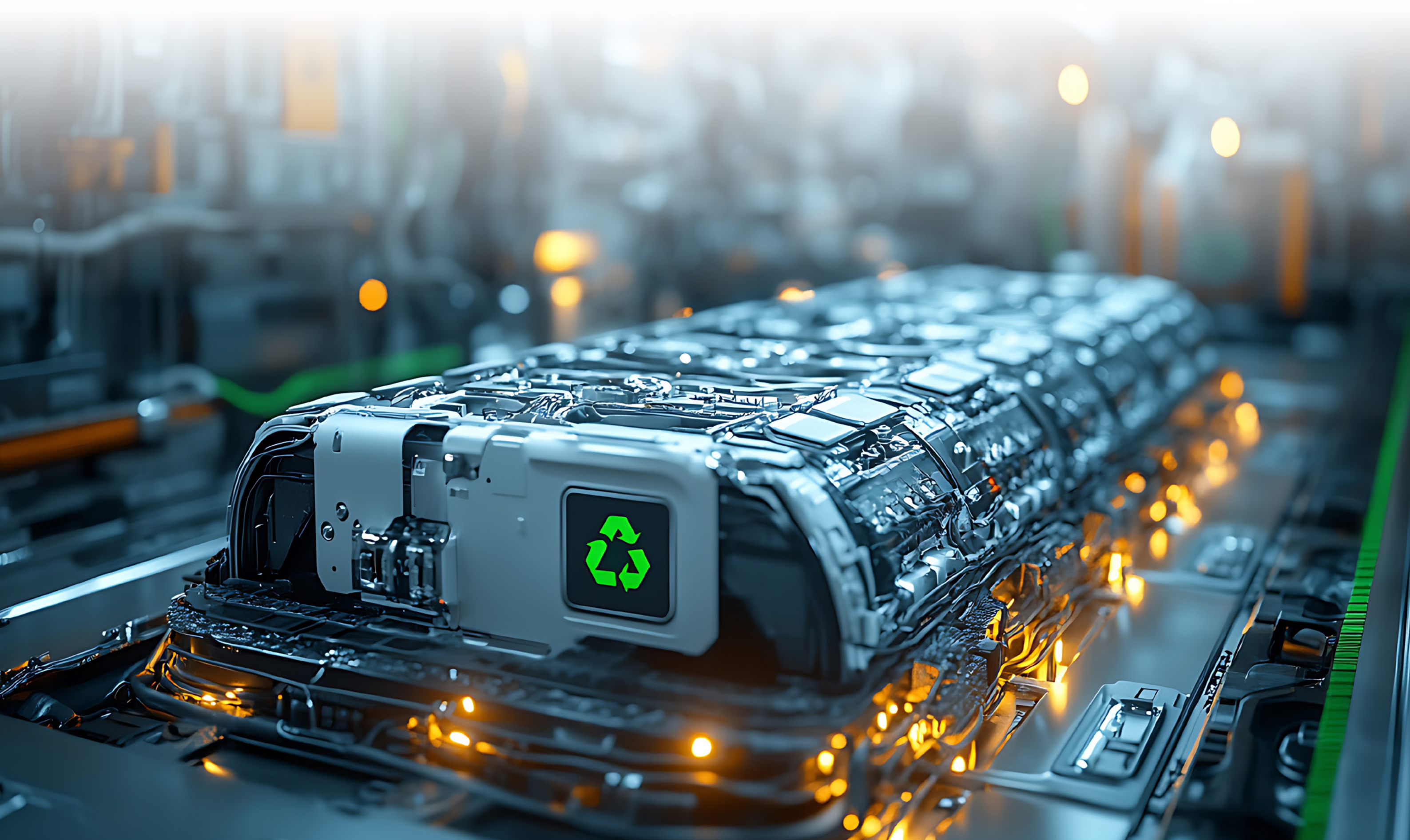
- The company is on a mission to enhance battery safety by enabling early identification of anomalies, malfunctions and degradation patterns.
- TWAICE aims to extend the useful life of batteries and reduce the rate of early replacements. By providing accurate insights into the state of health and degradation trends, the platform allows operators to optimize battery usage.

SUSTAINABILITY FACTORS, RECYCLING, TECHNICAL CHALLENGES AND SECOND LIFE APPLICATIONS

Sustainable battery manufacturing begins with eco-conscious design strategies that prioritize recyclability, energy efficiency, and reduced material complexity

Sustainable battery manufacturing begins with decisions made at the design stage, where the structure, materials, and chemistry of the battery are determined. **Eco-conscious design strategies** aim to reduce the environmental footprint of EV batteries by prioritizing **recyclability, material simplicity, durability,** and **energy efficiency** across the entire lifecycle. This includes selecting fewer and safer materials (e.g., reducing cobalt or toxic solvents), using standardized and modular components, and optimizing form factors for efficient integration and eventual disassembly. Design-for-sustainability also encompasses minimizing reliance on geopolitically sensitive or environmentally damaging elements such as nickel and rare earths, while ensuring that battery chemistries remain high-performance and cost-competitive.

Material selection is increasingly informed by **life-cycle assessments (LCA)** and **material criticality analyses**, which evaluate upstream environmental impacts, extraction toxicity, and recyclability. Chemistries like **lithium iron phosphate (LFP)** and emerging **solid-state systems** are gaining favour not only for cost and safety, but also for their more favourable sustainability profiles. Furthermore, embedding sustainability into early design stages enables greater alignment with evolving global regulations **(e.g. EU Battery Regulation 2023, California Zero Emission Mandates)**, which increasingly demand traceability, circularity, and reduced lifecycle emissions.



Furthermore, designing batteries for disassembly and end-of-life recovery simplifies recycling and minimizes resource loss in downstream processes

A central pillar of sustainable battery design is design for disassembly (DfD), a principle that facilitates easier dismantling, component separation, and material recovery at end-of-life. Traditional EV battery packs are often held together by adhesives, welded joints, or non-standardized fasteners that make disassembly labour-intensive and hazardous. In contrast, **DfD** prioritizes **modularity, reversible assembly**, and **material labelling**, reducing the time and energy required to access cells and valuable components. This approach enables more efficient recycling, reduces contamination, and increases the yield and quality of recovered materials.

Beyond environmental benefits, **design for disassembly** also supports the economic case for second-life applications, by enabling the safe removal of functional cells that can be tested, sorted, and reused. Initiatives such as the **EU-funded CIRPASS project** and automotive OEMs like **Renault (France) and BMW (Germany)** are investing in **DfD-compatible** battery architectures, integrating QR codes, RFID tags, and component passports to streamline reuse and recycling logistics. As EV batteries become more prevalent, scalable and intelligent disassembly will be critical to building closed-loop systems and meeting regulatory recovery targets.

In this context, modern gigafactories are integrating low-emission production lines and energy-efficient systems to reduce their overall carbon footprint

While upstream raw material extraction accounts for a significant share of battery-related emissions, the manufacturing phase, particularly electrode processing, drying ovens, and formation cycling, also carries substantial carbon and energy burdens. In response, modern gigafactories are being designed to operate with **low-emission production lines, waste heat recovery systems**, and **energy-efficient automation**. Critical steps such as solvent recovery in NMP (N-Methyl-2-pyrrolidone) drying, vacuum systems in electrolyte filling, and smart HVAC systems in clean rooms are being upgraded to reduce energy consumption and fugitive emissions.

Technologies like **dry electrode coating**, pioneered by **Tesla (US)**, eliminate the use of energy-intensive solvents altogether and can cut cathode production energy use significantly. Furthermore, **digital twins, AI-based process control, and predictive maintenance systems** are increasingly integrated into battery plants to optimize process efficiency and reduce resource waste. Companies adopting such systems are not only improving environmental performance but also reducing costs, as lower emissions often correlate with reduced electricity and maintenance bills. These developments form a core part of the industrial response to carbon neutrality goals and investor ESG pressure.

Therefore, renewable energy sources such as solar, wind, and green hydrogen are increasingly being used to power battery production facilities

The source of electricity used in battery manufacturing exerts a significant influence on the total embedded carbon footprint of an EV battery. In this context, the shift toward **solar, wind, and green hydrogen** in powering gigafactories is a transformative step toward sustainable production.

