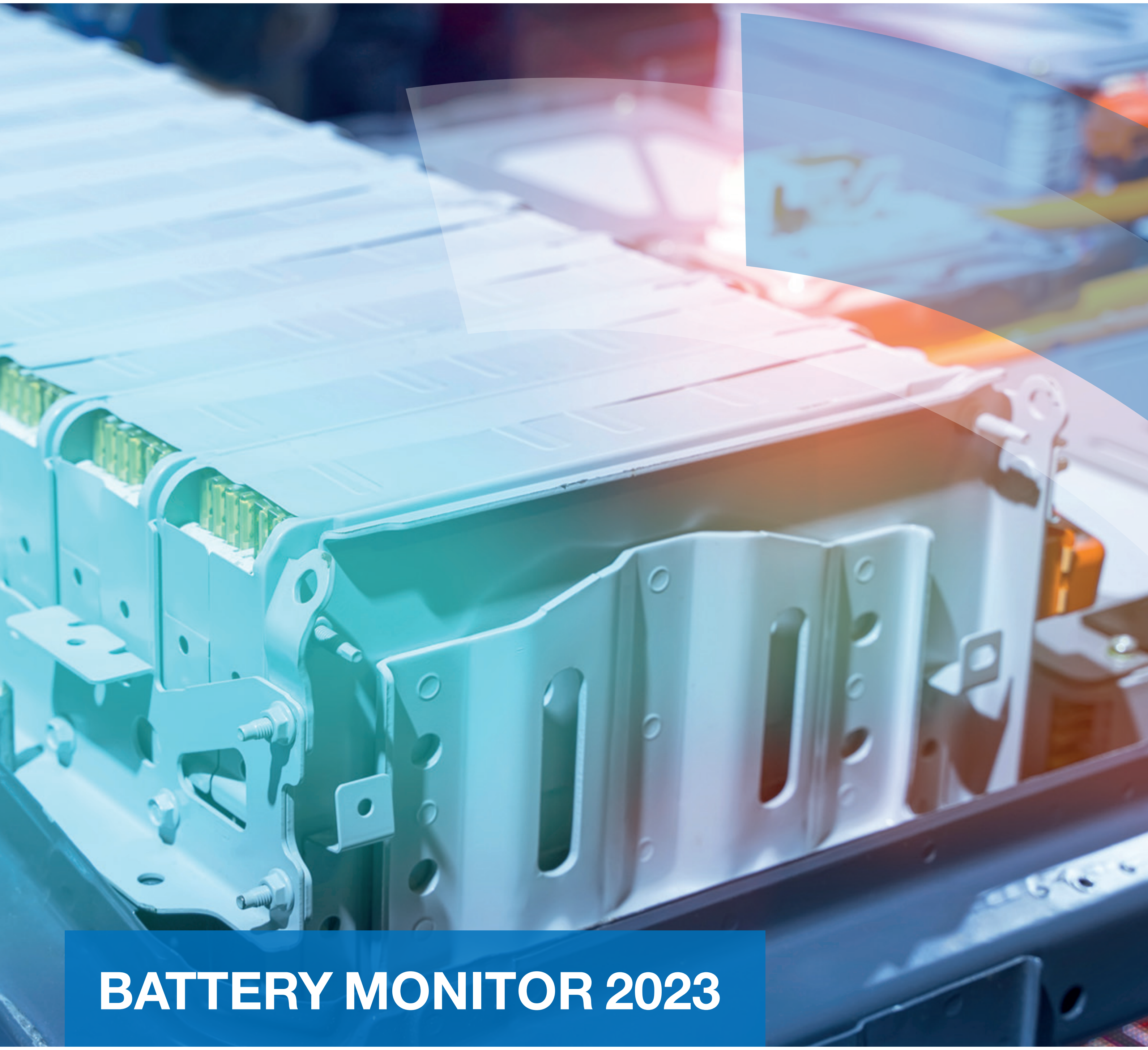

BATTERY MONITOR 2023

THE VALUE CHAIN BETWEEN ECONOMY AND ECOLOGY

PEM | RWTH AACHEN UNIVERSITY

Roland Berger

Dear readers,

In the recent past, the European battery industry has come in for a lot of criticism. Some media focus on the extent of the dependence on Asia, especially China. Even the quality press draw attention to the enormous backlog and lack of global competitiveness in the European battery industry in terms of R&D, production technology, material availability, and also sustainability. But how much truth is there in that? Has Europe already lost the global race for supremacy in battery production? If so, what actions can it take to turn the tide and secure a piece of the pie?

From the buyer's perspective in particular, there are concerns about the safety of electric vehicles in addition to the financial challenges. The recent fire onboard a cargo ship carrying 3800 vehicles (500 of them battery-electric) off the Dutch coast showed how hastily parts of the media rushed to condemn batteries as the cause of the blaze, when in fact nothing had been confirmed. But are batteries really as dangerous as their reputation suggests? What technologies can be used to mitigate potential risks? And do these affect the performance of the batteries and the range of the vehicles? It is with great pleasure that we present the third edition of the Battery Monitor, in which we get to the bottom of these questions. We aim to build on the success of the last edition by enhancing the close collaboration between Roland Berger and PEM RWTH Aachen. Once again, we focus on offering a comprehensive overview of the market, the battery materials needed for manufacturing, battery cell production, product performance, battery use, recycling, and battery reuse.

We apply key performance indicators to each of these stages and evaluate current developments in respect of sustainability, technology performance, profitability/competitiveness and innovation. This gives an up-to-date picture of the status of the market in the most relevant areas. As a new feature, Battery Monitor 2023 also points out the strategic implications for different user groups in each chapter, which we derived from the prevailing direction of the key performance indicators and the general market trends. Instead of just providing a factbook, we thereby outline why this matters for each link in the value chain and multiple stakeholder groups.

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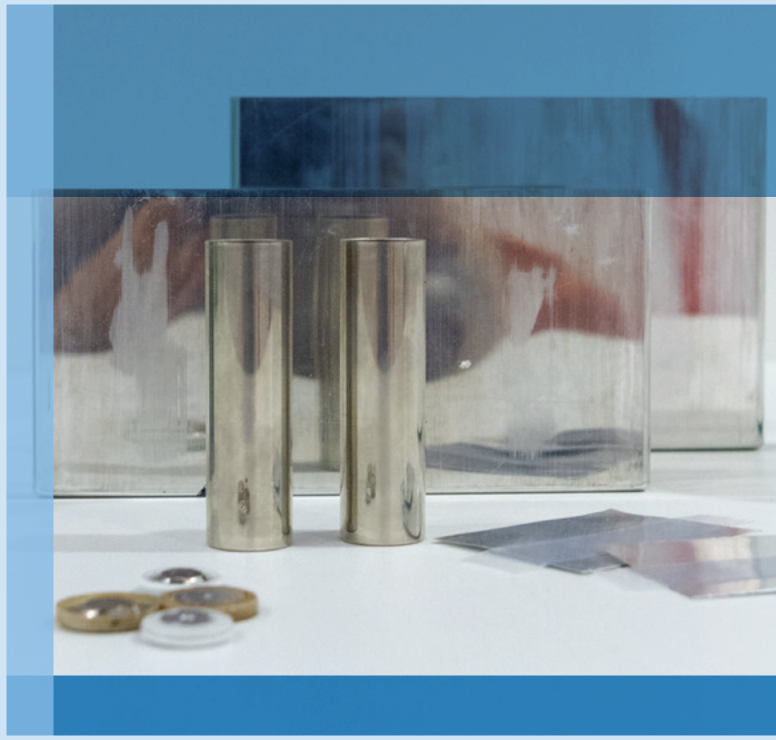
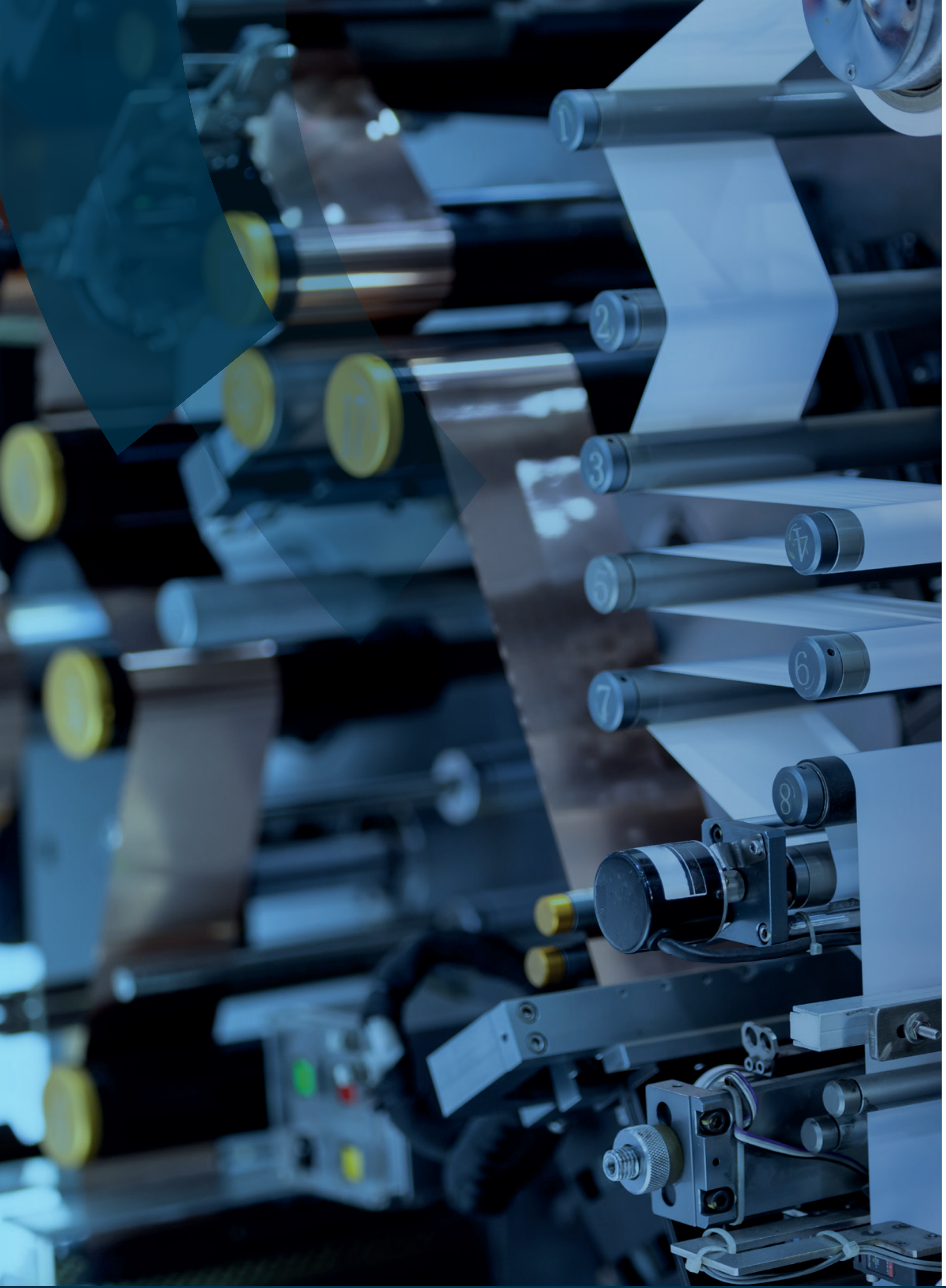
INTRODUCTION

The shift to green energy and sustainable transportation represents a major disruption to existing technologies and value chains. As the battery is the main component of these developments, this is reflected particularly in the battery market, which has seen a lot of movement in recent years. All over the world, a wide variety of players are trying to position themselves in this rapidly growing market. Policymakers face the challenge of shaping electrification targets in a way that achieves environmental goals while strengthening local economies and securing geopolitical status at the same time. For their part Original Equipment Manufacturers (OEMs) are scaling up production capacities and securing raw material supplies to meet these electrification targets while maintaining global competitiveness. While some companies are succeeding here, others are struggling badly or even failing. In the fast-moving and very complex environment, it is all too difficult to make the right strategic decisions. To support these to some extent, the Battery Monitor provides a broad overview of the recent industry news, highlights, and trends, and the various sub-aspects of and implications for the battery market.

Value chains and life cycles crisscross the globe, creating cross-border dependencies. In many places, there is therefore a trend towards making supply chains resilient. The Inflation Reduction Act (IRA), for example, was signed into law by the US government in late 2022 and has since shaken up the global economic and political landscape for batteries. It offers battery manufacturers huge subsidies, provided they move large portions of their value creation to North America and decouple their value streams from countries considered to be political adversaries. This results in enormous reshaping of the relationships between China, Europe and the US, and moves the focus for Chinese investments towards Europe.
Battery developments are driven by many forces. The sophisticated product features needed, such as high capacity, power and energy density, long lifetime and strong safety are set against cost pressure and efforts to make production as sustainable as possible. Efforts to meet these requirements have unleashed incredible innovation in recent years. The developments are not limited to battery production but affect the entire value chain, of which battery production is only a small part. Processes such as raw material extraction, material refinement, battery use, second-life applications and ultimately recycling also play major roles. All of this feeds into in the chapter structure of the Battery Monitor, wich illuminates all of these areas in terms of sustainability, innovation and technology performance in addition to the profitability aspect.





Wolfgang Bernhart, Tim Hotz, Konstantin Knoche

OVERARCHING MARKET VIEW AND POLICY

THE US IRA AND THE NEW EUROPEAN REGULATIONS ON SUSTAINABILITY AND 'FOREVER CHEMICALS' ARE THE KEY RECENT DEVELOPMENTS IN THE BATTERY MARKET.

The battery market continues to grow at pace with a global CAGR of 34% until 2030, resulting in a demand of around 4,900 GWh. This goes along with significant changes in sustainability requirements, technology performance, battery sustainability, competitiveness, and innovation (the four areas analyzed in each chapter of this report).

Sustainability: New European regulations on sustainability and 'forever chemicals' are the key recent developments. If a solution for PFAS-free batteries is found in Europe, a global shift can be expected.

Technology performance: New battery cells for niche segments such as commercial vehicles and passenger aircraft are emerging, with cell technology tailored to each niche's specific needs.

Competitiveness: As capacity and demand continue to grow, there will be increased competition between regions, driven by local regulations such as the Inflation Reduction Act (IRA) in the US affecting the global market.

Innovation: Lithium-ion technology is now near-optimal for most energy storage needs. Alternative solutions such as supercapacitors are only suitable for niche applications.

