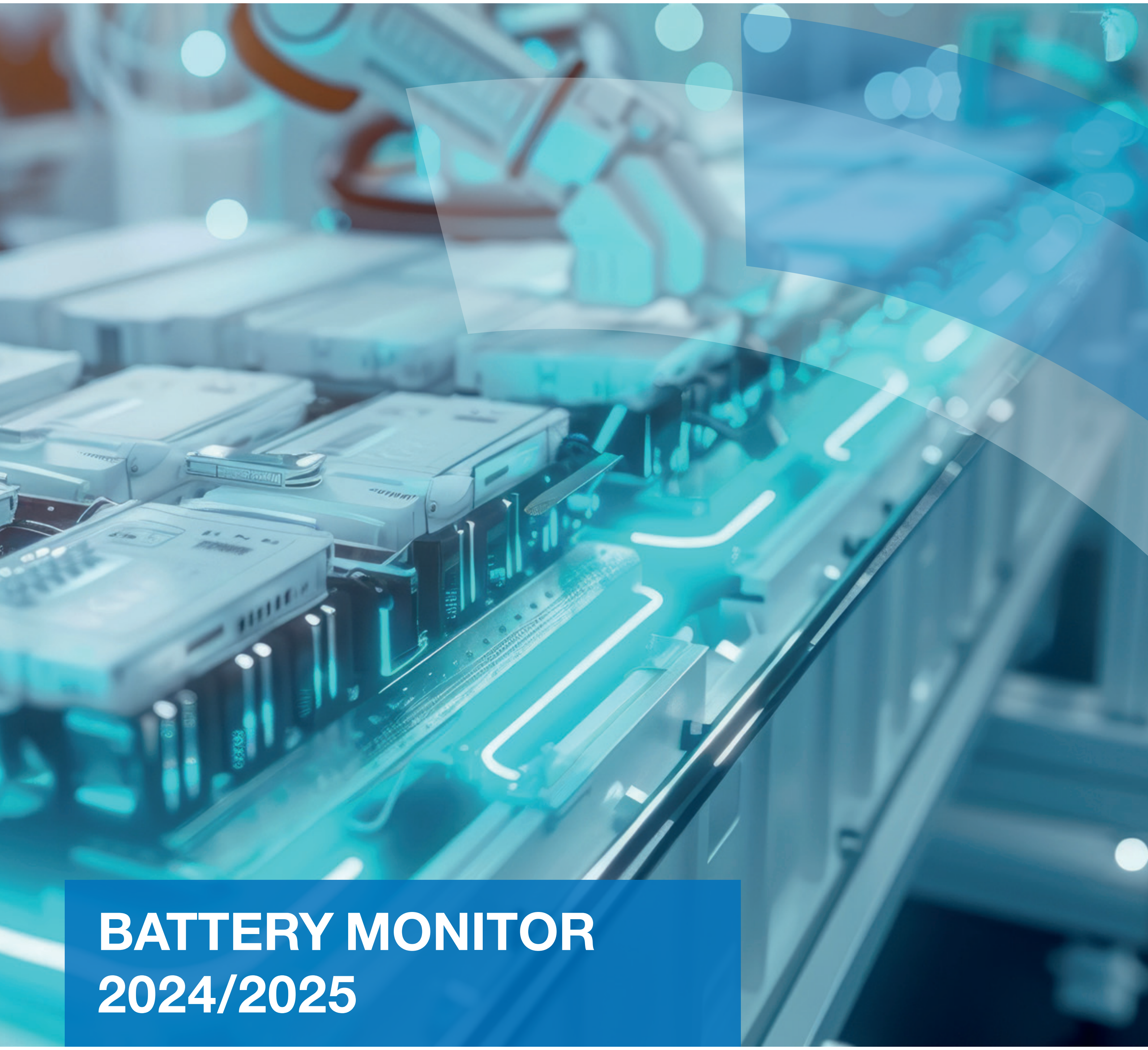


BATTERY MONITOR 2024/2025

THE VALUE CHAIN BETWEEN ECONOMY AND ECOLOGY

PEM | RWTH AACHEN UNIVERSITY

Roland Berger




Dear readers,

No world market is as dynamic as the battery industry currently: On the one hand, there is huge technological potential, the impact of which can only be guessed at so far; on the other hand, there are financial and political uncertainties that are causing massive short-term changes on the world stage. What was just recently considered a future market where it is almost impossible to go wrong has now become a tactical undertaking where each and every step needs to be carefully considered. Euphoria has given way to reality. Fundamental challenges are dominating events.

World trade is currently characterized by an unmistakable trend towards protectionism. The election of Donald Trump as the next President of the United States of America is causing quite some speculation and uncertainty. For example, there is even greater customs pressure on German automakers, as Trump has already indicated that his country should no longer be importing cars, but German and other major OEMs should produce in the United States instead. Meanwhile, the European Union has already imposed tariffs on electric vehicles from China – while Chinese manufacturers are making great efforts to penetrate the markets in Europe and the USA.

The tense economic situation throughout the EU is coming to a head in Germany. Several carmakers are faltering or already in the throes of a full-blown crisis as record production of electric vehicles is met with weak demand. The result? Overproduction of electric cars, announced factory closures, looming strikes by the workforce. Elsewhere, big-name battery manufacturers are experiencing a major disappointment as they have to cut back or even face serious financial difficulties. Factory projects that were once considered safe are now being put on hold or even withdrawn altogether.

Amid this mixed situation, we are proud to present the fourth issue of the "Battery Monitor," in which a team of authors from Roland Berger and PEM RWTH Aachen University analyzes the market in all its facets – be it the raw materials needed for manufacturing, or battery cell production, product performance, battery use, recycling, and battery reuse. Despite the global uncertainties – or perhaps because of them – we hope you find this report a useful read!

Prof. Dr.
Achim Kampker
Founder and head of the chair
PEM of RWTH Aachen University

Prof. Dr.
Heiner Hans Heimes
Member of Institute Management
PEM of RWTH Aachen University

Wolfgang Bernhart
Senior Partner
Roland Berger GmbH

Isaac Chan
Partner
Roland Berger GmbH

Heiner Heimes, Achim Kampker, Wolfgang Bernhart, Isaac Chan

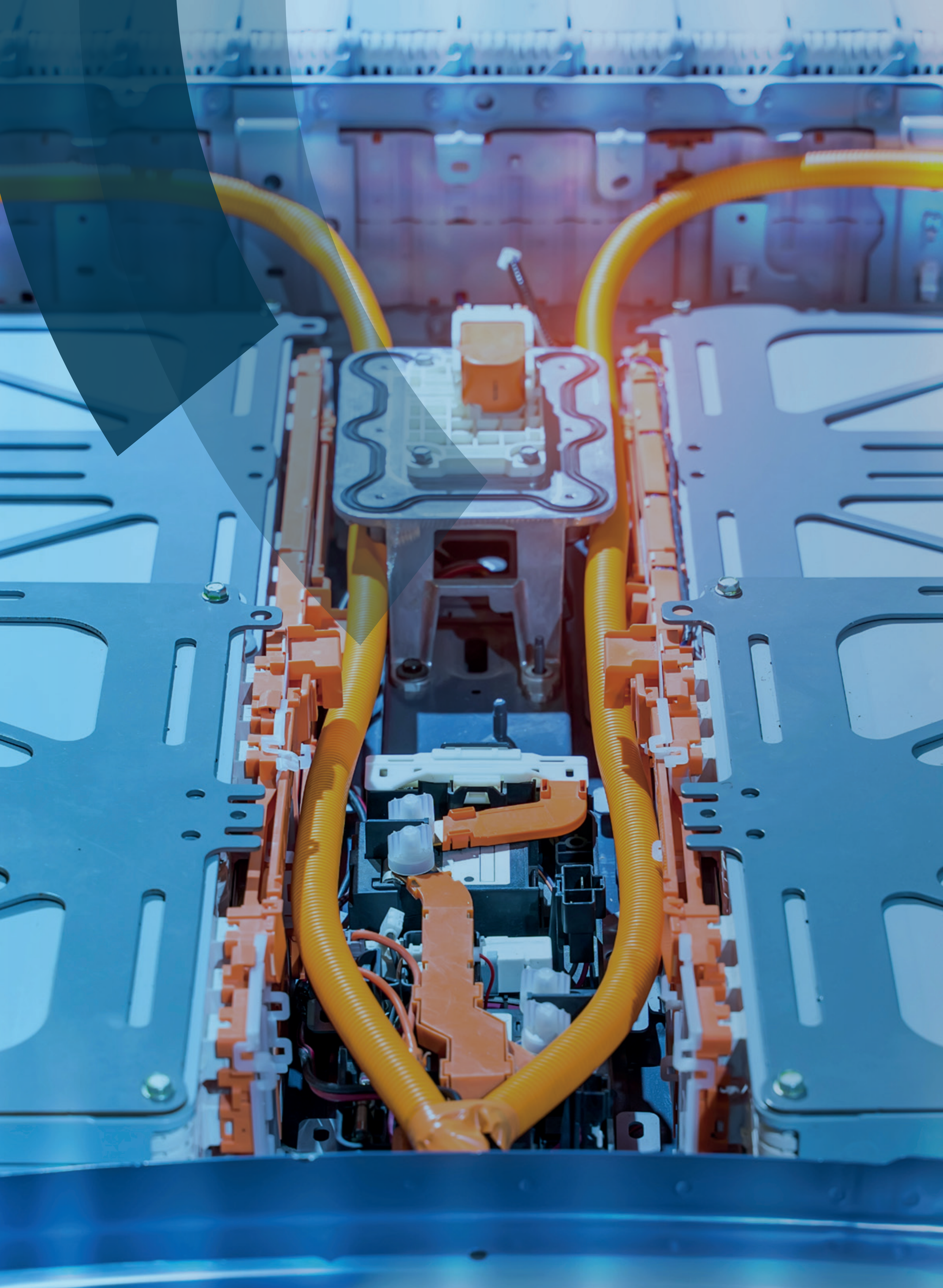
FOREWORD & INTRODUCTION

The battery industry has undergone significant turbulence over the past year, marked by volatile demand and escalating challenges as industrialization and ramp-up efforts accelerate in Europe and North America. For many new entrants, the anticipated production ramp-up has proven to be fraught with difficulties, exacerbated by uncertainties regarding electric vehicle (EV) market penetration. This has resulted in a demanding landscape for the industry as a whole. Furthermore, the production capacity of Chinese battery manufacturers has exceeded local demand, placing additional pressure on Western markets while simultaneously showcasing advanced technological capabilities.

To illuminate the most pressing challenges and transformative changes within the battery landscape, this report is structured along the battery value chain, consistent with previous editions. We aim to address the following key points:

- **Overarching Market View:** We will provide insights into forecasting the substantial EV demand and the various scenarios that must be considered. We will analyze how the competitive landscape is evolving and identify the technologies necessary for success in a market in which cost competitiveness is more crucial than ever.
- **Battery Materials:** This chapter will focus on recent changes in cell chemistries, particularly those designed for the EV segment, which are significantly reshaping the industry and the OEMs' planning. How can newly introduced cell chemistries like LMFP be leveraged and what new nickel-based chemistries need to be investigated?
- **Battery Production:** The chapter emphasizes the challenges associated with production ramp-up and explores how sustainability can be addressed amid growing competition. We will investigate the persistent challenges to achieving production goals in Europe.
- **Product Performance:** What are the drivers of further EV adoption and what challenges remain? We will assess whether these challenges can be effectively addressed through advancements in battery cell and system design, and if so, how.
- **Battery Usage:** This chapter will provide insights into the energy sector's response to the increasing demand for EVs. We will evaluate whether the energy transition is on track to support a sustainable transportation paradigm and analyze the impact of grid mix on overall CO_2 emissions, as well as the evolution of the charging sector.
- **Circular Battery Economy:** Renamed since previous editions to be more comprehensive, this chapter will address topics related to battery recycling, reuse, and refurbishment. We will explore how the EU Battery Regulation influences the circular economy approach for batteries and identify the challenges that persist for Re-X approaches, alongside major developments in this area.

As in previous editions of the Battery Monitor, this report will encompass a comprehensive analysis of sustainability, technology, competitiveness, and innovation throughout the battery value chain. Each chapter will be prefaced with a brief summary and strategic implications, providing a holistic view of the industry's current state and future directions.



Isaac Chan, Tim Hotz, Kyle Gordon, Konstantin Knoche

OVERARCHING MARKET VIEW

GIVEN THE CURRENT ECONOMIC CLIMATE AND EV MARKET STATUS, REDUCING COSTS IS CURRENTLY THE DOMINANT THEME IN THE BATTERY MARKET. DUE TO STRUCTURAL OVERCAPACITY IN CHINA AND PROFITABILITY CHALLENGES FACING AUTOMOTIVE OEMS, COST REMAINS KING IN THE BATTERY VALUE CHAIN.

Sustainability: European CO_2 reduction targets are achievable through combinations of cell production and value chain optimization levers, such as using 100% renewables and sourcing from low-CO_2 mining and refining operations, as well as increased use of recycled materials.

Technology performance: Developments are centered around balancing costs against performance, with a clear focus on cost. Cheap but lower energy-density lithium iron phosphate (LFP) based technologies are a focus for volume EV segments, with demand set to increase significantly by 2030.

Competitiveness: The volatile market and cheap Chinese battery and EV imports (due to Chinese overcapacity) are forcing the EU and US to take protective measures. But both must also adapt their production to remain competitive.

Innovation: The promising innovations that could shape the market by 2030 include lower-cost cathode chemistries (especially advanced LFP, LMFP), silicon anode materials, dry coating and cell-to-pack technologies.

STRATEGIC IMPLICATIONS

For regulators

The European electric vehicle (EV) and battery industry faces significant risks from inexpensive imports from China. While trade barriers, such as the recently imposed additional import tariffs on Chinese EV imports, may provide temporary relief, they are unlikely to serve as a long-term solution for ensuring competitiveness. Moreover, these measures could escalate into a tariff war that would adversely affect automotive players reliant on sales in China. Instead, the industry is advocating for local incentives on capital expenditures (CAPEX) and operational expenditures (OPEX), similar to those in the US and China.

For cell manufacturers

Cell producers are currently facing significantly lower plant utilization than initially anticipated, primarily due to decreased demand from original equipment manufacturers (OEMs). This challenging situation necessitates a thorough reevaluation of previous expansion plans in order to mitigate investment risks. To remain competitive, it is crucial for these producers to integrate recent advancements in cell chemistry into their production roadmaps, ensuring timely implementation. In particular, the development of chemistries tailored for entry-level and mid-range segments is essential, as reliance solely on high-nickel NMC for premium segments will not be sufficient. Furthermore, the establishment of resilient value chains is imperative to facilitate the flexible adoption of new cell chemistries, especially as innovations targeting the EV volume segment continue to evolve.

For automotive OEMs

To compete effectively with Chinese imports, Western OEMs must achieve significant cost reductions or they will require sustained gov-

ernment support. This can be accomplished through strategies such as adapting cell chemistry and optimizing pack design, including cell-to-pack configurations, along with improving research and development efficiency and shortening development timelines.
Moreover, OEMs need the courage to embrace new technologies, as many are hesitant to adopt advancements that have already been quickly integrated by Chinese manufacturers. Bold investments in key differentiating technologies and the timely introduction of these innovations are essential. Additionally, utilizing off-the-shelf solutions from leading players with unique technological advantages may be necessary to maintain competitiveness in this rapidly evolving market.

For investors

In today's volatile demand environment, secured offtakes are crucial for investors navigating market complexities. To remain competitive, investments must be supported by a strong low-cost position on the part of the investment target and be suitable for flexible technologies that allow adaptability to changing conditions.
Investment targets should also emphasize robustness in their supply chain strategies, especially given the uncertain geopolitical landscape that is affecting market stability. Moreover, any technology aimed at the automotive volume segment must be cost-competitive; otherwise, even those with significant advantages may only succeed in niche markets.

SUSTAINABILITY

With costs across the battery value chain rising in 2023, sustainability fell down the list of priorities for customers and producers. The industry in Europe is still striving to meet sustainability targets, particularly long-term carbon emissions goals. Measures will continue to be implemented with a focus on regulatory compliance, but costs shouldn't be significantly affected as sustainability is seen as more of a hygiene factor from an OEM and end-consumer perspective.

CARBON FOOTPRINT: REDUCTION TARGETS ARE ACHIEVABLE USING COMBINATIONS OF EXISTING LEVERS

The EU Battery Directive requires producers to make CO_2 footprint declarations and gradually increase the proportion of recycled content in each battery over the coming years, as outlined

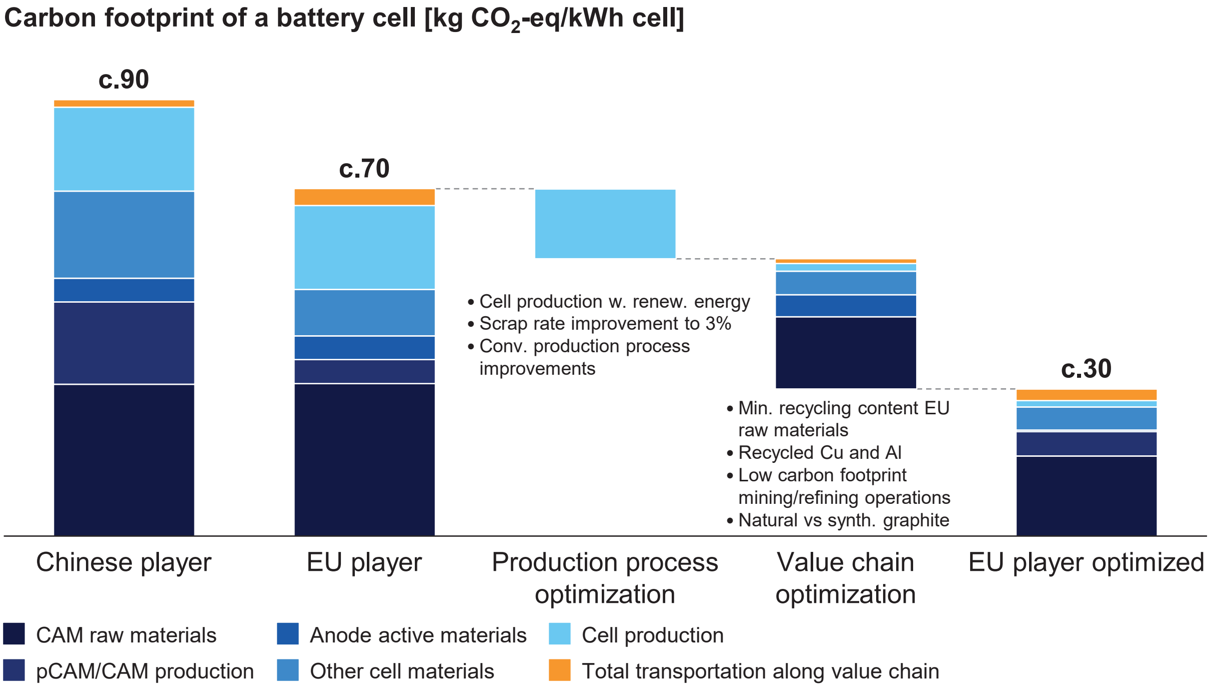


Figure 1: Carbon footprint comparison and optimization [kg CO_2-eq/kWh];
Source: Roland Berger LiB cell carbon footprint model

in Battery Monitor 2023. Lithium-ion (Li-ion) batteries produced in the European Union (EU) currently have an average carbon footprint of around 69 kg CO_2-equivalent per kilowatt hour, while China's reference figure is around 87 kg CO_2-eq/kWh. The range is wide, however, with some Chinese factories certified as net zero – the 87 kg CO_2-eq/kWh is based on a Chinese reference scenario with typical Chinese value chains underlying it. EU players aim to reduce the figure to 30-40 kg CO_2-eq/kWh and regulators are driving this reduction. But the proposed calculation methods as shown in the current draft of the Annex to the Commission Delegated Regulation supplementing Regulation (EU) 2023/1542 use an old definition of renewable energy. Industry representatives suggest employing different calculation methods akin to those outlined for producing "Green Hydrogen" under the RED III delegated acts. These methods focus on criteria such as additionality, and temporal and spatial correlation, which require a physical link between the renewable energy source and the plant.

Achieving the footprint target will require a shake-up of the entire battery value chain, from mining to cell production. Our analysis shows that there are several combinations of viable reduction levers that can result in footprint savings. If implemented together, these could ensure the target is met. They include:

1. **Cell production:** Using 100% renewable energy, reducing energy consumption by 30% and improving scrap rates to levels found in China (around 2-3%) could reduce the footprint by 14 kg CO_2-eq/kWh. However, strong interdependencies exist; for example, a lower-carbon grid mix as a basis will change the saving potential and a low-carbon value chain will lower the scrap impact.
2. **Value chain optimization – improved raw material sourcing:** Meeting minimum EU recycled-content requirements (6% lithium, 6% nickel, 16% cobalt by 2027), as well as using recycled aluminum and copper, natural graphite, and sourcing from local low-carbon mining/refining operations, can decrease the footprint by around 26 kg CO_2-eq/kWh (when used with an improved production process).
3. **Value chain optimization for pCAM/CAM – low-carbon grid:** Shifting energy-intensive production of pre-cathode active materials (pCAM) and cathode active materials (CAM) to European countries with significant renewable power operations (such as Finland), combined with local sourcing of critical minerals as mentioned above, could reduce emissions by almost 14 kg CO_2-eq/kWh – by far the biggest lever in value chain optimization.

As the levers are partly interdependent (for example, a switch to 100% wind energy will lower the effect of more efficient cell production), a total saving of 40 kg CO_2-eq/kWh is feasible if all combinations of levers are implemented. This would result in EU OEMs having a footprint of around 30 CO_2-eq/kWh – within the target of 30-40 CO_2-eq/kWh.

SUPPLY SECURITY: SOURCING VIRGIN MATERIALS FROM LOW-EMISSION MINING OPERATIONS IS A RISK IF PRICES FALL

The value chain optimization strategy includes sourcing materials from low-carbon mining operations. But the sourcing of virgin materials, such as nickel, from these mines is a risk. Raw materials extracted using low-emission mining operations are typically more expensive than those from conventional mines. If a new cheap supply opens up, the price of the material plummets, with more expensive operations being the first to close as a result. This is what happened when China opened up a new supply of cheap nickel in 2023. Without intervention, cleaner production methods are at risk of being pushed to the right on the supply curve by cheaper, higher-emitting raw material sources. The result is even more complexity in already challenging raw material sourcing strategies.

OTHER CHALLENGES: CELL MAKERS MUST IDENTIFY AND COMPLY WITH TIGHTENING ENVIRONMENTAL REGULATIONS

Battery sustainability is not just about emissions. Mining, refining, and production processes present several other environmental challenges, including soil degradation, air and noise pollution, habitat destruction, threats to biodiversity, and conflicts with local communities. The disposal of nickel tailings in deep-sea locations, for example, has triggered concerns about the impact on marine ecosystems, while cobalt extraction is associated with water pollution and depletion. Lithium mining and refining, on the other hand, presents challenges for water usage in arid climates.

Regulatory efforts are being made to address these issues. But the onus is on cell makers to determine which regulations affect their operations and ensure they comply with transparency and traceability rules across their supply chain.

TECHNOLOGY

The majority of battery applications is focused on driving down costs in the near term. This has led to increased interest in lower-cost chemistries, leveraging lithium iron phosphate (LFP) and associated technologies such as LMFP (lithium manganese iron phosphate). For each application and market segment, a dedicated analysis to balance cost and performance is key.

In this chapter, we will give a high-level overview of market penetration and the underlying reasons, while for more details, the Battery Materials chapter will provide deeper insights.

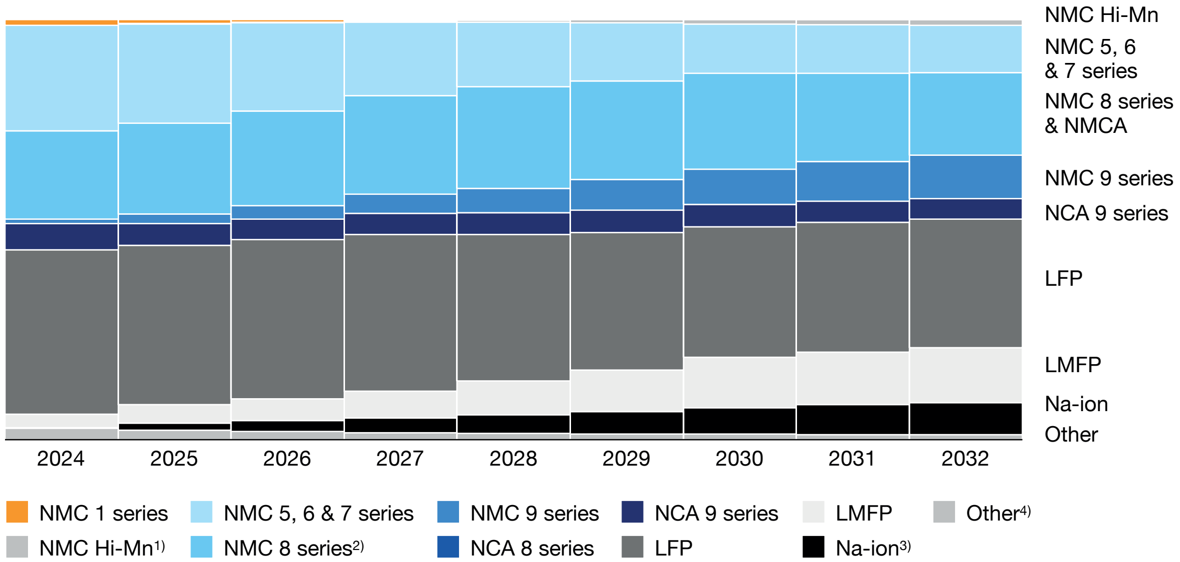
DEMAND: TECHNOLOGICAL IMPROVEMENTS WILL FURTHER INCREASE MARKET SHARES OF LFP

Our forecast shows that LFP-based (LFP + LMFP) technologies are expected to increase their global battery market share to up to 43% by 2030, based on current OEM plans, with further upside potential. There are several reasons for this growth.