Green hydrogen, used as a heat source or industrial reagent, is particularly valuable for reducing emissions in **thermal process steps** such as electrode drying or calcination. Meanwhile, solar and wind are increasingly deployed for direct power or coupled with **battery energy storage systems (BESS)** for load balancing. Integrating renewables also improves energy security, especially in regions with unstable power grids. Leading OEMs and battery producers are now co-locating factories with renewable assets or signing **power purchase agreements (PPAs)** to guarantee low-carbon energy input. This shift is not only environmentally beneficial but also increasingly economically competitive, given the declining cost of renewables.

Moreover, the combination of sustainable design and low-carbon production is essential to reducing the embedded environmental cost of EV batteries

True sustainability in EV batteries lies at the intersection of intelligent design and clean production. While low-carbon manufacturing reduces emissions during fabrication, upstream material impacts and downstream recyclability are primarily governed by design choices. For instance, selecting simpler, cobalt-free chemistries or standardizing module structures may reduce the energy required for both production and recycling. When combined with low-carbon energy and efficient industrial systems, these design choices lead to **substantial reductions in total lifecycle emissions.**

This synergy is critical as regulatory frameworks move from single-point emissions (e.g., tailpipe) to **full life-cycle analysis**. For manufacturers, aligning product design and factory operations with sustainability principles enables them to comply with new environmental labelling standards, carbon thresholds, and product stewardship responsibilities. It also strengthens brand equity, opens access to green financing mechanisms, and supports regional compliance. For example, with the **EU's Carbon Border Adjustment Mechanism (CBAM)**. The convergence of eco-design and clean manufacturing is thus both an environmental necessity and a strategic business imperative.

Here, The Toyota (Japan) battery manufacturing in North Carolina is demonstrating clean-energy powered gigafactory model in the US

A tangible example of sustainable battery manufacturing in action is Toyota's battery plant in North Carolina (US), which exemplifies a clean-energy powered gigafactory model. The facility started its operations in April 2025. It is powered by **100% renewable electricity** sourced from **on-site solar arrays and local renewable energy providers**, according to Toyota's North America sustainability roadmap. This site is expected to produce **up to 30 GWh of lithium-ion batteries per year**, supporting the company's hybrid and full EV product lines.

Toyota has also emphasized **energy efficiency** in the plant's layout, including waste heat reuse, smart ventilation systems, and water recycling loops. In alignment with its **"Environmental Challenge 2050"** goals, the company aims to reduce both operational emissions and upstream embedded emissions. Importantly, the project is located within proximity to emerging **battery recycling hubs and critical materials suppliers**, potentially enabling a more integrated and circular supply chain within the U.S. market. This initiative demonstrates how **large-scale production** can be reconciled with **clean energy integration and long-term climate targets.**

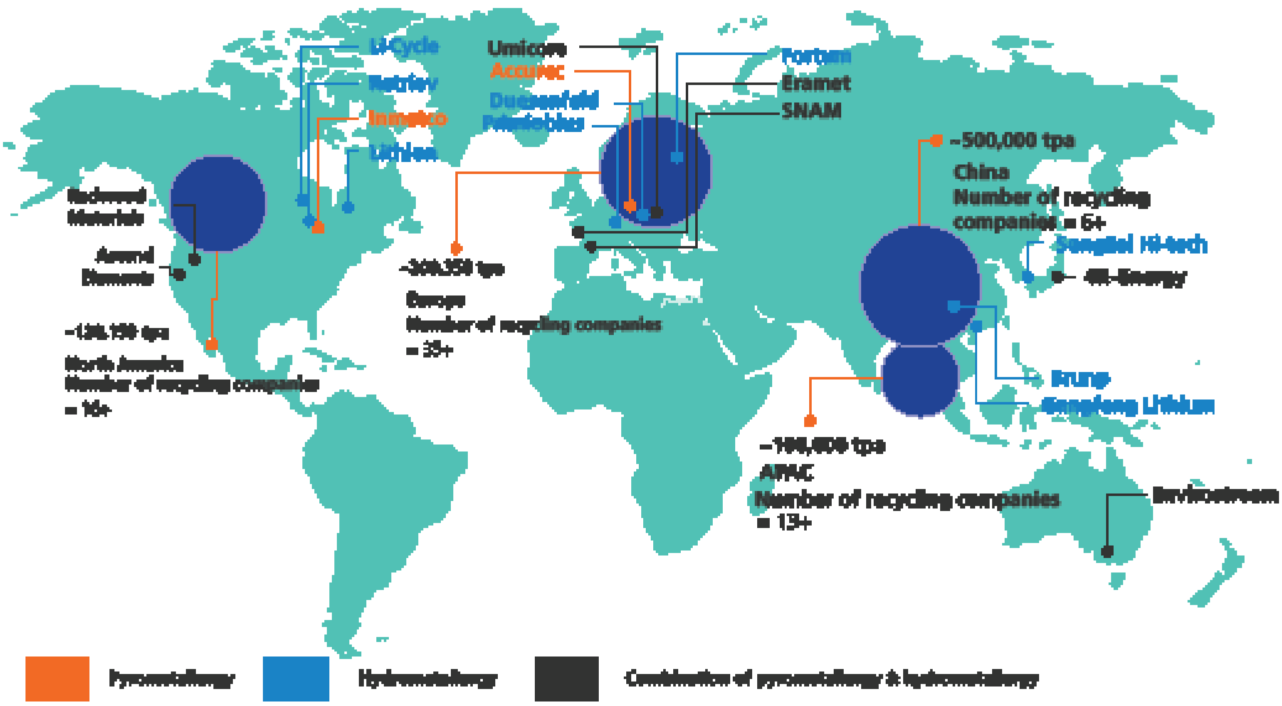
The Verkor (France) Gigafactory in Dunkerque exemplifies low-carbon EV battery manufacturing in Europe, integrating energy-efficient processes and circular economy principles to align with EU climate targets

Verkor (France), a high-profile French battery startup backed by Renault and Schneider Electric, is developing a low carbon gigafactory in Dunkerque that aims to set a new standard for sustainable battery production in Europe. Scheduled to reach 16 GWh annual capacity by 2028, the plant is powered by **a combination of renewable electricity and waste heat from local industrial partners**, taking advantage of Dunkerque's well-developed energy and logistics ecosystem. It also integrates **energy-efficient drying ovens, AI-controlled production lines**, and **advanced recycling partnerships** to minimize environmental impact.

Verkor's factory is not only focused on production emissions but is also designed with **circular economy principles**, including traceable material sourcing, modular pack designs, and partnerships with European recyclers. This aligns with the European Union's Green Deal and the Battery Regulation's stringent requirements on **carbon intensity disclosures, recycled content quotas, and material traceability**. Verkor aims to deliver batteries with a **carbon footprint below 30 kg CO_2 eq/kWh by 2032**, which is 70% below industry average according to them, placing it among the lowest in Europe. Its model is particularly relevant for regions seeking to **de-risk from imported battery components** and build sovereign, climate-aligned industrial value chains.

Recycling and reuse technologies are essential to closing the loop in the EV battery value chain and enabling a circular battery economy

EV battery reuse and recycling: Company distribution by region, major markets, 2024



As the number of electric vehicles (EVs) on the road increases exponentially, the **end-of-life management** of lithium-ion batteries has become a critical component of sustainable electrification. Recycling and reuse are no longer optional, they are strategic imperatives for reducing dependence on virgin raw materials, minimizing environmental impacts, and mitigating the supply risks of critical minerals such as cobalt, lithium, and nickel. A circular approach to the battery value chain not only closes material loops but also improves overall lifecycle emissions and energy efficiency. According to the **IEA (International Energy Agency) (2023)**, recycled materials could meet up to **10–20%** of global lithium, cobalt, and nickel demand by **2040** if recycling is scaled efficiently and early.