STRATEGIC IMPLICATIONS

For regulators

The European Union (EU) must ensure a level playing field between imports and local production. This means addressing additional burdens on local players. For example, the requirement to comply with strict EU environmental regulations should be reflected in import tariffs on products from countries with less strict regulation, at raw material, intermediate and final product level. If not, the huge investments made through the EU's IPCEI program will not drive sustainable competitiveness.

After the enactment of the IRA, Europe is now the primary target for Chinese battery investments and exports. This means European players face the major challenge of competing with Chinese prices as announced capacity in China exceeds local demand by a factor of around 2.5x and as announced production capacity by Chinese players in the EU has increased by 60% since the announcement of the IRA.

The IRA is shaking up the battery market, with the US now far more attractive to investors than Europe. However, the IRA's subsidies are expensive, and the US is frequently reaching its debt limit.

The economy is also troubling China. While huge subsidies gave Chinese battery players a competitive edge in the past and created global market leaders, China is currently experiencing deflation. An anti-subsidy investigation by the EU also represents a risk for the required exports.

European, US and Chinese regulations need to address sustainability as a whole – economically, environmentally, and socially – rather than focusing on only one aspect, as is the case now.

For battery manufacturers

Battery producers need to investigate PFAS-free binders, as a potential ban on PVDF and PTFE, currently under discussion in the EU, could put the European industry on hold. However, if a solution is found in Europe, other markets are expected to follow.

For investors

Announced capacities, especially in China, far exceed demand, which poses the risk of underutilization and market consolidation. Investors should therefore conduct due diligence with a focus on anchor clients and off-take agreements with the highest priority – complemented by available talent and secured raw materials.

SUSTAINABILITY

As concerns over the supply and environmental impact of battery materials grow, the adoption of a new battery regulation by the European Parliament and Council constitutes the most significant development in battery sustainability.

EU FINALLY AGREES ON NEW REGULATION COVERING THE ENTIRE BATTERY VALUE CHAIN

The 2022 edition of the Battery Monitor mentioned the EU's plans to replace its Batteries Directive of 2006 with updated regulations, but few details were available. These plans have now been announced. The new EU Battery Regulation, which affects all batteries sold in the bloc, entered into force on August 17, 2023 and shall apply six months later, on February 18, 2024.

The EU views batteries as strategically important, for both decarbonization and raw materials supply. It wants to ramp up production but is concerned about the environmental impact of mining, production and waste relating to batteries, especially key Li-ion battery raw materials such as lithium, nickel and cobalt. As such, the EU also wants to increase reuse and sustainability. To achieve this, its new sustainability regulation covers the entire battery life cycle. Each of the many articles specifies an estimated target date.

SEVERAL ARTICLES, INCLUDING ON CARBON FOOTPRINT AND RECYCLED CONTENT, HAVE MAJOR IMPLICATIONS

Four articles are particularly important for manufacturers:

Article 7: The carbon footprint of a battery, measured in CO$_2$ per kilowatt hour, must be declared. The target date depends on battery type; for EVs, for example, it is February 18th, 2025). Currently, no specific targets are given; likely to be based on industry averages.

Article 8: Mandatory recycled content requirements prescribe minimum levels of recycled materials in new industrial and automotive cells. These include now confirmed targets for lithium, nickel and cobalt of 6%, 6% and 16% by 2031, and 12%, 15% and 26% by 2036, respectively.

Article 48: By 2025, battery producers will have to create and publish a due diligence policy for suppliers and perform regular enforcement checks.

Article 56 - 60: Extended producer responsibility will make battery producers responsible for the collection, transport and treatment of waste batteries. Minimum collection rates for portable batteries are, e.g. 45% by December 31, 2023; LMT batteries are set at 41% by December 31, 2028 (no defined rate for EVs).

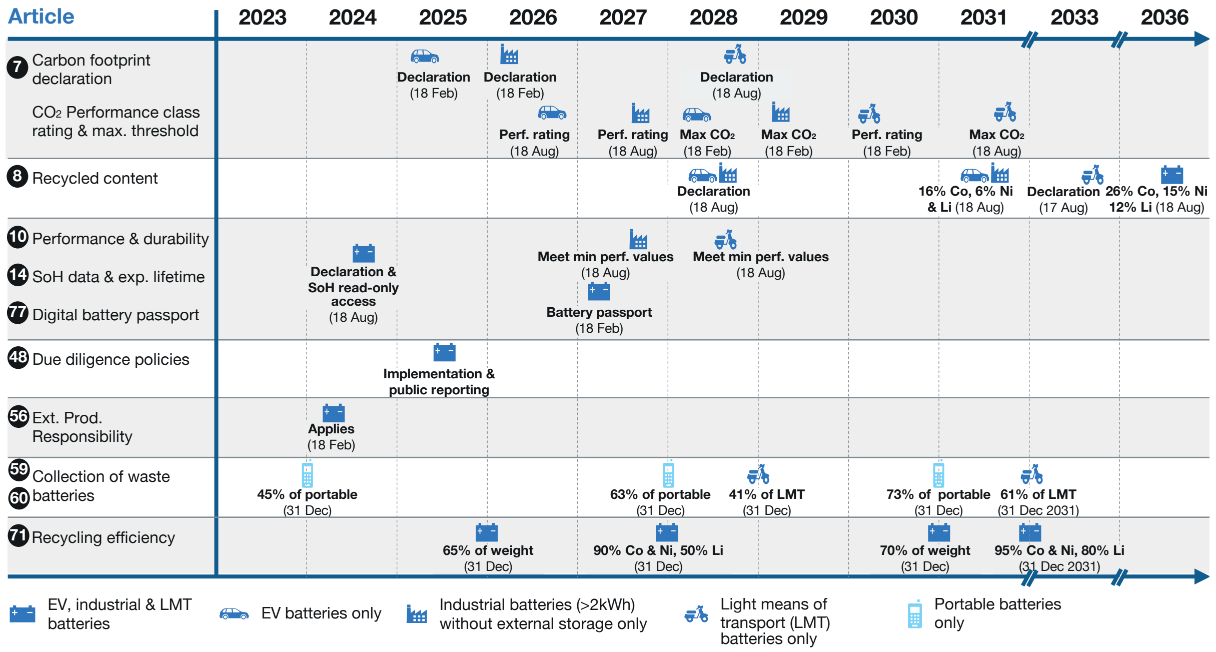


Figure 1: Summary of most relevant EU Batteries Directive articles with expected implementation dates; *Source: European Commission, expert interviews, Roland Berger*

The implications of the updated regulations for battery manufacturers and OEMs are numerous. Battery producers will need to implement robust circular economies to ensure they meet minimum recycling content targets and move to secure supplies in an increasingly competitive market. These tasks will significantly increase the importance of strategic procurement departments in companies where no in-house recycling or partnerships with recyclers exist, and the aftermarket department to take care of the extended producer responsibility. In addition, battery manufacturers will need to increase their share of renewable power to meet expected CO$_2$ targets. OEMs, meanwhile, will have to navigate the bureaucratic burden of the battery passport and develop extensive collection networks for waste batteries, or leverage third parties.

EU BAN ON HAZARDOUS PFAS CHEMICALS COULD HASTEN BATTERY MATERIALS SUSTAINABILITY

Another regulatory challenge for the battery industry is the possibility of a ban on many per- and polyfluoroalkyl substances, known as PFAS. These are used as coatings, for example Teflon, in many consumer and industrial products as they resist heat, oil, water and grease. But they are highly toxic and take many years to break down in the environment, earning them the name 'forever chemicals'. The European Chemicals Agency, an agency of the EU, announced proposals in January 2023 to ban around 10,000 PFAS. If agreed, it could enter into force in 2025.

One PFAS, polyvinylidene fluoride (PVDF), is a critical component of Li-ion cathode electrodes, meaning a ban could put the whole battery industry at risk. The binder is used as a 'glue' to hold the active particles together and maintain a strong connection between cathode particles (and current collector foil). PVDF makes up about 1-5% of the weight of a Li-ion cathode, with advanced players achieving the lowest values. EU demand is set to rise from 6,000 tons today to 20,000-30,000 tons in 2030, posing a significant health risk if the material leaks. However, the battery industry is currently focused on another problem – replacing the highly toxic solvent NMP. It is used to dissolve PVDF during the manufacture/recycling of electrodes and is removed after the coating process by evaporation. This requires large amounts of energy and produces large volumes of NMP that must be recycled.

ALTERNATIVES TO PFAS ARE AVAILABLE OR IN DEVELOPMENT, BUT NONE ADOPTED YET

As a result of regulatory pressure, the elimination of PVDF and a shift to more environmentally friendly binders is already on the agenda of most Li-ion producers. These include:

Polytetrafluoroethylene (PTFE, or Teflon): While also a 'forever chemical' and facing a potential ban, PTFE is considered a next-generation binder. It is favored for dry-coating technology.

UV-activated binders: Here, PVDF and NMP are replaced with less hazardous acrylate binders and solvents (propyl acetate). The acrylate binder composition is UV-cured to polymerize (activate) it.

Hydrogenated nitrile butadiene rubber (HNBR): This material can be produced at lower temperatures than other binders and is fluorine-free, but still requires the use of NMP.

Carbon nanotubes: Rather than using a conventional polymer binder, this technology leverages a 3D nanocarbon mesh to hold together the active materials. Carbon nanotubes are already used as an additive to increase conductivity, but developments to use them as a sole binder are underway.

As well as environmental benefits, the developers of the alternative binders claim advantages such as improved performance, cost reductions and compatibility with existing production equipment. However, as yet, no viable, cost-competitive and scalable alternative binder has emerged. Instead, many PVDF and cell producers are pushing hard for PVDF and other chemicals to receive an exemption from any bans, with some players arguing that the EU's green transition is incompatible with a ban on PFAS. Others, however, are very concerned by the prospect of a ban and are setting up task forces to address the issue.

EU CLAIMS SUSTAINABILITY LEADERSHIP, BUT CHINA CATCHING UP

The imminent prospect of an EU ban on PFAS means a non-PVDF binder solution is likely to materialize in Europe first. This could prompt the US, China and the rest of the world to regulate more strictly against PFAS, once a solution is found that reduces health risks. The current US Environmental Protection Agency position is that it wants to investigate PFAS and their impact before introducing regulations.

Regarding overall battery sustainability, Europe has the ambition to lead due to its new regulations, with the US and China still more focused on regulating competition. While sustainability rules in China remain somewhat opaque, interviews with market participants indicate that the regulatory environment there is tightening in terms of permitting, wastewater regulations and emission regulations. This raises the questions of whether potential EU bans will continue to give the bloc an edge in sustainability, and whether its sustainability regulation will affect competitiveness with the US and China (see Competitiveness subchapter). One point to underline this statement is that first certified 'net zero' gigafactories are located in China and, e.g. CATL has announced plans to reach carbon neutrality in its core operations by 2025.

TECHNOLOGY PERFORMANCE

In recent years, the technology focus of battery manufacturers has been on automotive cells. But the automotive market's long development and qualification times (up to three years), the significant cost advantage of established Tier 1 players and the high scale/investment barriers mean new players are now focusing on other market segments. These are gaining in size, making the development of dedicated cells economically viable.

DEDICATED BATTERIES FOR AIRCRAFT AND TRUCKS UNVEILED, BUT NICHE SEGMENTS CONTINUE TO FAVOR EV CELLS

In the past, most specialist battery segments, such as commercial vehicles, marine and passenger aircraft, relied on existing electric vehicle (EV) batteries to meet their needs. This made sense for two reasons. First, automotive batteries are highly reliable and stringently tested. Second, even though non-automotive firms must pay a price premium for EV batteries due to lower volumes, it is still cheaper than developing a dedicated cell.

However, as outlined in the previous Battery Monitor, several specialist segments have reached or are nearing sufficient scale (>1GWh) to develop dedicated cells. The first of these cells have now been announced. In April 2023, the Chinese battery giant CATL announced a high-performance condensed battery designed specifically for passenger aircraft. It has an energy density of 500 Wh/kg – nearly twice that of typical automotive cells.[1] In the same segment, German cell producer Customcells announced in March 2023 that it is ramping up production of its high-power, 330 Wh/kg battery designed exclusively for electric vertical take-off and landing (eVTOL) jet builder Lilium. The cell is a first in that it offers high power despite having 'only' automotive-level energy density. Outside the aviation segment, the Swedish automotive group Volvo said in late 2022 that it had begun developing a gigafactory in Mariestad, Sweden, to produce batteries for heavy-duty commercial vehicles (trucks) and machines.

REQUIREMENTS OF DEDICATED BATTERIES DEPEND ON THE USE CASE, WITH COST KEY IN VEHICLE SEGMENTS

So, what are the individual segment requirements for batteries, and how does this new generation of dedicated cells differ from automotive cells? Figure 2 look at success factors in key segments.

Light vehicles (cars, vans, etc.): Entry and performance segments have different requirements. In the entry segment, the key focus is on cost. This makes lower-cost, longer-lasting but less energy-dense lithium iron phosphate (LFP) batteries a good fit. In the high-performance and premium segments, there is a trend towards high-nickel chemistries, which have greater energy densities. But in times of high raw material prices, this comes at a cost. The volume segment can be seen as a compromise between the two – in addition to LFP and NMC, manganese-rich solutions are expected to be used in this segment as soon as they become available (see Battery Materials chapter for more on cell chemistries).

Commercial vehicles (trucks, buses, etc.): Choice here is largely driven by use case. In shorter-range applications, such as buses, vehicles can be charged overnight, making cycle life an important factor and LFPs a good fit. In longer-range applications, such as trucks, charging is opportunistic, making energy density and charging times key. Nickel-based materials like NMC or NCA are favorable here. In general, the commercial vehicle segment is highly cost driven. Total cost of ownership is most crucial. Price premiums per kWh have been observed in the market, as the premium was justified by greater lifespan performance.

Off-highway and material handling (diggers, mining vehicles, etc.): The key requirements here are robust, durable and customizable battery packs to absorb shocks and vibrations and fit around diverse packaging designs. Weight and cost constraints are lower than in on-highway applications.