Primarily, LFP has a strong cost advantage of c. 25-30% vs. conventional NMC cells (see figure 8 in Battery Materials – Technology) at a time when cost is a key concern of electric vehicle makers, and it consumes less critical minerals.

In addition, we see higher intrinsic safety in the cell, which leads to efficiencies in pack integration, resulting in further cost reduction potential but also compensating for the energy density disadvantage. The thermal propagation measures can account for USD 300 to 800 per nickel-based pack – a cost item that can be drastically reduced with LFP-based cells.

Furthermore, the technology is better suited for cell-to-pack concepts, where cells are directly integrated into the battery pack. These eliminate



1) Incl. NMX similar to NMC271; 2) Incl. NMCA; 3) Na-ion share consists of the two cell chemistries nickel-based layered oxide and Prussian white; 4) Incl. LMO/LCO/...

Figure 2: Global battery cell demand by cathode chemistry, market view case Q3/24, 2024-2032, [GWh/a]; *Source: interviews with market participants, Roland Berger battery cell demand model*

the need for intermediate battery modules, another cost item, which increases space for cells. More cells mean higher energy content, compensating for the lower energy densities of LFP at the cell level. In addition to cell-to-pack, the reduction of thermal propagation measures as mentioned, e.g., reducing the thickness of spacers between the cells by up to 50%, can create further space to integrate more cells. As a result, today the energy density of LFP packs is already close to comparable NMC designs – only 10-15% below.

Finally, the longer cycle life of LFP cells of up to 20,000 cycles is a better fit for stationary energy storage systems – a market segment accounting for c. 800 GWh of demand in 2030.

But there are also drawbacks to this technology when adapting it. Even though part of the energy density disadvantage at cell level can be compensated for, it is not a fit for all vehicle segments and niche applications, which rely on high energy density. The premium market will most likely still remain reliant on nickel-based chemistries. Furthermore, the technology's supply chain is strongly dependent on China – which makes it difficult to have a cost-effective local supply chain in North America and Europe.

LMFP, as an advancement of LFP, has been improved through the addition of manganese to the cathode, leading to higher energy density, but comes with challenges in terms of lifetime (see Battery Materials – Innovation). As this technology is quite new to the market, it is not yet widely established outside of China, but we see Western OEMs also investigating this technology for battery platforms in the medium term.

Despite the rise of L(M)FP, more expensive nickel-based chemistries are likely to retain a strong market presence, especially in the West. Demand for these currently exceeds that for L(M)FP, and demand for nickel-rich NMC 9 series cells is expected to grow strongly in the coming years due to their higher energy densities and lower cobalt content. Next-generation high-manganese cells, such as NMC271, which are aimed at the volume EV segment, are likely to enter the market at the end of the decade, once the technology meets automotive requirements. Sodium-ion (Na-ion) cells, suitable for energy storage and small EVs, might emerge as a challenger technology to LFP batteries at around the same time. For further information, please refer to **last year's Battery Monitor.**

For more detail on how the automotive market is differentiating cell chemistries, as well as advances in anode chemistries "see the Technology subchapter of the Battery Materials chapter".

IMPLICATIONS: PRODUCTION WILL NEED TO BE ADAPTED TO REFLECT CHANGES IN CELL CHEMISTRY DEMAND

Changes in cell chemistry demand are impacting the whole value chain, especially demand for raw materials. In particular, high-cost nickel mining operations are being pushed to the limits as market prices plummet. Cell producers will need to adapt accordingly.

SWITCHING TO AN L(M)FP BATTERY HOLDS NUMEROUS IMPLICATIONS ALONG THE VALUE CHAIN

High-cost nickel mining operations are being pushed to the limits as market prices fall – and as mentioned in the Sustainability subchapter, green nickel operations will be challenged the most.

Cell producers need to adapt their facility: LFP cells have a higher square meter per gigawatt hour production footprint, meaning a shift from nickel-based production to LFP production will require a bigger factory or a reduction in gigawatt hour output.

Automotive OEMs will need to requalify their cells and packs, associated with high costs and time requirements.

Increased LFP adoption will likely lead to adaptations in pack design, e.g., due to better suitability for the cell-to-pack concept.

Recyclers will need to develop recycling strategies for LFP cells, e.g., direct recycling, as the economic feasibility is currently challenging, especially outside China.

COMPETITIVENESS

China continues to dominate the battery market, with more capacity than domestic demand at almost every point along the battery value chain. As a result, cheap Chinese exports are putting pressure on the competitiveness of EV and battery players in other regions, especially the EU. Uncertain EV market penetration is adding to this pressure in the mid- and entry-level EV segments.

CHALLENGES: A VOLATILE MARKET AND OVERCAPACITY IN CHINA POSE A THREAT TO US AND ESPECIALLY EU BATTERY PLAYERS

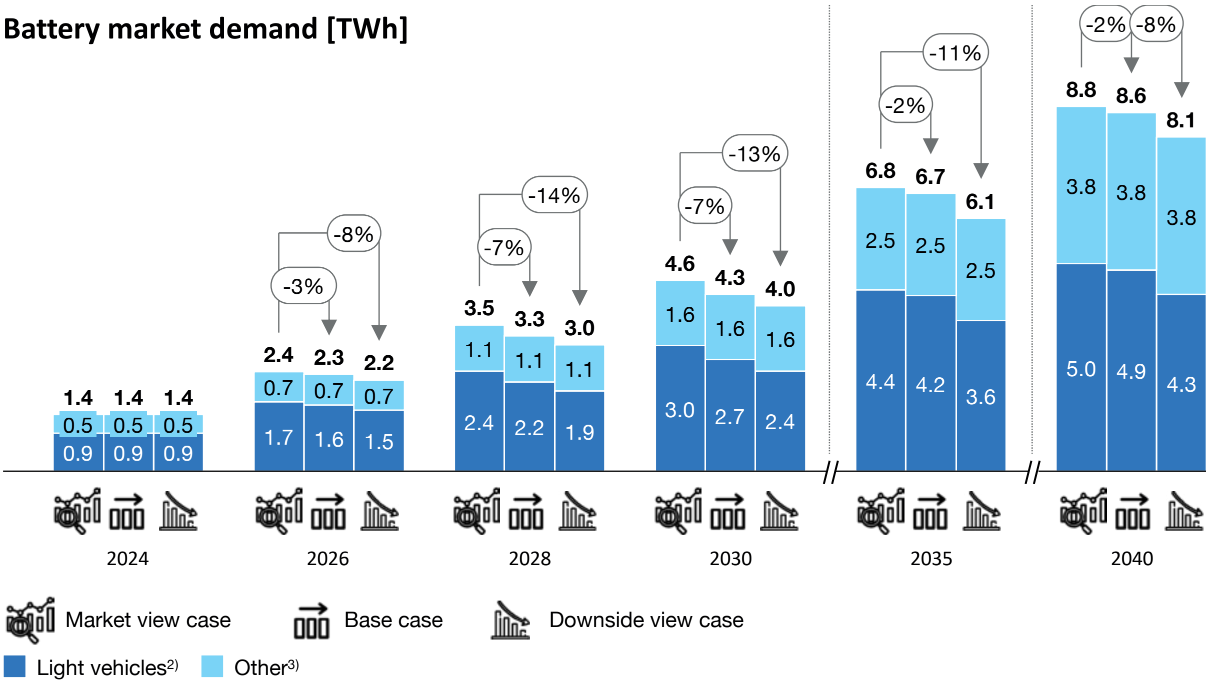
In addition to costs, two factors are currently impacting overall competitiveness in the battery market. First, demand is volatile and forecasted BEV adoption rates slowing down. Second, announced installed capacity for cell production outstrips demand, with existing overcapacity particularly high in China. Therefore, imports of cells and EVs from China are offered at highly competitive prices. Both of these factors have a significant impact.

VOLATILITY IMPACT

The underlying reasons behind the current volatility in the market lie in the uncertainty of BEV market adoption: 1) Market acceptance and volatility in demand, as most Western OEMs have had to lower their BEV sales expectations; 2) Uncertainty of regulatory regimes in Europe (reheated debate over dropping the internal combustion engine vehicles ban as of 2035) and the US (election year with uncertainty over a potential revised green strategy); 3) OEMs to leverage hybrid vehicles to a larger extent to meet emission regulations.

To gauge their effect, we modeled three potential scenarios for electrification forecasts with an impact on the battery market demand (Li-ion and Na-ion) to 2040. These were based on planned region-specific regulations and adoption of hybrid rather than fully electric EVs.

1. The market view scenario is based on announcements from automotive OEMs and is



1) Sodium-ion batteries; 2) Includes battery electric and hybrids – Light vehicle: Passenger cars and light commercial vehicles up to 6 tons;
3) Includes battery electric and fuel-cell electric medium-duty/heavy-duty trucks & buses, battery electric energy storage systems, consumer electronics, electric two- and three-wheelers, eShips and eVTOL

Figure 3: Market demand for Li-ion and Na-ion[1)] batteries by application and scenario, Q3/2024 update, 2024-2040 [TWh]; *Source: Roland Berger battery cell demand model*

the most positive outlook for electrification, with OEMs dropping hybrids in favor of fully electric EVs.

2. The base case scenario factors in a short-term downturn in EV sales, but the fulfillment of US and EU emissions targets.
3. The downside view scenario incorporates delays to regulation (for example, a two-year delay to the EU's ICE production ban) and stronger hybrid adoption.

The variation in forecasted demand across the three scenarios in 2030 – between 4.0 TWh and 4.6 TWh – highlights the level of volatility expected. It is further underscored by past Battery Monitor forecast figures from 2022 and 2023, when 2030 demand was expected to reach 3.9 TWh (2022 forecast) and 4.9 TWh (2023 forecast), respectively.

The high level of volatility makes it challenging for automotive OEMs and cell producers to correctly forecast production levels. It also has a wider impact across the value chain, as demonstrated in 2023 after the sharp fall in lithium and nickel prices (see Battery Materials – Competitiveness).

OVERCAPACITY IMPACT

Established players have announced significant new cell production capacity. This is resulting in overcapacity, primarily in China, where announced capacity exceeds the local demand, now as well as forecasted. Exports from the country will therefore increase, putting pressure on US and European producers that have added new capacities.

Total announced capacity in Europe also exceeds expected future demand. However, not all projects will materialize, and various players have already announced plans to scale down or pause individual projects. Additionally, a large share of announced capacities comes from newcomers to the battery market, who have little operational experience and a competitive disadvantage against the leading or OEM-backed battery producers. Therefore, buildup of overca-

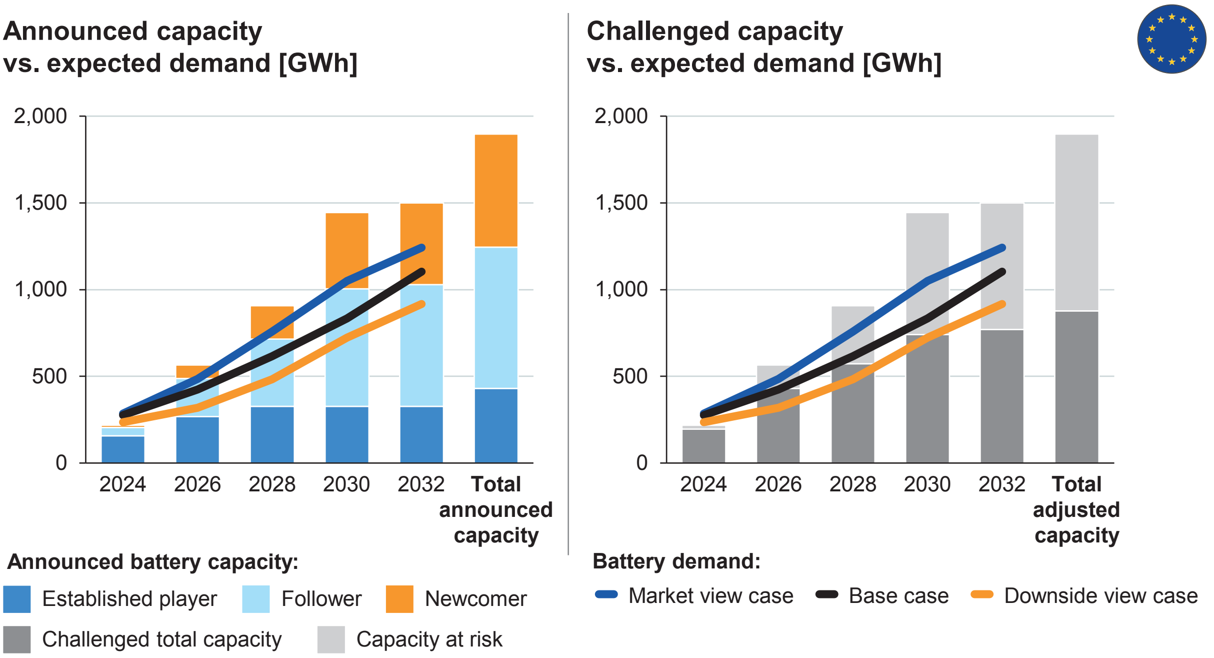


Figure 4: Battery demand vs. announced battery capacity by type of player, 2024-2032 [GWh];
Source: Press releases, company announcements, interviews with market experts, Roland Berger

pacity is unlikely and a consolidation of the market can be expected. With project delays and financing for newcomers becoming more difficult due to the slowdown in EV sales, there is even a risk of undersupply in Europe.
The result of overcapacity challenges is likely to drive further market consolidation, postponement of builds, and right-sizing of facilities. Therefore, we see an announced capacity of c. 740 GWh in 2030 as realistic.

REACTION: THE US IS HEIGHTENING PROTECTIVE MEASURES AGAINST CHINA, WHILE THE EU IS ENCOURAGING LOCALIZATION

The EU and US are taking different approaches to deal with the market uncertainty and overcapacity.

The US strategy to protect local players is two-pronged. First, under the 2022 Inflation Reduction Act (IRA), which aims to kick-start the US green economy, EVs are ineligible for certain tax credits if they contain battery components or critical minerals sourced from a "foreign entity of concern." This limits how Chinese players can participate in key parts of the battery value chain. Second, high tariffs have been imposed on imports of Chinese cells (25%) and EVs (100%). These and other measures are designed to dissuade Chinese players, while incentivizing localization of cell, pack, and battery component production.
However, barring a major escalation in tensions, it is difficult to see how China can be completely excluded from the US supply chain. For example, the bright-line definition of a foreign entity of concern leaves room for Chinese players to relocate facilities (i.e., to third-party countries with free trade agreements with the US) or set up partnerships/licensing agreements to participate in the US battery market. However, the US policies do create a window of opportunity for new players to establish a foothold with reduced pressure from Chinese imports.
The EU, meanwhile, is focusing on developing a local value chain, using the CRMA (Critical Raw Materials Act), the Battery Directive, and emissions targets as drivers. But so far, those regulations are missing clear incentive mechanisms to support the value chain localization and ensure competitiveness against Chinese imports. The bloc has implemented an addi-

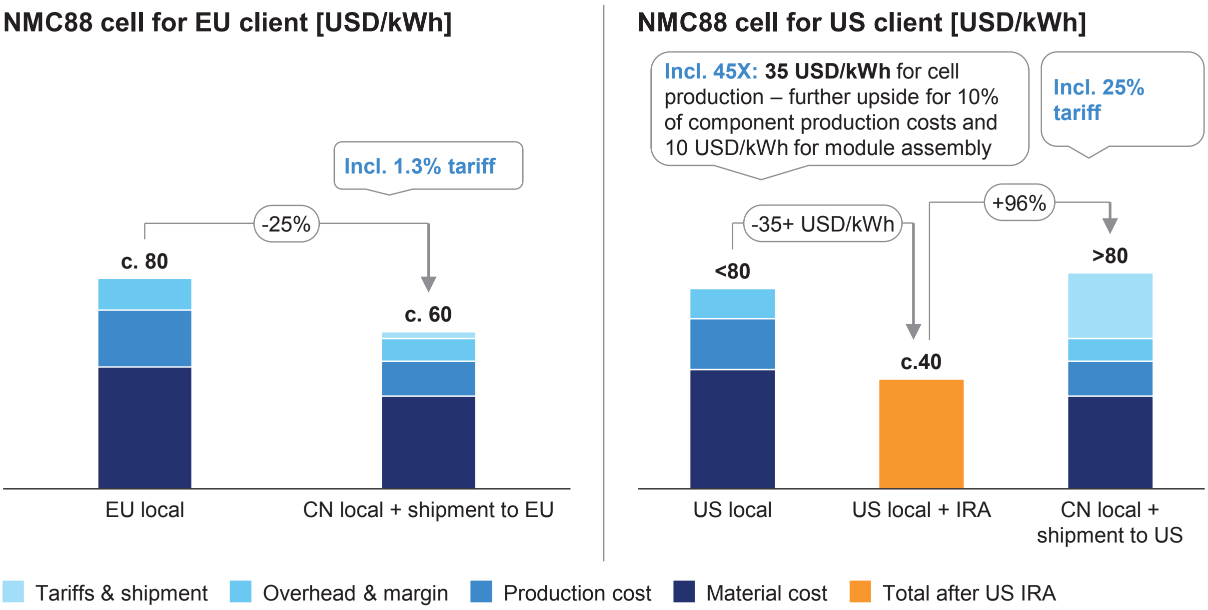


Figure 5: Comparison of cell should-costs for prismatic cell with raw material prices of Q3/2024 [USD/kWh];
Source: Roland Berger integrated LiB cell cost model

tional tariff on Chinese EVs to protect domestic automotive OEMs. However, this policy has provoked responses from China and created tensions among member states with significant exports to China.

COST COMPARISON: CHINESE CELLS STILL HAVE A COST ADVANTAGE IN THE EU, BUT THE US IS NOW UNATTRACTIVE TO CHINA

Chinese cells are typically cheap to produce due to the country's low energy, labor, and CAPEX costs, as well as low battery component prices and scrap rates. But taking into consideration US and EU protectionist measures, do they still have a cost advantage?

Our should-cost analysis shows a c. 20 USD/kWh (25%) advantage for Chinese cells imported into the EU. But US-produced cells have a c. 41 USD/kWh advantage over imported Chinese cells, making imported cells nearly twice as expensive. This highlights the difference in EU and US tariffs (1.3% and 25%, respectively), although they are subject to change through negotiations, and the effect of the IRA incentives. In addition, the high tariff makes the US highly unattractive for Chinese battery suppliers. Note that these are should-costs and do not necessarily reflect the current pricing environment, where some players may be pricing as low as 45-50 USD/kWh in Europe, indicating the high pressure in the market.

Europe, however, is a much more attractive proposition for Chinese exports, especially as the EU is unlikely to increase tariffs as mentioned and lacks an established local supply chain/battery industry. Chinese companies are building local capacities and pressuring European newcomers due to their advantages in scale and experience. To level the playing field, voices in the European battery industry are growing louder for OPEX incentives comparable to the US IRA.

COMMERCIALIZING INNOVATION WILL BE CRITICAL TO REMAIN COMPETITIVE

Considering these challenges, European and US automotive OEMs and cell makers need to act now to remain competitive. Comparing cost structures and input factors, it is implausible that European and North American companies will become cost competitive with leading Chinese players by producing the same products and technologies (excluding all incentives and protectionist policies).

Catching up to China will require continued regulatory support to fund world-class battery supply chains to level out the input factors. In addition, EV makers and Western battery makers need to catch up in multiple dimensions:

- Battery chemistry
- Pack component & integration
- "Battery first" product designs
- Vertical integration
- R&D efficiencies

Innovation is currently driven out of Asia and Western players need to find a way to get ahead of Asian competitors, but they have structural cost disadvantages, which can only be overcome with next-gen technology and sustained government support.

INNOVATION

Several existing or development-stage technologies promise to reduce costs, energy consumption, and/or emissions as depicted in the previous chapter. In this section we examine a few of them in more detail.

LATEST DEVELOPMENTS: THE MOST HIGH-PROFILE BATTERY INNOVATIONS PROMISE A COST ADVANTAGE

Low-cost cathode chemistries: New L(M)FP technologies are well suited to entry-level and volume segments, while high-manganese NMC cells could take a share of the high-nickel chemistries, which are currently used in the premium segment. Advantages were discussed in Overarching Market View – Technology and are further laid out in the chapter on Battery Materials – Technology and Innovation.

Silicon anode materials: While silicon anodes currently lead to a price premium over conventional graphite anodes, the raw material itself is abundant and low cost. Some battery makers already believe it offers a cost advantage, although this will need to be leveraged through scale (for more detail on silicon anodes, see Battery Materials – Technology and Innovation.

Process improvements: Multiple evolutionary adjustments to speed up or ease the process chain are available or in development, such as laser drying of electrodes, process step consolidation (for example, the introduction of integrated calendering and slitting machines), and the elimination of the vacuum drying step (used to remove residues in batteries). These present fewer risks than disruptive technologies.

Dry coating: The coating of active materials on electrodes is traditionally carried out by mixing the materials with solvent, forming a "wet coating" slurry. But this must then be dried, a significant time, cost, and carbon expense. Dry coating uses a solid, non-solvent binder (PTFE instead of PVDF), avoiding the drying stage. The technology is expected to be ready by the end of the decade – despite a US automaker having already announced the

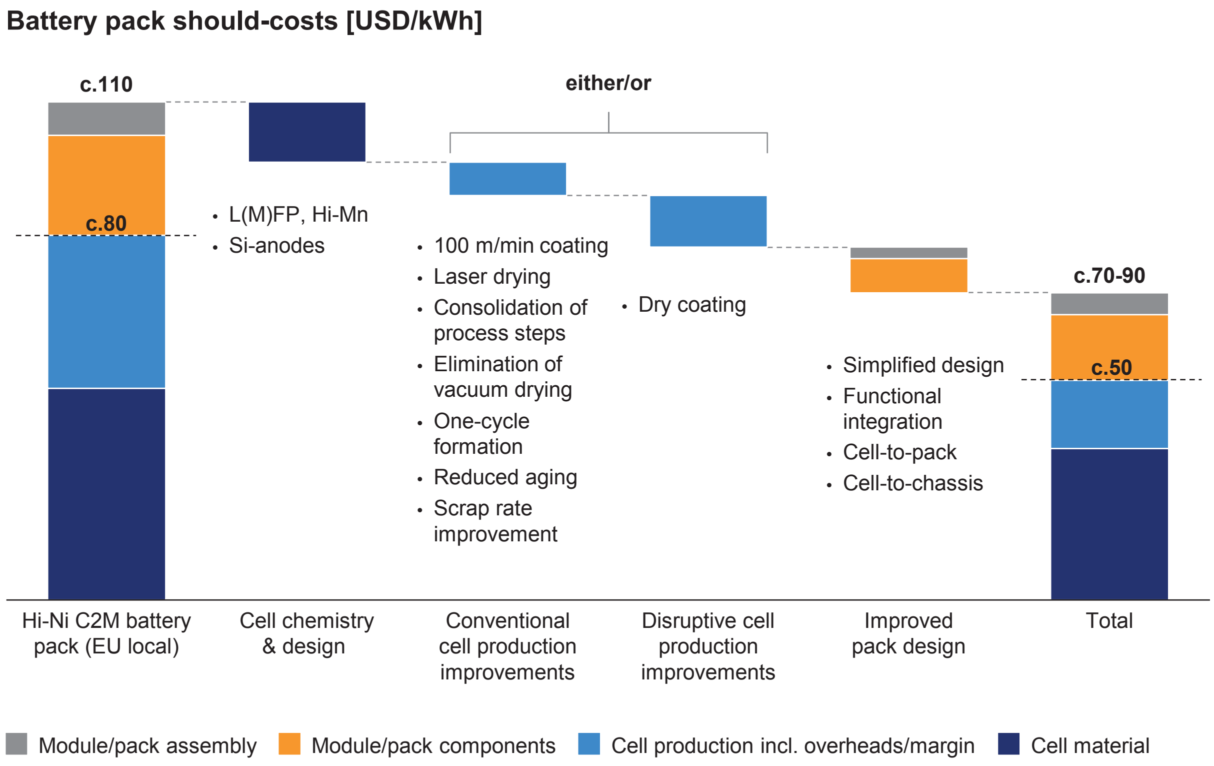


Figure 6: Pack cost potential for European volume OEM EV pack – cell chemistry impact depending on raw material prices;
Source: Roland Berger integrated LiB cell cost model

first vehicles with dry-coated cathodes. However, it may take time before it can compete with the throughput and low scrap rates of wet coating.

One-cycle formation: Formation activates the cell's materials and usually requires 2-3 charging and discharging cycles. Reducing the process to one cycle, which some companies are working on, reduces costs, energy consumption, and carbon footprint significantly.

Reduced aging: Aging, the process of maturing cells after formation, can mean storing cells for up to two weeks at high temperatures. Accelerated aging mechanisms, for example, or new measurement methods, reduce the aging time to several hours, lowering energy consumption and production footprint.

Cell-to-pack technology: Eliminating battery modules and integrating cells directly into packs reduces the amount and therefore the costs of passive pack components while also increasing energy densities. Battery pack cost savings of more than 10% are possible.

However, few of the innovations promise success in isolation, with most dependent on external factors. For example, while L(M)FP can reduce overall cell costs by 10-15% and offers synergies at the pack level, the technology has lower production throughput, slightly increasing production costs. Also, the impact of dry coating will be much more significant in countries with high energy and labor costs – in combination, we see a potential of 67-87 USD/kWh on pack level for should-costs based on index prices. As mentioned earlier, this does not necessarily reflect the offered prices. Vertically integrated players have been observed to offer at c. 50 USD/kWh due to their ability to use marginal costs and the market pressure with overcapacities in China.

Tim Hotz

"Battery cost-down is currently the biggest challenge for BEV producers. We see further room for improvement of up to 40%, taking all levers into account."