The design of battery packs, including the choice of chemistry, form factor, and housing, heavily influences recyclability. Increasingly, manufacturers are exploring **design-for-disassembly** strategies and integrating **digital battery passports** to streamline recycling operations. Effective recycling must also accommodate a growing diversity of chemistries (e.g., LFP, NMC, solid-state) and degradation profiles, requiring technological flexibility across recovery methods. Today, three primary recycling technologies are under development and commercialization: **pyrometallurgy, hydrometallurgy**, and **direct recycling**, each offering different trade-offs in energy consumption, recovery efficiency, and material value preservation.

Source: Frost & Sullivan

… Here, Pyrometallurgical recycling uses high-temperature processing to extract valuable metals but results in lithium loss and high energy consumption.

Pyrometallurgy remains one of the most widely implemented methods for battery recycling, particularly due to its industrial maturity and compatibility with mixed or contaminated feedstocks. The process involves **high-temperature smelting** (often above 1,200–1,500°C) of battery scrap, producing metal alloys that can be further refined into usable materials such as **nickel, cobalt**, and **copper**. While effective for recovering high-value metals, pyrometallurgical processes suffer from **two major limitations**. The first one the fact that **lithium is typically lost in the slag phase** and not recovered without additional post-processing. Secondly, the process is **energy-intensive and carbon-intensive**, often requiring fossil-fuel-based thermal input.

These environmental trade-offs reduce the circularity and sustainability of pyrometallurgy in the context of modern battery systems. Furthermore, it destroys cathode architecture, preventing functional component reuse. Despite these shortcomings, it remains a key fallback for handling heterogeneous and end-of-life battery streams where other processes might not be viable. Innovations such as **renewable-powered furnaces** and **hybrid pyro-hydro systems** are being explored to reduce emissions and broaden the metal recovery spectrum, especially in regions where industrial infrastructure is already oriented toward high-temperature metallurgical processes.

In this context, Umicore's (Belgium) pyrometallurgical plant in Belgium recovers key metals from lithium-ion batteries but struggles with lithium loss and high energy use

A notable industrial-scale example of pyrometallurgy in action is the **Umicore (Belgium)** battery recycling facility in Hoboken. It has become one of Europe's largest and most technically advanced operations, capable of processing over **7,000 tonnes** of spent lithium-ion batteries per year. Umicore's system uses a **closed-loop pyrometallurgical process** to recover key metals, particularly **cobalt, nickel, and copper**, with high yields and market-ready purity levels. These metals are then refined and reintroduced into the production of new cathode active materials.

However, **lithium recovery remains a weak point** in Umicore's process, as it is not captured during smelting and requires additional hydrometallurgical post-processing, an area the company is actively investing in. Moreover, the energy intensity of the pyrometallurgical step remains high, raising concerns about lifecycle carbon emissions. Umicore has responded by exploring **process electrification** and **renewable heat sources**, but these upgrades require capital and regulatory support.

Despite its limitations, Umicore's model illustrates the industrial reliability of pyrometallurgy, particularly for cathode chemistries rich in high-value transition metals. Yet, in a future increasingly dominated by **lithium-iron-phosphate (LFP)** and low-cobalt chemistries, this model may need to evolve or be complemented by more selective technologies.

… Hydrometallurgical methods use chemical leaching to recover a broader range of metals with higher efficiency and lower environmental impact

***Hydrometallurgy, based on aqueous chemical leaching, offers a more selective, efficient, and environmentally favourable* pathway for lithium-ion battery recycling**. This process involves dissolving battery components into liquid reagents (e.g., sulfuric acid with reducing agents), followed by **precipitation, filtration, and solvent extraction** to isolate metals such as **lithium, nickel, cobalt**, and **manganese.** Unlike pyrometallurgy, hydrometallurgy allows for **high recovery yields across a wider range of elements**, including lithium and aluminium, and operates at much **lower temperatures**, resulting in a smaller energy and carbon footprint.

The ability to recover battery-grade salts (e.g., lithium carbonate, nickel sulphate) directly from black mass makes hydrometallurgy well-suited to the emerging needs of a **closed-loop battery materials economy.** However, the method is sensitive to feedstock quality and requires **complex chemical handling, wastewater treatment**, and **reagent recycling** systems. These considerations are critical when designing large-scale hydrometallurgical facilities that must meet both **economic** and **environmental** benchmarks. While the process is already commercialized in some markets, ongoing R&D aims to improve selectivity, throughput, and solvent sustainability to enable wider global adoption.

Li-Cycle's (Canada) hydrometallurgical facility in North America pioneers efficient metal recovery from lithium-ion batteries despite recent financial and operational challenges

Li-Cycle (Canada) is one of the leading companies commercializing hydrometallurgical battery recycling at scale. Its distinctive **hub-and-spoke architecture** separates mechanical preprocessing from chemical recovery: "spokes" located near EV manufacturing or collection centers shred batteries into "black mass," which is then sent to centralized "hubs" for chemical separation. This system reduces transport costs and enables regionally distributed collection while maintaining centralized quality control over critical recovery processes.

Li-Cycle reports **over 90% recovery rates** for key materials including lithium, nickel, and cobalt, positioning its method as a **low-emission, high-yield alternative** to pyrometallurgy. However, the company has faced several operational and financial hurdles, including **construction delays**, cost overruns, and **scaling challenges** at its major U.S. facilities.

These issues underscore the complexity of hydrometallurgical systems, which must carefully manage reagent stability, waste effluents, and consistent material flow. Despite this, Li-Cycle remains a critical North American player in battery recycling, supported by partnerships with **LG Energy Solution (South Korea)** and **Glencore (Switzerland)**. If technical refinements continue and capital efficiency improves, the model could become a cornerstone of localized circular battery infrastructure in the Americas.

… Direct recycling is an emerging technique that preserves entire battery components like cathodes, reducing processing and retaining material quality

Direct recycling represents a third and highly promising approach to battery recycling, focused on preserving the structure and electrochemical integrity of battery components, particularly cathode and anode materials, rather than breaking them down into elemental metals. This technique involves **gentle disassembly, surface cleaning**, and re-lithiation, restoring the active material's structure and chemistry for direct reuse in battery manufacturing. The benefits are substantial: **reduced processing energy, lower emissions**, and **higher retained material value**. Unlike hydro- and pyrometallurgy, direct recycling maintains the original crystal lattice and avoids complex chemical separation steps.

While technically demanding and requiring a complete, circular battery redesign, direct recycling is particularly attractive for **chemistry-specific, high-volume battery returns**, such as standardized consumer electronics or EV packs managed under OEM-controlled return logistics. Challenges remain in **feedstock sorting, degradation variability**, and **quality assurance**, but ongoing research aims to automate key steps and optimize reconditioning protocols. This method aligns well with trends in **battery passport integration** and **sensor-augmented lifecycle tracking**, where detailed knowledge of each battery's history can guide intelligent recycling decisions. As second-life and reuse applications grow, direct recycling may become the most resource-efficient and cost-effective end-of-life strategy.

Here, Redwood Materials (US) is advancing direct recycling by refurbishing cathode materials from spent batteries to preserve quality and reduce processing energy

Redwood Materials (US) is pioneering the **direct recycling** of lithium-ion batteries as part of a vertically integrated circular supply chain. In contrast to elemental recovery, **Redwood (US)** focuses on **refurbishing cathode materials** through advanced cleaning and re-lithiation techniques, allowing them to be reintroduced into new batteries with minimal structural degradation. This preserves the **crystal morphology and electrochemical performance** of high-value materials like NMC and NCA and **significantly reduces processing energy** compared to traditional hydrometallurgical flows.

Redwood's operations combine collection, mechanical disassembly, materials recovery, and precursor synthesis in a closed-loop system. The company has secured partnerships with **Ford (US)** and **Panasonic (Japan)** to create **localized supply chains** for battery materials in North America. Redwood claims its Nevada-based facility will be capable of producing cathode and anode materials for **over 1 million EVs annually by 2025**. While direct recycling is still being scaled, Redwood's hybrid approach, blending elements of hydrometallurgy and direct reuse, sets a strong precedent for low-emission, high-circularity battery manufacturing. Its strategy exemplifies how **intelligent recycling**, backed by sensor data and process automation, can bridge sustainability with industrial scalability.