Marine (commercial, recreational): While safety is the overriding focus, technical requirements in

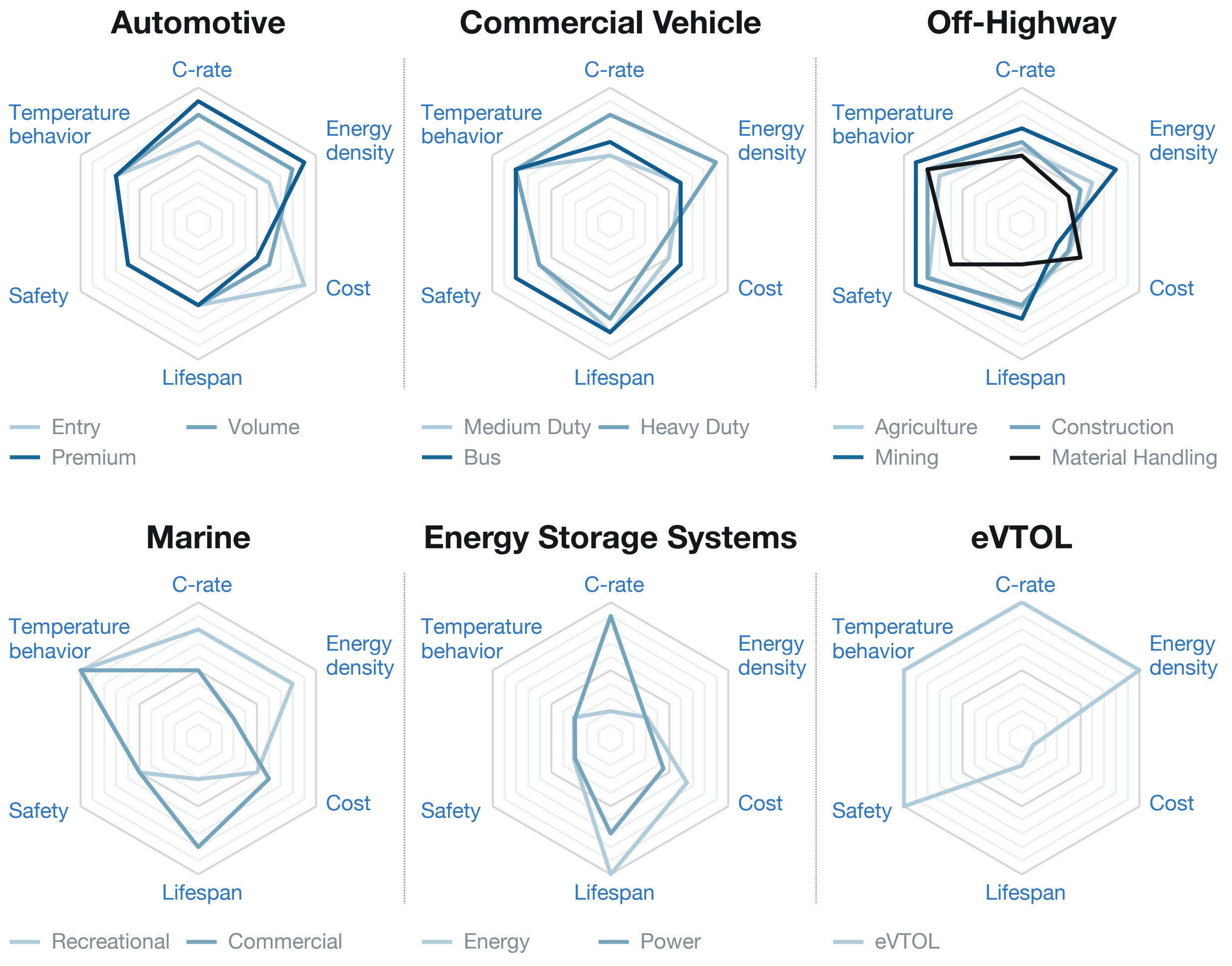


Figure 2: Comparison of key battery requirements across different specialist battery segments; *Source: Expert interviews, Roland Berger*

the marine segment differ. Commercial vessels prefer long cycle lives, while recreational users prefer high energy densities and charging speeds, as well as the flexibility that comes with a lack of standardization.
Energy storage systems (grid frequency regulation, reserve capacity, etc.): Most ESS projects require long-life (around 20 years) batteries and are less constrained by weight, size or high power need. LFP and sodium-ion technologies are a good fit here. However, batteries used for back-up power (at data centers, etc.) must be able to deliver high power and withstand high C-rates (intermittent use). eVTOLs (and other electric aircraft): eVTOLs require by far the highest performance in terms of C-rates, energy density and costs. However, with electric aircraft still in early development, costs and lifespan requirements are currently of lower priority.

COMPETITIVENESS

Battery Monitor 2022 stated that demand for cells, especially in the EV market, was insatiable and that producers were at the limit of their capacities in trying to meet it. The same is true in 2023. However, there have been several developments that could shift the balance of power in the market.

FORECASTS INDICATE SIGNIFICANT DEMAND AND CAPACITY GROWTH BY 2030

Market demand forecasts for Li-ion and Na-ion batteries continue to skyrocket, driven by the EV sector. Demand is expected to reach 4,900 GWh in 2030, a significant increase on last year's projection of around 4,000 GWh. This is mainly driven by new projections for the ESS segment.

Announced global capacity has also increased significantly and is now expected to reach around 8,930 GWh in 2030. The figure jumps to around 11,000 GWh when projects that have no communicated timeline are included. This means announced capacities far exceed demand. However, significant overcapacity is not expected to build up as some projects will not materialize and the market is likely to consolidate. Lack of secured sales, financing, battery materials, talent and equipment will be key reasons for some announced projects to miss their deadlines or fail to materialize.

ANNOUNCED CAPACITIES DIFFER SIGNIFICANTLY BETWEEN CHINA, EUROPE AND US

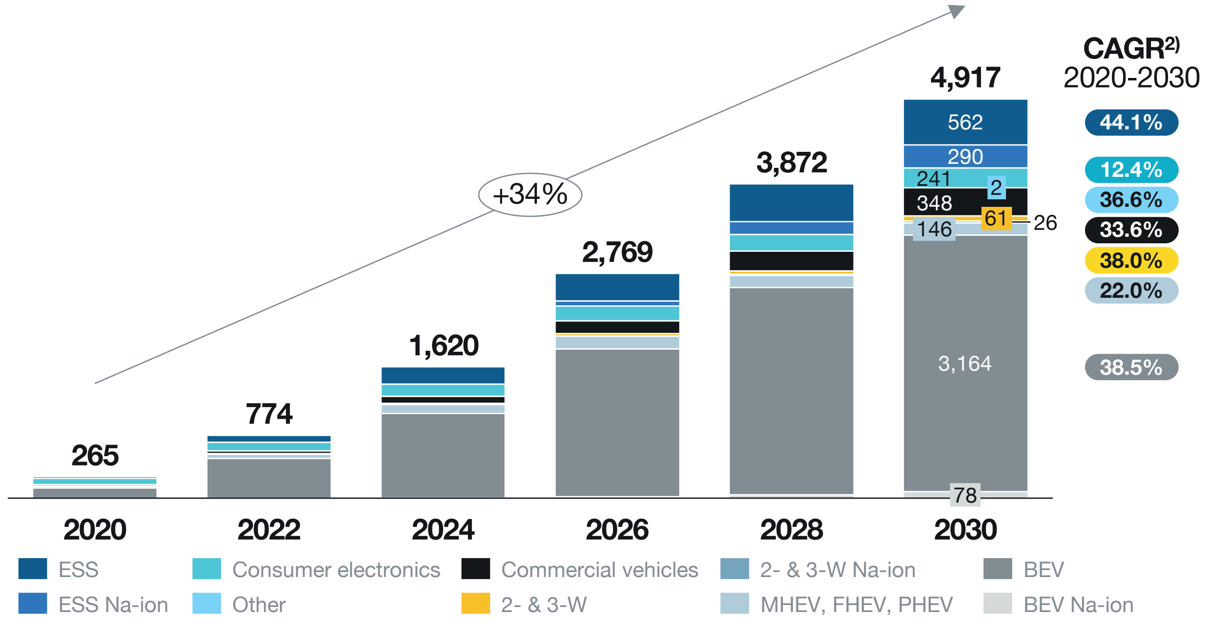
In terms of overall capacity, Europe and North America show a clear trend towards localization, whereas China clearly intends to continue as the primary exporter of battery products. This is especially the case for exports to Europe, as the US is making trade unattractive with a 25.4% tariff on battery cells from China.

China ambitious

China once again leads the way in announced capacity, making up more than half of the total announced for 2030. Its producers have made ambitious statements of intention in recent months, likely to attract the attention of investors and gain market share. For example, CATL has announced aggressive plans for an extra 1,300 GWh of capacity. In addition, Chinese companies have announced 125 GWh of new Na-ion capacity from 2025.

Europe catching up

In Europe, announced capacities exceed expected local demand. This makes it very difficult for new and inexperienced players to meet their ambitious capacity targets as they have little scope to build a customer base. The collapse of the British newcomer Britishvolt, which filed for administration due to 'insufficient equity investment' in early 2023, serves as a warning. Initial investment in the sector is immense and the dry spell for newcomers while they develop their battery cell can be long.
In addition, due to the US Inflation Reduction Act (IRA) of 2022 (see box on page 15), investment in the US is now more attractive than in Europe. Some major players have slowed down their European plans while prioritizing North America.
The EU Commission is, however, developing its own incentives to grow capacity. These include



1) Na-ion base case penetration; 2) BEV, 2- & 3-W and ESS CAGR including Na-ion demand; Abbreviations: BEV: Battery Electric Vehicle; MHEV, FHEV, PHEV: Mild Hybrid, Full Hybrid and Plug-in Hybrid Electric Vehicle; Light vehicle: Passenger cars and light commercial vehicles up to 6 tons in weight; LSEV: Low Speed Electric Vehicle; 2W: Electric Two Wheelers

Figure 3: Market demand for Li-ion and Na-ion batteries by application [GWh]; *Source: IHS, SMM, Roland Berger*

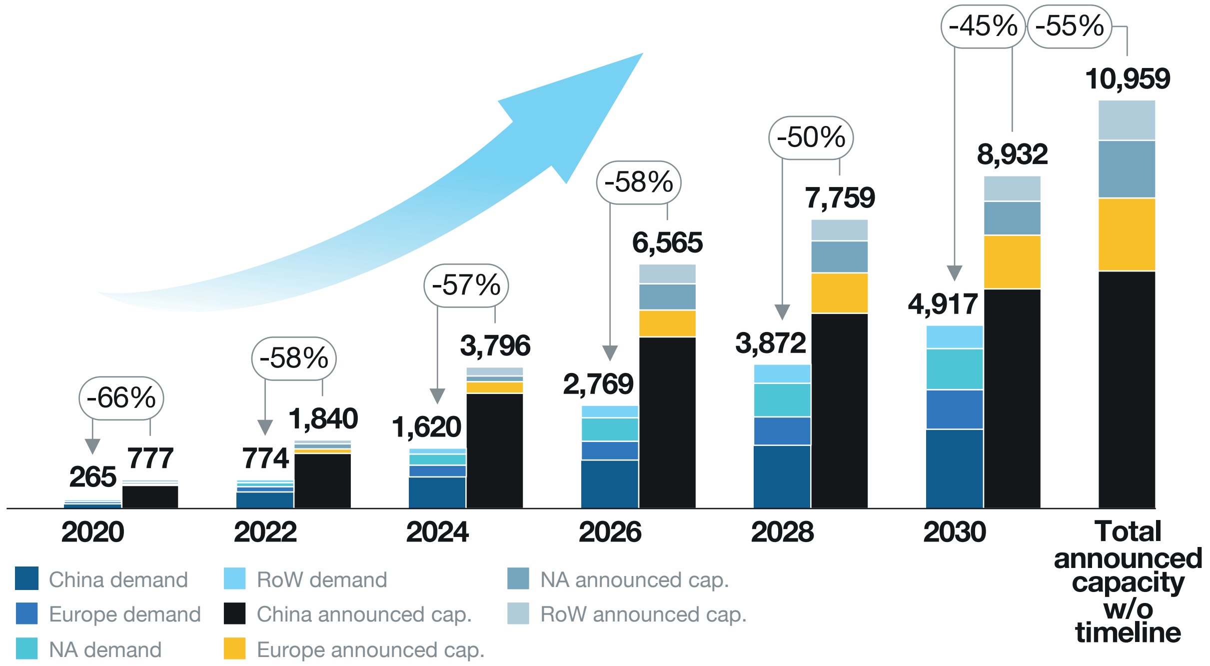


Figure 4: Announced global capacity vs. expected demand by region for Li-ion and Na-ion batteries [GWh]; *Source: IHS, SMM, company announcements, Roland Berger*

establishing targets for EU-based production shares of cell materials: 10% for mining; 40% for processing and precursor CAM; 90% for cell manufacturing; not more than 65% of materials sourced from a single third country. However, the targets currently still lack a carrot or a stick mechanism. The EU has also been pursuing critical raw material partnerships and free trade agreements with countries with relevant raw materials, such as Australia or Canada.

US boosted by IRA

Capacity problems are not as acute in North America, but the IRA is expected to shift capacity to the US. Currently, the country also has a strong trend of partnerships between automotive OEMs and battery producers, especially Korean firms. In these partnerships, the battery producers bring in the know-how, IP and talent for manufacturing, while the OEMs bring in secured off-takes, lobbying and marketing power.

Such Joint Ventures (JVs) limit the potential of new market entrants to gain a foothold in the automotive market. However, potential opportunities exist in the ESS market. This segment has strong demand and is unlikely to be covered by automotive OEMs and their JVs. As a result, the market entry barriers are lower, giving newcomers the biggest chance to secure larger sales volumes and gain a foothold.