Kyle Gordon, Dennis Gallus, Konstantin Knoche, Iskender Demir

BATTERY MATERIALS

THE SLOWDOWN IN EV SALES IS PUTTING PRESSURE ON THE BATTERY MATERIALS SUPPLY CHAIN. ALTHOUGH DEMAND IS FALLING, THE KNOCK-ON EFFECT OF FALLING RAW MATERIAL PRICES MEANS MINERS AND REFINERS ARE RETHINKING SUPPLY VOLUMES, FOR EXAMPLE BY SHUTTING MINES OR POSTPONING NEW PROJECTS. FUTURE SUPPLIES COULD THEREFORE BE STRETCHED. THIS IS ADDING IMPETUS TO NEW INNOVATIONS SUCH AS LMFP, MANGANESE-RICH CHEMISTRIES AND SOLID-STATE BATTERIES.

Sustainability: An end-to-end low-carbon supply chain could reduce the footprint of EU cell producers by 30 kg CO_2-eq/kWh per battery (from 69 kg CO_2-eq/kWh), with most savings in the production of CAM materials.
Technology: There is no longer a one-size-fits-all cathode chemistry for EVs – instead, different types are being targeted at segments according to their characteristics. Silicon-rich anodes are becoming the new frontier in anode chemistry.
Competitiveness: The downturn in EV adoption has seen raw material prices fall sharply, putting pressure on miners and refiners. Supplies, especially of lithium, are set to tighten as a result.
Innovation: New developments are focused on LMFP (already introduced), silicon-rich anodes (in pilot phase) and solid-state batteries (in development).

STRATEGIC IMPLICATIONS

For regulators

Regulators are vital in promoting the growth of emerging technologies, which may necessitate new funding mechanisms to scale these innovations effectively. To support the financing of junior and early-stage mining & refining projects that are not yet bankable, regulators can consider initiatives like the Minerals Security Partnership Finance Network. Furthermore, providing a clear and stable regulatory framework is essential to reduce uncertainties for investors. By fostering an investment-friendly environment, regulators can stimulate the development of critical technologies and projects crucial for the industry's future.

For cell manufacturers and automotive OEMs

In the rapidly evolving cell chemistry landscape, maintaining resilient value chains is essential for success. A product portfolio must include low-cost options, such as lithium iron phosphate (LFP) and lithium manganese iron phosphate (LMFP), alongside mid-cost alternatives like mid-nickel chemistries. Relying solely on high-nickel NMC cells will most likely not suffice for competitiveness. Production setups and value chains must be adapted to accommodate these diverse chemistries.

For investors

The recent decline in EV demand in key regions has caused raw material prices to plummet, prompting some companies to shut down operations due to intense cost pressures. As a result, maintaining a strong cost position has been shown once more as crucial for ensuring resilient investments in operations. With certain facilities being closed and the reopening process taking considerable time, there is a growing risk of underinvestment, which could lead to a supply gap in major upstream raw material value chains by the end of the decade.

SUSTAINABILITY

As outlined in the Overarching Market View chapter, value chain optimization is a key tool to lower the carbon footprint of batteries. Battery raw materials are responsible for 70% of the carbon footprint of an average European cell producer, so a value chain fully focused on lowering CO_2 levels will heavily influence the overall footprint. We estimate that an end-to-end low-carbon supply chain could reduce the current footprint of an EU cell producer (69 kg CO_2-eq/kWh per battery) by more than half, to around 30 kg CO_2-eq/kWh.

KEY LEVERS: CAM MATERIALS, ESPECIALLY NICKEL AND LITHIUM, HAVE THE BIGGEST POTENTIAL FOR CARBON FOOTPRINT SAVINGS

The potential footprint savings from battery materials are realized through the following levers:

CAM raw materials: A ~14 kg CO_2-eq/kWh saving is possible through a combination of, for example:

- Nickel: Sulfidic-ore mining and processing in Finland
- Lithium: European operation using renewable energy
- Cobalt: Renewable operation in China
- Manganese: Sourced from the EU
- Minimum recycled content: Meeting the EU Battery Directive targets of 6% lithium, 6% nickel, 16% cobalt

Anode materials: The production of conventional synthetic graphite anodes is energy intense and most often carried out in China, where there is a low share of renewable energy. While synthetic production in lower carbon footprint Western countries is increasing, the most sustainable option is to use natural graphite. This lowers the carbon footprint by another ~4 kg CO_2-eq/kWh.

Other cell materials: Recycling aluminum and copper in the cell housing and current collector can save ~5 kg CO_2-eq/kWh.

Carbon footprint optimization levers of battery cell materials, value chain optimization only [kg CO_2-eq/kWh cell]

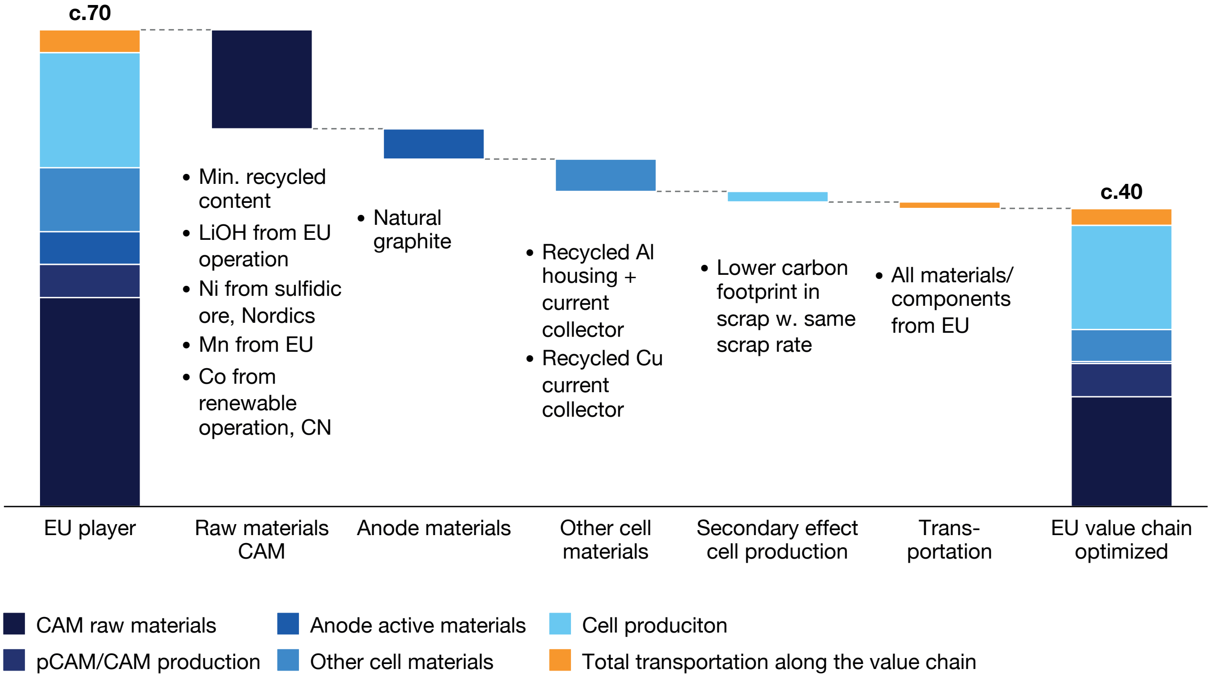


Figure 7: Carbon footprint optimization for value chain levers;
Source: Roland Berger LiB cell carbon footprint model

Secondary effects: The carbon footprint of scrapped materials is lowered if they came from low-CO_2 sources. The footprint of scrap can therefore be reduced (by around 2 kg CO_2-eq/kWh) even if the scrap rate stays the same.

Transportation: Choosing a full local EU setup for the whole value chain can reduce the transportation footprint by ~1 kg CO_2-eq/kWh.

TECHNOLOGY

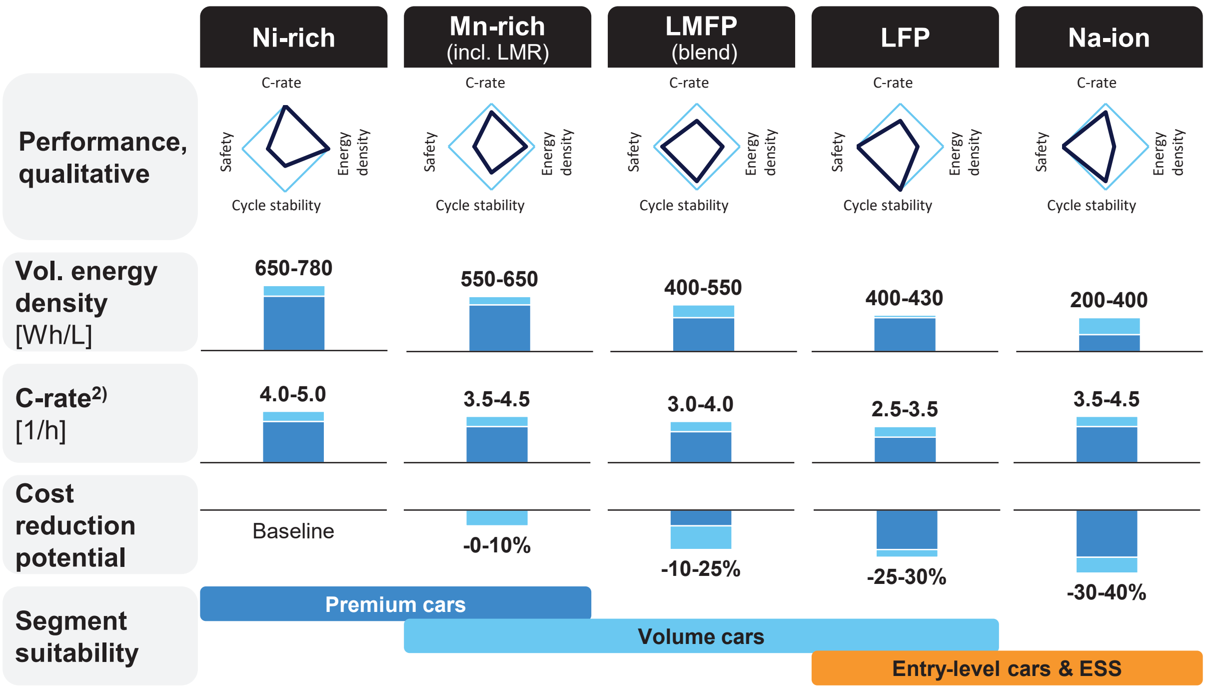
Two Li-ion cathode chemistry families dominate the EV market: nickel-based and L(M)FP (blends). The auto industry is increasingly using variants of each to target particular market segments depending on their cost/performance characteristics. Meanwhile, Na-ion cells are beginning to challenge the dominance of Li-ion batteries in certain entry-segment vehicles and stationary applications. In anode chemistry, improvements are centered on silicon anode technologies, where graphite is partially or wholly replaced by silicon.

CATHODE CHEMISTRIES: HIGH-NICKEL IS STILL KING FOR PREMIUM EVS, BUT LMFP AND MN-RICH ARE EATING INTO THE VOLUME SEGMENT

Broadly speaking, nickel-rich cells tend to be used for higher-performance premium EVs, while L(M)FP cells are focused on the entry-level and, increasingly, volume segments. Nickel-rich and LFP cells are well established, while use of LMFP technology is growing rapidly, especially in China.

High-nickel (Hi-Ni) cells offer volume densities of up to 290 Wh/kg (or 780 Wh/L) in cells with liquid electrolyte, and fast charging capabilities of more than 5C (full charge in 12 minutes). These industry-leading figures have changed little in recent years as nickel contents have reached a ceiling. As laid out in figure 5, the average cost of a Hi-Ni cell is 58 USD/kWh when produced in China and 81 USD/kWh in the EU – assuming raw material prices of Q3/2024.

L(M)FP (blend) technologies are more cost competitive with a discount of 10-30%. But they have lower energy densities, around 200-260



1) Standard market specifications for automotive cells with a time horizon of 2027; 2) C-rate performance can theoretically be adjusted as required via layer thickness

Figure 8: Comparison of cell technologies by cathode chemistry on cell level[1)] – cost reduction potential depending on raw material prices; *Source: Announcements from cell manufacturers, interviews with market participants, press clippings, Roland Berger*

Wh/kg (or 400-550 Wh/L) at the cell level – with new off-the-shelf packs that can be fast charged at 6C rates, equaling 80% charge in 8 minutes. Recent gains in performance have seen LFP and LMFP cells break into the wider volume segment – mainly due to higher integration efficiency on pack level as already discussed in Overarching Market View – Technology. A further deep dive on the LMFP cell technology is provided in the Battery Materials – Innovation chapter.

The performance of manganese-rich batteries and mid-nickel cells sits between Hi-Ni and L(M)FP, meaning they straddle the premium and volume markets. However, manganese-rich cells have only a very small share of the EV market to date, while conventional mid-nickel cells (e.g., NMC622) are rapidly being overtaken by Hi-Ni and L(M)FP. A potential comeback of mid-nickel cells remains to be observed, as cell makers announced the introduction of single-crystal mid-nickel technologies like NMC631 in the medium term, which offer a higher voltage level and increased energy density compared to conventional mid-nickel cells. The challenge of the high-voltage NMC lies in the lifetime – with the aim being to compensate for that with the single-crystal approach, reducing the reactivity of the particles.

SODIUM-ION CELLS: WHILE SUITABLE FOR MICRO CARS, THE TECHNOLOGY STILL STRUGGLES TO COMPETE WITH LFP

Sodium-ion batteries are currently being explored for use in the very low-cost entry-level EV segment (A0 segment). They are expected to gain small amounts of market share from LFP, particularly in China. However, low energy densities of a maximum of 160 Wh/kg (or 400 Wh/L) limit their potential in automotive. In addition, the price competitiveness of Na-ion is highly dependent on lithium prices. The breakeven point for Na-ion versus LFP is a lithium price of USD 20-22 per kilogram of lithium carbonate equivalent – above this threshold, OEMs will most likely choose LFP (or LMFP) due to its better performance, which is currently the case. In addition, Na-ion cells are only usable in micro vehicles or hybrid packs (for example, Na-ion cells mixed with LFP cells). The latter have additional system costs due to their increased management efforts, lowering the cost advantage of Na-ion cells.

ANODE CHEMISTRIES: CURRENTLY, ONLY SILICON DIOXIDE DOPANTS ARE AN ALTERNATIVE TO PURE GRAPHITE ANODES

Anodes have a strong potential for technological improvement, with several new anode materials being investigated.

Graphite, either natural or synthetic, is currently the anode material of choice as it is abundant and offers a satisfactory specific capacity (the amount of electric charge a material can deliver per gram) of 345 to 360 mAh/g. However, this figure cannot be increased using graphite alone, limiting the energy density and charging capability of cells. Synthetic graphite offers better charging rates and cycle life but has higher costs and lower capacity than natural graphite.

Silicon is the most promising replacement, or dopant, for graphite, offering higher energy densities and faster charging capabilities. Several silicon-based solutions exist or are in development, while only silicon dioxide as a dopant has been implemented in the mass market so far. Silicon-carbon composite and, e.g., silicon nanowires are innovations waiting for market implementation and are therefore further outlined in the Innovation subchapter.

In its pure form, SiO_2 has a specific capacity of around 1,965 mAh/g. However, the material can be used only up to a maximum share of 10% in a blend with graphite as it limits the service life of a cell due to its volume expansion and storage behavior. This also limits scalability. A 10% SiO_2, 90% graphite anode has a specific capacity of between 450 and 600 mAh/g. Such mixes can be "dropped in" to existing production lines and are already being used in premium segment EVs.

COMPETITIVENESS

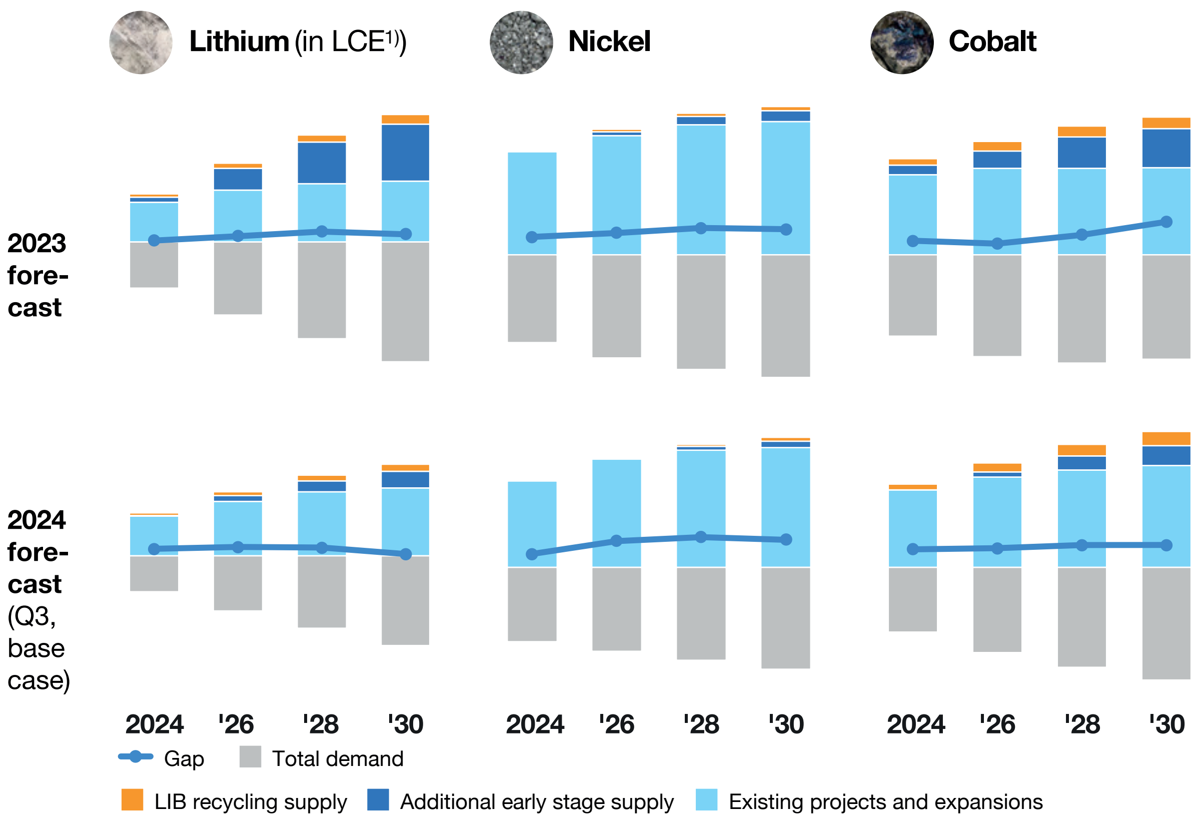
The current slowdown in EV adoption has

resulted in highly volatile demand for battery materials. To help better predict future demand and supply, we modeled market view, base case, and downside scenarios to 2030 for the key raw materials: lithium, nickel, and cobalt – the base case depicted in figure 9. This shows that the downturn in electrification will have a clear effect on supplies, putting pressure on players' competitiveness.

DEMAND & SUPPLY: THE EV DOWNTURN IS PUSHING DOWN MATERIAL PRICES, PRESSURIZING MINERS/ REFINERS

The base case assumes OEMs just meet emissions targets set by regulators and is based on Q3 2024 figures. In this scenario, supplies of nickel and cobalt are still expected to continue to meet or outstrip demand through to 2030. However, compared to the forecast from 2023, the expected lithium supply in 2030 has dropped from 3.8 million tons LCE to 3.0 million tons LCE. This results in a relative change of -21%, while the expected demand has "only" fallen by c. 17% compared to last year's forecast. Note that capacity cannot adjust at the same pace as market signals, and it is easier to turn off supply than to turn it back on. Thus, there will be, even in the medium term, periods of scarcity if the supply response remains as drastic as it is currently, especially if the EV market experiences an upside shock to demand.

The volatile demand/supply situation is already resulting in the cancellation or postponement of mining projects. For example, uncertainty over future demand resulted in prices for nickel sulfate falling to four-year lows in Q1 2024, of around 4.0 USD/kg. This has put significant pressure on mining operations, making some unprofitable. Various miners and refiners have already suspended or canceled plans in Australia and Indonesia as a result.



1) Lithium carbonate equivalent

Figure 9: Lithium, nickel, and cobalt mined supply/demand forecast, 2024-2034, base case scenario [million t LCE, million mt metal equivalent]; *Source: Roland Berger battery raw materials supply & demand model*

Kyle Gordon

> "Recent mine closures and project delays show that battery raw material supply will adjust to reduced expectations for BEV demand, leading to expected market volatility and cycles of overcapacity and undercapacity."

In the case of lithium, market prices of the raw material now sometimes hover around or just above average production costs for the metal (currently 11.6 USD/kg), meaning some operations make little or no profit.

The risk is that falling EV penetration and raw material prices could lead to underinvestment in mining, further tightening supplies, especially of lithium. And the impact is not just on mining – while nickel supplies should continue to meet demand, a bottleneck is building up around sulfate refining.

Looking at the demand from the perspective of the market view case, which assumes the highest level of electrification, we would see similar pressure as in the base case scenario. Electrification until 2030 is stronger in that scenario, but potential higher recycling volumes can only compensate for a small amount of the increased demand, leading to a potential supply bottleneck at the end of the decade (not depicted in the base case). While announced projects for nickel and cobalt mining are still sufficient, bottlenecks in refining will remain. These supply challenges are good news for raw material suppliers as they would mean higher market prices, and therefore higher investor interest. They also suggest that meeting the high level of electrification envisaged under the scenario will require alternative technologies such as Na-ion to fulfill demand.

In the downside view scenario, the supply chain for lithium, nickel, and cobalt mining and refining is tight but still sufficient.

ACTIONS: BATTERY PLAYERS NEED TO BUILD RESILIENT SUPPLY CHAINS TO ENSURE SECURE MATERIAL SUPPLIES

Mining and refining is not the only part of the battery materials value chain to feel the pinch of slowing EV sales – CAM players are also affected. For example, Umicore announced in July 2024 that it is pausing construction works on a new battery plant in Canada, while BASF Spain put its battery recycling project in Tarragona on hold the same month.

Project cancellations and postponements by CAM producers and miners/refiners highlight the fact that resilient supply chains are a key priority for battery players in their efforts to meet cost, supply, and CO_2 targets. Failing to secure supplies will mean paying a premium compared to spot market prices to ensure they can fulfill orders.

To build resilient supply chains, raw material sourcing strategies need to be flexible in order to adapt to changing EV demand. This can be achieved by, for example, avoiding take-or-pay terms and conditions, where buyers who have agreed to purchase materials must pay a charge even if they later decide they do not want them. This trend is increasingly common in the industry.

INNOVATION

Innovations in battery materials are currently focused on three main technologies: LMFP and Mn-rich cathodes, silicon-rich anodes, and solid-state batteries.

LMFP AND MN-RICH FOR COST-EFFECTIVE SOLUTIONS

LMFP chemistry offers greater thermal stability than NMC cells and is therefore safer and offers significant cost advantages. The technology was introduced to the Chinese EV market in 2023. The vehicle's battery uses an LMFP/NMC blend, which can propel the vehicle up to 705 kilometers according to official Chinese figures. It can be charged from 30% to 80% in 15 minutes. Several other Chinese cell producers and automakers have announced LMFP batteries, but it is not yet known when they will be launched. Western OEMs are investigating the technology and plan to introduce it to the market later in the decade.

The LMFP/NMC blend is seen as a stepping stone to full LMFP cells as it offers comparable cell lifetime and a smaller energy-density trade-off to conventional cells. But while it is already bringing cost savings, LMFP's full potential will not be realized until pure LMFP cells can be made stable – a technological challenge. So far, mainly Chinese cell makers are working on this and it is expected that LMFP capacity will exceed 100 GWh in 2028.

The additional energy density is caused by an increased manganese content raising the cell voltage. However, this also results in a double voltage plateau, complicating the estimation of the battery's state of health (SoH) and state of charge (SoC). This is partly addressed by adding NMC as a blend to the LMFP, smoothing the voltage curve. Additionally, challenges arise in maintaining cycle life at a 70% manganese ratio, the stoichiometry needed for the desired energy density. At this composition, LMFP tends to degrade, necessitating the development of gradient particles with iron on the shell and manganese in the core to mitigate these issues.

Manganese-rich cells, including LMR cells and high-manganese-share NMC chemistries like NMC271, promise similar benefits to LMFP. The technologies are advancing, although challenges around lifetime requirements are yet to be resolved. Market introduction is expected later this decade.

SILICON-RICH ANODES TO IMPROVE FAST CHARGING AND ENERGY DENSITY

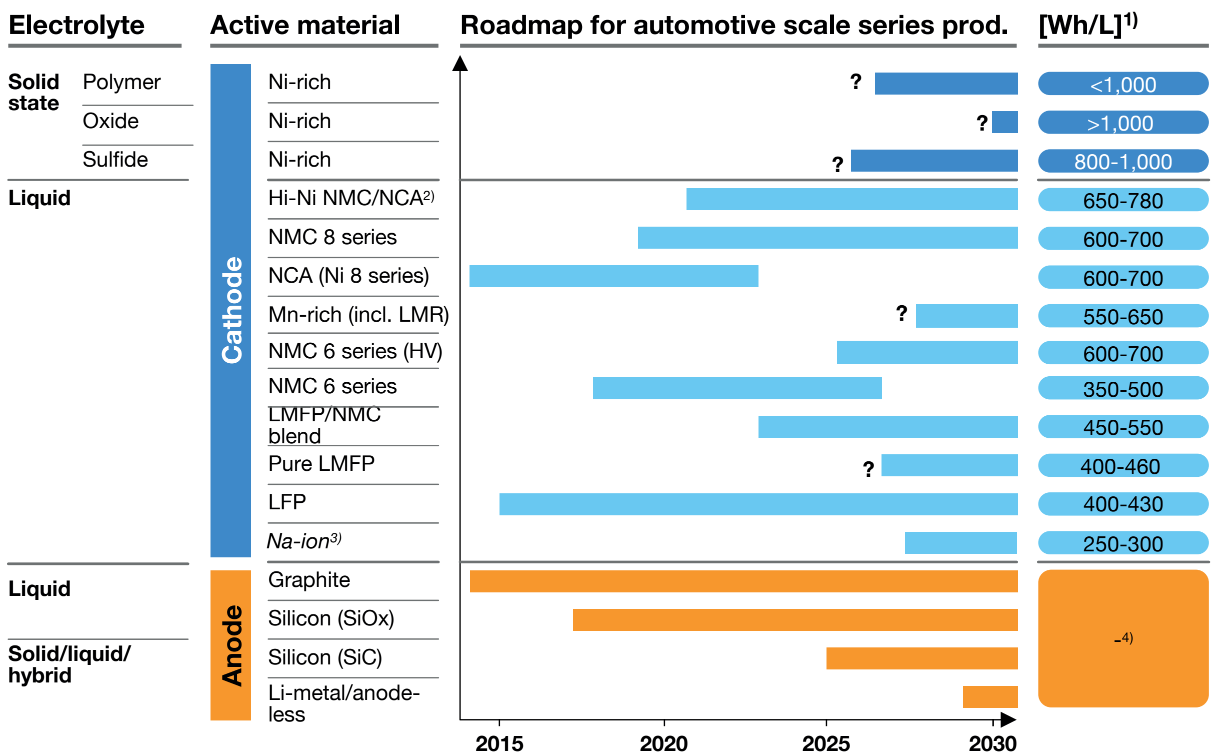
Silicon-carbon composites, which offer significantly faster charging times and high energy densities, are already in use, albeit only in small-scale applications so far. A Chinese cellphone maker has introduced silicon-carbon composites in the cells of consumer electronics, for example. However, a German OEM plans to use silicon-carbon composites in its luxury SUV model from 2024/2025, and specialist producers are working towards developing the first production facilities on a large scale.