The battery industry continues to face critical technical risks, including fire hazards, raw material bottlenecks, and recycling limitations

Despite significant progress in manufacturing, electrification, and sustainability, the **battery industry continues to face critical technical risks** that threaten safety, scalability, and economic viability. These include **fire hazards, thermal instability, resource bottlenecks**, and the **technological inertia** of recycling systems that struggle to adapt to rapidly evolving chemistries. As demand for EVs grows, these risks are amplified across supply chains and usage environments, from high-power charging stations to harsh climate deployments and aging second-life applications. According to **UL Solutions**

(US), battery-related fire incidents increased in parallel with global EV uptake, underscoring the need for robust engineering and operational safeguards.

Simultaneously, challenges in the **sourcing and recovery of critical materials** such as lithium, cobalt, and nickel are becoming more pronounced, especially as demand projections outpace confirmed reserves and refinery capacity. These technical and geopolitical vulnerabilities limit the speed at which clean transportation goals can be met. Moreover, as battery formats and chemistries diversify, **legacy recycling infrastructure** becomes increasingly mismatched with new material flows, raising the risk of inefficiencies or environmental leakage. Addressing these interconnected risks requires a multipronged **strategy combining safety engineering, material innovation**, and **recycling agility.**

Thermal runaway and overheating remain primary safety risks, especially under fast-charging or extreme-use conditions

Thermal runaway remains one of the most dangerous and well-documented risks in lithium-ion battery systems, characterized by **a self-reinforcing chain reaction** triggered by internal short circuits, overcharging, or mechanical damage. Once initiated, the temperature rise accelerates the decomposition of electrolyte and separator layers, generating flammable gases and leading to combustion or explosion. This risk is particularly acute under **fast-charging, high-load**, or **abusive environmental conditions**, such as high temperatures or deep discharge cycles. Incidents like the Chevy Bolt battery recall and multiple e-scooter fires globally illustrate how even mature platforms remain susceptible.

Lithium-ion cells, especially high-energy-density formats like NCA and NMC, are especially prone to thermal instability due to their oxygen-releasing cathode structures. Solid electrolyte interface (SEI) breakdown, dendritic growth (in lithium-metal systems), and manufacturing defects (e.g., metal particles) are key contributors to thermal events. Regulatory bodies such as **UN 38.3, part of the United Nations Manual of Tests and Criteria, developed by the United Nations Economic and Social Council (ECOSOC)**, and **UL 9540A, a fire safety test method for evaluating thermal runaway and fire propagation risks in energy storage systems (ESS) that use lithium-ion batteries**, have introduced stringent testing and safety protocols, but physical protection alone cannot eliminate the risk. Therefore, **proactive thermal management and smart monitoring systems** are essential components of next-generation battery safety strategies.

Advancements in thermal management systems, such as liquid cooling and phase-change materials, are key to improving battery safety and stability

To counteract thermal runaway and overheating, battery developers are increasingly focusing on **advanced thermal management systems (TMS)** that stabilize temperature across cells and prevent local hot spots. Passive systems, including high-conductivity materials, flame-retardant additives, and pressure vents, are being combined with **active cooling methods**, such as **liquid-based heat exchangers, forced-air systems**, and emerging **phase-change materials (PCMs)** that absorb latent heat during transitions. These systems ensure uniform temperature distribution, enhance charging safety, and extend battery lifespan.

Liquid cooling, commonly deployed in high-performance EVs and commercial applications, offers superior thermal control compared to air-cooled systems, particularly during **DC fast-charging events exceeding 150 kW**. PCMs are gaining interest for their **zero-energy operation** and potential to delay runaway by absorbing spikes in heat flux without needing pumps or fans. Meanwhile, **AI-driven thermal models** are being integrated into battery management systems (BMS) to predict heat zones in real time and adjust operating conditions accordingly. As battery packs become denser and faster-charging, TMS will continue to play a pivotal role in achieving safe and stable electrification at scale.

The sector is under pressure to reduce dependence on critical materials like lithium, cobalt, and nickel due to supply constraints and ethical sourcing issues

The battery industry is under mounting pressure to reduce dependence on critical raw materials such as lithium, cobalt, and nickel due to their geopolitical concentration, supply volatility, and environmental and ethical sourcing challenges. **Cobalt**, largely sourced from the **Democratic Republic of Congo** under contested labour conditions, has been the primary target of elimination efforts. **Nickel**, while energy-dense, poses both environmental burdens during refining and risks of future price spikes as global demand surges. **Lithium**, though abundant, is subject to water-intensive extraction in **South America** and refining capacity constraints, particularly in **China**.

These concerns have prompted R&D efforts to develop low- or no-cobalt cathodes (e.g., LFP, LNMO) and to optimize recycling pathways that recover lithium and nickel more efficiently. Simultaneously, material substitution strategies are gaining momentum, focusing on sodium, sulphur, silicon, and organic-based chemistries.

OEMs and cell manufacturers are now integrating sustainability screening alongside performance testing when evaluating new materials. This shift reflects not only market risk mitigation but also increasing alignment with regulatory pressures such as the EU Critical Raw Materials Act and IRA domestic content incentives in the U.S.

Here, China's early deployment of sodium-ion batteries in grid storage and electric scooters highlights a strategic shift toward alternative chemistries that could reduce EVs' reliance on lithium and cobalt

China has taken a **first-mover position in deploying sodium-ion batteries** as part of a broader strategy to reduce dependence on lithium and cobalt while diversifying its domestic energy storage options. Sodium-ion cells, which substitute sodium for lithium in the electrolyte and cathode, offer **lower raw material costs, simplified sourcing**, and **strong thermal stability**, albeit at the expense of lower energy density. Their suitability for **stationary energy storage, two- and three-wheel vehicles**, and **low-range EVs** has made them attractive for large-scale deployment across China's rapidly urbanizing and electrifying regions.

By mid-2024, companies like **CATL (China)** and **HiNa Battery (China)** had begun commercial shipments of sodium-ion cells for **grid-scale storage, electric scooters**, and micro-EVs. The rapid deployment of these systems reflects not only technological readiness but also **government-backed industrial policy**, which favours supply chain resilience over peak energy density. China's progress signals a strategic pivot in battery diversification that could reverberate globally, especially in emerging markets where cost and safety take precedence over range.

CATL's (China) 2025 launch of its Naxtra sodium-ion battery series demonstrates rapid progress in commercializing next-gen chemistries with energy densities approaching those of mainstream lithium-ion cells

CATL (China), the world's largest battery manufacturer, is leading the **commercialization of sodium-ion technology** through its **Naxtra battery series**, with initial deployment targeted for 2025. CATL claims its second-generation sodium-ion cells achieve energy densities of **160 Wh/kg**, rivalling early lithium iron phosphate (LFP) batteries, and support fast-charging up to 80% in 15 minutes. The company is actively integrating these cells into **low-range EVs, urban mobility platforms**, and **grid storage systems**, including hybrid packs that combine sodium-ion and lithium-ion cells to balance energy and power density.

The **Naxtra** platform represents a significant milestone in validating sodium-ion's commercial potential and offers a **blueprint for global diversification** away from lithium. CATL has also emphasized its ability to **localize supply chains**, leveraging more abundant sodium and iron inputs, and has collaborated with OEMs such as **Chery Auto (China)** and **SAIC (China)** for vehicle integration. The success of CATL's deployment will likely influence global investment in alternative chemistries and could spark a wave of **regional sodium-ion innovation** as countries seek to buffer against lithium volatility.