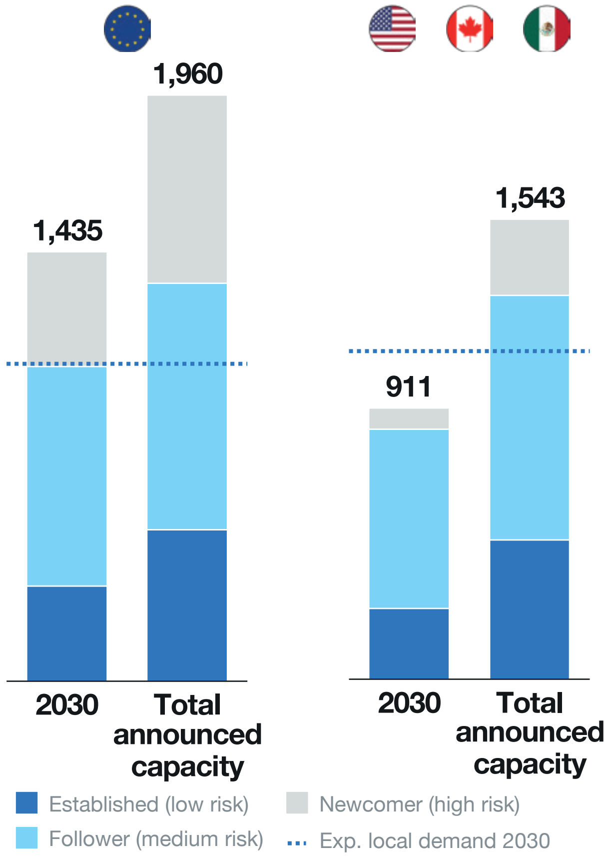
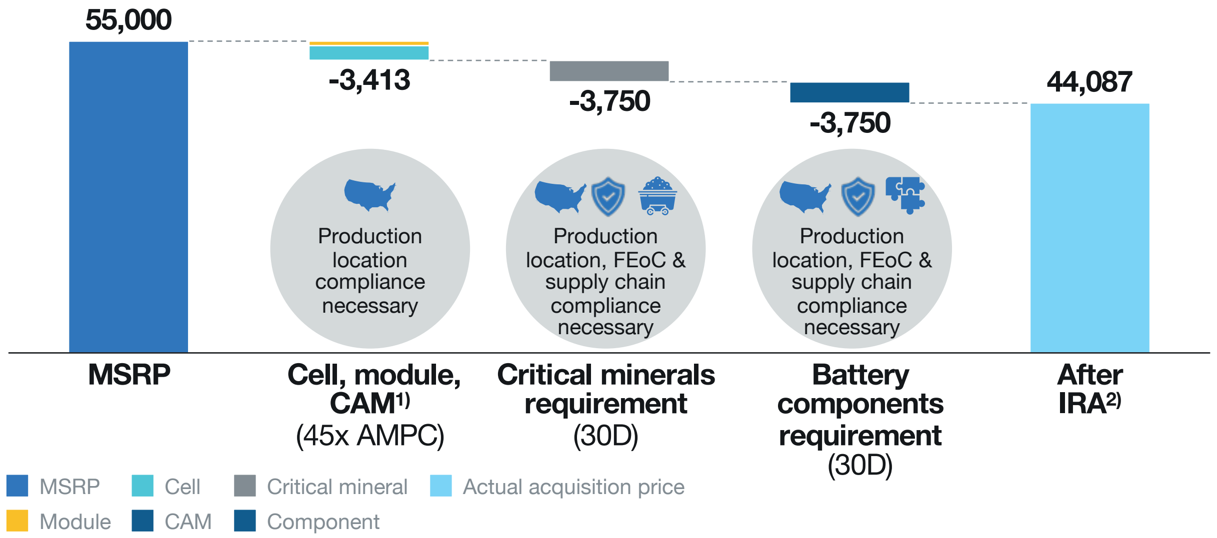


Figure 5: Announced gigafactory capacity in Europe and North America by type of player [GWh]; *Source: Company announcements, Roland Berger's Gigafactory Tracker*

THE US INFLATION REDUCTION ACT: A BRIEF OVERVIEW FOR BATTERY PRODUCERS

The IRA is one of the biggest US investment programs focusing on green energy and climate change. For battery producers, the most important section is '45X: Advanced manufacturing production tax credit (AMPC)'. It gives USD 35/kWh tax credits for cell production in the US, USD 10/kWh tax credits for module production in the US, and tax credits of 10% of the production costs of electrode active materials and critical minerals produced in the US. These tax credits exceed the current production costs (energy costs, labor costs, etc., not including materials) of cells and modules – essentially letting players manufacture for free. Automotive OEMs can also leverage USD 3,750 per vehicle if more than 40% (rising to 80% by 2027) of the critical minerals value in the vehicle is sourced from North America or countries with whom the US has a free trade agreement (for example, Australia, Chile, South Korea) or a critical minerals agreement (Japan, EU in negotiations). A further USD 3,750 per vehicle can be gained if more than 50% (rising to 100% by 2029) of the battery components are from such countries. Similar tax credits are in place for commercial vehicle and ESS manufacturers. To qualify, companies linked to Chinese, Russian, or North Korean entities must be fully excluded from the value chain.



1) Only accounting for CAM production costs of assumed USD 5 per kWh to calculate tax credit; 2) All benefits count towards consumer benefit

Figure 6: IRA impact on reference vehicle with USD 55,000 manufacturer suggested retail price (MSRP) and 75 kWh battery;
Source: Inflation Reduction Act (enrolled version), media research, Roland Berger

INNOVATION

The focus of innovation is clearly on Li-ion and Na-ion battery technology, which is covered in more detail in the Battery Materials chapter. In this chapter, we would like to introduce two alternative energy storage technologies: supercapacitors and vanadium redox flow batteries.

HYBRID SUPERCAPACITORS ENHANCE CHARGING SPEEDS AND SAFETY OF LI-ION CELLS, BUT USE CASES ARE LIMITED

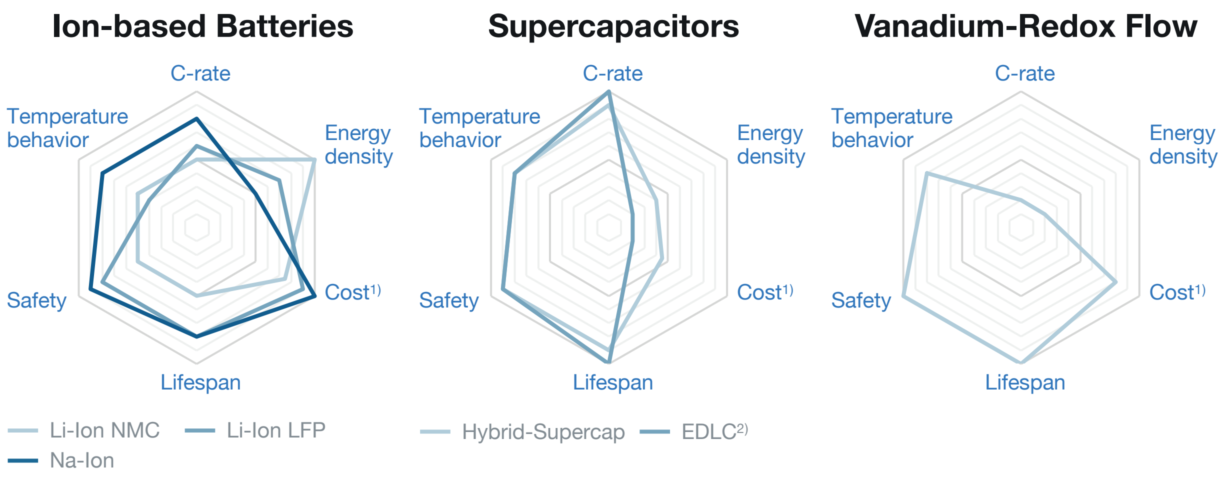
Supercapacitors vastly increase the 'speed' at which cells can deliver and receive energy, with C-rates of 150C and above possible. But they have low energy densities, between 10-75 Wh/kg and 10-150 Wh/L. Hybrid supercapacitors aim to overcome this problem, while also improving cell safety and lifespan. However, the technology is not expected to be used in traction batteries. The Li-ion hybrid supercapacitor is an electrochemical capacitor that combines electrodes of a Li-ion battery with an electric double-layer capacitor (EDLC). This enables superior energy density, as well as increased power density, safety and charging efficiency.

However, hybrid supercapacitors and EDLCs are likely to remain useful only for niche applications requiring ultra high power, such as so-called uninterruptible power supplies (UPS).

VANADIUM REDOX FLOW BATTERIES OFFER AN ENTIRELY NEW TECHNOLOGY, BUT ARE BIG AND HEAVY

Vanadium redox flow batteries (VRFBs) are a completely different concept. They use vanadium ions as charge carriers in different oxidation states to store energy. Flow batteries consist of two separate tanks of electrolyte solutions (containing vanadium ions in different states of oxidation), one for the cathode and one for the anode. The electrolytes are pumped along opposing sides of a membrane where they react to charge and discharge energy.

The biggest advantage of VRFBs is that they can be endlessly scaled and there is no self-discharge, in addition to almost indefinite operational lifespans. This makes them suitable for stationary storage applications. However, VRFBs have several drawbacks, primarily their large size/weight, low energy density (20 Wh/kg) and the high price of vanadium.

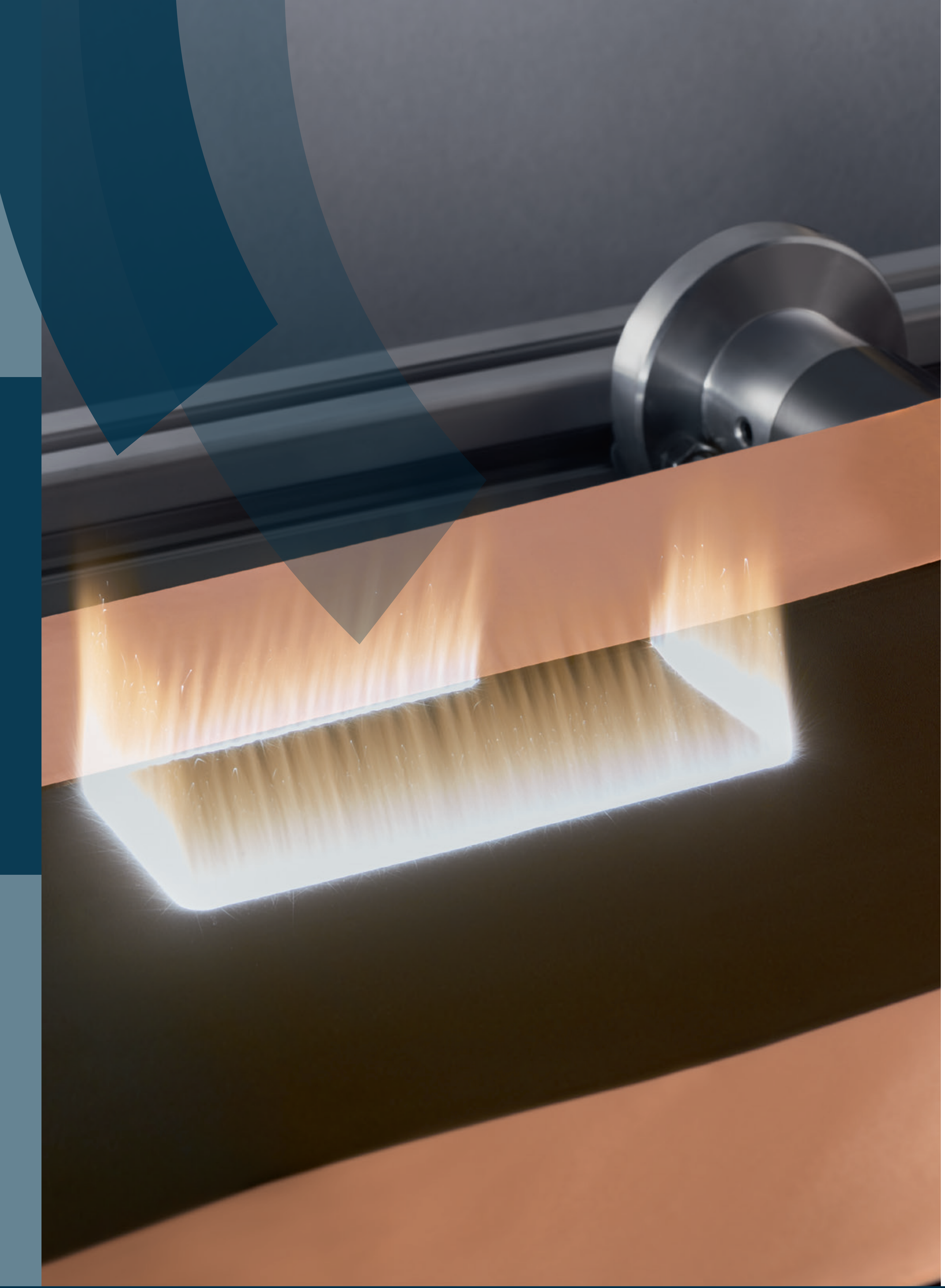


1) Cost level by energy [EUR/kWh]; 2) Electric Double Layer Capacitors

Figure 7: Characteristics of Li-ion, hybrid supercapacitors, sodium-ion and vanadium redox flow technologies;
Source: Interviews with market participants, company announcements, Roland Berger

> "Lithium-ion and sodium-ion batteries are suited for most use cases. Especially the development of sodium-ion batteries should be looked at, as the lower energy density of sodium-ion comes with a much lower cost position. On the other hand, supercapacitors and redox flow batteries offer unique specialties, which can make them the perfect fit for some niche markets."

Konstantin Knoche



Dennis Gallus, Konstantin Knoche, Iskender Demir

BATTERY MATERIALS

THE FOCUS IN BATTERY MATERIALS IS ON IMPROVING PRODUCTION TECHNOLOGIES, SECURING SUPPLIES AND EXPLORING ALTERNATIVES TO LI-ION CELLS.

Sustainability: New production technologies such as direct lithium extraction have lower environmental impact, but are unproven at scale.
Technology performance: Nickel-based chemistries are being further improved, with high Ni-share and single-crystal products now available. LFP is further gaining market share and LMFP has been announced to fill the white spot between NMC and LFP in terms of balanced energy density and cost.
Competitiveness: Global supply and demand of key cathode raw materials (lithium, nickel, cobalt) is still tight and producers are moving to secure supplies through partnerships and agreements with miners.
Innovation: To avoid dependency on raw materias, and also potentially realize cost advantages, sodium-ion cells are emerging as an alternative. Deep-sea mining could exploit huge metal resources in nickel, cobalt and other metals, but it is controversial.

STRATEGIC IMPLICATIONS

For regulators

One of the goals of the EU's Critical Raw Materials Act is to conclude free trade agreements with countries with relevant battery raw material capacities, such as Australia, Indonesia and Argentina. This would simplify deals and investment for member states.
The EU must further clarify its goal of building a local supply chain. The bloc's Green Deal Industrial Plan defines targets for production but not what will happen if they are not met.

For battery manufacturers

Battery producers should ensure flexibility in their cell technology to anticipate challenges in sourcing raw materials. With rapid developments in lower-cost battery materials and cells, particularly in China, producers should also consider offering alternatives to nickel-based cells. Battery producers need to balance standardized products to lower the costs with being flexible enough to adapt to raw-material market prices.
Battery producers must continue to invest and conclude long-term agreements (LTAs) with mines and refineries, as well as actively manage risks, including potential project delays.
Smaller battery producers should target strategic partnerships with the upstream value chain, as well as with strategic customers, to secure their supply.