In addition, an Israeli fast charging specialist has demonstrated a silicon-carbon composite anode with 40% silicon content in an EV. Its battery can charge from 10% to 80% in just 10 minutes and has a high energy density (340 Wh/kg). Several startups are also investigating the use of silicon-material anodes in solid-state batteries (see below). In general, two silicon-dominant materials are mainly being investigated, silicon-carbon composites and silicon nanowires.

Silicon-carbon composite: The material has a specific capacity of around 1,850 mAh/g. The material's structure, which consists of a carbon scaffold around the silicon molecules, prevents rapid cell aging caused by volume expansion (a normal process in cells, but one that is drastically increased when using silicon). It can completely replace graphite, allowing for a high (up to 60%) silicon content and therefore a high potential for improvements in energy. Silicon-carbon composites are currently produced in pilot-sized production facilities and are expected to be introduced in premium applications in the coming years. However, while drop-in and scalable, the building of large-scale facilities to increase production output will be associated with challenges.

Silicon nanowires: Technologies such as silicon nanowires use almost 100% silicon, leading to significant advancements in supercharging and improvements in energy density and cell aging. Pilot production has begun, but scaling is difficult due to technical challenges. This limits their cost reduction potential, making them more suitable for specialized applications, such as military uses. Growing Si-nanowires with shares between 10% and 30%, using on-site produced Silan in a controlled reaction, could be used to improve capacity (e.g., from c. 400 mAh/g to 800 mAh/g for 10% Si share) and significantly reduce costs not only of the material (per kWh) but also on cell level.
Ultimately, the extent to which silicon anodes become established on the mass market will be determined by the price trend of the materials in the coming years.

(Semi-)solid-state batteries (SSB): Solid-state batteries replace liquid electrolyte (lithium salt solutions in Li-ion cells) with a solid electrolyte, such as ceramics or solid polymers. The primary reason for employing a solid electrolyte is to facilitate the use of lithium metal anodes, which leads to a higher energy density in the cell. This is enabled by suppressing dendrite formation, a phenomenon that occurs when lithium metal anodes are paired with liquid electrolytes. Dendrites can grow through the separator, leading to safety and lifetime issues. In addition, the removal of the liquid promises better safety properties due to the elimination of the flammable liquid electrolyte. However, due to persistent challenges in fast charging performance, the approach is currently switching to hybrid solutions – using a combination of liquid and solid electrolytes. A Chinese automaker is already using such a semi-solid-state cell with around 350 Wh/kg (or about 750 Wh/L) in its 150 kWh packs. The company's business model,



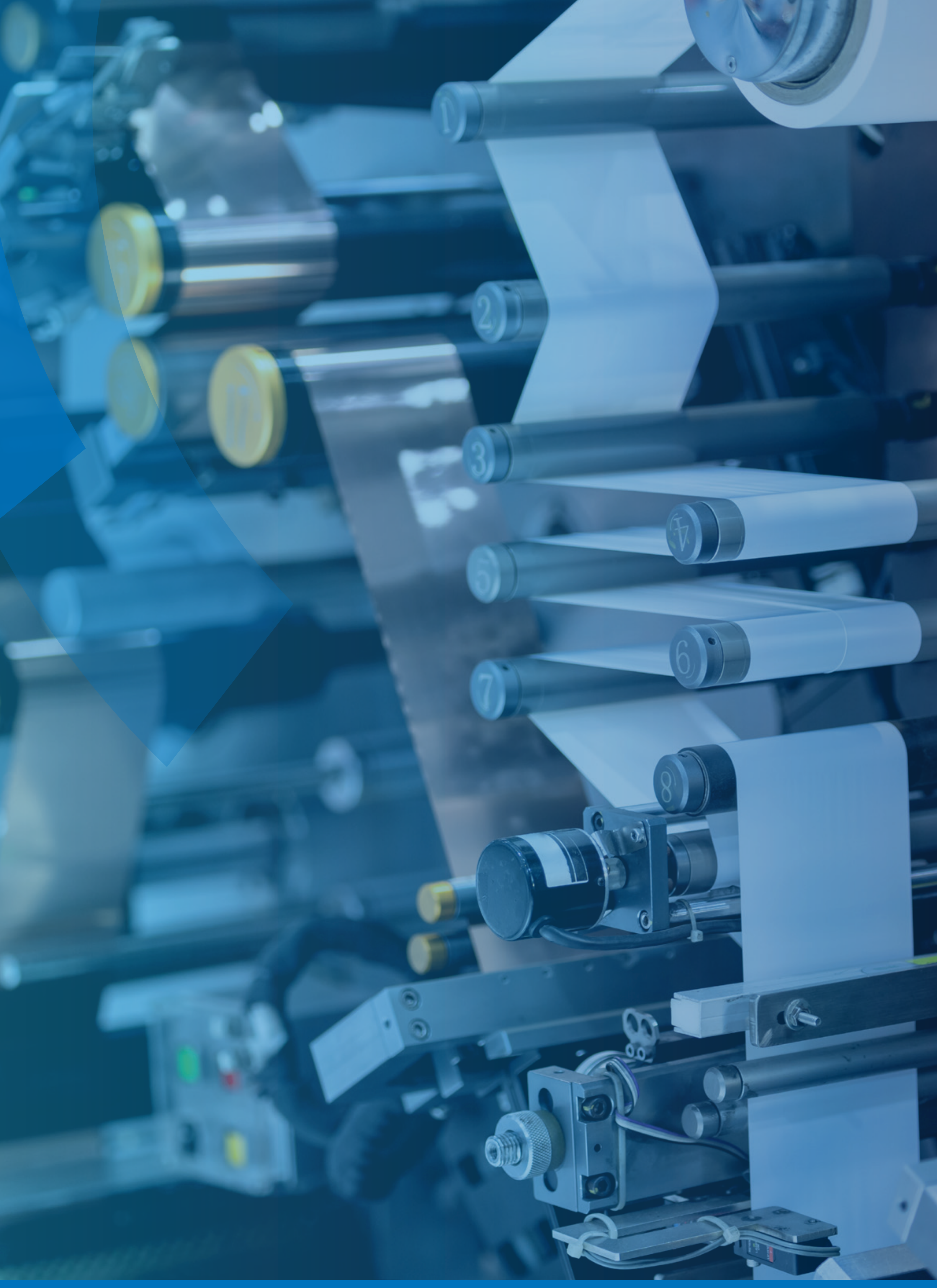
1) Target values for supplier of pouch or prismatic cell; 2) Ni 9 series; 3) Not only cathode chemistry per se but listed for simplification; 4) Primarily driven by cathode chemistry

Figure 10: Battery cell chemistry roadmap; *Source: Announcements from cell manufacturers, interviews with market participants, press clippings, Roland Berger*

however, is based on battery swapping, where the entire car battery is exchanged at a swapping station rather than being recharged by the user. This eliminates the need for fast charging (swapping times can be as low as three minutes), which remains one of the main challenges for solid-state batteries.
The use of fully solid-state batteries in EVs is still a long way off, as the current technology still cannot compete with conventional LIB cells in terms of fast charging, cost, and lifetime. While European players have historically led the development of the technology in the past few decades, China is now investing heavily in solid-state batteries to catch up. The country's government has allocated around USD 830 million to local battery and automotive giants with the aim of making China a leader in the technology.

> "OEMs need to develop a strategy and processes that allow them to quickly adjust cell chemistry to adapt to raw material prices and also allow the rapid introduction of new chemistries such as LMFP."

Iskender Demir



Sebastian Wolf, Jessica Schmied

BATTERY PRODUCTION

EUROPEANS ARE ADDRESSING SUSTAINABILITY AND COMPETITIVENESS BY INNOVATING PRODUCTION PROCESSES, OPTIMIZING EFFICIENCY, AND ADOPTING RENEWABLE ENERGY TO REDUCE COSTS, EMISSIONS, AND WASTE. HOWEVER, CHALLENGES IN SCALING INNOVATIONS, SECURING TALENT, AND REDUCING DEPENDENCIES PERSIST AMID STRONG GLOBAL COMPETITION AND SUBSIDY DISPARITIES.

Sustainability: Issues around high costs and energy demand in key production processes can be resolved with innovations like laser drying and dry coating, while reducing GHG emissions and waste can be achieved through renewable energy adoption and process optimization.

Technology: Driven by the need to reduce costs and aim for higher product quality, current efforts focus on improving efficiency through reduced cycle times, enhanced OEE, minimized scrap rates, and early defect detection.

Competitiveness: Europeans focus on sustainability, quality, and innovation to differentiate themselves from cost-efficient Asian producers and technology-driven American firms but face challenges in scaling production, securing talent, and achieving technological sovereignty amid strong government subsidies and supply chain dependencies.

Innovation: New process innovations and next-gen batteries are expected to enhance efficiency and sustainability but scaling these technologies and transitioning to affordable mass production present challenges that require significant research and collaboration.

STRATEGIC IMPLICATIONS

For regulators

- Given the regional differences in greenhouse gas (GHG) emissions, the adoption of renewable energy in battery production should be further incentivized. Setting targets for carbon neutrality and reducing scrap rates through optimization initiatives will be critical for achieving sustainable production.
- Addressing the skills gap by promoting partnerships with educational institutions and industry to train skilled labor for battery manufacturing could support rapid scaling efforts.

For cell manufacturers

- Prioritizing adoption of innovations such as laser drying and dry coating can significantly reduce energy costs and improve environmental performance. Adoption is crucial to achieve cost efficiency and meet regulatory demands for carbon reduction. Focusing on low-emission production, quality, and innovation could help in competing with cost-focused Asian counterparts.
- The use of inline cross-process control systems to enhance OEE will be essential in improving manufacturing efficiency and achieving quality consistency. This is particularly vital for new players in Europe and the US, who may lack the experience of established manufacturers in Asia.

For automotive OEMs

- Focusing on strategic partnerships with cell manufacturers that are adopting advanced and sustainable production technologies could enable OEMs to secure high-quality, low-cost batteries for electric vehicles and other applications while meeting sustainability commitments. Alignments will help minimize production time and costs, facilitating better end product economics and competitiveness in the market.

For investors

- The introduction of new technologies promises lower production costs, energy savings, and enhanced sustainability, making them attractive areas for investments.
- In Europe, government support for sustainability initiatives offers lower CAPEX opportunities, whereas in China, robust subsidies and established supply chains promise stable growth. However, uncertainty in regulatory incentives, especially in regions like Europe where funding might fluctuate, could pose a risk to rapid technology development.
- Companies that effectively close the skills gap and ramp up production efficiently will be well positioned to capture market share in the expanding battery industry.

SUSTAINABILITY

Sustainable battery production faces challenges due to the high costs and energy demands of key processes like coating, drying, and formation. Waste management is another key factor, as high scrap rates, particularly during early production stages, contribute significantly to energy consumption and GHG emissions. A part of the solution can be found in innovations such as laser drying and dry coating, which offer energy-efficient solutions to reduce costs and environmental impact. In addition, reducing scrap rates through process optimization and moving towards renewable energy for carbon neutrality is critical to enhance sustainability in battery production.

ELECTRODE MANUFACTURING IS A CRITICAL TARGET FOR REDUCING ENERGY DEMAND AND ACHIEVING PROCESS OPTIMIZATION IN BATTERY PRODUCTION

Battery production aims to meet the growing demand for energy storage solutions while minimizing environmental impact. However, achiev-

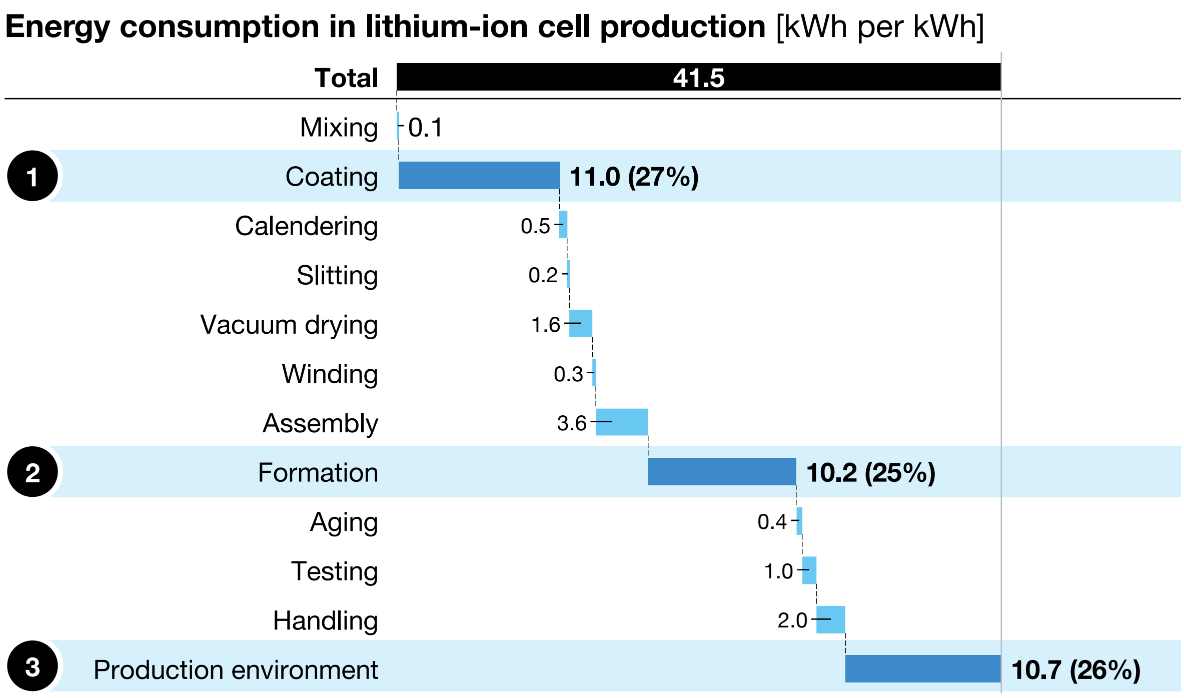


Figure 11: Energy consumption in battery production; *Source: PEM of RWTH Aachen University Production Model*

ing sustainability in this field is challenging due to the high costs and energy demands associated with key production processes (see figure 11). In particular, coating and drying are among the most expensive steps in electrode manufacturing, together accounting for approximately 54% of the total electrode production costs. Moreover, the success of all subsequent production steps relies on the quality and efficiency of these initial processes in electrode production, making them critical targets for technological innovation and sustainability improvements.[1]

INNOVATIONS IN ELECTRODE PRODUCTION: LASER DRYING AND DRY COATING PROMISE TO REDUCE BOTH ENERGY DEMAND AND COSTS

Among the most promising innovations are laser drying and dry coating, both of which offer substantial benefits in terms of energy efficiency, cost reduction, and environmental impact. Laser drying can reduce energy usage in convection drying processes significantly, making it a much more sustainable option. Dry coating is another innovative and promising technology in electrode production. Bypassing the solvent evaporation stage, dry coating can reduce energy consumption by approximately 20%. Additionally, dry coating improves material efficiency, which further enhances the sustainability and cost effectiveness of battery production.[2]

ADOPTION OF RENEWABLE ENERGY SOURCES AND OPTIMIZED WASTE MANAGEMENT AS AN OVERALL SOLUTION FOR ACHIEVING CARBON NEUTRALITY

The sustainability of battery production is also influenced by the energy mix used during manufacturing. GHG emissions can vary depending on the geographic region due to differences in the local electricity grid. For example, GHG emissions in China are around 570 g CO_2/kWh due to coal reliance. In the United States, the average emissions are about 361 g CO_2/kWh due to a mix of fossil fuels and renewable energy sources, while in Europe, they average about 200 g CO_2/kWh, with much lower emissions in countries like Norway. Manufacturers are increasingly adopting renewable energy sources to mitigate these emissions, with companies such as Tesla leading the charge towards carbon neutrality by 2030 and 2035, respectively. Waste generation in battery production is a critical factor that directly affects sustainability. High scrap rates, especially during the ramp-up phase of production, can exceed 30%, contributing significantly to energy consumption and GHG emissions. Reducing scrap rates to around 5-10% through process optimization is essential for improving the overall sustainability of battery manufacturing.[3]

TECHNOLOGY

Optimizing technology performance in battery production involves a multifaceted approach. Especially new manufacturers face challenges in achieving cost-efficient OEE, making real-time cross-process control systems crucial for success. Early detection of defects is vital to prevent costly errors and ensure a quality standard. Waste reduction strategies such as predictive maintenance can help lower defect rates and improve quality even more, and scrap recycling has the potential to lower overall production costs by reusing materials in production scrap.

KEY METRICS FOR OPTIMIZING BATTERY PRODUCTION

In terms of optimization, key metrics for the evaluation of battery production technologies involve the ability to reduce cycle times, enhance overall equipment effectiveness (OEE), and minimize scrap rates, and the option to implement early defect detection systems to improve efficiency and product quality. These efforts not only drive down costs but also improve the quality and reliability of the final product, ensuring competitiveness in the battery industry. A key aspect of this is the cycle time of various manufacturing processes, particularly in cell finalization, where prolonged process times such as wetting and formation can significantly drive up costs.

OVERALL EQUIPMENT EFFECTIVENESS AS A CRUCIAL METRIC FOR NEW MARKET PLAYERS

OEE as a metric encompasses equipment availability, process performance, and product quality. Achieving high OEE is essential for optimizing production efficiency. However, the reliance on experience-based process control, typically managed by experienced operators, poses a challenge for newer battery manufacturers, particularly in Europe and the United States. To address this, it is imperative to implement inline cross-process control systems that can monitor and adjust processes in real time, thereby enhancing OEE and reducing variability in product quality.[4]

QUALITY MANAGEMENT AND WASTE REDUCTION STRATEGIES MITIGATE PRODUCTION DEFECTS AND COSTLY ERRORS

Identifying and addressing bottleneck processes prone to quality issues is essential for reducing waste. A significant challenge is that many defects are only detected in EOL tests during cell finalization, even though their root cause is in earlier production processes such as coating and electrolyte filling, which are especially susceptible to defects. Continuing to process Not-Ok (NOK) cells results in high costs, as a substantial portion of the value added has already been invested in the cells during electrode manufacturing and assembly (see figure 12). To reduce overall scrap rates, the implementation of quality management, which aims to reduce waste, and the application of direct scrap recycling processes that help manage the remaining waste are investigated. Recent research in this area shows promising results. Predictive maintenance, for example, can enhance OEE by preventing equipment failures before they occur. Especially in the ramp-up phase of production, scrap rates can be alarmingly high, ranging from 30% to 50%. However, with targeted efforts, these rates can be reduced to 5% to 10%.[5]

COMPETITIVENESS

The global battery production market is dominated by Asian companies, especially from China, South Korea, and Japan, known for their cost leadership through efficient processes and large-scale production. However, European and US firms are increasing their

Added value in European lithium-ion battery cell production [USD mn/GWh]

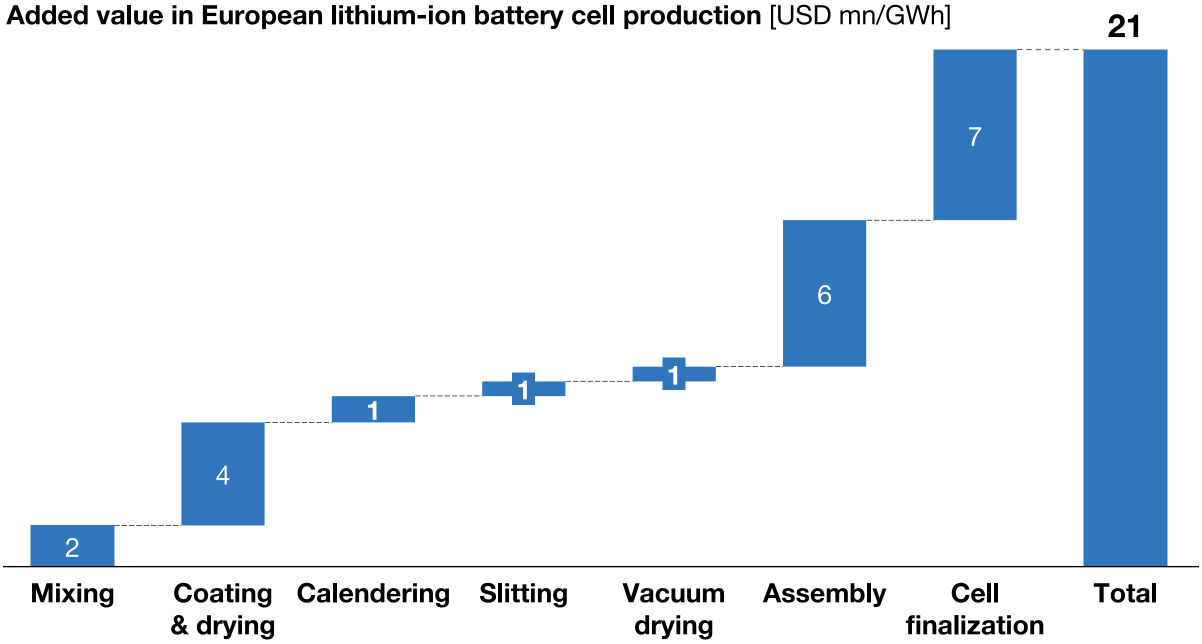


Figure 12: Added value structure in lithium-ion battery production in Europe; *Source: PEM of RWTH Aachen University Production Model*

capacities in response to rising electric vehicle demand and the need for energy independence. Despite challenges, Europe is emerging as a key player by developing high-quality process technologies and boosting production capacity.

EUROPE VS. ASIA AND THE US: COMPARATIVE ADVANTAGES AND GOVERNMENT INFLUENCE

European battery manufacturers are focusing on differentiating themselves from their Chinese and American competitors by emphasizing sustainability, quality, and innovation. They are investing heavily in green battery initiatives due to EU regulations aimed at reducing CO_2 emissions, which could provide a competitive advantage as global markets prioritize eco-friendly technologies. In contrast, Asian manufacturers excel in cost efficiency and production scale, supported by established supply chains and government subsidies. US companies are leveraging advanced technologies in battery chemistry to enhance performance and safety.

Government support plays a major role in the market. Subsidies significantly influence the competitiveness of battery production across regions. In China, support is even more substantial, with total subsidies estimated to be three to nine times greater than those in other OECD countries. The US, following the Inflation Reduction Act of 2022, has introduced incentives like tax credits and grants to reduce CAPEX and promote domestic production. In Europe, these subsidies can lower capital expenditures (CAPEX) and operational costs, facilitating investments in large-scale facilities.[6]

AS PRODUCTION CAPACITIES SCALE UP, THE COMPETITION FOR EXPERIENCED WORKERS AND SKILLED TALENT INTENSIFIES

Europe is rapidly expanding its battery production capacity (see figure 13), with numerous projects and gigafactories underway, led by companies like Tesla, and PowerCo. This growth creates significant demand for skilled workers, engineers, and battery experts, presenting both opportunities and challenges. Intense competition for talent could hinder European companies' ability to scale production quickly. To address this issue, various initiatives are being launched by companies and

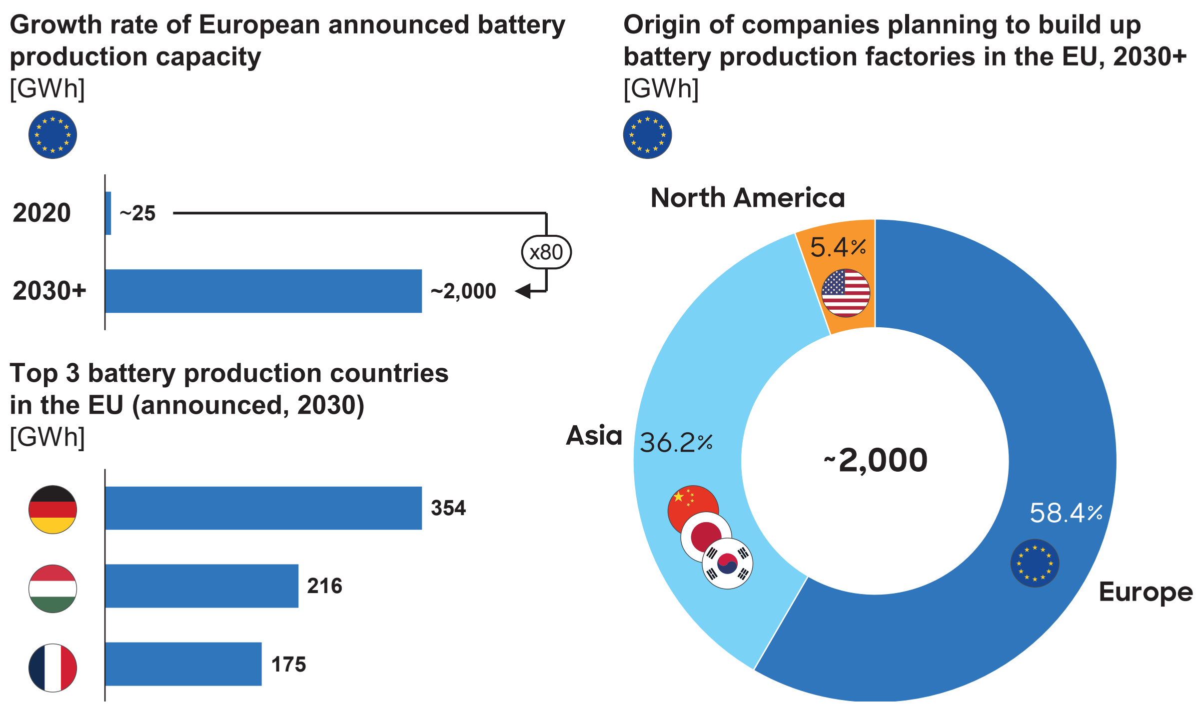


Figure 13: Estimated project costs for the setup of a gigafactory battery cell production by manufacturer origin; *Source: PEM of RWTH Aachen University, Battery Atlas 2024*

Jessica Schmied

> "Achieving sustainability in battery production demands a balance between energy efficiency, reduced GHG emissions, and technological innovation, driving the industry's transition to renewable energy sources."

governments, including training programs and partnerships with educational institutions. The European Battery Alliance has introduced programs aimed at closing the skills gap in the industry.[7]

CHALLENGES AND MARKET DYNAMICS

Despite the growth in Europe's battery production capacity, the market remains challenging. Several high-profile projects have been delayed or canceled due to financial constraints, supply chain issues, and regulatory uncertainties. Achieving technological sovereignty is difficult without strong political and financial support, particularly given the dependency on raw materials from outside Europe. The ramp-up phase of production is critical, as quickly achieving high yields can significantly affect a company's market position. European and US firms face pressure to optimize their ramp-up processes to compete with established Asian manufacturers that have mature production lines.