Recycling methods must adapt to evolving battery designs and chemistries, requiring flexible and scalable systems that can process a diverse range of cell types

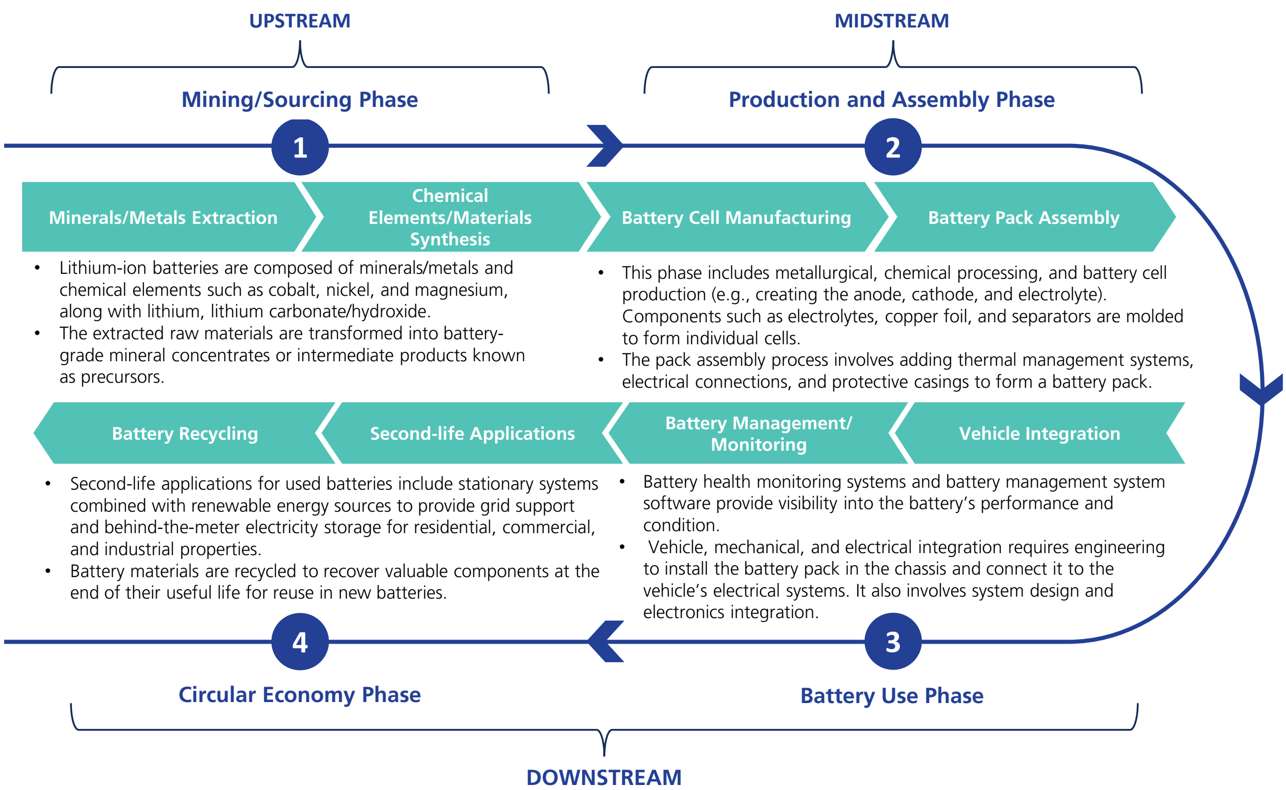
As battery technologies evolve toward **chemistry diversification, recyclers face a growing challenge**: legacy recycling systems, optimized for cobalt and nickel-rich lithium-ion chemistries, may be poorly suited to emerging formats such as **LFP, sodium-ion**, and **solid-state batteries**. For example, LFP cells contain less economically valuable material, making traditional pyrometallurgical approaches financially unattractive. Sodium-ion batteries introduce entirely new elemental profiles that may not fit current hydrometallurgical separation processes. Moreover, newer battery formats often lack standardized designs, increasing sorting complexity and contamination risk in recycling streams.

To address this, the industry must develop **flexible, chemistry-agnostic recycling technologies**, capable of adjusting leaching agents, separation flows, and recovery targets in real time. Innovations in **modular hydrometallurgy, AI-based battery identification**, and adaptive direct recycling are promising directions.

Additionally, regulatory frameworks should adapt to account for new chemistries in **eco-design rules, extended producer responsibility (EPR), and recovery efficiency targets**. A forward-compatible recycling infrastructure will be essential not only for sustainability but also for **resource security and industrial competitiveness** in a diversifying battery landscape.

After their automotive lifespan, EV batteries can be repurposed for second-life applications in stationary energy storage systems

EV battery supply chain flow chart



After completing their automotive lifespan, typically once battery State of Health (SoH) declines below **70–80%** of original capacity, EV batteries often retain sufficient functionality for less demanding, stationary energy storage applications. Rather than immediate recycling, these batteries can be repurposed into second-life systems, extending their utility for several additional years. Applications include **residential and commercial storage, microgrids, emergency backup, and grid-scale renewable integration**, where power and energy density demands are more flexible than in transport.

Second-life deployment contributes to both **economic and environmental sustainability** by delaying the resource- and energy-intensive recycling process, reducing electronic waste, and deferring the need for new battery production. This represents a key lever in building a circular battery ecosystem, where materials and energy are preserved as long as technically feasible before entering the recycling loop.

These batteries undergo testing, certification, and repackaging to ensure performance, safety, and suitability for grid or off-grid use

Before EV batteries can be deployed in second-life applications, they must undergo rigorous **testing, certification, and repackaging** to ensure they meet the performance, safety, and regulatory standards for stationary use. Key assessments include measuring **residual capacity, internal resistance, cycle life potential**, and **thermal behaviour** under various load conditions. Batteries that pass inspection are often **disassembled, resorted**, and repackaged into new modules with adapted **Battery Management Systems (BMS)** and housing designed for fixed installations.

Several certification frameworks, including **UL 1974 (USA)** and **IEC 62933-5-2 (International)**, provide guidelines for the safe and reliable reuse of lithium-ion batteries. Additionally, national standards **(e.g. VDE-AR-E 2510-50 in Germany)** are evolving to account for second-life deployment scenarios. Engineering challenges include ensuring **cell consistency, preventing thermal propagation, and updating software for different use conditions**.

These steps are critical to avoid safety incidents and ensure that second-life systems can integrate seamlessly with grid infrastructure or isolated energy systems. Advanced testing tools such as **Electrochemical Impedance Spectroscopy (EIS) and machine-learning-based SoH (State of Health) estimation** are increasingly being adopted to streamline the assessment process.

Second-life battery systems support renewable energy integration by balancing solar and wind fluctuations and providing backup storage

Second-life battery systems play a vital role in supporting the global transition to **intermittent renewable energy sources**, particularly **solar and wind**, which suffer from production volatility and misalignment with demand cycles. By acting as **energy buffers**, repurposed EV batteries can absorb excess electricity during peak generation periods and release it during shortfalls, thereby **smoothing power fluctuations, enhancing frequency regulation**, and reducing curtailment. In distributed applications, they also provide **off-grid reliability**, particularly in remote or disaster-prone regions.

As battery energy storage becomes increasingly important to grid decarbonization strategies, second-life systems offer a **cost-effective alternative** to new batteries, often at **30–70% of the cost per kWh**, depending on repackaging and integration needs. For grid operators, this creates new value streams such as **demand response, black start capability, and virtual power plants (VPPs)**. Several pilot projects across Europe, Japan, and the U.S. have already demonstrated the **technical viability and economic value** of second-life storage, particularly in renewable-heavy systems like microgrids, community solar, and commercial peak-shaving installations.

Here, A second-life project by Enel (Italy) and Nissan (Japan) repurposed used EV batteries into a 2.1 MWh storage system at Rome’s Fiumicino Airport, supporting solar energy integration and grid stability

A landmark example of second-life battery integration is the joint project between **Enel (Italy)** and **Nissan (Japan)**, which deployed a **2.1 MWh energy storage system at Rome’s Fiumicino Airport**. The system repurposes used Nissan LEAF battery packs to **store solar-generated electricity** and support **on-site grid stability**. It provides peak shaving during high-demand airport operations, helps balance renewable energy flow, and acts as an emergency backup during outages.

This project illustrates how second-life batteries can meet **real-world technical and regulatory requirements** while supporting sustainability and energy security goals in critical infrastructure settings. It also serves as a model of cross-industry collaboration, combining vehicle OEMs' expertise in battery lifecycle management with utilities' knowledge of grid integration. The successful operation of the Fiumicino project demonstrates the feasibility of second-life storage at scale and opens pathways for **decentralized renewable integration** in urban and industrial settings.