For investors

The continued development of Li-ion cells and production capacities is an entry barrier for new technologies, such as solid-state cells.
Given strong competition and uncertainties around technology maturity, thorough market due diligence and in-depth technical know-how is still essential for making new investments.

SUSTAINABILITY

The carbon footprint of battery materials depends on several factors. These include: the cell chemistry; the origin of the raw materials; the type of ore; mining and transport routes; the refinery technology; the energy grid mix; and the share of renewable energy used in a specific plant. In Battery Monitor 2022, we looked at the carbon footprint of nickel; here we take a closer look at lithium.

LITHIUM BRINE MINING HAS LOWER EMISSIONS, BUT SPODUMENE MINING HOLDS ADVANTAGES FOR HIGH-NICKEL CELLS

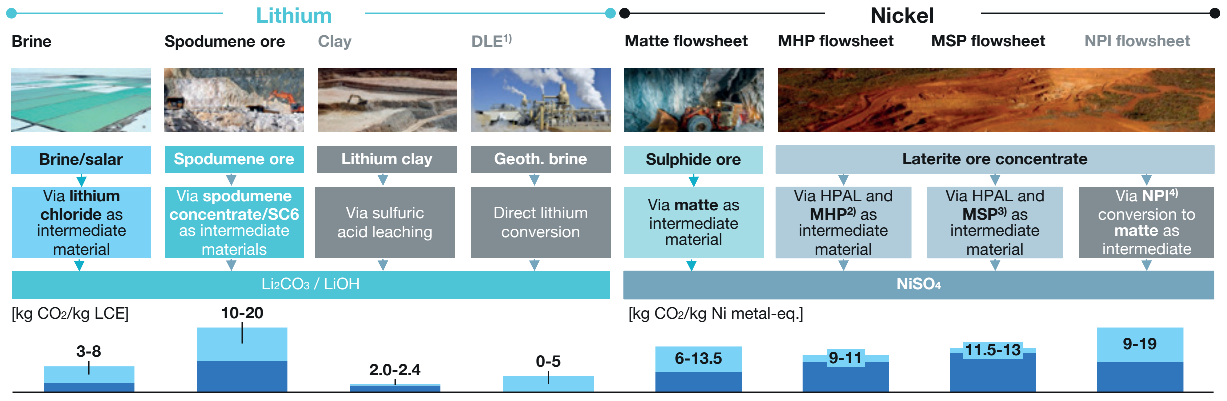
There are currently two established routes for the production of battery grade lithium – from brines and from spodumene ore. Lithium carbonate, used in low-nickel chemistries and LFP cells, is typically produced from brine. The brine process, which today accounts for around 40% of mined lithium, is protracted. First, the brine is extracted from salt flats (salar) in South America (mainly Argentina, Bolivia, Chile), placed in a pre-pond, then processed in a lime plant to remove magnesium. This takes one or two days. Second, the brine is pumped into evaporation ponds where it is left for between nine and 18 months to dry out naturally. Lastly, the resultant lithium salts are further processed into lithium carbonate. As the sun is doing most of the work, the energy consumption and the carbon footprint of brine mining are very low, at about 3-8 kg CO_2 per kg LCE (lithium carbonate equivalent).[2]

Spodumene mining, which produces around 50-60% of the global supply of lithium, involves a more conventional mining operation. Spodumene ore is extracted from open pits – mainly in Australia and, increasingly, the US – and then calcinated (roasted) to produce lithium hydroxide which is required for high-nickel chemistries. Due to the more energy intense mining and conversion processes, CO_2 emissions from spodumene mining are nearly 3x higher than in brine mining (10-20 kg CO_2 per kg LCE).[2] Energy intensity is driven by the calcination process, which requires high temperatures for long durations. To lower emissions from lithium mining and meet future demand, new production technologies are required.

NEW PRODUCTION TECHNOLOGIES: LITHIUM CLAY MINING PROMISES LOWER EMISSIONS, BUT IS UNPROVEN ON A LARGE SCALE

Two novel lithium production routes have emerged to address the high emissions and water usage of the established processes. The first is extraction from lithium clay. Here, lithium-rich clay is mined from open pits (for example, in Nevada, USA, and Mexico), mixed with an acid, such as sulfuric acid, and then heated to leach out lithium carbonate.

As the technology is still emerging, there is only limited emissions data. But the Final Environmental Impact Statement of the Thacker Pass project in Nevada, operated by Lithium Americas, gave some first indications. Based on its first phase output capacity of 33 kt LCE per annum, it is expected to have greenhouse gas emissions of around 80 kt per annum CO_2 equivalent.[3] This means roughly 2.4 kg CO_2 per kg LCE. The second, larger capacity phase is expected to be more efficient, at around 1.6 kg CO_2 per kg LCE. Both figures are below brine mining emissions. However, this does not factor in emissions from the production of acids for the leaching process.



1) Direct lithium extraction; 2) Mixed hydroxide precipitate; 3) Mixed sulfide precipitate; 4) Nickel pig iron

Figure 8: Lithium and nickel routes and carbon footprint; *Source: Benchmark Minerals, Roskill, interviews with market participants, desk research, Roland Berger*

In addition, there are concerns about the use and potential leakage of highly corrosive sulfuric acid.

NEW PRODUCTION TECHNOLOGIES: DIRECT LITHIUM EXTRACTION IMPROVES SPEED, SUSTAINABILITY, CAPACITY

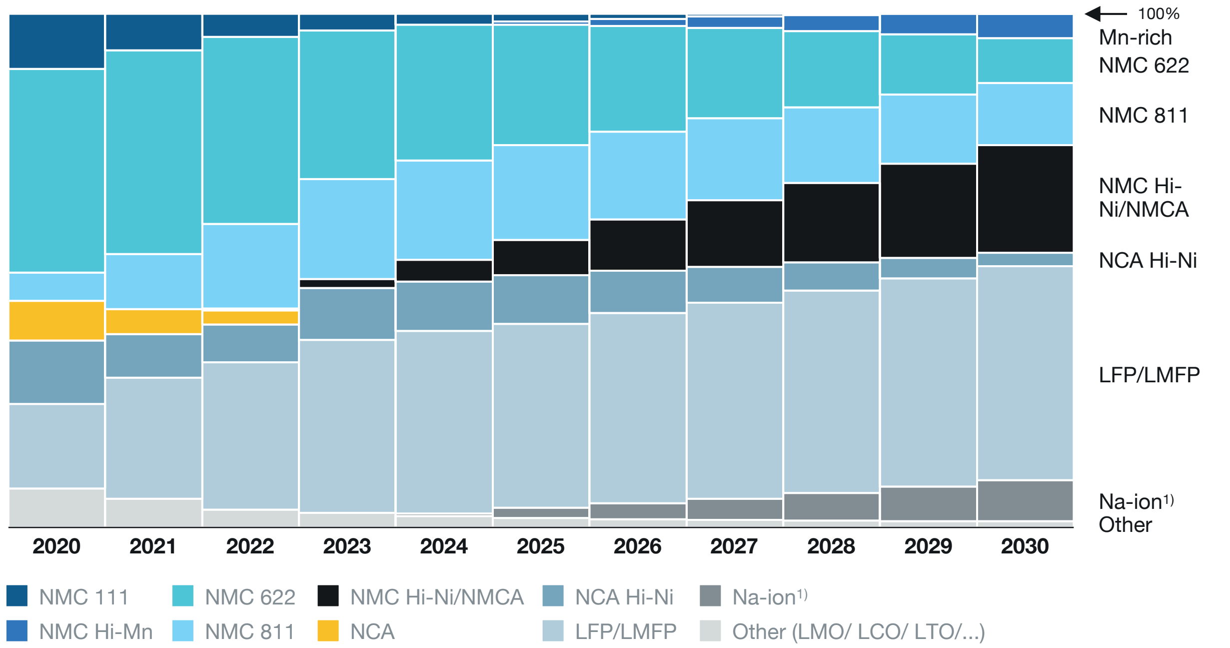
Direct lithium extraction (DLE) removes the lengthy evaporation ponds stage of brine operations, with the whole process taking just a few hours or days. Brine from a salar is pumped into a DLE module where a highly selective absorbent removes the lithium from the brine. The lithium is then further processed into lithium carbonate or lithium hydroxide (potentially removing the need for energy-intense spodumene mining), and the leftover brine reinjected into the salar to collect more lithium.

As well as saving time, DLE has several other advantages. Importantly, it is potentially more sustainable than conventional brine extraction. Emissions are between 0 and 5 kg CO_2 per kg LCE, and the process has lower overall water consumption and requires less space due to the elimination of the evaporation ponds. However, fresh water consumption can exceed the amount used in a state-of-the-art brine mine. Another advantage is that DLE recovers up to twice as much lithium and can be used for lower-grade brines. These factors mean that the process could increase the capacity of brine projects in South America, and also be transferred to other locations with previously unviable geothermal brine sources. This has already been done in California (Controlled Thermal Resources) and Germany (Vulcan Energy).

However, DLE is still under development. The first large-scale projects are currently being built and have faced delays and CapEx increases due to scaling and engineering challenges. For example, the CapEx estimate of Australia-based Lake Resources, project in Argentina increased from USD 544 million to USD 1,000 to 1,500 million for a 25.5 kt operation.[4,5] But the technology still has the potential to broaden the base of lithium extraction.

TECHNOLOGY PERFORMANCE

Li-ion cells are likely to remain the dominant technology for use cases requiring high energy densities, such as EVs, making them the main focus of research efforts. Developments in Li-ion materials are currently centered on better, cheaper cathode active



1) Na-ion share consists of the two cell chemistries nickel-based and Prussian white

Figure 9: Battery cell demand by cathode chemistry, 2020-2030, base-case scenario [GWh/a]; *Source: B3, BMO, IHS, SMM, ICCSINO, interviews with market participants, Roland Berger*

materials (CAM) and anode active materials (AAM).

CATHODE ACTIVE MATERIALS: SINGLE-CRYSTAL NMC CELLS ARE THE LATEST DEVELOPMENT TO HIT THE MARKET

Developments in CAM are centered around incremental improvements to achieve cell densities similar to or higher than cell densities of conventional Li-ion cells by using a higher share of more easily sourced, and therefore cheaper, raw materials. Research is currently split into two main areas: ternary materials, such as nickel-manganese-cobalt (NMC), and LFP chemistries.

NMC cells, which now have nickel contents of more than 90%, are capable of achieving energy densities of 240-320 Wh/kg, the highest among Li-ion cell chemistries. They also offer good fast-charging capabilities, making them a mainstream choice. However, their reliance on increasing nickel contents to improve performance means they are relatively expensive. NMC costs are highly dependent on nickel and lithium prices – while targets are set below USD 100 per kWh, prices in the past year peaked at up to USD 140 per kWh.

While research is under way to investigate the possibility of reducing the cobalt share in NMC cells to lower costs and improve ESG risks, another area of NMC research is currently in the spotlight – single-crystal cathodes. In this technology, the cathode's nickel-based oxide particles are made out of one large crystal instead of several crystals, as in conventional NMC material. Multiple crystals mean that the crystals radiate out in different directions, accelerating cell degradation. This is one of the main pain points of nickel-rich materials. Single-crystal cathodes, however, have up to 30% better lifetime behavior, and can increase the capacity by 10%. However, as the material requires different and additional production steps which result in more costs, it will most likely be mixed with poly-crystal material to begin with, in ratios of 20:80.[6]

Several companies have already implemented or are planning to implement single-crystal materials, including Posco Future M, which produces up to 6,000 tons of single-crystal NMCA per year and started shipping the material in April 2023, and LG Chem, which started shipping in July 2023, targeting 50,000 tons production capacity for single-crystal CAM by 2027.[6,7]

LFP TECHNOLOGY IS BEGINNING TO CHALLENGE NICKEL-RICH CELLS FOR MARKET SUPREMACY

LFP cells are already established in the market, and are expected to be the dominant cathode chemistry with around 42% (LFP + LFMP) of market share by 2030, with potential to increase further. While their energy density (160-220 Wh/kg) and charging times are lower than other new Li-ion chemistries, they are significantly cheaper (around USD 50 to 70 per kWh, meaning USD 70 to 90 per kWh cheaper than in early 2023 price peak), longer lasting and nickel- and cobalt-free. This makes them a good fit in entry segment EVs and stationary storage. With continuous improvement of LFP-based chemistries, the technology is targeting higher vehicle segments. For example, Chinese automaker and cell producer BYD is using LFP cells in all its EVs, and US giant Tesla is using the technology in its mid-range models. In addition, CATL recently announced a fast-charging capable LFP-based battery pack, offering 700 km of range in a Changan EV and charging rates of up to 4C, which is quite competitive with today's nickel- and silicon-based chemistries.[8]

Lithium-manganese-iron-phosphate (LMFP) batteries have similar properties to LFP cells but are more energy dense (200-240 Wh/kg). The downside is that they are not as long lasting. Several companies are expected to launch the first LMFP cells in 2023/24. For instance, CATL has already started production of its M3P technology, with Tesla reportedly in discussions about being one of the first customers for the cells. Manganese-rich cells offer even higher energy densities (250 Wh/kg) and good cost competitiveness (USD 70-80 per kWh), positioning them between NMC and LFP cells.[9] But they are not expected to enter the automotive market until 2025. Umicore and BASF both plan to industrialize this chemistry in the coming years. Volkswagen has also announced its intention to use the technology in its future EV platforms.

ANODE ACTIVE MATERIALS: INTRODUCTION OF SILICON/GRAPHITE ANODES BEGINS BUT CHALLENGES REMAIN

The situation regarding the development of anode active materials is much the same as reported in Battery Monitor 2022. The main aim is to move from pure graphite anodes to anodes with an increasing share of silicon (up to 100%), which has a higher reversible capacity (the theoretical capacity of a 100% silicon anode is around 4,200 mAh/g, roughly 10x higher than graphite). This helps to improve charging and discharging speeds and allows for higher energy densities. This topic is covered in more depth in Battery Monitor 2022.

COMPETITIVENESS

Growing demand and dwindling supplies of CAM mean it is becoming necessary for battery producers to invest in or strike deals with miners and refiners to secure materials and prices.

SUPPLY OF KEY BATTERY MATERIALS IS FORECASTED TO ONLY JUST KEEP UP WITH FUTURE DEMAND

As in 2022, the supply of key cathode materials, namely lithium, nickel and cobalt, remains very tight. Globally, sufficient deposits exist, but current mines and announced new mining projects do not exceed the expected demand in the coming years, leading to a tight supply/demand situation. This could push up prices. Below we look at the current mining and refining situation for each metal.