INNOVATION

Collaborations in China and North America demonstrate the global race for technological leadership in advanced battery technologies. The future of next-generation batteries, like solid-state batteries, and new process innovations present opportunities for all market players, especially for new participants, though reduced funding in Europe may slow innovation. Still, early adopters benefit from competitive advantages and can find themselves in leading positions quickly, but scaling these technologies for mass production remains challenging due to material qualifications and long time-to-market processes.

HIGH-IMPACT INNOVATIONS FOR COST-INTENSIVE PRODUCTION PROCESS STEPS

The battery production landscape is evolving significantly, driven by emerging process technologies developed through collaborations among equipment manufacturers, technology providers, and research institutions. Innovations like laser drying, dry coating, cross-process control systems, and adaptive cell formation aim to enhance efficiency, quality, and sustainability. Technologies such as laser drying and dry coating address high energy demand and carbon emissions in electrode manufacturing. Laser drying reduces drying times on pilot lines, leading to savings in capital (CAPEX) and operational expenditures (OPEX). Dry coating techniques also offer cost-saving opportunities by minimizing extensive drying processes. However, scaling these technologies for large-scale production is challenging due to stringent material qualifications for PTFE-containing binders. Research into PFAS-free binders is crucial for overcoming these hurdles. Trajectory mixing and adaptive data-driven cell finalization processes can further reduce manufacturing time and enhance overall production efficiency. As these technologies develop, they are expected to lower production costs and provide competitive advantages for manufacturers.

CHALLENGES AND OPPORTUNITIES IN SCALING MASS PRODUCTION

Several companies are integrating advanced technologies, benefiting from cost reductions and improved production cycle times. These early adopters offer valuable insights into how innovation drives competitive advantage. However, broader adoption faces challenges in Europe, particularly due to reduced funding for battery research by the German government, which may slow innovation and hinder technology development. Additionally, the long time to market for new processes can make companies hesitant to adopt unproven innovations, potentially delaying commercialization of transformative technologies.

ALL-SOLID-STATE (ASS) BATTERIES DOMINATE THE RACE FOR NEXT-GENERATION BATTERIES

Next-generation batteries present significant opportunities for new players to enhance their global market position due to their higher energy densities and improved safety. In China, companies are collaborating under the “China All-Solid-State Battery Collaborative Innovation Platform (CASIP)” to expedite this transition. Meanwhile, innovative startups in North America, often supported by major OEMs, are working to industrialize solid-state battery innovations, indicating that the race for technological leadership in next-gen battery technologies is still open. However, transitioning these technologies from laboratory demonstrations to mass production poses challenges that require intensive research and adjustments in the process chain. This situation also offers the European machinery sector a chance to create a unique selling proposition (USP) against large Asian suppliers.[8]

Maximilian Graaf, Niklas Kisseler

PRODUCT PERFORMANCE

ELECTRIC VEHICLE ADOPTION IS DRIVEN BY COST SAVINGS AND ENVIRONMENTAL BENEFITS, BUT CHALLENGES RELATED TO COST, CHARGING, AND BATTERY SAFETY STILL EXIST. ADVANCES IN BATTERY TECHNOLOGIES, ALTERNATIVE CHEMISTRIES, AND INNOVATIONS IN DESIGN AND MANAGEMENT SYSTEMS ARE CRUCIAL FOR IMPROVING PERFORMANCE, COMPETITIVENESS, AND SUSTAINABILITY IN THE GROWING EV MARKET.

Sustainability: Customers are adopting electric vehicles primarily due to maintenance cost savings and environmental benefits, but challenges like high purchase costs, charging concerns, and battery safety remain crucial factors for wider adoption.
Technology: Battery chemistries and advanced cell-to-X designs impact energy density, safety, and efficiency, influencing electric vehicle performance and sustainability.
Competitiveness: Global electric vehicle sales are rising, but BEV market share is challenged by high costs, depreciation, and competition from hybrids and imported Chinese models, prompting OEMs to diversify offerings and update technologies.
Innovation: Sodium-ion batteries offer a sustainable, cost-effective alternative to lithium-ion batteries, while innovations like cell-integrated sensors and wireless BMS aim to improve battery safety and efficiency despite technical challenges.

STRATEGIC IMPLICATIONS

For regulators

- To alleviate consumer range anxiety, regulators need to support the development of fast charging infrastructure and ensure equitable geographic coverage, making EV ownership more appealing and practical.
- As consumers increasingly prioritize the sustainability of the entire battery lifecycle, regulators must implement standards to ensure manufacturers adopt best practices for battery production, usage, and recycling.
- Safety standards need to be updated to account for evolving battery technologies like new cathode chemistries, advanced coatings, and thermal management systems.
- Imposition of tariffs on imported vehicles, like those imposed by the EU on Chinese EVs, could influence market dynamics. The tariffs might help protect domestic industries but could also increase costs for consumers, requiring regulators to balance these trade-offs.

For cell manufacturers

- Enhanced safety features will be a key selling point as consumers and OEMs seek to mitigate perceived risks associated with EV batteries. Differentiation of products in terms of both longevity and reliability could be achieved by integrating advanced materials such as ceramic coatings and enhanced thermal insulation.
- Diversification of cell chemistry portfolios should be investigated, exploring alternatives like LFP, LMFP, and SIBs to meet various market or vehicle needs.
- Incorporation of cell-integrated sensors and wireless BMS into battery packs can support predictive maintenance, reducing downtime and adding to customer confidence, and provide value-added safety and efficiency.

For automotive OEMs

- Further diversification of products should be targeted with the aim of offering EVs that address common customer concerns.

Especially budget-friendly options will appeal to cost-sensitive consumers.
- OEMs face a strategic choice between advanced integration, which increases energy efficiency, and modular battery systems, which offer better opportunities for maintenance, recycling, and upgrades – appealing to consumers with sustainability.
- Strategic partnerships with battery manufacturers specializing in chemistries like LMFP and SIB can help OEMs mitigate reliance on costly materials like cobalt and lithium, allowing them to offer more affordable EVs. In light of tariff policies like those in the EU, OEMs should also consider localizing production to circumvent import duties.

For investors
- Battery chemistry and architectures that promise cost efficiency, safety, and sustainability are likely to gain regulatory and consumer support, enhancing the market potential of the companies involved.
- The long charging times and range anxiety associated with EVs create investment opportunities in charging infrastructure, including fast charging solutions and energy storage systems.
- Investors should identify only startups with a clear differentiation strategy, strong technology partnerships, and the capability to adapt to market and regulatory challenges, avoiding insolvency risks associated with market consolidation.

SUSTAINABILITY

Customers are increasingly adopting electric vehicles due to expected lower ownership costs, environmental awareness, and sustainability considerations, although high purchase costs and charging concerns remain significant barriers. Achieving even higher sustainability longevity and therefore battery safety must be ensured, driving investments in advanced materials and thermal management. These technologies further support sustainable energy storage solutions and build consumer confidence in EV technology.

CUSTOMER EXPECTATIONS FOR E-MOBILITY ADOPTION

Several factors influence customers' decisions when purchasing electric vehicles. Key reasons to buy an EV include lower ownership costs from reduced maintenance and fuel expenses, along with growing environmental awareness. Sustainability has risen in importance, moving from the third to the second most significant factor between 2023 and 2024. Customers consider not only the sustainability of driving an EV but also the overall environmental impact of the battery throughout its lifecycle. However, concerns such as long charging times hinder EV adoption. Compared to conventional vehicles that refuel in five minutes, EVs face longer wait times, leading to range anxiety – especially since many EU EVs average a range of around 400 km compared to over 800 km for combustion vehicles. Purchase cost is another critical factor: electric vehicles typically cost more than their combustion counterparts, averaging about EUR 46,000 in Europe. This is especially true for small cars. This poses a financial challenge for many families as confidence in this technology evolves. While safety is generally seen as a basic attribute met by modern EVs, it remains a concern in some regions like India and Korea. Although media coverage often highlights fire risks in EVs, they do not have a higher fire risk than traditional internal combustion engines. Nevertheless, OEMs are addressing safety proactively to boost consumer confidence and acceptance of electric vehicles.

SAFE ENERGY STORAGE SYSTEMS (ESS) CONTRIBUTE TO SUSTAINABLE BATTERY TECHNOLOGIES ALONG THEIR ENTIRE LIFECYCLE

Batteries are essential for transitioning to sustainable energy solutions, but sustainability encompasses more than just energy efficiency; it includes the entire lifecycle of the battery, focusing on safety and longevity. A truly sustainable battery must have a long operational life to offset its environmental and economic costs. Therefore, high safety standards are crucial not only to prevent hazards but also to enhance overall sustainability.[9]

To achieve this, advanced materials and technologies must be integrated into battery designs to mitigate risks such as thermal runaway and mechanical failures. Ceramic coatings applied to electrodes and casings improve safety by preventing thermal runaway and chemical degradation. For instance, aluminum oxide (Al_2O_3) and silicon carbide (SiC) coatings provide exceptional thermal stability. Additionally, silicon nitride (Si_3N_4) protects electrodes from corrosive electrolytes, while titanium nitride (TiN) offers corrosion resistance for current collectors. Real-world applications in electric vehicles demonstrate their effectiveness in enhancing safety.

Thermal insulation is critical for managing heat within battery packs. Potting compounds like epoxy resins encapsulate components for protection against temperature fluctuations, while polyurethane foam provides lightweight thermal barriers. Silica aerogels offer advanced insulation with low thermal conductivity. Thermal interface materials (TIMs), such as gap fillers and phase change materials (PCMs), enhance heat dissipation between components, maintaining optimal performance.

The use of these advanced materials not only improves safety but also extends the lifespan of batteries by reducing the risk for battery replacements. This lowers the demand for raw materials and mitigates the environmental impact associated with production and disposal. As the push for greener energy solutions continues, integrating fire-resistant materials along with effective thermal management strategies will be vital in driving innovations that support both safety and sustainability in energy storage systems.

TECHNOLOGY

Though cell design is an important influence, the product performance of EV batteries is mostly determined by two major configurations: battery chemistry and system architecture. Different battery chemistries vary in energy density, safety, and cost, influencing electric vehicle range, charging speed, and thermal management needs. Innovations in chemistry are seeing both evolutionary and disruptive development, with new chemistries and compositions emerging almost yearly. On architecture level, a general trend towards heavily

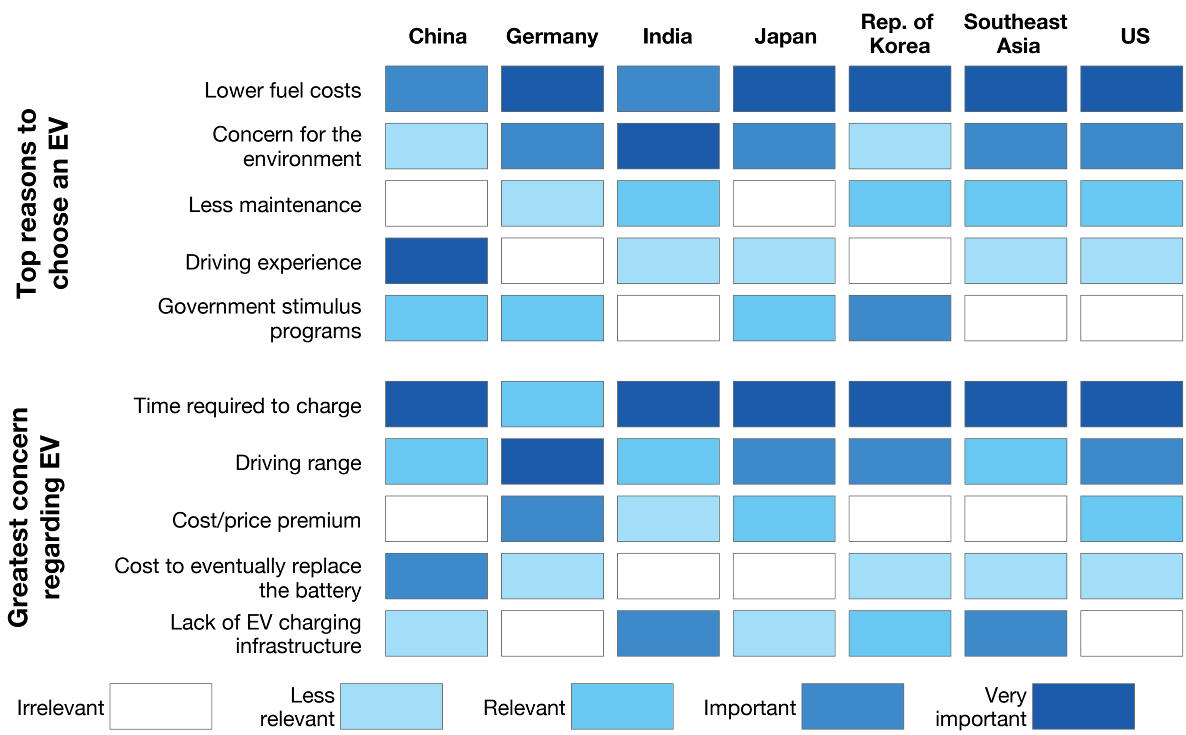


Figure 14: Customer performance expectations for e-mobility adoption;
Source: PEM of RWTH Aachen University, 2024 Global Automotive Consumer Study

integrated systems with the aim of reducing as much passive ESS material as possible can be identified. Although these approaches often enhance safety and energy efficiency, they fall short on sustainability aspects. Few players work on improving modularity, enabling repairability, and enhancing sustainability simultaneously.

IN EVALUATIONS OF THE MARKET POTENTIAL OF DIFFERENT CELL CHEMISTRIES, ENERGY DENSITY AND SAFETY ARE KEY METRICS FOR COMPARISON

Current popular cathode chemistries in EVs include lithium iron phosphate (LFP), nickel manganese cobalt (NMC), lithium manganese iron phosphate (LMFP), and sodium-ion batteries (SIB). Direct comparison shows significant differences in performance indicators such as energy density, cost, safety, and thermal management design. Especially energy density is crucial for vehicle range. NMC, and foremost among them high-nickel variants like NMC 811, offers superior energy density (up to 300 Wh/kg) but raises safety concerns due to increased reactivity, necessitating robust thermal management. This can slightly reduce pack-level energy density compared to cell-level potential.

LFP provides lower energy density (up to 190 Wh/kg) but excels in thermal stability and safety, allowing simpler pack designs with lower cooling needs due to lower heat generation, reducing weight and costs. In failure scenarios, LFP releases less gas than NMC and has a higher thermal runaway onset temperature (see figure 16). LMFP as a new variant combines LFP's safety with improved energy density without compromising stability. The higher safety of LFP, and potentially LMFP, allows for efficient cell-to-pack designs that offset their lower cell-level energy densities compared to NMC.[10]
SIBs are still developing for EVs; they offer lower energy densities but significant cost benefits and less demanding thermal management. Their pack-level advantages closely resemble those of LFP, but further research, technological development, and experience is needed to enable SIBs to compete on the EV market.[11]

CMP VS. CTP

System architecture is crucial for increasing a battery system's energy density and competitiveness. Currently, there is no clear trend in

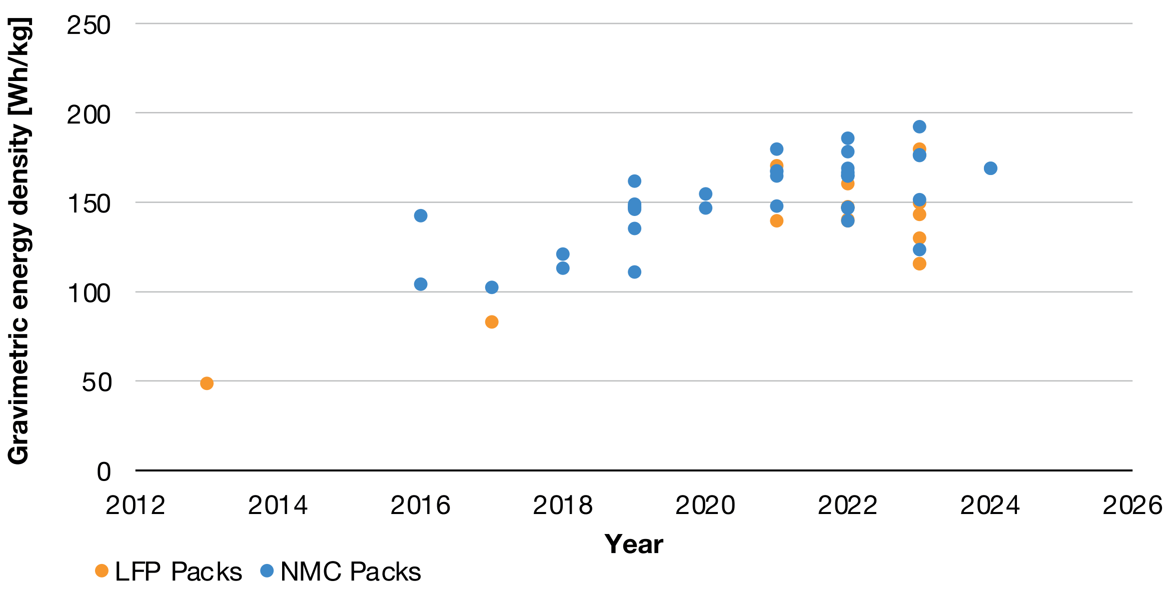


Figure 15: Energy densities of NMC and LFP based battery packs of various electric vehicles over their release year; *Source: Desk research*

preferred architectures. The conventional cell-module-pack (CMP) approach divides the battery into modules, each with its own housing. Newer methods aim to enhance energy density by integrating cells directly into the system, known as cell-to-pack (CTP) architecture. An even more advanced method is cell-to-chassis (CTC), which integrates cells into the vehicle chassis, saving space and weight but requiring complex manufacturing processes (see figure 17). These innovations can significantly improve energy density by reducing components and enhancing structural benefits. Continuous development of these architectures will further boost battery performance and integration possibilities across various vehicle types.

FOLLOWING TESLA'S INITIAL ADVANCE, SKIPPING-THE-MODULE ARCHITECTURE IS GROWING MORE AND MORE POPULAR, COMPROMISING ON SUSTAINABILITY

In the automotive industry, more players like BMW are currently moving towards cell-to-X approaches, following Tesla's architecture design. These architectures enhance battery system design by reducing passive ESS materials and mechanical protection, improving mechanical safety and energy efficiency, but they also compromise on sustainability aspects. Without a division of battery packs into independent modules, thermal events are harder to isolate to prevent catastrophic failures, even though thermal stability is enhanced. Modular designs, on the other hand, reduce waste by allowing only compromised modules to be replaced rather than entire packs, minimizing material use and environmental impact. They also promote repairability and support a circular economy by facilitating maintenance and recycling. The ease of replacing defective modules lowers downtime and operational costs, making systems more reliable. Additionally, this approach allows for upgrades without discarding entire systems, further conserving resources, reducing waste, and limiting environmental impact, while enhancing performance as technology evolves. As demand for efficient energy storage grows, these approaches will play an increasingly vital role in battery innovation.[12]

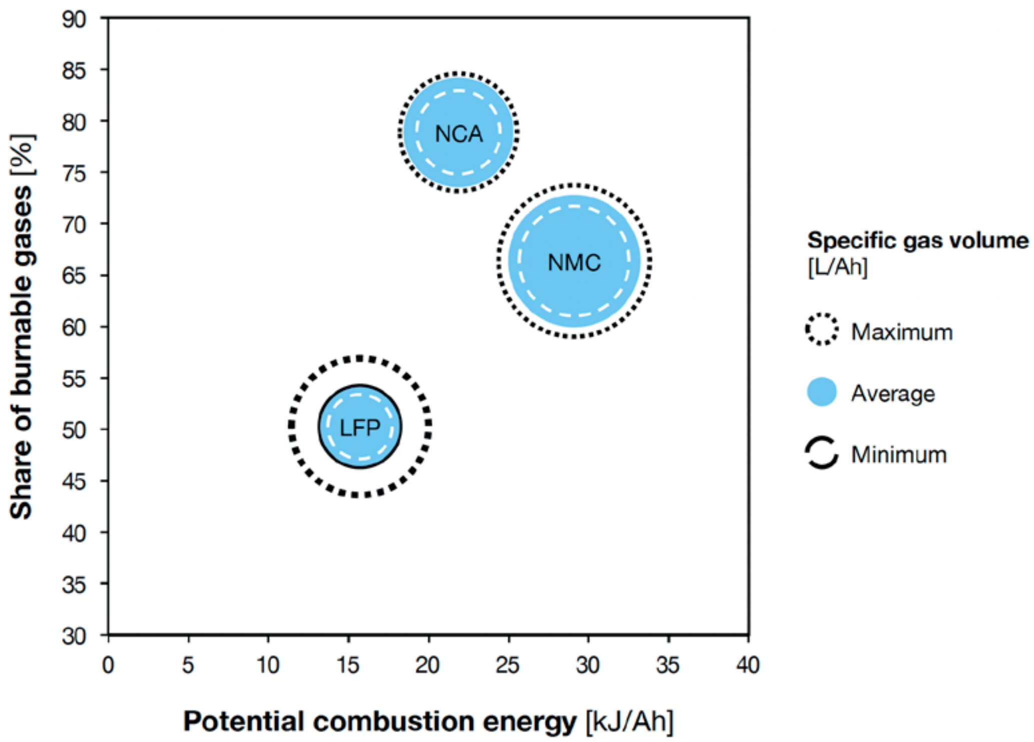


Figure 16: Comparison of the combustion energy potential of different cathode chemistries vs. their share of burnable gases and specific gas volume; *Source: PEM of RWTH Aachen University*

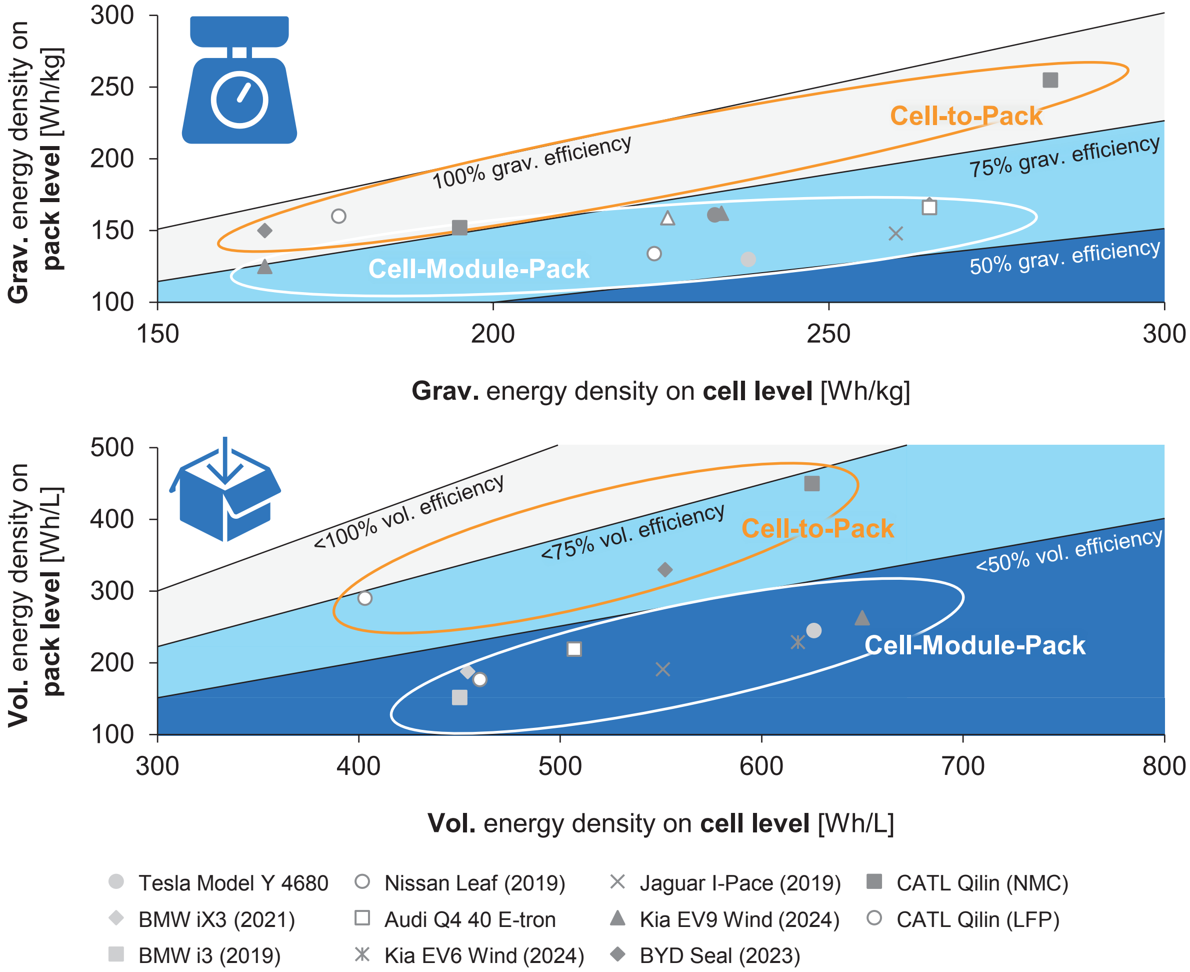


Figure 17: Gravimetric vs. volumetric energy densities on cell and pack level with respect to different pack architectures; *Source: PEM of RWTH Aachen University*

COMPETITIVENESS

Global electric vehicle registrations have increased, but the BEV market share has dropped due to rising sales of hybrids and internal combustion vehicles, along with high costs and depreciation challenges. To adapt, OEMs are expanding their offerings, updating models with improved battery systems, and, facing competition from Chinese EVs, looking to imposed EU tariffs to protect local markets.