Furthermore, repurposing used batteries reduces waste, delays recycling demand, and enhances grid stability through affordable energy storage solutions

Repurposing EV batteries for second-life applications offers **multiple system-level benefits.** First, it helps **delay the influx of large-format batteries into recycling facilities**, easing pressure on immature recycling infrastructure and providing time for technological improvements in recovery methods. Second, it supports **waste minimization** by extracting additional utility from batteries that would otherwise be prematurely discarded. This extends material lifespans, reduces embedded emissions per functional kWh, and supports the circular economy.

Economically, second-life systems offer **lower capital costs** than newly manufactured batteries, making them attractive for **low-margin applications, community microgrids**, or **small- to mid-scale commercial installations**. Their reduced cost per cycle, particularly when integrated into existing renewable systems, allows for **faster payback periods** and improved energy access. Finally, second-life deployments improve **grid resilience** by decentralizing storage capacity and enabling local balancing services, a crucial factor as grids adapt to distributed and variable generation.

Here, Jaguar Land Rover's (UK) partnership with Allye Energy (UK) created a mobile second-life storage unit from Range Rover PHEV batteries, offering clean, portable power as an alternative to diesel generators

A compelling example of mobile second-life storage is the collaboration between Jaguar Land Rover (UK) and Allye Energy (UK), which repurposed Range Rover PHEV battery packs into a clean, portable power unit. Designed as a drop-in alternative to diesel generators, this solution targets construction sites, outdoor events, and temporary installations that require emissions-free and noise-free electricity supply. The units are containerized, modular, and equipped with smart BMS and IoT monitoring systems, ensuring operational safety and energy efficiency.

This project exemplifies the modular and mobile potential of second-life storage, highlighting how retired EV batteries can serve non-grid-tied applications with demanding performance requirements. It also supports broader UK goals under the Net Zero Strategy by replacing fossil-fuel-based equipment with electrified alternatives.

Importantly, Jaguar Land Rover's involvement demonstrates how OEMs are beginning to internalize end-of-life value chains, using second-life systems not only for sustainability compliance but also for new revenue opportunities in decentralized energy.

EVYON

COMPANY OVERVIEW

Industry Segment:
Sustainability factors, technical challenges and second life applications

Brief Description:
Evyon provides stationery battery solutions by repurposing high quality automotive batteries for multiple energy storage applications.

Maturity:
On the market

Website:
https://www.evyon.com

Multimedia:
https://www.youtube.com/watch?v=aSukhnUI-00

COMPANY STRUCTURE

FOUNDED: **2020**

COUNTRY: **NORWAY**

OF EMPLOYEES: **20 – 50**

TOTAL FUNDING: **$16.3M**

PRODUCT OVERVIEW

Technology Focus

- Evyon develops and commercializes stationery battery systems converting EV batteries into second-life energy storage systems. It is a combined hardware-software platform including battery control units and a cloud ecosystem.
- The battery control unit manages the daily operations and it is the bridge to the cloud ecosystem to which all installed units are connected, allowing constant learning with the aim of maximizing batteries lifetime value.
- The cloud ecosystem also allows constant monitoring, trends and anomalies identification while also being the means for over-the-air updates of battery systems. Units are also provided with a proprietary fire-suppression system preventing fire propagation.

Main Competitive Advantage

Evyon has developed a battery storage platform combining a cloud ecosystem for monitoring and intelligence with batteries coming from the automotive sector. The company is currently working with high quality batteries, partnering with Mercedes-Benz Energy, but the platform is adaptable to different models and technologies. The solutions are suitable to meet the needs of both commercial and industrial applications, EV charging, construction sites and backup power units. Evyon solutions, through repurposing, reduce the carbon footprint of deploying battery systems by up to 85% compared to new systems.

Value Proposition

- Evyon is committed to maximizing the lifetime value of EV batteries by exploiting them as second-life energy storage solutions meeting the rising demand for energy storage.
- The company intends to provide energy storage systems that are sustainable from both a financial and an environmental point of view.

REBABA

COMPANY OVERVIEW

Industry Segment:
Sustainability factors, technical challenges and second life applications

Brief Description:
Rebaba repurposes end-of-life automotive batteries into circular energy systems for commercial and industrial use, supporting load shifting, peak shaving and grid services.

Maturity:
On the market

Website:
https://rebaba.se

Multimedia:
N.A.

COMPANY STRUCTURE

FOUNDED: **2023**

COUNTRY: **SWEDEN**

OF EMPLOYEES: **2 – 10**

TOTAL FUNDING: **N.A.**

PRODUCT OVERVIEW

Technology Focus

- Rebaba has developed a modular, scalable and compact system for EV battery repurposing by approaching used vehicle batteries as multiple-use assets and promoting their circularity.
- Rebaba manufactures two systems, a compact one ranging 40-400 kWh, available for indoor/outdoor applications and a containerized one for industrial and utility applications, designed for outdoor installation and featuring specific environmental protections, offering 360 - 720 kWh and flexible load voltage options (400 V - 30 kV).
- The company solutions incorporate a smart monitoring function to maximize uptime and offer optimized charge and discharge patterns.

Main Competitive Advantage

Rebaba has developed a circular energy storage system for commercial properties, industries and charge-point operators that aims at providing backup power, resilience and reducing operating costs for energy-intensive infrastructures. The solution allows to turn energy infrastructure into revenue-generating assets by leveraging Battery Energy Storage System – BESS to participate in frequency regulation and grid services. Rebaba's system also helps cut operational costs thanks to the modular design allowing easy upgrades, replacements, maintenance, real time monitoring and optimization. The company solutions are provided via two possible business models: direct purchase to own and operate or as a hands-off service.

Value Proposition

- Rebaba is committed to providing the energy sector with a sustainable and efficient storage alternative, while ensuring the full traceability of its supply chain and compliance with ESG directives.
- The company aims to make circular Battery Energy Storage System - BESS - a more widely adopted solution to minimize environmental impact of EV batteries while enabling cost and efficiency improvements to the grid.

BROKKR MINERAL RESOURCES

COMPANY OVERVIEW

Industry Segment:
Sustainability factors, technical challenges and second life applications

Brief Description:
Brokkr Mineral Resources uses a nature-based, sustainable process exploiting electrogenic bacteria to extract battery-grade nickel, cobalt and manganese from lateritic deposits.

Maturity:
Under development

Website:
https://www.brokkrresources.com

Multimedia:
N.A.

COMPANY STRUCTURE

FOUNDED: **2020**

COUNTRY: **CANADA**

OF EMPLOYEES: **2 – 10**

TOTAL FUNDING: **$0,799M**

PRODUCT OVERVIEW

Technology Focus

- Brokkr developed and patented a bio-chemical processing technology that eliminates 99% of GHG emissions associated with the processing and refining of nickel, cobalt and manganese, enabling a clean and direct supply chain for the battery and EV industry, eliminating the need for intermediate product shipping and refining.
- Brokkr's three-stage process uses electrogenic bacteria to bioleach lateritic deposits, dissolving nickel, cobalt and manganese into a solution.
- The target metals are then separated into battery-grade sulfates, while water and reagents are continuously recycled. The process also yields cement additives and iron-rich by-products.

Main Competitive Advantage

Brokkr has developed a low-capex, modular and nature-based mineral processing technology that enables on-site extraction and refining of materials for batteries from laterite deposits. The system produces battery-grade NCM (nickel, cobalt, manganese) sulfates directly at the deposit site. This approach drastically reduces environmental impact compared to conventional methods, cutting CO_2 emissions by ten times and eliminating hazardous tailings. By removing the need for costly, centralized facilities and intermediate shipping or refining steps, the technology shortens the supply chain for lithium-ion cathode active materials, lowering infrastructure investment and unlocking the potential of smaller laterite resources.

Value Proposition

- Brokkr aims at providing solutions for the processing of strategic metals for EV batteries production found in complex ore bodies and low-grade deposits.
- The company aims to provide an alternative that minimizes environmental impact, improving the industry's ESG performance and reducing dependence on geopolitically complex areas.