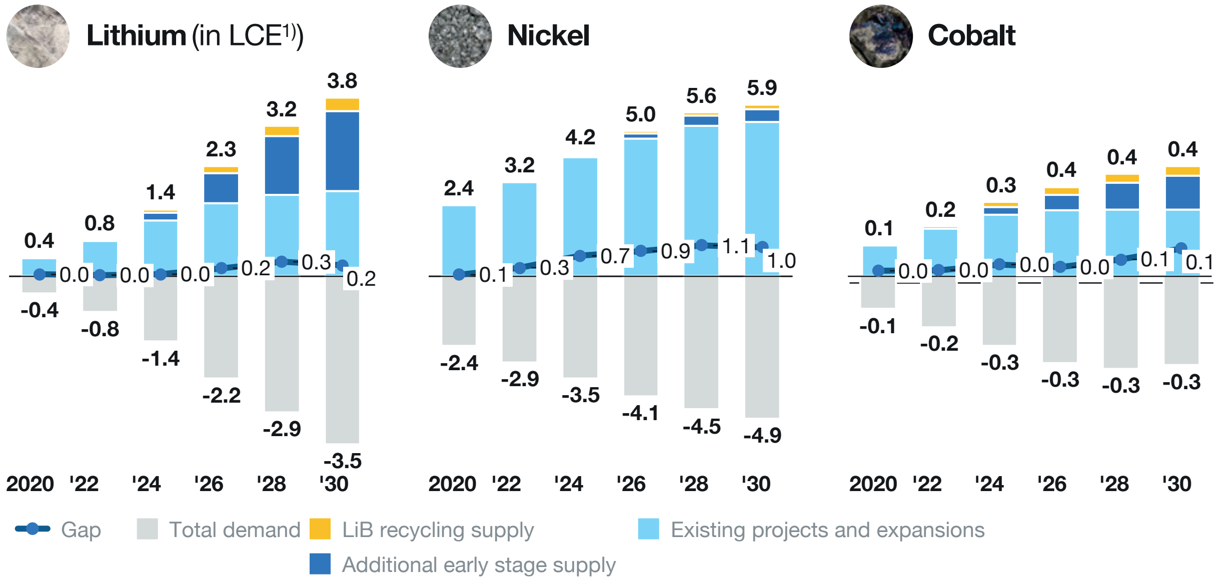
LITHIUM: SUPPLIES OF REFINED LITHIUM CARBONATE AT RISK

The future supply/demand situation for lithium is particularly tight. Li-ion batteries are expected to account for 94% of global lithium demand by 2030, and existing and planned mining capacities are only just enough to meet the forecasted demand.

While sufficient capacities of lithium hydroxide (mined from spodumene; typically used in nickel-rich cathode materials) have been announced, a supply gap of lithium carbonates (mined from brine; typically used in low-nickel and LFP cells) is projected at the end of the decade. To address this, additional hard rock operations are expected to be converted to meet carbonate demand.

NICKEL: MORE PROCESSING CAPACITY URGENTLY NEEDED

Mined nickel supplies currently look healthy, with announced capacities up to 2030 expected



1) Lithium carbonate equivalent

Figure 10: Lithium, nickel & cobalt mined supply/demand forecast, 2020-2030, base-case scenario [mt metal equivalent]; *Source: BMO, Deutsche Bank, Fastmarkets, Roskill, Wood Mackenzie, Roland Berger*

to comfortably exceed demand, which comes from a broad range of industries. Indonesia is expected to be by far the biggest producer, with more than 3,500 kt in 2030.

However, the situation with processed nickel is very different, as displayed in figure 11. Battery materials require 'class 1' nickel to produce nickel sulfate. Currently, demand for class 1 nickel comes mainly from stainless steel and non-ferrous alloy production, with demand from Li-ion cells making up only about 15% of total demand in 2020. But this figure is set to reach 70% in 2030, strongly driving class 1 nickel demand. Demand for nickel sulfate comes almost exclusively from the Li-ion industry.

Capacity gaps are projected for refined class 1 nickel in the coming years, with additional processing capacity urgently required. This is challenging – lead times for new mines and refineries are between six and 13 years (four years for HPAL plants in Indonesia).

COBALT: FALLING DEMAND BUT POLITICAL RISKS

As the production of nickel-rich and LFP Li-ion cells grows, demand for cobalt is expected to ease off from 2024 (figure 10), resulting in sufficient supply. But risks exist. For example, significant amounts of cobalt are mined in the Democratic Republic of the Congo and refined in China, with both presenting political risks. In addition, the Li-ion industry is still set to drive demand for processed cobalt over the next few years, with demand share projected to rise from 47% in 2020 to 79% of total cobalt demand in 2030.

BATTERY PRODUCERS NEED TO MOVE TO SECURE CRITICAL MATERIAL SUPPLIES WHILE NAVIGATING REGULATION

The overall supply situation for cathode materials presents a clear risk for players in the battery market. Measures to secure raw material supplies are therefore necessary.

Some large CAM producers, cell producers and automotive OEMs have already made large investments in mining, refining and material production to secure supplies and prices. Others have struck long term agreements (LTAs) with suppliers, often bound to index prices. Competition has been fierce – by mid-2022, more than 40% of available production in 2025 had been reserved.

INVESTING IN MINERS OR AGREEING LONG-TERM DEALS CAN ENSURE SIGNIFICANT SAVINGS ON CELL COSTS

Material prices account for a large proportion of cell costs. For example, at Q1 2023 prices, cathode active materials made up more than 50% of cell costs in an NMC 811 cell, at 78 USD/kWh out of a cell total of 144 USD/kWh.

Due to increasing demand caused by the recovery from COVID-19 and supply shortfalls, raw materials prices have shot up in recent years. Cell cost for LFP cells jumped by 41% between January 2021 and January 2022 due to raw material price increases, and costs for NMC811 cells rose by 28%. This badly affected cell manufacturing costs and the profitability of EVs. Prices for raw CAM materials are expected to remain above pre-COVID levels for the foreseeable future.

Companies that have been able to secure raw material supplies through investments or LTAs therefore have a clear advantage over competitors who are reliant on rising and volatile spot market prices. CATL, for example, bought stakes in or signed LTAs with miners including Australian lithium specialists Pilbara Minerals and AVZ Minerals. This enabled them to reportedly offer a fixed price of RMB 200,000 per ton of lithium carbonate to their Chinese key customer OEMs if they dedicate 80% of their battery demand to CATL. This is less than half the spot price of around RMB 427,000 at the time of the announcement, reflecting a saving of around 30% on total cell costs.[10]

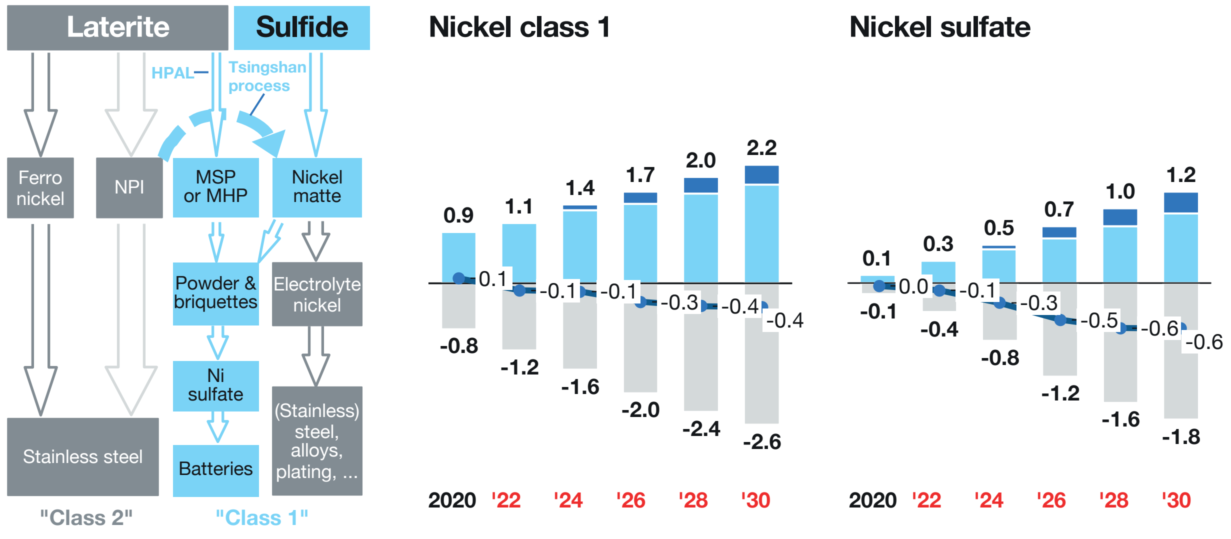


Figure 11: Nickel sulfate production pathways and supply/demand forecast for refined nickel, 2020-2030, base-case scenario [mt metal equivalent]; *Source: Fastmarkets, Roland Berger*

INNOVATION

Battery Monitor 2022 covered the search for sulfate-free ternary cathode materials, which allow for more efficient cells and reduced CO_2 emissions during production. Industrialization of these technologies remains elusive, however. In this subchapter we instead focus on two emerging technologies – sodium-ion cells and deep-sea mining.

SODIUM-ION CELLS: NOW A REAL ALTERNATIVE TO LFP IN CERTAIN APPLICATIONS

Sodium-ion batteries are the most advanced new battery technology, having recently been introduced for commercial applications. They use cheap, abundant sodium ions as charge carriers instead of lithium ions, but otherwise the cell design is very similar. Three main chemistries exist, each with different cathode materials:

Prussian blue: Uses an iron, carbon and nitrogen compound as the cathode material. This allows for low-cost materials, but the energy density is low.

Sodium layered oxides: In this technology, the sodium and transition metal (iron, manganese, copper, nickel, etc.) oxide cathodes cost more, but offer higher energy densities, leading to

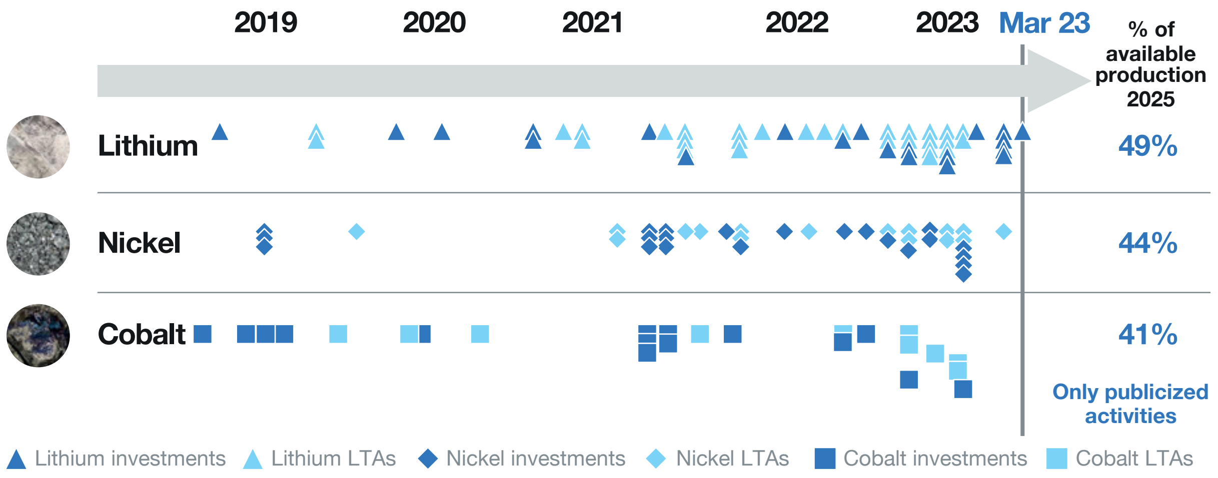


Figure 12: Announcements of investments and long-term agreements for cathode materials
Source: Research, Roland Berger

questionable cost competitiveness with LiB technology.

Polyanionic materials: Here, the sodium superionic conductor used in the cathode offers good cycle performance, but raw material costs are higher & energy densities lower than in the other cells.

Na-ion cell energy densities average around 160 Wh/kg, with an industry target of 200 Wh/kg. This ranks them below Li-ion LFP cells. Sodium layered oxide cells are expected to gain the largest market share (65% by 2025) due to their higher energy densities. They can have a cost position of around USD 70 per kWh when fully scaled up (Prussian blue cells USD 50 per kWh), giving them a potential cost advantage over LFP cells (the cheapest Li-ion option), dependent on the price of lithium.

CHINA IS THE MARKET LEADER, WITH PRODUCTION FOR EV CELLS BEGINNING IN 2023

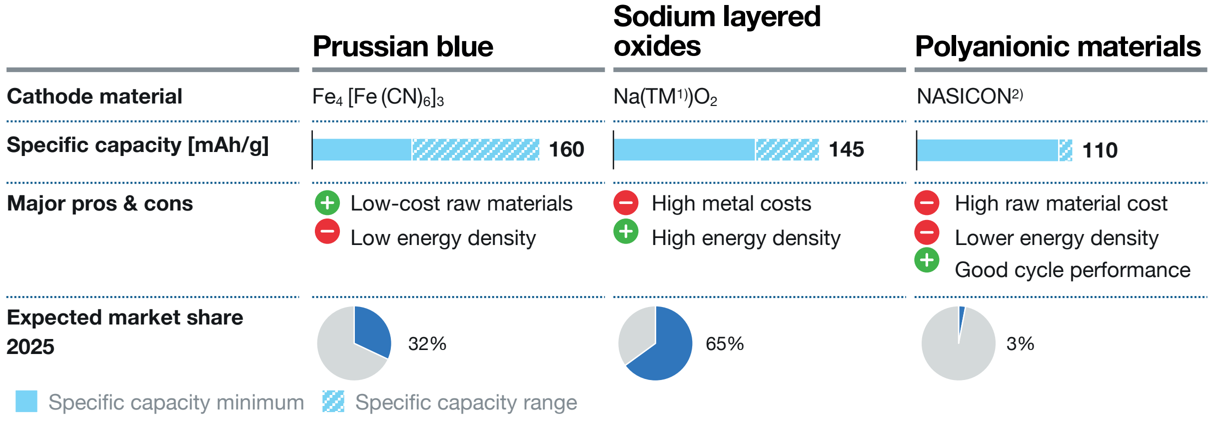
The Chinese battery manufacturers HiNa and CATL launched or plan to launch layered oxide and Prussian blue Na-ion cells in the automotive market in 2023, for entry-level models such as the Chery EV. Meanwhile, China's BYD aims to use its own hybrid Na-ion/Li-ion battery in its entry-level Seagull EV, planned for release in 2023. However, ESS remains the most likely future market segment for Na-ion batteries because of their low energy densities, at least in the Western world.