THE CURRENT STATE OF ELECTRIC VEHICLE REGISTRATIONS

Last year saw a global increase in electric vehicle registrations, with Europe experiencing 29% month-on-month growth. However, the market share of battery electric vehicles (BEVs) fell from 20% in December 2023 to 12% in January 2024, largely due to rising sales of combustion engine and hybrid vehicles. Despite more BEVs being sold, the overall increase in non-BEV sales led to this decline. High purchase costs and significant depreciation also contribute to the lower BEV market share.[13]

COST AND RESALE CHALLENGES FOR BEVS

In 2023, the average price of a BEV was around EUR 46,000 – nearly double that of a conventional vehicle. The battery system accounts for 30-35% of total vehicle costs and its deterioration over time affects resale value and driving range. Accurately assessing battery health for used EVs remains complex.[14]

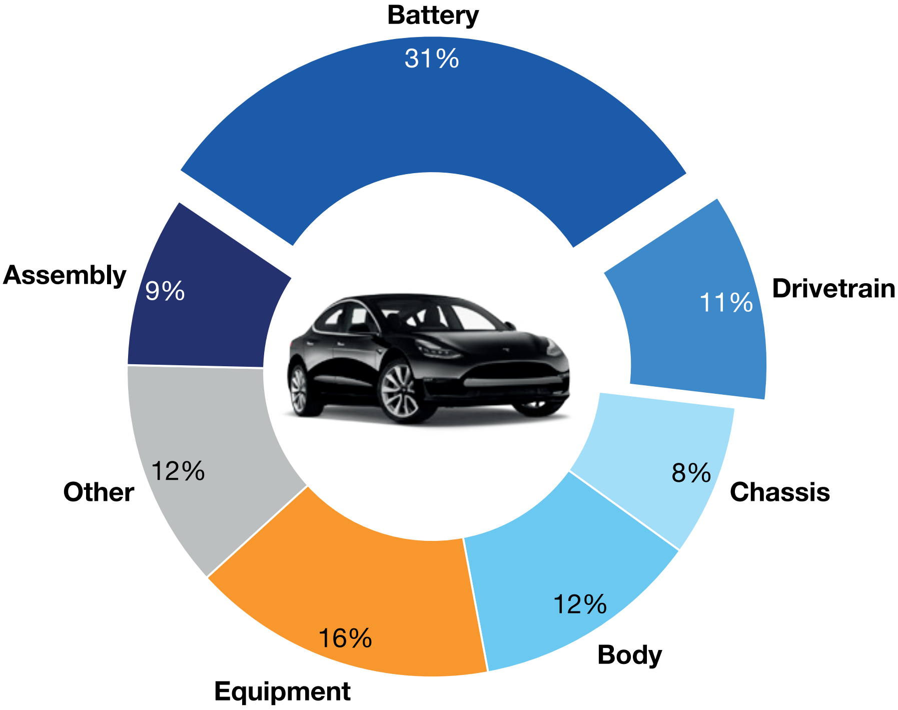


Figure 18: Proportionate manufacturing costs for an EV; *Source: PEM of RWTH Aachen University*

STRATEGIES FOR MARKET ADAPTATION

To enhance customer appeal, OEMs are diversifying their offerings across ranges, performance classes, and vehicle types like SUVs and compact cars. This variety is reflected in the Gartner hype cycle, which shows the evolution of EVs amid increasing competition from new manufacturers. By 2027, about 15% of recently founded EV companies may face insolvency or acquisition.

Additionally, existing models are undergoing facelifts with improved battery systems through new architecture and cell chemistries. Manufacturers aim to attract customers with minimal adjustments while under pressure from the growing presence of Chinese EVs in Western markets. To protect domestic industries, the EU imposes tariffs on imported Chinese EVs starting July 5, 2024, raising prices for consumers across Europe.[15]

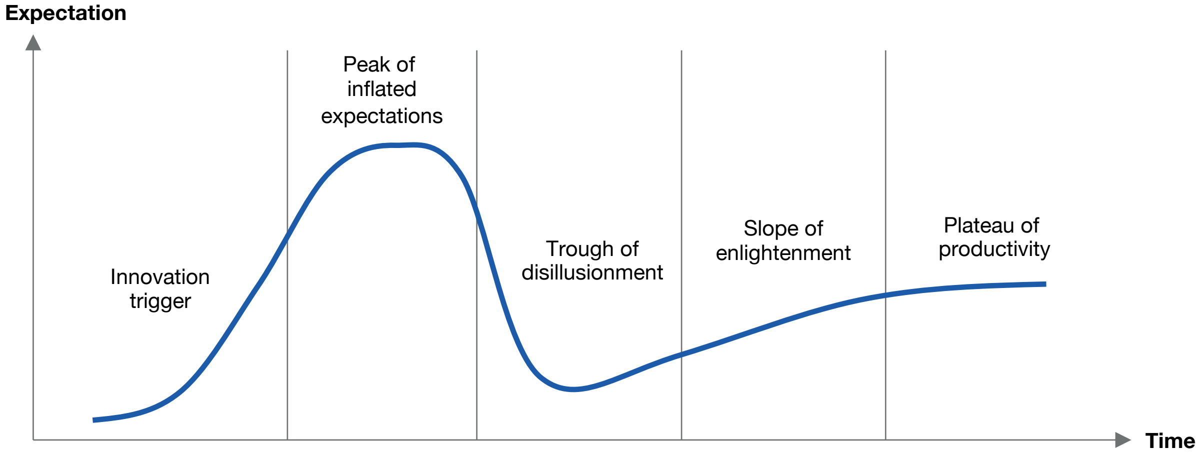


Figure 19: The Gartner hype cycle; *Source: Gartner*

Maximilian Graaf

> "High acquisition costs and charging issues are still challenging broad EV adoption – driving the push for innovations in battery chemistry and architecture. Today's trade-off in architecture lies between a higher structural integration for range and cost benefits and a classic modular design enabling repairability."

INNOVATION

Sodium-ion batteries (SIBs) present a sustainable, cost-effective alternative to lithium-ion batteries, with better thermal stability and design flexibility, although challenges like lower energy density persist. Innovations such as cell-integrated sensors and wireless battery management systems aim to enhance battery safety and performance but require technical and economic hurdles to be overcome for widespread adoption.

SODIUM-ION AS A PROMISING ALTERNATIVE FOR SUSTAINABILITY, SAFETY, AND COSTS

Sodium-ion batteries have gained interest due to their use of abundant materials, resulting in lower costs and environmental impact compared to lithium-ion batteries. For successful adoption, consumers and OEMs must recognize the SIB advantages. SIBs feature various cathode materials: polyanionic anodes offer longer cycle life, O3-based layered oxides provide higher energy density, and Prussian blue cathodes excel in low-temperature applications and high discharge rates. However, SIBs face challenges like lower voltage levels and energy density, and a less stable solid electrolyte interphase (SEI) layer. These shortcomings can be mitigated through battery design adjustments and appropriate electrode/electrolyte choices. SIBs also demonstrate better thermal stability, with thermal runaway occurring at temperatures 40% lower than lithium-ion batteries, reducing catastrophic failure risks. Flexibility in SIB design allows for a focus on safety or performance rather than cost. Using aluminum as a current collector reduces expenses compared to copper used in lithium-ion batteries and enables safe deep discharging without damage. This characteristic enhances safety during transport and storage while lowering production costs. Consequently, battery management systems for SIBs must adapt to the voltage-capacity correlation unique to these batteries.[16]

SMART BATTERIES OF TOMORROW: CELL-INTEGRATED SENSORS AND WIRELESS BMS

The evolution of battery technology is crucial for advancements in electric vehicles, consumer electronics, and renewable energy storage. With growing demand for efficient and safe energy solutions, the development of smart batteries has become essential. A significant advancement could be the integration of cell-level sensors and wireless battery management systems (BMS), though challenges must be managed for successful adoption. Traditionally, battery monitoring relied on external sensors providing generalized data. Cell-integrated sensors enable real-time monitoring at the individual cell level, tracking parameters like temperature and voltage to optimize usage and extend lifespan. However, manufacturing costs and sensor reliability are critical for broad implementation. New materials can alter the chemical environment, potentially affecting performance. Advances in sensor technology may mitigate these issues, while robust calibration methods can address inaccuracies. Wireless BMS aims to simplify battery management by eliminating wiring harnesses that add weight and complexity. Key improvements in signal integrity and communication protocols will enhance safety and efficiency. However, wireless systems often consume more power than wired ones, which could offset efficiency gains. The lack of standardization across wireless protocols also poses compatibility challenges for manufacturers. Innovations in power management may help reduce energy consumption in wireless systems, making them more viable for various applications. These technologies have the potential to revolutionize battery management, offering unprecedented levels of safety, performance, and scalability. However, realizing this potential will necessitate overcoming the demonstrated technical and economic challenges.[17]


Section 1
Section 2
Section 3
Section 4
Section 5
75%
ELECTRIC
MOTOR
SYSTEM
((GPS))
((HEADLIGHT))
((CAMERA))

Wolfgang Bernhart, Martin Weissbart, Tim Hotz, Konstantin Knoche

BATTERY USAGE

DESPITE THE CURRENT EV SALES SLOWDOWN, BATTERY USAGE WILL CONTINUE TO RISE IN THE FUTURE. THIS WILL MEAN BATTERIES NEED TO BECOME MORE SUSTAINABLE OVER THEIR ENTIRE LIFECYCLES, EV CHARGING NETWORKS WILL NEED TO BE EXPANDED, AND ALTERNATIVE TECHNOLOGIES WILL EMERGE.

Sustainability: Sales penetration rates and grid mixes are key to the sustainability of the transportation sector and EVs. A greener grid mix has a greater impact on battery usage emissions than cutting cell production emissions.
Technology performance: Range, determined by battery size and powertrain efficiency, is still a concern of EV buyers. Chinese customers have higher range expectations due to announced 1,000+ km ranges by Chinese OEMs and a more efficient test cycle overall, leading to higher ranges on paper.
Competitiveness: Charging is the key area of competitiveness in battery usage. China is the clear market leader, but the US and several European countries perform well in charging station density.
Innovation: Battery swapping is the only competitor to fast charging, but the market is nascent. China is leading in the rollout of EV battery swapping stations thanks to significant government subsidies and pioneering OEMs – but overall market acceptance will be decided per usage profile per segment.

STRATEGIC IMPLICATIONS

For regulators

Our analysis reveals that the greenhouse gas emissions associated with the lifetime of an electric vehicle are significantly more strongly influenced by the grid mix than by the emissions generated during battery production. Therefore, implementing regulations to improve the grid mix could have a more substantial impact on decarbonizing the transportation sector. Additionally, EV demand has stagnated and fallen short of market expectations in several regions. Recent discussions about reversing the phase-out of internal combustion engines (in Europe) have created uncertainties for consumers and hinder planning security for stakeholders across the value chain, ultimately impeding necessary investments in capacity expansion and localization.

For automotive OEMs

Based on customer survey and market data, there is a mismatch between the desired range of electric vehicles and the product offerings available in the market. While consumers are increasingly seeking vehicles with a range of over 500 kilometers, only a limited selection of models can meet this demand. However, it is important to note that range should not be equated with battery size: a more efficient powertrain can effectively enhance range without significantly increasing costs.

For investors

The charging infrastructure for electric vehicles requires further development, despite advancements in leading markets. Europe has an average of 70 to 80 EVs per fast charger (50 kW+), while China boasts just 17 EVs per fast charger, indicating a need for additional investments in Europe. Battery swapping, currently relevant only in China, presents an alternative solution. However, any large-scale investments must first assess specific use cases and regional applicability, as feasibility varies significantly. Moreover, investments in charging infrastructure are evolving beyond mere charging capabilities to include the creation of business models centered around stationary storage systems. This shift allows for revenue generation through multiple streams and enables sites with lower grid capacity to leverage battery power for expansion to higher charging powers.

SUSTAINABILITY

The sustainability impact of EVs on the transportation sector is dependent on two factors: market penetration (in relation to ICE vehicles) and the CO_2 intensity of the electricity used to charge their batteries over the lifetime of the vehicle. The second factor is dictated by the grid mix of the country where they are charged and now exerts a more significant impact than the production footprint of battery cells.

EV PENETRATION: EV SALES AND MARKET PENETRATION ARE SLOWING BUT WILL RECOVER IN THE MEDIUM TERM

After a period of rapid expansion in EV sales, growth slowed in 2023 and 2024. The slowdown was due to numerous headwinds, including inflation rises, reduced purchase subsidies as governments shifted their funding focus to charging facilities (as shown in the latest edition of the Roland Berger EV Charging Index), and higher electricity costs. However, we believe it is only a matter of time before EV growth rates recover.

In absolute terms, China sold the largest number of EVs in 2023 – around 5.4 million. This represents a market penetration rate of around 25% of all personal and light vehicles sold in 2023. Sales in the first three quarters of 2024 were 3.5 million, representing a market penetration of c. 26%.
Norway, meanwhile, has the highest market penetration rates, with fully battery electric vehicles making up 87% of vehicle sales in the first three quarters of 2024. If plug-in hybrid electric vehicles (PHEVs) are included, the figure rises to 90%.
Overall, however, EV penetration rates are falling or stalling year-on-year. While 2022 and 2023 saw significant growth, several markets flatlined between 2023 and Q3/2024. However, it should be noted that EV market penetration rates have historically increased at the end of the year in particular, as OEMs push into the market to fulfill emissions targets.
The markets in Germany and Sweden declined between 2022 and Q3/2024 due to the removal of subsidies, while the UK and South Korea more or less stalled. In the US market, growth in BEV sales stalled in Q1 2024 as new requirements on OEMs (i.e., IRA 30D critical mineral requirements) went into effect, reducing available incentives for some models. However, OEMs are expected to establish IRA-compliant supply chains in the near to medium term (see Battery Monitor 2023 for more details).

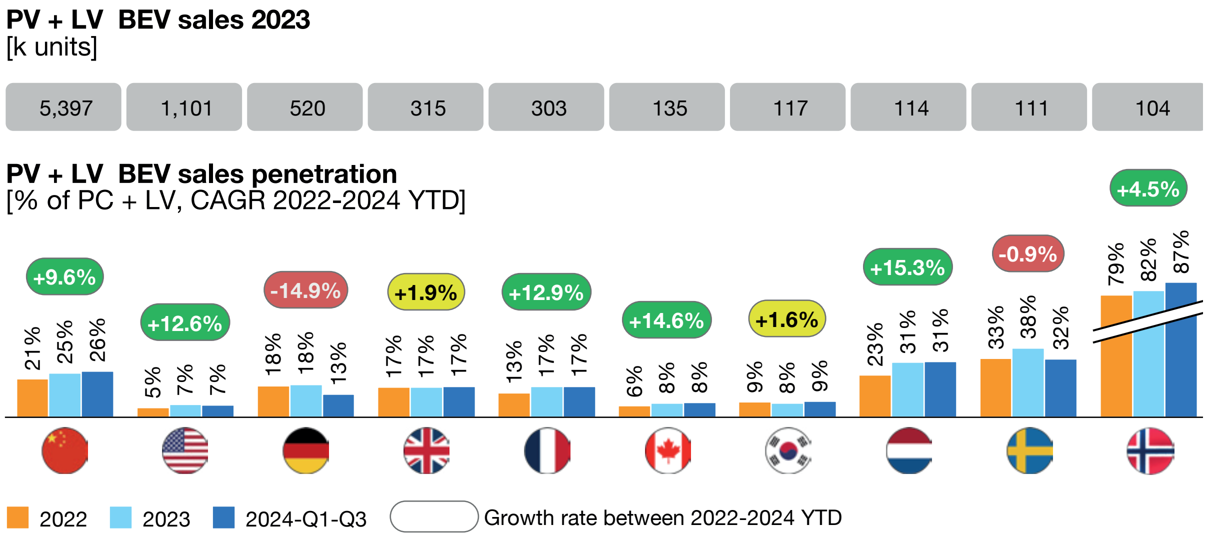


Figure 20: EV vehicle sales and market penetration in major EV markets;
Source: EV Volumes

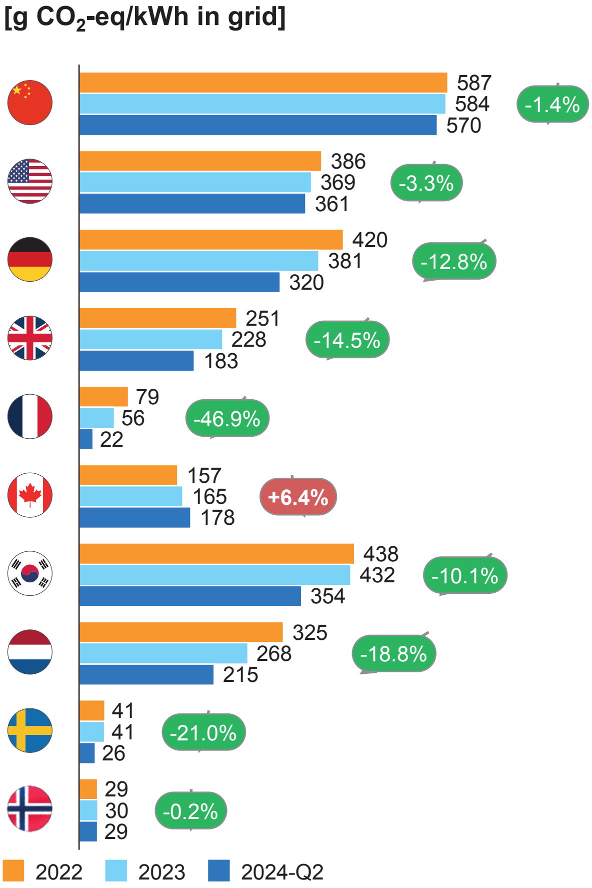


Figure 21: Carbon intensity of electricity grid [g CO_2-eq/kWh in electricity production]; *Source: Ember Climate*

The slowdown in EV sales – and therefore battery sales – combined with continued market volatility was the rationale behind the scenario modeling in the Overarching Market View chapter. We believe both will be temporary phenomena, but the market uncertainty must be factored into major decisions.

GRID MIX: GREENER GRIDS IMPACT BATTERY USAGE EMISSIONS MORE THAN CELL PRODUCTION EMISSIONS

A country's grid mix heavily influences the sustainability of an EV and its battery, as it determines how green the power used to charge the EV is. In many countries, shares of renewable power in grid mixes now compete with those of fossil-based fuels. This rise in clean energy led to a significant decrease in grid carbon intensity in almost all major EV markets between 2022 and H1 2024. Intensity levels fell even in China, where the country's huge recent investment in wind power offset its heavy reliance on coal-fired power plants.

Canada was the only market that saw a rise in carbon intensity levels, but the figure is still noticeably low. While the country produces around 60% of its power from hydroelectric sources and 14% from nuclear plants, its share of gas-fired electricity generation increased from 13% to 15% between 2022 and H1 2024.

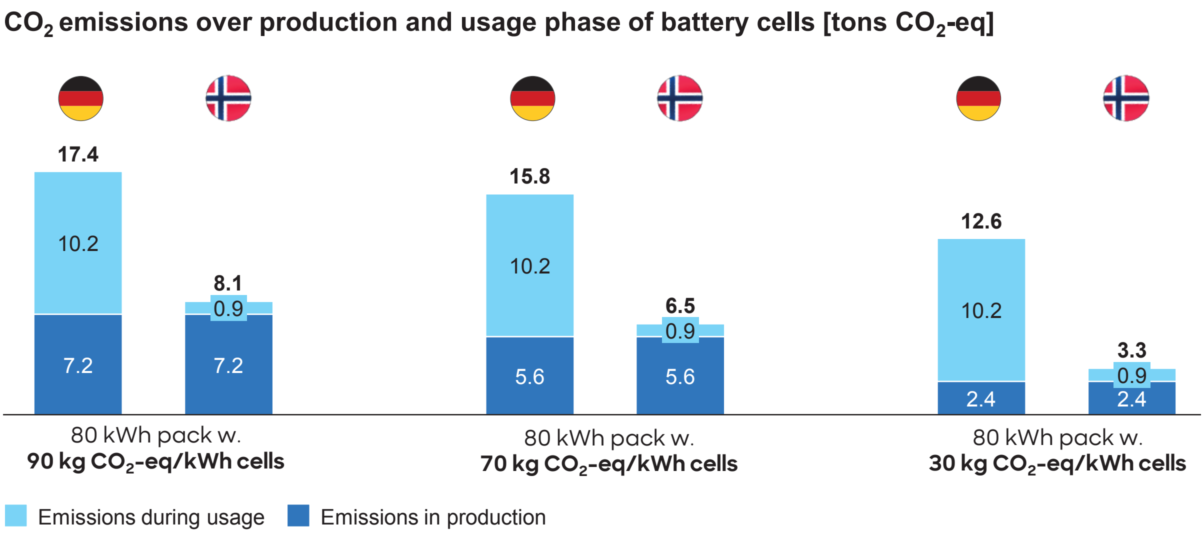


Figure 22: Comparison of production and usage phase emissions for different cell carbon intensities in Germany and Norway [tons CO_2-eq]; *Source: Roland Berger Battery carbon footprint model*

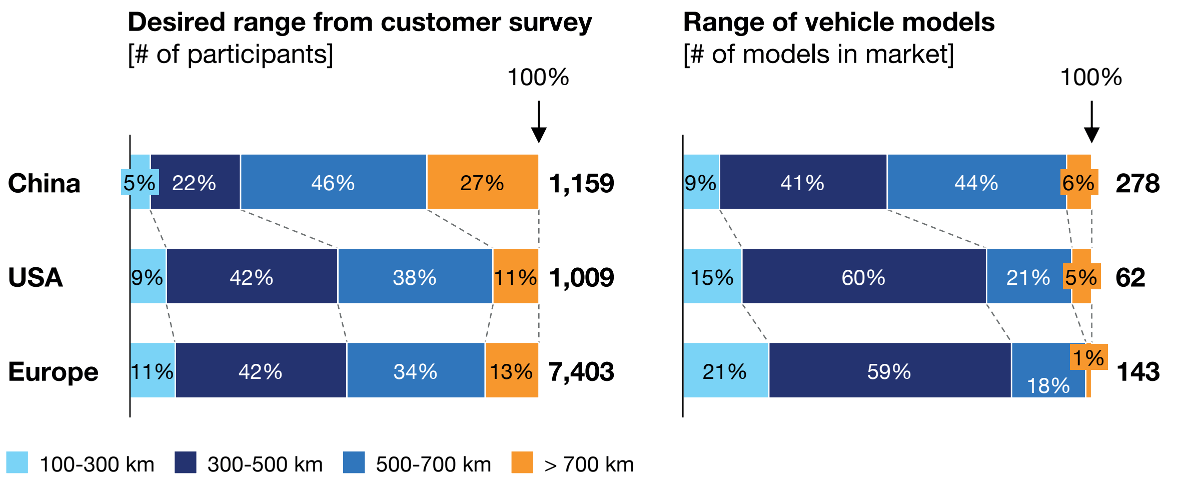
The overall lifetime footprint of an EV is influenced by the battery production footprint (see Overarching Market View – Sustainability and Battery Materials – Sustainability) as well as the grid mix. But how big is its impact in terms of emissions compared to the impact of the grid mix? We modeled different cell carbon footprints to determine production and usage emissions in two countries with very different grid mix carbon intensities – Germany (320 grams CO_2-eq/kWh) and Norway (29 grams CO_2-eq/kWh) (see figure 22).

As a guide, for an 80-kWh battery pack with a carbon footprint of 90 kg CO_2-equivalent per kWh of battery cell, the total footprint backpack these cells take into operation is 7.2 tons (left bars), compared to 2.4 tons CO_2-eq for cells with 30 kg CO_2-eq/kWh intensity (the target as pointed out in the Overarching Market View chapter) – a difference of about 4.8 tons. Usage emissions and their differences are much higher: Germany's relatively high grid carbon intensity results in usage phase emissions of around 10.2 tons CO_2-eq, while Norway's much greener grid results in 0.9 tons CO_2-eq – a difference of about 9.3 tons, nearly double the impact of the production footprint.