Source: Crunchbase, BROKKR MINERAL RESOURCES

CARRAR

COMPANY OVERVIEW

Industry Segment:
Sustainability factors, technical challenges and second life applications

Brief Description:
Carrar has developed a two-phase immersion cooling system to improve battery safety by controlling temperature spikes and dissipating heat, allowing to extend battery life and range.

Maturity:
On the market

Website:
https://www.carrar.net

Multimedia:
https://www.youtube.com/watch?v=Yt6YtvvnmNo

COMPANY STRUCTURE

FOUNDED: **2019**

COUNTRY: **ISRAEL**

OF EMPLOYEES: **20 – 50**

TOTAL FUNDING: **$5.3M**

PRODUCT OVERVIEW

Technology Focus

- Carrar manufactures battery systems for vehicles combining cooling units and a software to optimize temperature control across battery components with different heat dissipation needs.
- The company solution employs a two-phase immersion cooling system, allowing thermal management via on-chip cooling that exploits latent heat from liquid vaporization.
- Carrar Thermal Management System - TMS allows energy-efficient heat dissipation also by adapting the system to external weather and charging factors. In addition, it optimizes cell behavior by adjusting internal pressure through a patented software algorithm. This allows maintaining temperatures in the 25-27 °C range.

Main Competitive Advantage

Carrar produces battery systems for passenger and commercial vehicles that increase driving range by at least 7% per charge while achieving the performance of conventional packs with 10% less battery cells, thus lowering the system weight. This is achieved through the combination of heat-dissipation and temperature control technologies and a patented algorithm. The solution enhances vehicle safety by preventing thermal propagation, runaways and fires. Carrar systems allows for ultra-fast charging without the typically associated degradation effects and it extends batteries lifetime compared to conventional units. It ensures compatibility with multiple battery architecture, chemistry, density and current.

Value Proposition

- The company aims at enabling consumers to get more value from cars and supporting a greener EV batteries economy by providing systems with ultra-fast charging and over 1.5 million kilometers lifespan.
- Carrar intends to contribute to the decarbonization mobility allowing access to increasingly safe and efficient battery systems for EVs.

TOZERO

COMPANY OVERVIEW

Industry Segment:
Sustainability factors, technical challenges and second life applications

Brief Description:
Tozero recovers critical raw materials from end-of-life lithium batteries through a low-emission hydrometallurgical process.

Maturity:
On the market

Website:
https://www.tozero.solutions

Multimedia:
https://www.youtube.com/watch?v=b-NqmiUDy5E

COMPANY STRUCTURE

FOUNDED: **2022**

COUNTRY: **GERMANY**

OF EMPLOYEES: **20 – 50**

TOTAL FUNDING: **€17M**

PRODUCT OVERVIEW

Technology Focus

- Tozero recycles lithium batteries to extract valuable materials like lithium and cobalt, making them reusable in new battery production. Tozero adopts a hydrometallurgical recycling technology to recover lithium, nickel, cobalt, manganese and graphite from end-of-life batteries, with reduced energy and chemical consumption.
- The technology enables the production of secondary raw materials with purity levels up to 99.5%, suitable for direct use in industrial cell manufacturing processes.
- The process is designed to separate individual chemical components: recovered metals are sorted by type, while graphite is processed separately and reintegrated into the value chain. Digital tracking also ensures verification of the origin, purity, quantity and destination of the recovered materials.

Main Competitive Advantage

Tozero has developed a hydrometallurgical process to recover critical raw materials from end-of-life lithium batteries. Its proprietary technology reduces environmental impact, ensures high recovery rates and delivers high-purity materials ready for industrial use. Tozero's recycling process extracts lithium, nickel, cobalt, manganese and graphite with low energy and chemicals consumption, reducing emissions by up to 80% compared to conventional methods. The process is compatible with multiple battery types and enables the recovery of materials with purity levels suitable for reintegration into industrial production chains.

Value Proposition

- Tozero is on a mission to support European autonomy in the supply chain of lithium and other critical materials by turning end-of-life batteries into high-quality industrial resources.
- The company aims to address the growing demand in the battery sector and contribute to the decarbonization of the battery industry by reducing CO_2 emissions.

Source: Crunchbase, TOZERO

AUTOMOTIVE CELLS COMPANY

COMPANY OVERVIEW

Industry Segment:
Sustainability factors, technical challenges and second life applications

Brief Description:
Automotive Cells Company develops high-performance lithium-ion batteries for electric vehicles.

Maturity:
On the market

Website:
https://www.acc-emotion.com

Multimedia:
https://www.youtube.com/watch?v=G_AzH4q-GzQ

COMPANY STRUCTURE

FOUNDED: **2020**

COUNTRY: **FRANCE**

OF EMPLOYEES: **1500 – 2000**

TOTAL FUNDING: **$4740M**

PRODUCT OVERVIEW

Technology Focus

- The company develops lithium-ion cells based on Nickel-Cobalt-Manganese – NCM chemistry, optimized to combine range, power and thermal stability and specifically designed for next-generation electric vehicles.
- Automotive Cells Company's batteries support fast charging, enable operations across a wide range of temperatures and ensure high reliability and long lifespan.
- Each cell is equipped with a digital identifier to ensure full traceability, from raw materials to final assembly.

Main Competitive Advantage

Automotive Cells Company develops and commercializes high-energy-density battery cells and modules offering advanced performance in terms of range, power and safety. The battery systems are designed to enable fast charging, reduce weight and volume and reduce the carbon footprint by 50% compared to current models. This is achieved using materials with low environmental impact and localized European supply chains. Battery modules are designed to be adaptable to a wide range of electric vehicle architectures, offering customizable configurations for voltage and capacity.

Value Proposition

- Automotive Cells Company provides strategic production capacity for battery cells within Europe, reducing import dependency and reinforcing supply chain resilience.
- The company aims to reduce the environmental impact of battery production. Its processes target a 50% reduction in carbon footprint and reduced use of cobalt and nickel. The cells are recyclable and the energy used in manufacturing comes from renewable sources.

LIONVOLT

COMPANY OVERVIEW

Industry Segment:
Sustainability factors, technical challenges and second life applications

Brief Description:
LionVolt is developing lightweight batteries using 3D lithium-metal technology and roll-to-roll production.