Global Na-ion announced capacity in 2025 already exceeds 125 GWh, with more than 90% in China. There are currently only a handful of non-Chinese players planning to scale the technology, including Altris (Sweden), Amte (UK), Faradion (UK/India), Natron Energy (USA) and Indi Energy (India).

Na-ion cells offer a promising, cheaper alternative to LFP cells, and can be produced on conventional Li-ion production lines. However, due to their lower energy density, the Na-ion market share is expected to be 8% by 2030, depending on lithium price development and availability.

DEEP-SEA MINING: THE SEABED HOLDS HUGE RESERVES OF CELL MATERIALS, BUT MINING IT IS CONTROVERSIAL

The seabed plains of the Clarion-Clipperton Zone (CCZ) deep under the Pacific Ocean are dotted with potato-sized nodules of nickel, cobalt, manganese and copper. Together, these nodules hold more than three times the Earth's land reserves of nickel and six times the planet's land reserves of cobalt. Mining companies, including the Metals Company, Global Sea Mineral Resources and numerous Chinese players, have been exploring opportunities in the zone for several years. They plan to deploy large robots to the seafloor to harvest the nodules, pump them to a support vessel and then ship them to a refinery on land.



	Prussian blue	Sodium layered oxides	Polyanionic materials
Cathode material	$Fe_4[Fe(CN)_6]_3$	$Na(TM^{1)})O_2$	NASICON2)
Specific capacity [mAh/g]	160	145	110
Major pros & cons	⊕ Low-cost raw materials ⊖ Low energy density	⊖ High metal costs ⊕ High energy density	⊖ High raw material cost ⊖ Lower energy density ⊕ Good cycle performance
Expected market share 2025	32%	65%	3%

1) TM = transition metal(s) such as Fe, Mn, Cr, Cu, V, Ni, Co, Ru or Ir; 2) Sodium (**Na**) **S**uper **I**onic **CON**ductor

Figure 13: Alternative sodium-ion cathode technology pathways;
Source: ICCSINO, desk research, interviews with market participants

This disruptive technology has several advantages. Extracting the deposits is potentially highly cost competitive, and the materials can be taken to a refinery in a country with a high share of renewable energy, enabling a lower carbon footprint. But deep-sea mining is not without its challenges. Depending on technology used, the extraction process could be indiscriminate, posing a threat to the seabed ecosystem and wildlife that is almost impossible to gauge. Lobbying by environmental groups against the process is therefore strong. However, some experts and the companies' publications indicate deep-sea mining could potentially have a lower impact on biomass than land mining, especially in places like Indonesia.

Mining in the CCZ also requires an agreement to be reached between members of the International Seabed Authority, the UN-backed regulator. The ISA aims to finalize rules on deep-sea mining by July 2025. Other projects, for example in the Cook Islands, may be easier to realize. The Cook Islands projects have local support and the islands' government aims to ensure sustainable mining operations. One approach is, for example, the selective pick-up of nodules enabled by vision systems.

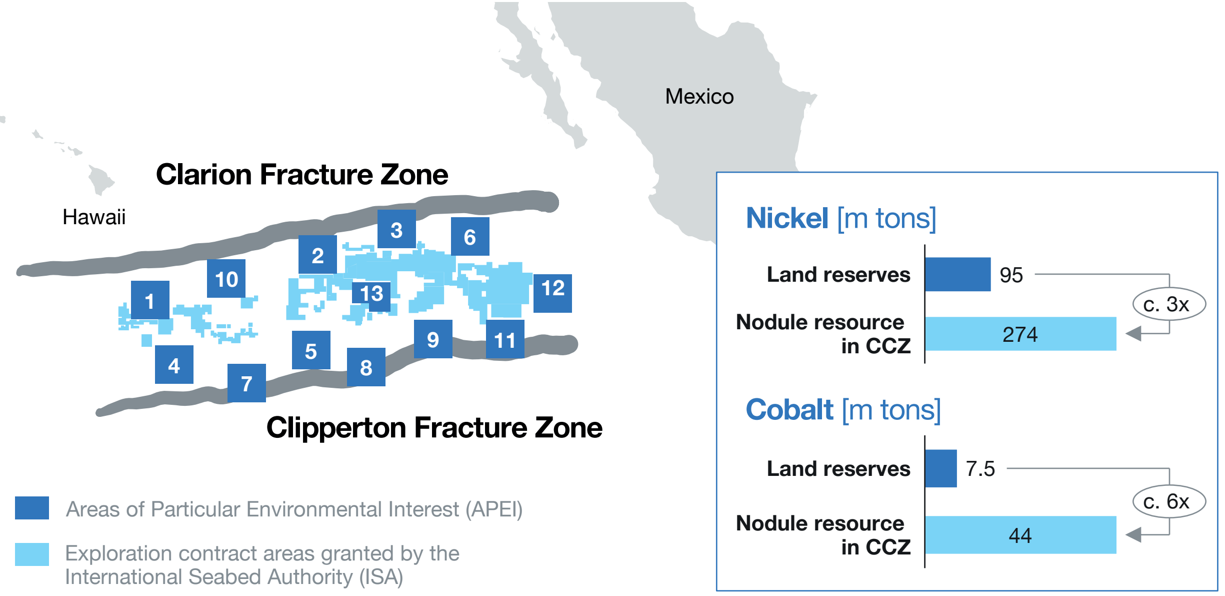
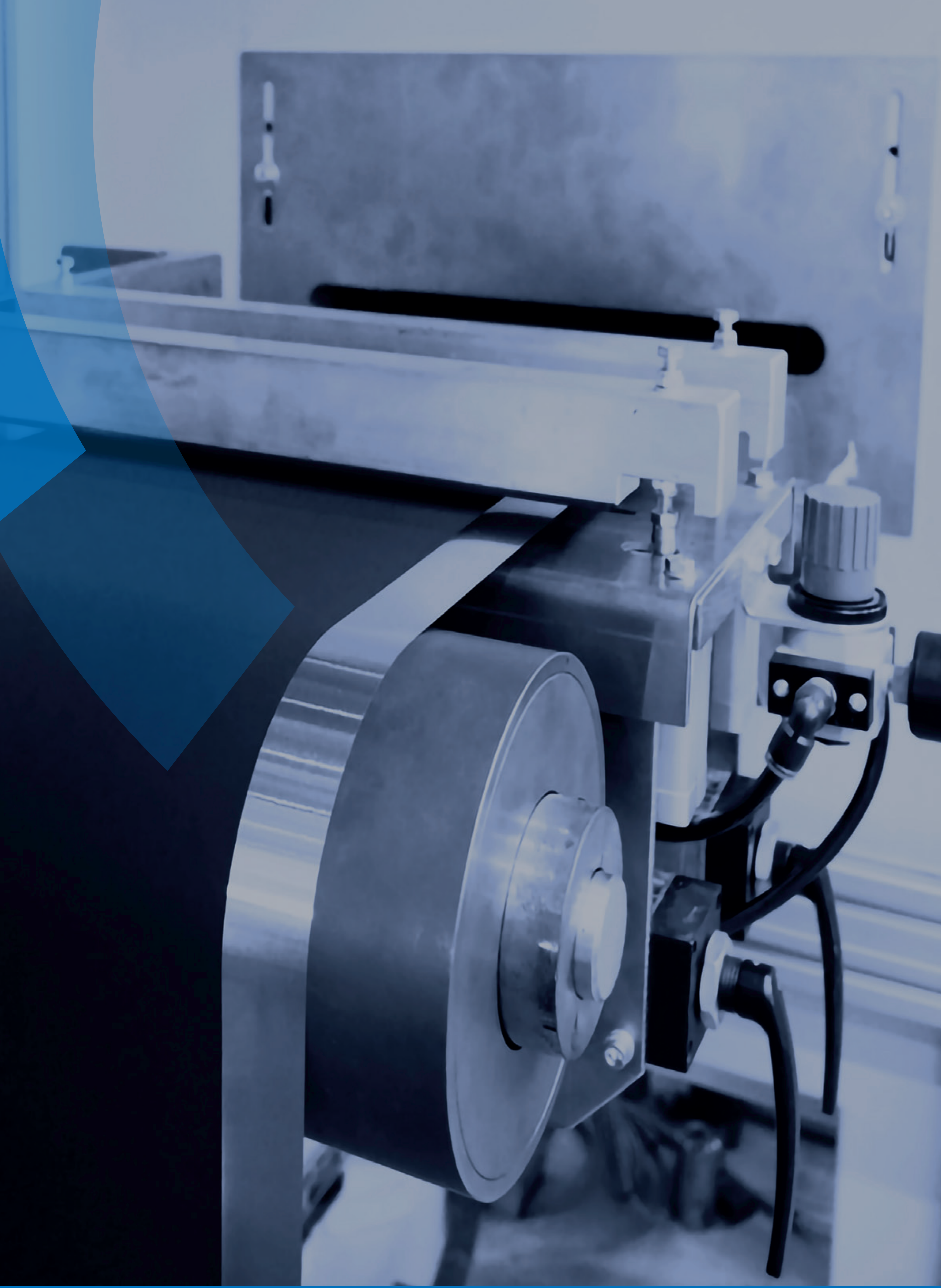


Figure 14: The Clarion-Clipperton Zone and its potential nickel and cobalt reserves;
Source: Company announcements[11, 12, 13, 14]



Sarah Wennemar, Daniel Neb

BATTERY PRODUCTION

With the automotive industry's general shift towards battery-electric vehicles, demand for batteries is increasing, especially in America and Europe. As a result, new battery production hotspots are emerging in those regions, in addition to the existing market in Asia. Achieving sustainability in battery production involves reducing emissions, optimizing processes, and making sustainable material choices. At the moment, Chinese factories have the highest CO_2 emissions (~530 g CO_2/kWh) due to their electricity mix compared to Europe (~200 g CO_2/kWh) and North America (~370 g CO_2/kWh). But a lot of investments are being made to integrate renewable energy to reduce the emissions. Additionally, Asian factories, benefiting from their extensive experience and longer running times, tend to have higher cycle times, lower scrap rates and better OEE than their European and American counterparts. To counteract the greater experience of Asian factories, in recent years new innovative product and process technologies have become increasingly important in the battery sector, e.g. laser drying to reduce the lengthy drying in ovens and increase process speed. As a result, despite the long-standing dominance of Asia, there has been an increasing trend in patents from America and Europe. The development of new manufacturing technologies is an important prerequisite for efficient and thus cost-effective battery production. At the same time, they play a key role in the continuous improvement of battery cell quality.

STRATEGIC IMPLICATIONS

For battery manufacturers

Battery producers, especially in Europe, prioritize sustainability as a key USP in their operations. But the current grid energy mix may not be entirely representative of sustainability goals. As some gigafactories show us, individual efforts by battery producers can result in much lower greenhouse gas emissions than the local electricity mix would suggest. To ensure global competitiveness in both sustainability and pricing, European manufacturers should invest further in sustainable energy sources for their production processes.

Facilities in the EU and North America (NA) are ramping up production to meet the increasing demand for batteries. However, a crucial aspect is reducing scrap rates as quickly as possible. Implementing digitalization and 'Industry 4.0' technologies can optimize manufacturing processes, improve quality control and lessen waste.

For equipment providers

Reducing the cost of equipment is vital to attract battery manufacturers who seek cost-effective solutions. Examples of European gigafactories being equipped with Chinese machinery show the need for cheap solutions to ramp up capacities. This may also be linked to the gap in the market for European turnkey solution providers. Companies that can offer comprehensive solutions, from equipment to process optimization, could find a niche and support European and North American manufacturers.

For policymakers

Chinese battery manufacturers enjoy a significant advantage in capital expenditure (CapEx). EU and NA policymakers should consider measures to level the playing field. For instance, tariff policies similar to the 25% tariff on cells in North America could be explored. While protecting domestic battery manufacturing is essential, policymakers should be cautious not to make local Original Equipment Manufacturers (OEMs) uncompetitive. Striking the right balance between promoting local production and allowing for international competitiveness is a delicate task. In the EU, fostering collaboration among member states for a unified approach to battery production and sustainability can be beneficial. A coordinated strategy can help mitigate the CapEx gap and ensure a sustainable and competitive European battery industry.

SUSTAINABILITY

The aim of sustainable production is to achieve and maintain certain standards in order to enable a sustainable economy for present and future generations.[15]

The sustainability of battery cells is mainly dependent on three aspects: greenhouse gas emissions (GHG) per kWh produced, process efficiency and control as well as the characteristics of the materials used. The largest part of the CO_2 emissions in the production of lithium-ion batteries comes from electricity usage for formation, drying processes, and the utilization of clean rooms and drying rooms.[16] Therefore, the electricity mix is a critical factor for GHG emissions. In Asia, the emissions are about 531 g CO_2/kWh (for the Chinese grid mix), for the US about 367 g CO_2/kWh, and an average of about 200 g CO_2/kWh for Europe, with higher carbon emissions in countries like Germany and lower carbon emissions in Norway and Sweden.[17, 18, 19]

In addition, however, individual efforts by battery manufacturers to decouple themselves from the grid and thus from the local energy mix must also be considered. In that regard, the energy supply with green electricity via solar parks is illustrated by the examples of Northvolt (Europe), Tesla (North America), and CATL (Asia). Northvolt plans to cover 100% of its energy consumption with fossil-free energy by 2030. Tesla is also focusing on integrating renewable energy into their factories and charging infrastructure. According to their 2021 sustainability report, they were able to produce more energy than was consumed by their factories and charging infrastructure. This is no longer stated in the 2022 report due to significant growth, but it is clear that the use of non-fossil energy continues to be an important lever for Tesla. In 2022 alone, the company claims to have already produced 26.6% of its electricity from sources of renewable energy and aims to be carbon neutral by 2035.[20, 21, 22, 23]

Current activities are focusing on reducing emissions through more energy-efficient equipment and on integrating new lower-emission technologies (e.g. dry coating, microenvironment). By implementing an innovative drying concept throughout the production line, energy consumption can be reduced by up to 85%. Another critical aspect is that in battery production, components that are harmful to humans and the environment are used, e.g. the electrolyte LiPF6 which reacts with water to form hydrofluoric acid.[24] In a factory, hazardous waste material is about 120 to 130 kg/GWh.[25] Currently, there are hardly any differences between the regions in terms of hazardous substance consumption. Efforts across the value chain can lead to a reduced consumption of hazardous materials, e.g. the use of water-based LFP instead of NMP-based NMC.