While CO_2 targets in battery production (such as those imposed by the EU) are crucial, these findings highlight the even greater importance of low grid emissions in developing a sustainable transportation sector. How can this be achieved? One potential solution, already in use in several EU countries, is to provide subsidies for private renewable energy generation, such as solar panels. Also, changing the design of energy markets has a significant impact. For example, the German plan to switch from an energy to a hybrid capacity mechanism significantly encourages the building of storage capacity at grid level together with renewable energy sources, instead of incentivizing the construction of thermal power plants for base load.

TECHNOLOGY

As discussed in previous Battery Monitor reports, advances in battery and vehicle technologies mean EV range is not as important a factor to buyers as it once was. However, consumers do still want maximum range for their money. To gauge how well current technologies match range requirements, we compared customers' desired range against the range of models available in several countries.



Note: For China, CTLC values used for range; for USA, EPA values used for range; for Europe, WLTP ranges used for range. Differences in real-life driving as well as between different test cycles can occur – local standards used to match survey participant point of view

Source: Roland Berger Charging Index, Ed. 5; EV Volumes

Figure 23: Comparison of desired driving range and EV model offering; *Source: Roland Berger Charging Index, Ed. 5; EV Volumes*

RANGE SURVEY: CHINESE-MADE EVS OFFER MUCH HIGHER AVERAGE RANGES THAN EVS PRODUCED IN THE WEST

By way of measuring customer range demands, the survey conducted for the latest Roland Berger Charging Index gives a good overview of desired range, complemented by details of the range levels offered in the market. The ranges of vehicle models are based on local standards (for example, WLTP in Europe). It should be noted that these standards do not represent the real driving range, which can be 20-40% below the communicated range, especially in winter time. In addition, range is not only dependent on battery size; it is also impacted by powertrain efficiency and the respective test cycle – therefore, Chinese consumers' higher desired range is partly triggered by higher announced ranges due to the more efficient test cycle. Implications on battery sizes therefore need to be taken with a grain of salt: merely scaling the battery will not lead to the desired customer ranges, and the discrepancy in evidence is most likely to be stretched even further when compared to real driving ranges.

In China, the survey showed that 27% of customers want EVs with a range below 500 km, with the remainder wanting longer ranges. This compared to 51% in the US and 53% in Europe.

The higher range requirements in China are most likely the result of the country's rapidly advancing industry, with perceptions of a "standard" range now much higher than just a few years ago. This is borne out by the fact that half of EV models offered in China have a range of more than 500 km, compared to around a quarter in the US and a fifth in Europe. There have also been several announcements in the past year by Chinese battery and EV manufacturers, for example CATL and Nio, of vehicles with 1,000 km-plus ranges, adding to expectations.

The figures for the US and Europe highlight the significant gap between customer desire for ranges above 500 km and the number of models available to service this market. The two markets are much more focused on the 300-500 km segment, adding to overall perceptions of shorter ranges compared to Chinese customer expectations. They also lag far behind China in terms of total number of EV models available: China has 278, compared to 62 in the US and 143 in the EU.

A key question is whether desired ranges are actually matched by a customer's real-life usage. Most consumers tend to overestimate their range needs, contributing to the "range anxiety" that persists in the US and Europe.

ACTIONS: OEMS SHOULD INCREASE THEIR OFFERING OF HIGHER-RANGE EVS AND REIGN IN RANGE EXPECTATIONS

There are two key takeaways from the survey data:

- OEMs, especially those in the US and Europe, will need to expand their product offering of high-range vehicles. The next generation of EV platforms will likely make this possible with technological progress. But to avoid major additional costs, which is currently the most pressing challenge, this must be scaled with powertrain efficiency and cost-effective cell chemistries.
- Consumer education campaigns and improved charging infrastructure can be leveraged to convince potential customers that a 500 km range is sufficient in most cases. This philosophy can also be integrated into next-gen platforms, whose faster charging capabilities will spur the building of fast charging infrastructure.

COMPETITIVENESS

Competitiveness in battery usage can be summed up in one metric – charging. Roland Berger's annual EV Charging Index report analyzes developments in the sector, and its 2024 edition is the basis for this subchapter. Please refer to the main report for more details.

EV CHARGING INDEX: CHINA IS THE CLEAR CHARGING MARKET LEADER, BUT ITS INFRASTRUCTURE IS FALLING BEHIND

The EV Charging Index ranks 32 leading EV markets in Asia, the Americas, Europe, and the

Middle East based on their performance in areas such as EV sales, public charging infrastructure, local charging sufficiency, charge point growth, and EV to charge point ratios. It also takes into account qualitative factors such as EV sales subsidies, ICE bans, and charging infrastructure funding, as well as investment activities and key charging technology advancements such as vehicle-to-grid concepts.

The 2024 edition found that the positive trend in global charging development is continuing, albeit at a slower pace due to the slowdown in EV sales from 2023. China (82 points), the US (71), and Germany, France, the Netherlands, and the UK (69) led the way in the overall rankings, with all of the biggest EV markets scoring above the global average. Canada was the lower-performing big market, due mainly to its poor EV sales penetration rate and low number of charging stations per 100 km (Canada 1.9/100 km, the Netherlands 102/100 km) – but still above the global average.

Despite China topping the Index ranking, the charging picture in the country was mixed. For example, while EV penetration rates in China rose until 2023, charging infrastructure has not kept pace. The number of EVs in the national parc per charging point is now 2.4, whereas the ratio in top-ranking France is 0.6. This explains why China has shifted its state subsidies from vehicles to charging networks. However, when it comes to fast charging, China is the clear leader, with a ratio of just 17 EVs per fast charger (charger with charging power of 50+ kW) compared to the European average of 70-80.

INNOVATION

While ultra-fast charging remains the holy grail in battery usage innovation, other technologies are now making up ground. Battery swapping, in which drained EV batteries are replaced by charged ones at a swapping station, offers an alternative to charging points, with waiting times similar to refueling ICE vehicles. Services are growing, especially in Asian markets, although hurdles remain.

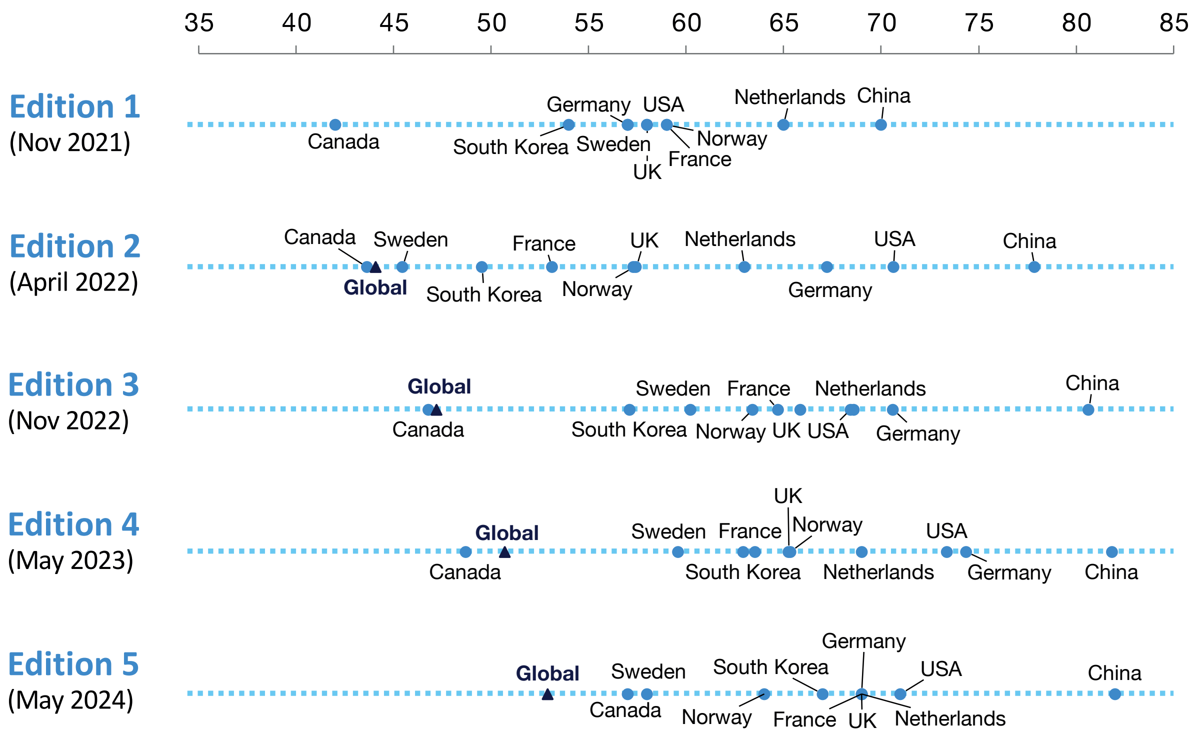


Figure 24: RB Charging Index Ranking, Ed. 1 to 5 [score out of 100];
Source: Roland Berger EV Charging Index

BATTERY SWAPPING: THE TECHNOLOGY HAS SEVERAL ADVANTAGES OVER CHARGING, BUT COMPATIBILITY IS AN ISSUE

Battery swapping has several advantages:

- EVs do not need to be fast charged at charging stations, so cell components that facilitate fast charging but reduce energy densities can be adapted (can lead to increased electrode thickness, for example). This results in higher energy densities and lower costs per kWh, and opens the door to solid-state technologies, which struggle to fulfill fast charging requirements, among others.
- Battery health can be checked every time the battery is swapped at a swapping station, increasing efficiency.
- Consumers are guaranteed a stable supply of batteries. This is especially important in countries with volatile grid supplies, where power cuts can interrupt charging at charging stations, which is less of an issue for swapping.
- Upfront costs for consumers can be reduced (although running costs are higher, see below).
- Battery swap EV owners lease their batteries under battery-as-a-service contracts, offering an additional revenue stream for OEMs.
- OEMs can gain further revenue from virtual power plant concepts, where idle batteries at swapping stations provide power to business customers.

However, there are also challenges:

- The infrastructure is not as mature as the charging infrastructure.
- The need for multiple batteries per EV sold increases overall costs, raw material consumption, and carbon/environmental footprint.
- Customers must agree to battery leasing contracts, which requires the re-education of consumers.
- Batteries must be compatible with the swapping technology, which is not a given across brands/platforms and is expected to be challenging. This is hindering widespread adoption compared to fast charging, where charging ports are standardized.

REGIONAL STATE OF PLAY: CHINA IS BY FAR THE LEADER IN SWAPPING TECHNOLOGY; OTHERS ARE EXPLORING USE CASES

Due to the technology's advantages and disadvantages, as well as other more localized factors, the swapping market is evolving at different speeds in different regions:

China: The Chinese swapping market is the most advanced. In 2020, the government officially recognized battery swapping as a key technology to support EV adoption. It has provided subsidies and other incentives to automakers and infrastructure providers, which are reflected in the high growth rate of swapping stations nationwide – China had more than 3,500 stations at the end of 2023. The country is also home to swapping pioneers, such as Nio, Changan, Geely, JAC, Chery, BAIC and SAIC, which are pushing for growth in their commercial vehicle fleets as well. In addition, battery maker CATL is developing individual platforms for automakers to adopt.

India, Indonesia, Thailand: The swapping focus in these countries is on two- and three-wheeler vehicles rather than EVs. In these markets, there are numerous simple swapping mechanisms that can be carried out by hand, removing complexity and compatibility issues. The Indonesian company Swap, for example, operates more than 1,500 swapping stations for e-motorcycles; the country aims to have 14,000 stations by 2025. The governments of all three countries have recognized battery swapping as a driver of electrification, offering subsidies to manufacturers and infrastructure developers, or aiming to standardize regulations to encourage market adaptation.

Europe: Battery swapping is only slowly gaining acceptance in Europe. Nio is the main driver of the technology; however, it has only 50 swapping stations in Europe, mostly located in Germany, Norway, and the Netherlands, compared to a six-digit number of public charging points. In addition, automaker Stellantis has signed a strategic partnership with Ample, a

Konstantin Knoche

> "Battery swapping can enable technologies that do not fulfill fast-charging requirements but can reduce battery costs and increase energy density, e.g., increased sheet thicknesses."

US-based swapping specialist, to integrate Ample's modular battery solution in its EVs. A plan to create a fleet of 100 Fiat 500e EVs with battery swapping capabilities in 2024 has not yet materialized, however. Meanwhile, researchers are investigating using swapping technology in commercial vehicles. The "eHaul" project, led by the Technical University of Berlin, aims to exchange a 440 kWh battery (big enough to power large trucks) inside 10 minutes, significantly improving the business case of the technology for long-haul trucks.

US: The battery swapping sector in the US is also nascent and evolving. Ample is the most prominent player, having signed partnerships with Uber in the US and Japan's Mitsubishi Fuso, as well as Stellantis. However, developments are primarily driven by private companies, explaining the low number (double digits) of swapping stations in the country.

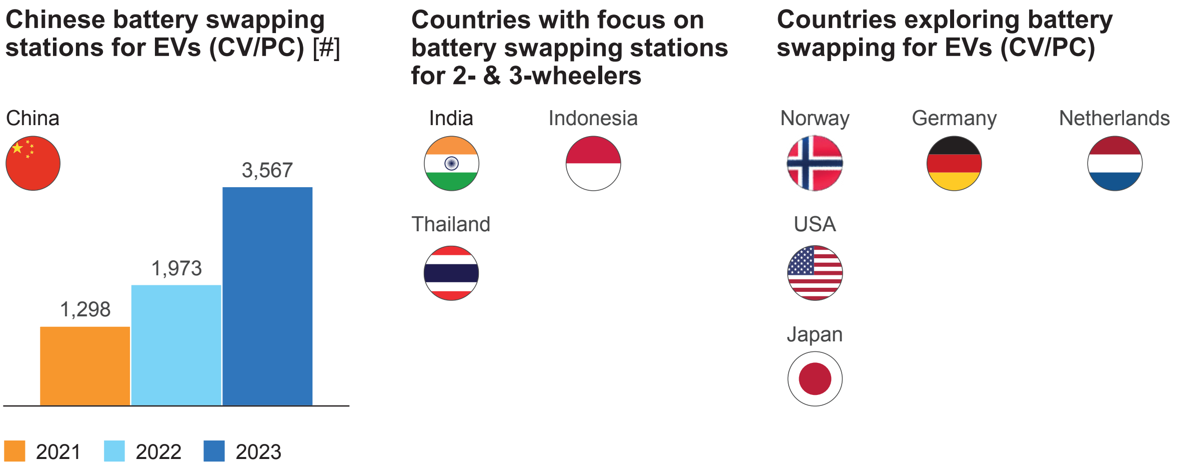


Figure 25: Current status of established and developing battery swap markets; *Source: RB Charging Index, Ed. 1-5*

Japan: The main development in Japan is the deal between Ample and Mitsubishi Fuso, which involves testing swapping technology in electric light-duty trucks on public roads in Kyoto. The aim is for a fully automated process that is complete in five minutes. To maximize speed, the swapping bay is drive through, a key difference to Nio's technology, in which the EV autonomously reverses into the swapping bay.

While battery swapping technologies are evolving, it is clear that they have a long way to go to catch up with more established fast charging networks.

> "The potential applications for battery swapping are limited, and standardization presents a significant challenge. Even within a single country or region, there are multiple, incompatible standards in place."

Martin Weissbart

Nikolaus Lackner

CIRCULAR BATTERY ECONOMY

ESTABLISHING A CIRCULAR ECONOMY FOR LITHIUM-ION BATTERIES IS KEY IN ACHIEVING A GLOBAL TRANSFORMATION TOWARDS SUSTAINABLE ENERGY PRODUCTION AND USAGE. ADVANCEMENTS IN LIFE CYCLE MANAGEMENT SUCH AS SECOND-LIFE APPLICATIONS AND AUTOMATED RECYCLING OFFER EFFICIENCY AND COST BENEFITS, BUT CHALLENGES IN INFRASTRUCTURE, SAFETY, AND REGULATORY ALIGNMENT REMAIN.

For battery manufacturers

Sustainability: Integrating lithium-ion batteries into a circular economy, supported by advancements in lifecycle management and regulations like the EU Battery Regulation 2023, is essential for sustainability, though challenges in recycling infrastructure remain.

Technology: Repurposing lithium-ion batteries for second-life applications offers sustainability and cost-saving benefits, but challenges in matching battery state to applications, recycling regulations, and cost dynamics need to be addressed.

Competitiveness: Despite regulatory efforts to enhance battery sustainability, global challenges in recycling capacity, operational costs, and infrastructure gaps remain significant.

Innovation: Automated disassembly and direct recycling offer significant efficiency and cost benefits for lithium-ion battery recycling, though challenges in safety and material separation remain.

STRATEGIC IMPLICATIONS

For regulators

- Regulatory frameworks similar to the EU Battery Regulations could be adopted globally to standardize sustainability practices across regions.
- Incentives to achieve carbon neutrality like tax benefits or subsidies can be offered to manufacturers that relocate production to areas with lower-carbon energy sources and integrate recycled materials in their production, as well as to companies that invest in recycling infrastructure and second-life applications and help create a viable ecosystem.
- Implementing traceability measures (e.g., Battery Passport) will enhance transparency and ensure that batteries are managed sustainably throughout their lifecycle. This will also help regulators and industry players verify compliance with sustainability standards and recycling targets.

For cell manufacturers

- To improve recovery rates of critical materials, manufacturers should invest in advanced recycling technologies, such as hydrometallurgy and direct recycling. Integrating recycled materials into new cells will lower the carbon footprint, which aligns with regulatory demands and consumer expectations for more sustainable products.
- Collaborations with renewable energy providers can also help reduce the carbon footprint associated with manufacturing processes.
- Standardization of battery designs could support automation in disassembly processes, reducing the cost and complexity of recycling end-of-life batteries.

For automotive OEMs

- OEMs could actively engage in a circular economy for LIBs by establishing take-back programs for used batteries and promoting second-life applications. This can also present an opportunity to build consumer trust and brand loyalty by demonstrating a commitment to sustainability.

- OEMs can partner with energy companies to repurpose used EV batteries in energy storage systems.
- Integrating advanced thermal management and safety features can ensure batteries retain value after their first life in EVs, making them attractive for second-life usage.
- OEMs can invest in the automation of battery disassembly to reduce labor costs and increase efficiency. This is especially important as battery return rates increase.

For investors

- Investments in advanced recycling technologies can capture the rising demand for recycled materials driven by global regulations and sustainability targets.
- Investments in growing markets for second-life LIBs can capitalize on the increasing focus on renewable energy and grid stability.
- Innovative recycling solutions, such as direct recycling, are well positioned to become industry standards as recycling efficiency and sustainability become key priorities.

SUSTAINABILITY

Integrating lithium-ion batteries into a circular economy is essential to minimize environmental impacts. Advancements in battery lifecycle management are driven by new regulations, such as the EU Battery Regulation 2023, which sets strict standards for emissions tracking, transparency, and environmental performance. Innovations in material extraction, production efficiency, reuse, and recycling are crucial for improving sustainability, though challenges remain in addressing diverse battery designs, underdeveloped recycling infrastructure, and regulatory consistency.

CIRCULAR ECONOMY INTEGRATION OF LITHIUM-ION BATTERIES IS KEY TO REDUCING ENVIRONMENTAL IMPACT

The rising demand for lithium-ion batteries in the automotive sector underscores the need to integrate them into a circular economy to minimize environmental impact. The battery

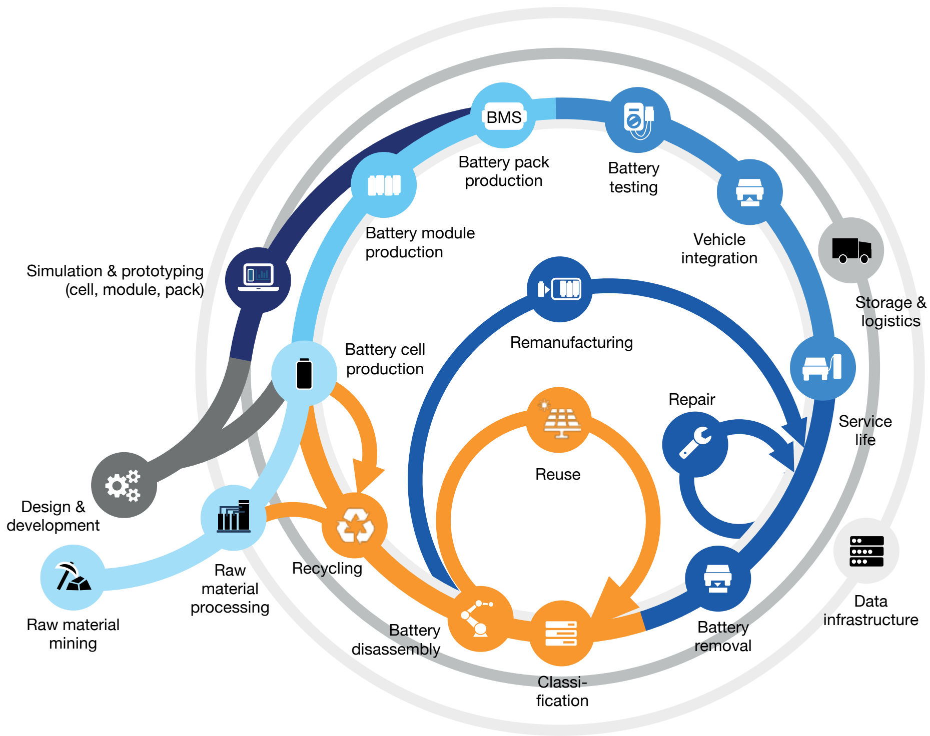


Figure 26: Battery lifecycle with different phases; *Source: PEM of RWTH Aachen University*

lifecycle includes raw material extraction, manufacturing, usage, and end-of-life recycling. As batteries degrade during use, they lose capacity but remain functional for other applications. Depending on their state of health (SoH), LIBs can be reused in stationary energy storage systems or repaired to extend their lifespan. Ultimately, they can be recycled to recover materials for new batteries.[18]

Throughout these stages, carbon emissions and waste are generated, particularly during raw material extraction and battery production. Quantifying these emissions is essential for developing mitigation strategies. Notably, Chinese cell manufacturers dominate the market; thus, analyzing their greenhouse gas emissions provides valuable insights into industry impacts. Lifecycle analyses indicate that carbon emissions from producing nickel-rich LIB cells range from 85 kg to 108 kg CO_2-equivalent per kWh, with only 25% to 35% attributed to cell manufacturing. Supply chain choices and production locations significantly influence sustainability; the carbon footprint can vary by as much as a factor of three based on mining and refining processes.[19] Manufacturing emissions can be reduced by relocating production facilities to areas with low-carbon energy sources. During battery utilization, emissions depend on the electricity grid's renewable energy percentage. A closed-loop cycle for battery materials offers significant sustainability potential by maximizing material reuse and minimizing waste. Strategies such as using recycled materials in cell manufacturing – especially through hydrometallurgical processes – can lower carbon footprints effectively. Reusing batteries in second-life applications also reduces environmental impact by avoiding new battery production. Despite these opportunities, challenges remain in establishing efficient collection systems for used LIBs and developing robust recycling technologies. The carbon footprint of LIBs is heavily influenced by the local electricity mix used during the production and consumption phases. While the EU has made strides with its Battery Regulation introduced in 2023, its immediate environmental impact is confined to Europe. Furthermore, lifecycle assessments often

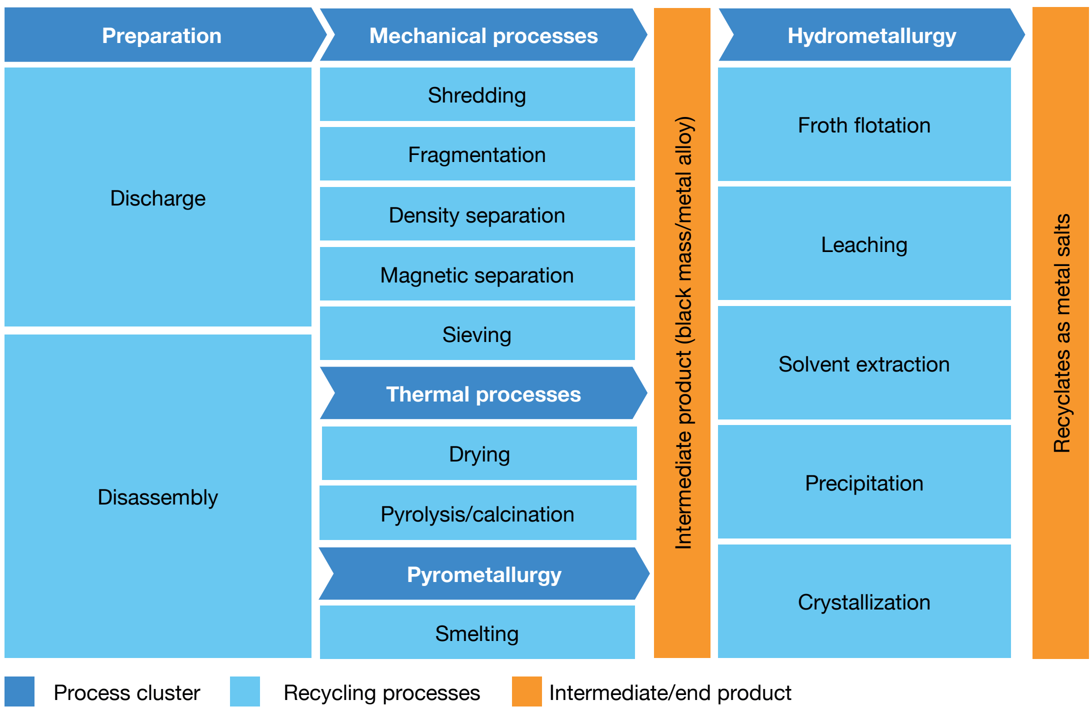


Figure 27: Different battery recycling processes; *Source: PEM of RWTH Aachen University*

yield diverse results for GHG emissions due to methodological uncertainties despite the existence of ISO standards. Addressing these challenges is crucial for sustainable LIB production and usage.