Maturity:
Under development

Website:
https://lionvolt.com

Multimedia:
https://www.youtube.com/watch?v=i0oDJXB45dc

COMPANY STRUCTURE

FOUNDED: **2022**

COUNTRY: **GERMANY**

OF EMPLOYEES: **20 – 50**

TOTAL FUNDING: **€17M**

PRODUCT OVERVIEW

Technology Focus

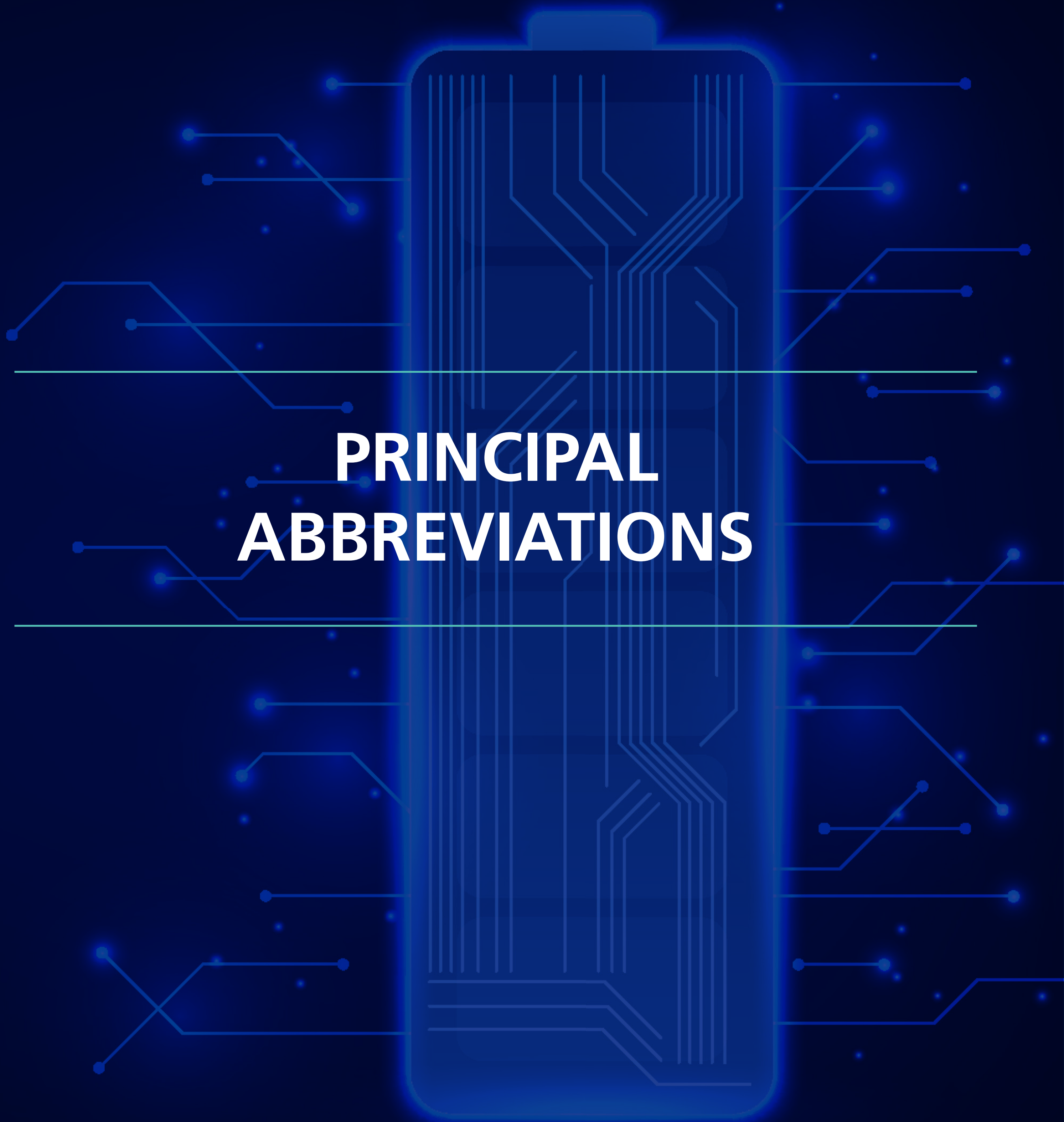
- LionVolt uses a three-dimensional design for a key battery component, the anode, made of lithium metal. This increases the energy the battery can store and enhances overall performance.
- The cell design is free of flammable liquid electrolytes, making the batteries inherently safe, heat-resistant and less vulnerable to thermal instability.
- The batteries are manufactured using a process called roll-to-roll, similar to an industrial printer. This manufacturing method is scalable and optimized for cost-efficiency in industrial-scale production environments.

Main Competitive Advantage

LionVolt is developing safe, fast-charging and lightweight batteries using 3D lithium-metal technology. The solution eliminates the use of flammable liquid electrolytes and supports ultra-fast charging, delivering high performance and enhanced safety. Compared to traditional batteries, LionVolt's cells last longer, weigh less and recharge more quickly. The technology is compatible with various battery chemistries, including lithium-ion, sodium-ion and future solid-state systems. The company manufactures its batteries in Europe through low-impact processes, avoiding the use of critical or hazardous materials.

Value Proposition

- LionVolt aims to reduce the inherent safety risks of conventional lithium-ion batteries by eliminating flammable liquid electrolytes.
- The company is committed to developing a manufacturing process that enables minimizing environmental impact, reducing reliance on hazardous components.
- LionVolt is on a mission to support European strategic autonomy in energy storage technologies.



PRINCIPAL ABBREVIATIONS

AI	*Artificial Intelligence*
°C	*degrees Celsius*
3D	*3 dimensions*
BMS	*Battery management systems*
BESS	*Battery energy management system*
CBAM	*Carbon Border Adjustment Mechanism*
CO_2	*Carbon Dioxide*
DBP	*Digital Battery Passport*
DfD	*Design for disassembly*
DPP	*Digital Product Passport*
ECOSOC	*United Nations Economic and Social Council*
EIS	*Electrochemical Impedance Spectroscopy*
EoL	*End-of-Life*
ESG	*Environmental, Social, and Governance*
ESS	*Energy storage system*
EU	*European Union*
EV	*Electronic vehicle*
GBA	*Global Battery Alliance*
GDPR	*General Data Protection Regulation*
GHG	*Greenhouse gases*
GWh	*Gigawatt-hour*
ICE	*Internal combustion engine*
IEA	*International Energy Agency*
IoT	*Internet of Thing*
IRA	*Inflation Reduction Act*
Km	*Kilometres*
kV	*Kilovolt*
KWh	*Kilowatt-hour*
LCA	*Lifecycle assessments*
LFP	*Lithium Iron Phosphate*
Li-ion	*Lithium-ion*
Li-S	*Lithium- Sulphur*
LMT	*Light transport vehicles*
M	*Million*
ML	*Machine Learning*
MWh	*Megawatt-hour*
NCA	*Nickel Cobalt Aluminium*
NMC	*Nickel Manganese Cobalt*
OEMs	*Original Equipment Manufacturers*
PCM	*Phase-change materials*
PHEV	*Plug-in Hybrid Electric Vehicle*
PPAs	*Power purchase agreements*
QR	*Quick Response*
RBSs	*Redox flow batteries*
SEI	*Solid electrolyte interphase*
SSBs	*Solid-state batteries*
TCO	*Total cost of ownership*
TMS	*Thermal management systems*
TPA	*Tons per annum*
UK	*United Kingdom*
UN	*United Nations*
UNECE	*United Nations Economic Commission for Europe Regulation*
US	*United states*
V	*Volt*
V2G	*Vehicle-to-Grid*
Wh/kg	*Watt-hour per kilogram*
ZEVs	*Zero-emissions vehicles*

Source: Frost & Sullivan

ABOUT INTESA SANPAOLO INNOVATION CENTER:

Intesa Sanpaolo Innovation Center is the company of Intesa Sanpaolo Group dedicated to innovation: it explores and learns new business and research models and acts as a stimulus and engine for the new economy in Italy. The company invests in applied research projects and high potential start-ups, to foster the competitiveness of the Group and its customers and accelerate the development of the circular economy in Italy.

Based in the Turin skyscraper designed by Renzo Piano, with its national and international network of hubs and laboratories, the Innovation Center is an enabler of relations with other stakeholders of the innovation ecosystem - such as tech companies, start-ups, incubators, research centres and universities - and a promoter of new forms of entrepreneurship in accessing venture capital. Intesa Sanpaolo Innovation Center focuses mainly on circular economy, development of the most promising start-ups, venture capital investments of the management company Neva SGR and applied research

For further detail on Intesa Sanpaolo Innovation Center products and services, please contact
businessdevelopment@intesasanpaoloinnovationcenter.com

ABOUT FROST & SULLIVAN:

For over five decades, Frost & Sullivan has become world-renowned for its role in helping investors, corporate leaders and governments navigate economic changes and identify disruptive technologies, Mega Trends, new business models and companies to action, resulting in a continuous flow of growth opportunities to drive future success.

For further details on Frost & Sullivan's coverage and services, please contact

LIVIO VANINETTI
Director of Frost & Sullivan's Italian operations;
livio.vaninetti@frost.com

Published: September 2025

MOST
CENTRO NAZIONALE PER LA MOBILITÀ SOSTENIBILE

This work has been supported under the National Recovery and Resilience Plan (NRRP), Mission 4 Component 2 Investment 1.4 - Call for tender No. 3138 of December 16, 2021 of the Italian Ministry of University and Research, funded by the European Union - NextGenerationEU [Award Number: CNMS named MOST, Concession Decree No. 1033 of June 17, 2022, adopted by the Italian Ministry of University and Research, CUP: B13D21011590004, Spoke 14 "Hydrogen and New Fuels"]