EU BATTERY REGULATION 2023 DRIVES SUSTAINABILITY THROUGH STRICTER STANDARDS, EFFICIENCY INNOVATIONS, AND RECYCLING ADVANCEMENTS

Recent advancements in tracking waste and carbon emissions are being driven by new regulations aimed at improving corporate processes. The EU Battery Regulation 2023 sets strict environmental standards for batteries throughout their lifecycle, requiring EV battery carbon emissions to be declared from February 2025. By August 2026, batteries will also be rated on their carbon footprint, with a maximum limit established by February 2028. To enhance transparency, the EU will introduce a mandatory Battery Passport by February 2027, featuring QR codes that provide access to essential battery information. Innovations in material production aim to reduce the environmental impact of mining and refining through less energy-intensive extraction methods. A cradle-to-gate lifecycle assessment suggests that deep-sea mining could significantly lower emissions compared to land mining for metals like Ni, Mn, Co, and Cu[20]. Electrification of mining equipment and a cleaner electricity mix can further reduce emissions. Improvements in cell and system production are enhancing efficiency and lowering emissions. For instance, increased production efficiency could cut carbon emissions by up to 40%, while diode laser drying has shown potential for reducing energy consumption by 85%. Lower scrap rates in gigafactories will also positively impact the carbon footprint of lithium-ion batteries. Battery reuse is a way to extend their useful life, thereby reducing the need for new materials and minimizing environmental impact. However, challenges such as unclear regulations and diverse battery designs complicate the process of establishing effective business models. Nevertheless, more companies are entering this space to address these issues.[21]

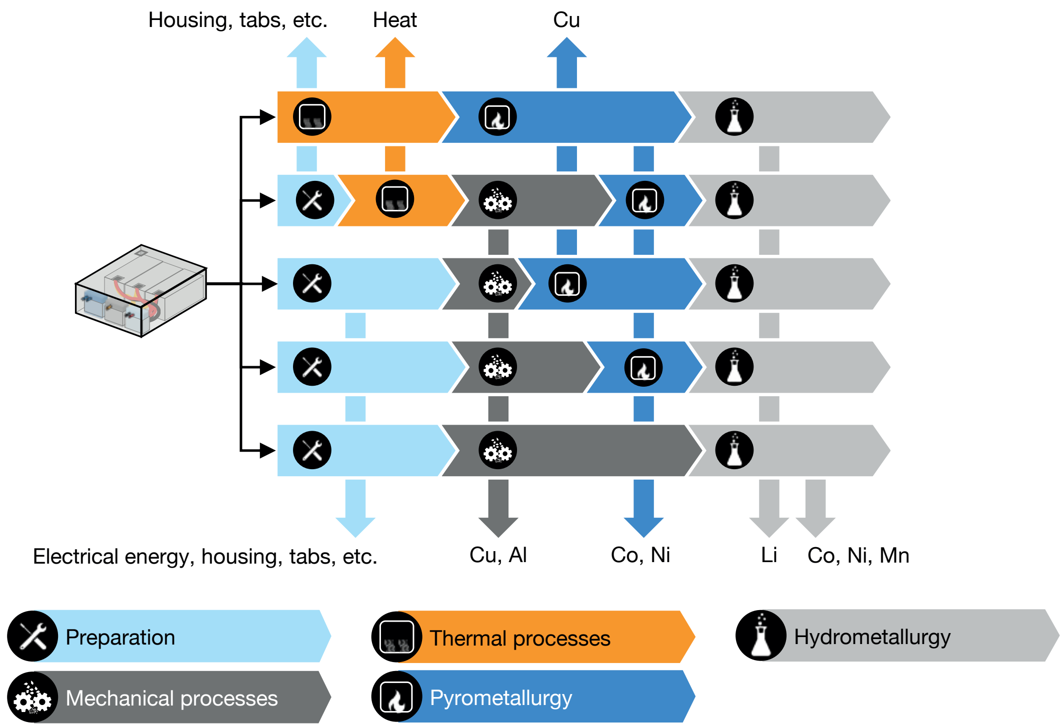


Figure 28: Recovered materials in the different recycling stages;
Source: PEM of RWTH Aachen University

Advancements in recycling technologies are improving recovery rates for end-of-life batteries while reducing environmental footprints. Hydrometallurgical processes offer high recovery rates with low energy consumption but lack an industry standard for LIB recycling due to the diversity of battery packs. As of 2024, a robust ecosystem and effective logistics for large-scale recycling remain underdeveloped.

TECHNOLOGY

Repurposing lithium-ion batteries for second-life applications presents opportunities for sustainability and cost savings, benefiting stakeholders involved in reusing, supplying, and utilizing these batteries. Common uses include energy storage and grid stability, and although the market is still developing, various projects across the EU highlight its potential while emphasizing the need to address challenges like battery state matching, recycling regulations, and cost dynamics.

SECOND-LIFE LIBS: SUSTAINABLE SOLUTIONS AND COST SAVINGS FOR ENERGY STORAGE AND GRID STABILITY

Second-life applications for lithium-ion batteries offer sustainable potential and cost savings for stakeholders, including OEMs required to take back used batteries, suppliers repurposing them, and customers utilizing second-life batteries. Common uses include stationary energy storage for balancing renewable energy generation and maintaining grid stability, as well as temporary storage in EV charging infrastructure.[22]

Various projects across the EU highlight the potential and challenges of second-life LIB applications. These initiatives provide valuable insights into current developments. For instance, Enel's project in Melilla, Spain, uses second-life Nissan batteries to supply electricity for 15 minutes during power plant outages. RWE's Anubis project repurposes bus batteries in the Netherlands to stabilize the grid and store renewable energy during

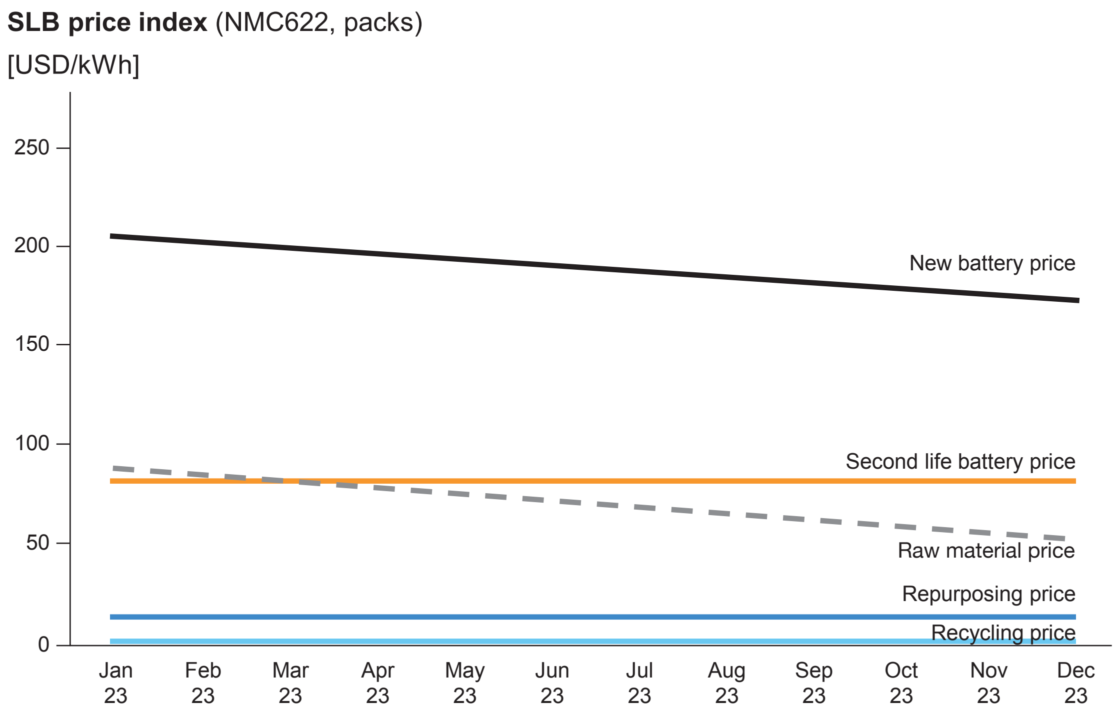


Figure 29: Battery pack-level prices from the current price index for SLBs (NMC622 cathode chemistry); *Source: PEM of RWTH Aachen University*

periods of low demand. In Portugal, Renault collaborates with EEM and TMH to decarbonize Porto Santo using second-life batteries alongside renewable energy production.

CHALLENGES AND OPPORTUNITIES IN DEVELOPING A VIABLE SECOND-LIFE BUSINESS MODEL FOR LITHIUM-ION BATTERIES

The second-life business model for LIBs is still at an early stage of development due to the young EV market in combination with long vehicle lifetimes. Consequently, there are several barriers in various thematic fields, complicating the rededication process for LIBs. Addressing these challenges is essential for making battery reuse a viable option.
Studies show that the battery's aging and its price play important roles in the viability of a second-life application. Comparing reused batteries for stationary applications reveals important insights into cost-effectiveness and performance trade-offs. It is also important to match the application with a suitable battery based on its state to extend its lifetime. Furthermore, repurposed LIBs could reduce the final selling price of an EV.[23]

IMPACT OF REGULATIONS AND MARKET DYNAMICS ON LITHIUM-ION BATTERY RECYCLING AND SECOND-LIFE APPLICATIONS

Regulations significantly shape battery recycling practices, with the EU's Battery Regulation influencing global standards. In China, directives enhance recycling efficiency, while North America offers tax credits for recycled materials under the US Inflation Reduction Act. Understanding these legal implications is crucial for future planning. The demand for sustainable sourcing and recycling of lithium-ion batteries is increasing, driven by regulations like the EU Battery Regulation that require recycled materials in new LIBs. However, secondary sources are projected to meet only 9% to just over 15% of lithium demand and up to 51% of cobalt demand by 2040. Nickel estimates vary from 15% to 42%. A fully closed loop for battery lifecycles is unlikely, though nearly full recycling could cover about 60% of active material demand by 2040. Technological advancements will impact battery recycling economics by lowering costs and improving recovery rates. High capital and operational expenses currently challenge the industry, particularly in hydrometallurgical recovery. A recent study by RWTH Aachen University created a price index for second-life batteries (SLBs) to compare them with used cars. Unlike used car dynamics, SLB pricing is affected by different business models and a lack of transparency. The index serves as a price indicator and predictive tool, highlighting substantial profit opportunities in repurposing SLBs while cautioning against neglecting functional SLBs due to opportunity costs.[24]

While competition between new batteries and SLBs may stabilize over time due to similar cost reduction potential, product-specific price fluctuations will occur based on quality levels and state of health. Overall, this research emphasizes unique pricing mechanisms for SLBs compared to used vehicles and offers strategic insights into market trends.

COMPETITIVENESS

While the EU Battery Regulation pushes for higher sustainability standards, challenges in recycling capacity, operational costs, and infrastructure gaps persist globally, with Europe, China, and the US each developing their own strategies to address these issues.

IMPACT OF EU BATTERY REGULATION AND GLOBAL POLICIES ON SUSTAINABILITY AND RECYCLING IN BATTERY PRODUCTION

The EU's Battery Regulation aims to enhance sustainability and competitiveness in battery production. Key points include increasing minimum recovery targets for materials – 95% for cobalt, copper, and nickel, and 80% for lithium by 2031. Recycling efficiency will rise from 65% in 2025 to 70% in 2030. From 2031, new batteries must contain a minimum of recycled content. Specifically, 16% for cobalt, 6% for lithium, and 6% for nickel, increasing to 26%, 12%, and 15%, respectively, by 2036. Compliance with these standards is driving innovation in the European battery industry.
In contrast, the US lacks federal battery recycling regulations but has programs that impact recycling indirectly. The Inflation Reduction Act incentivizes using critical minerals extracted or processed in

North America for tax credits. China's interim policy framework mandates high recovery rates (98% for cobalt and nickel; 85% for lithium) and includes lifecycle management guidelines but does not specify recyclate content for new batteries.
Japan regulates battery recycling through general laws aimed at achieving a circular economy. Overall, the EU regulation encourages manufacturers to design more sustainable products, while influencing OEM business strategies towards compliance with environmental standards and consumer demand. However, existing battery architectures often prioritize performance over sustainability, complicating recycling efforts and second-life applications.[25]

ECONOMIC CONSIDERATIONS AND CHALLENGES IN THE LITHIUM-ION BATTERY RECYCLING MARKET: CAPEX, OPEX, AND THE ROLE OF BLACK MASS DEMAND

The lithium-ion battery recycling market involves various players from collection to material recovery, creating a comprehensive ecosystem. The expanding demand for black mass – a valuable output of recycling – highlights the economic potential driven by regulations for battery-grade materials. Efficient logistics and material streams are crucial for optimizing recycling costs and processes. Economies of scale significantly affect cost efficiency in final recycling steps, with different recovery strategies offering tailored economic and environmental benefits. Capital expenditure (CAPEX) for recycling plants includes significant initial setup costs, ranging from USD 6,000 to USD 9,000 per ton of recycling capacity, covering mechanical recycling, hydrometallurgy, land, and planning. These figures apply primarily to larger facilities processing over 10,000 tons annually; smaller plants incur higher costs due to inefficiencies in low-volume operations. Operational expenditure (OPEX) reflects ongoing costs, impacting the feasibility of recycling operations. For hydrometallurgical plants, operating costs are estimated at USD 1,600 per recycled ton per year, largely driven by

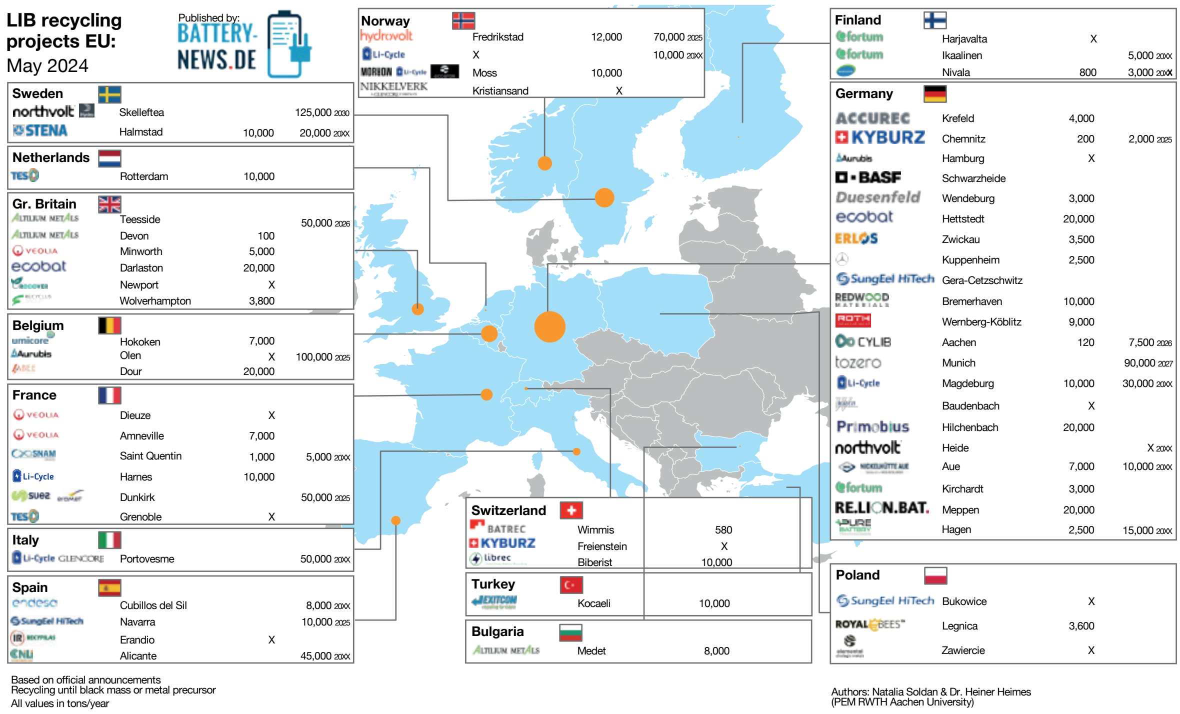


Figure 30: Announced battery recycling projects in Europe with their respective capacities as of May 2024; *Source: PEM of RWTH Aachen University, Battery News*

treatment processes and variable factors like energy prices and maintenance.

COMPARATIVE ANALYSIS OF EUROPEAN RECYCLING CAPACITIES

The growing amount of announced recycling capacities worldwide reflects a growing commitment to building recycling infrastructure, with strategic implications for regional and global markets. This is especially relevant for the core automotive sales and production markets of Europe, the US, and China. By 2030 an expected global recyclable volume of 466 GWh will not be covered by the announced recycling plants' capacities of 266 GWh. By 2030 there will be approximately 100 GWh in recyclable batteries in Europe, whereas the announced recycling plants' capacity reaches approximately 110 GWh. However, it is expected that the recyclable volume will grow faster than the recycling capacity, leaving a capacity gap from 2030 onwards.[26]

The recycling market in Europe is especially driven by the lack of abundance of large raw material deposits and the EU Battery Regulation. China has the greatest recycling capacities, having reached approximately 500 kilotons by 2023. The US had an approximate battery recycling capacity of 105 kt as of September 2023. However, including announced recycling capacity, the figure could reach up to 650 kt by 2030, which would be sufficient to recycle end-of-life batteries until 2044. The US battery recycling industry is especially driven by smaller companies, with some of them having received major investments from the US government and venture capital firms to build recycling plants in the expectation of rapidly increasing demand.[27]

INNOVATION

Automated battery disassembly can significantly reduce safety risks and costs in the LIB recycling process, with automation offering up to 97% cost reduction, while direct recycling provides an efficient, less energy-intensive alternative to traditional recycling methods, though challenges remain in separating materials without impurities.

AUTOMATED BATTERY DISMANTLING

The disassembly of batteries plays a central role after the use phase of a LIB, being the step before a possible reuse or the recycling of cells. Currently, the disassembly presents significant challenges, including safety risks and complexity. Addressing these challenges requires the development of advanced disassembly technologies. During the dismantling process, the high voltage of the batteries while the modules and cells are still interconnected poses a safety risk for workers if the first steps are performed manually. Additionally, the electrolyte in the cells poses a further potential hazard in the event of leakage due to mechanical deformation caused by an accident or even during handling while dismantling. The robotization of battery disassembly holds great potential for reducing safety issues. A challenge faced during disassembly of battery packs from different OEMs is the variety in their design, which would not enable the standardization of the disassembly process, thus making its automation even more complex. The process is also highly affected by welded joints, adhesive joints, and plug-in connections, requiring innovative solutions. Rising return rates projected for the late 2020s drive the demand for automated disassembly solutions with higher efficiency and lower costs. Analysis of a potential reduction of the disassembly costs of six commercially available battery packs by semi-automating and by fully automating the process indicates that due to the time saving and higher throughput, the disassembly labor costs of a single pack operation can theoretically be reduced by 76% in a semi-automated operation and by up to 97% in a fully automated process. Analysis of the disassembly process of a plug-in hybrid EV with an emphasis on automation potential shows that 54% of disassembly time was readily automatable and 24% partially automatable with human intervention. Given those results, and based on a case study of a human-robot collaborative workstation, the disassembly costs could be reduced by 46.84%. The achievement of improved process capabilities with higher throughput and efficiency via the introduction of robots

Nikolaus Lackner

> “In the short term, upcoming regulations will drive innovation in the sustainable use and management of batteries. In the long term, profitable business models around sustainable batteries will continue to support innovation and the broader ecosystem.”

highlights the economic benefits of disassembly automation.[28]

POTENTIAL IN DIRECT RECYCLING

Traditional recycling methods (pyrometallurgy and hydrometallurgy) in the LIB recycling industry consist of extracting elements of spent batteries using thermal or chemical processes by destructing the composition and structure of their active materials. The output of these processes comes in the form of transition metal hydroxides or salts, which are later reprocessed into active materials by energy-intensive operations. In this context, direct recycling offers significant advantages over traditional methods by reconditioning active materials in their original state. Therefore, direct recycling requires fewer processing steps, less energy, and less chemicals input. Furthermore, the recovered products are more valuable than precursors obtained by traditional recycling methods, which also reveals potential economic benefits.[29]

Direct recycling applications are expanding, driven by their environmental potential and especially due to the great potential of recycling production scrap efficiently, since there are no degradation effects in the active materials due to cycling. Despite the very promising results and positive environmental aspects of direct recycling, there are several challenges that the industry needs to overcome. The pre-processed materials in the current recycling industry are composed of cathode and anode materials, conductive agent, PVDF binder, and other residuals, which cannot be direct recycled due to the impurities. Establishing a standardized process with high efficiency to separate anode and cathode materials without damaging the structure is the biggest barrier now. Nevertheless, the battery production scrap of electrode materials is a source of cathode and anode materials already separated, representing the best available source for the direct recycling route.[30]

Tim Hotz, Kyle Gordon, Konstantin Knoche, Maximilian Graaf

KEY TAKEAWAYS, CLOSING WORDS & OUTLOOK

To summarize the report, we will now explore the subchapters on sustainability, technology, competitiveness, and innovation, offering a holistic overview and providing insights from a different perspective.

Sustainability
Achieving the EU's CO_2 targets necessitates a focus on renewable energy and robust local sourcing, with the goal of reducing emissions to 30-40 kg CO_2 per kWh being attainable if pursued diligently, particularly through improved material sourcing. Innovations such as laser drying and dry coating can address energy demands associated with key production processes and therefore improve sustainability and costs.
In general, many automotive OEMs currently prioritize being cost competitive over implementing sustainability initiatives beyond regulatory compliance. While customers are attracted to electric vehicles for their environmental benefits and maintenance cost savings, barriers such as high prices, charging challenges, and battery safety concerns hinder broader adoption. Additionally, repurposing lithium-ion batteries for second-life applications presents opportunities for both sustainability and cost savings.

Technology
Lithium iron phosphate (LFP) batteries dominate cost-sensitive applications due to their pricing efficiency, but low-cost production within Western local value chains is hindered by supply chain challenges. Incorporating up to 10% silicon dioxide into graphite anodes can be easily integrated into existing production lines, while other silicon-based technologies remain in the innovation phase and are not yet produced at scale. Current production focuses on cost reduction and quality improvement through enhanced efficiency, reduced cycle times, increased overall equipment effectiveness, minimized scrap, and early defect detection. Advanced cell-to-X designs improve energy density, safety, and efficiency, enhancing electric vehicle performance but potentially compromising sustainability. Lastly, for reusing batteries after the first life, challenges persist in matching battery states to applications after initial use, together with recycling regulations and cost dynamics.

Competitiveness
The decline in electric vehicle demand, combined with overcapacity in China, has put significant cost pressure on Western markets, especially in Europe. This downturn has led to falling raw material prices, which are expected to lower battery cell and vehicle costs. Since the peak during the COVID-19 pandemic, battery cell prices have decreased consistently, with some trading below USD 50 per kWh. However, this trend is not seen as sustainable, and prices may rise again. The effects of these fluctuations on EV demand will be evaluated in next year's Battery Monitor edition.
Challenges remain in scaling cell production in the US and EU, securing skilled talent, and achieving technological sovereignty. European manufacturers are focusing on innovations that may be able to be integrated in the next generation of batteries to compete with cost-effective Asian firms and technology-driven American companies. The overcapacity in China and

low-cost exports from Chinese producers have increased tensions in the global market. In response, the US has imposed tariffs on Chinese battery imports, and Europe on Chinese EVs. The EU and US must transition to affordable mass production, which requires significant research and collaboration among companies to catch up with Asian leaders.

Innovation

The battery industry is currently focused on innovations aimed at cost-saving measures in cell chemistry, production, and pack integration, crucial for entering high-volume markets like automotive and stationary energy storage. LMFP technologies from China are being explored by Western players. Manganese-rich (in the very early stages) and single-crystal high-voltage mid-nickel chemistries are expected to target the EV volume segment once ready, while sectors like aerospace and eVTOL require next-generation technologies and are not as reliant on cost-effective solutions.

Despite the potential cost savings of silicon anodes, the market implementation of high-silicon anodes is still limited. Technologies such as silicon-carbon composites and silicon nanowires could enhance energy density and fast charging but have yet to reach their theoretical potential. Additionally, innovations like cell-integrated sensors and wireless battery management systems aim to improve safety and efficiency, despite technical challenges. Automated disassembly and direct recycling methods offer significant efficiency and cost benefits for lithium-ion battery recycling, although challenges remain.

Outlook

The ongoing cost pressure from Chinese suppliers raises questions about their economic sustainability, particularly as many Chinese automotive, cell, and material suppliers are currently unprofitable. It remains to be seen how long this pressure can be maintained. If this situation changes, the implications for the market could be significant.

Additionally, the extent to which environmental sustainability will become a major priority again is uncertain. Currently, consumer willingness to pay a premium for sustainable options is low; however, OEMs will need to begin implementing measures to meet EU regulations set for 2027. Sustainability was a key focus at the industry's inception, but its importance has diminished due to cost concerns – will this trend reverse?

The year 2025 is anticipated to be pivotal for affordable mass production, as several players enter the ramp-up phase. Future funding will heavily depend on operational excellence during this phase and the ability to reduce scrap rates. If challenges persist, it will raise questions about investors' commitment to long-term success and whether government support will be necessary to assist struggling companies.

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AUTHORS

Achim Kampker, Heiner Hans Heimes, Moritz Frieges, Henrik Born, Niklas Kisseler, Jessica Schmied, Sebastian Wolf, Nikolaus Lackner, Maximilian Graaf

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AUTHORS

Wolfgang Bernhart, Isaac Chan, Andrew Yi, Martin Weissbart, Tim Hotz, Kyle Gordon, Dennis Gallus, Konstantin Knoche, Iskender Demir, Licheng Su, Abdus Samad Ismail, Jaeyong Hyun

EDITORS

Heiner Heimes,
Production Engineering of E-Mobility Components (PEM) | RWTH Aachen University
Bohr 12 | 52072 Aachen
Phone +49 241 80 230 29
E-mail info@pem.rwth-aachen.de
Web www.pem.rwth-aachen.de

Wolfgang Bernhart,
Roland Berger GmbH
Loeffelstraße 46 | 70597 Stuttgart
Phone +49 711 3275-7421
E-mail wolfgang.bernhart@rolandberger.com
Web www.rolandberger.com

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