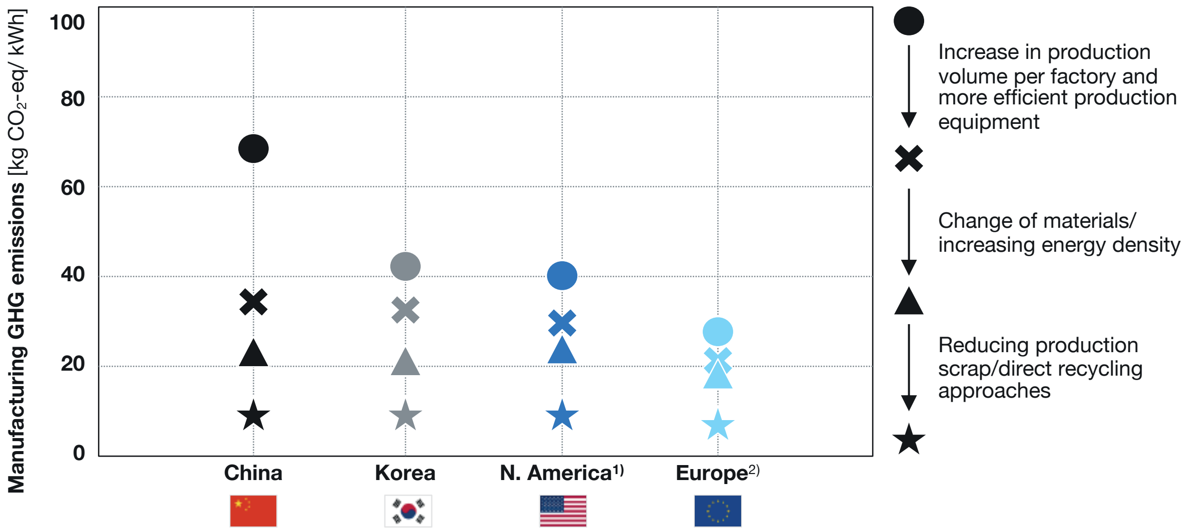
Depending on the material used, there are also differences in the amount of capacity produced: For example, LFP has a lower energy density than NMC, so significantly more must be produced to achieve the same capacity per factory area.[26] The high complexity of the production process results in high scrap rates along the entire battery value chain.[27] During the ramp-up phase, a production line can have a reject rate of over 30%, but with a well-established line the reject rate is reduced to almost 5 to 10%.[28, 29] As a result, well-established Asian factories currently outperform their European and American counterparts, which are still in the early stages of ramping up production. CATL has just announced that they have decreased the defect rate for EV batteries to the PPB level.[20] Figure 15 shows how different drivers of sustainable production would individually affect different regions. In general, it can be said that all regions are following a similar path to more sustainable battery production.[30]

TECHNOLOGY PERFORMANCE

In order to increase the competitiveness of the battery cell, the production technology and the plant engineering are decisive factors.

Performance and stability of a battery cell production line can be evaluated using various metrics. One key indicator is cycle time, which measures the speed of product manufacturing. Achieving high process speed while maintaining product quality is a key challenge during the ramp-up phase and the first few years of operation, and it relies heavily on effective process control in factories. During ramp-up phases, scrap rates of 30 to 50% can occur compared to established production lines with around 5 to 10% of overall scrap rate. Industrializing the production process at high speeds requires comprehensive overall process control and understanding. Another important metric is the Overall Equipment Effectiveness (OEE), which assesses equipment performance in three areas: availability, performance, and quality. Improving OEE in battery cell production can be achieved through process enhancements, increased equipment utilization, autonomous and planned maintenance activities, and employee training. Asian factories, benefiting from their extensive experience and longer time in operation, tend to exhibit shorter cycle times and higher OEE than their European and American counterparts.

The manufacture of lithium-ion battery cells requires precision and a controlled process environment. Automated processes are generally less error-sensitive than manual steps, making automation a key driver for optimizing process steps, quality, yield and throughput. Today's established production lines manage to produce electrodes with a coating and drying speed of 80 to 100 m/min and a coating width of 1 to 1.2 m with a yield of around 95%. In comparison, lines in the ramp-up phase can only produce at half the speed and with a much lower yield. Gigafactories, in particular, have already embraced fully automated individual processes. However, the extent of automation may vary between different process interfaces. Minimizing human intervention can greatly



1) US as representative example; 2) France, Germany, Poland and Sweden as representative examples

Figure 15: The effect of different production and material changes on the manufacturing eco-efficiency in different regions;
Source: Xu et al. 2022 [26]; Christian Aichberger and Gerfried Jungmeier 2020 [31]

improve product quality and process stability. Fully automated processes are best suited for factories with high process OEE and minimal interventions, making longer-operating factories more conducive to achieving higher levels of automation. Asian battery manufacturers, with their overall longer operating times (shown in figure 16), tend to exhibit higher levels of automation in their production lines, resulting in superior technology performance compared to their European and US counterparts.[32, 33]

COMPETITIVENESS

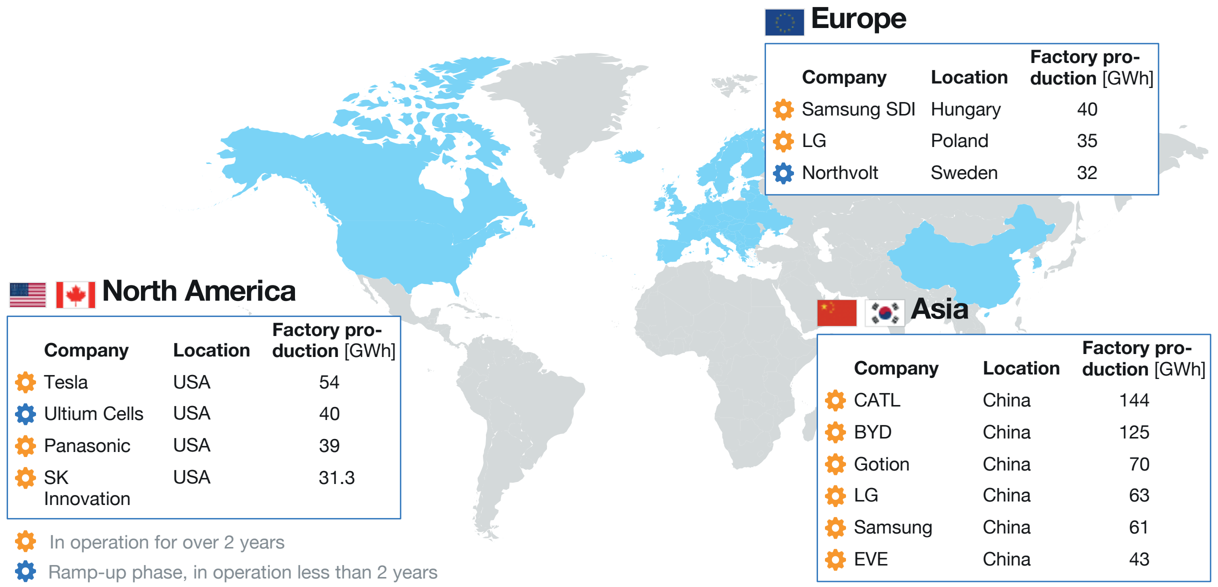
The market for manufacturing battery cells and production equipment is still dominated by Asian players who excel with their cost leadership. However, many high-quality process technologies 'made in Europe' are emerging.

PRODUCTION CAPACITIES

In 2022, three Asian companies accounted for 70% of global battery sales. Yet, the e-mobility shift has caused battery demand to skyrocket in Europe as well.[34, 35] Current projects of battery manufacturers, OEMs and emerging players make Europe the new hotspot for battery cell production. Meanwhile, the European Union's ambitions will tighten the requirements for 'green batteries', which is going to limit the sales of leading players unless they invest in research and development and focus on optimizing raw materials.[36]

PRODUCTION INVESTMENT

An important driver in setting up battery cell production is economies of scale. A study[37] shows that the investment costs for production equipment have a major impact on cell costs for small production volumes. A meta-study conducted by PEM in 2022 (see figure 17) shows that Asian battery manufacturers currently invest only half as much in production facilities as European players do. Asia continues to assert its price leadership in production equipment and turnkey solutions for battery cell manufacturing.



North America

Company	Location	Factory production [GWh]
🟠 Tesla	USA	54
🔵 Ultium Cells	USA	40
🟠 Panasonic	USA	39
🟠 SK Innovation	USA	31.3

Europe

Company	Location	Factory production [GWh]
🟠 Samsung SDI	Hungary	40
🟠 LG	Poland	35
🔵 Northvolt	Sweden	32

Asia

Company	Location	Factory production [GWh]
🟠 CATL	China	144
🟠 BYD	China	125
🟠 Gotion	China	70
🟠 LG	China	63
🟠 Samsung	China	61
🟠 EVE	China	43

🟠 In operation for over 2 years
🔵 Ramp-up phase, in operation less than 2 years

Figure 16: Overview of current status of cell manufacturing lines in Asia, North America, and Europe (only 30 GWh and above); *Source: PEM RWTH Aachen University*

OPERATIONAL EXPENDITURES

The global trend in battery cell production costs has been steadily declining over the past few years. This reduction can be attributed to several factors, including advancements in manufacturing processes, economies of scale as production volumes increase, and improvements in battery chemistry. Additionally, increased competition in the electric vehicle market has driven manufacturers to innovate and find cost-effective solutions. Government incentives and investments in the green energy sector have also played a significant role in reducing production costs. As a result, the overall cost of manufacturing battery cells has been on a downward trajectory, making electric vehicles and renewable energy storage solutions more affordable and accessible on a global scale.

HORIZONTAL PROCESS INTEGRATION

In Europe, there are numerous specialists in plant engineering with extensive know-how in process technologies who have thus become leading suppliers of specialized production equipment in individual processes. To meet the high demand for production equipment, enormous capacities are currently being built up at local manufacturers. This includes the expansion of infrastructure as well as the number of employees. From the battery manufacturers' point of view, however, there is a desire for turnkey suppliers. Turnkey solutions can be sourced from companies, but mainly in Asia. This is driven by the overwhelming size of companies explicitly focused on battery equipment.

INNOVATIVE STRENGTH

Companies from Asia have patented the majority of the manufacturing innovations of the last few decades. Recently, however, process innovations from Europe and America are emerging, driven by collaborations.

SUSTAINABLE PRODUCTION CONCEPTS

In the battery industry, research and development (R&D) is shifting to enable the production of a 'green battery'.[38] Essential aspects such as investment costs and energy consumption are addressed by innovative production concepts. Furthermore, a trend towards the

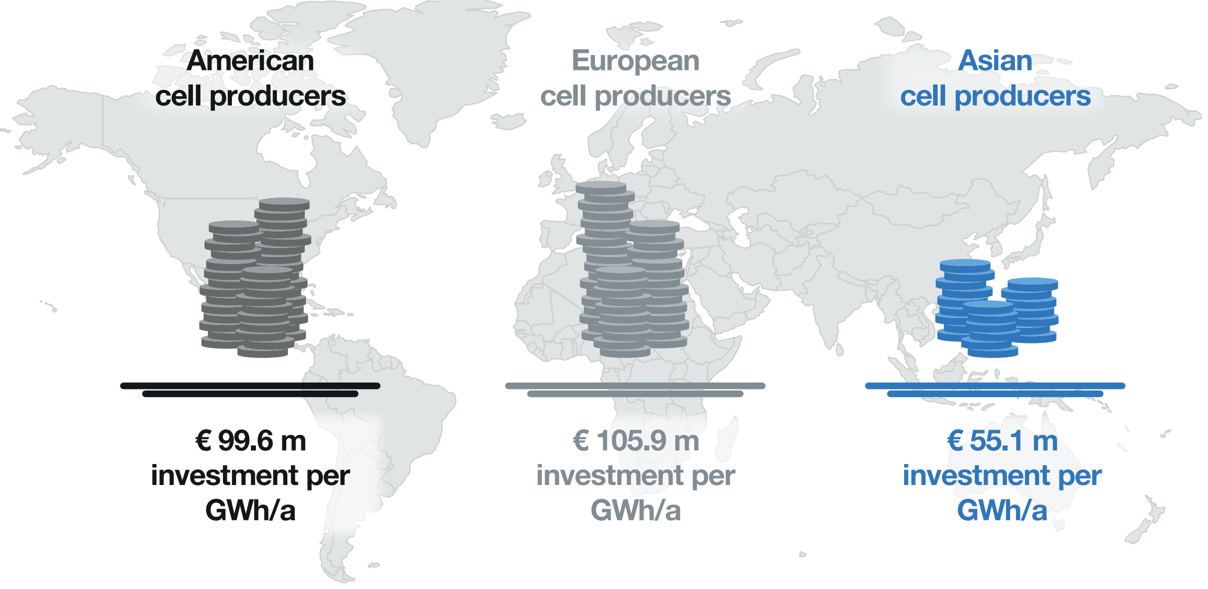


Figure 17: Estimated project costs for the setup of a gigafactory battery cell production by manufacturer origin; *Source: PEM RWTH Aachen University*

development of new production technologies for the processing of environment-friendly materials is noticeable. One example is the replacement of toxic solvents such as NMP with water-based cell formulations. Streamlining supply chains and implementing recycling programs for used batteries also holds the potential to cut costs and reduce environmental impact. Overall, by focusing on these strategies, the battery cell production industry can make electric vehicles and renewable energy solutions even more economically competitive, further driving the transition to a sustainable energy future.

COST-DRIVEN POTENTIALS

Cost-driven potentials in battery cell production lie primarily in optimizing the various stages of the manufacturing process to reduce expenses. This includes advancements in materials sourcing, such as securing more affordable and sustainable raw materials, like lithium and cobalt, as well as improving energy efficiency in production facilities to lower operational costs. Additionally, enhancing production technologies and automation can lead to higher yields and reduced labor expenses. Another way of cutting costs is by digitalizing battery cell production. For example, vast investment costs in formation and aging[39] can be reduced by data-based charging and conditioning cycles. Furthermore, solutions like microenvironments aim to downsize energy-intensive clean rooms and dry rooms to a minimum process volume. The dry coating process also opens up a further method for increasing cost-effectiveness and sustainability. In this process step, which is still under development, the active material is applied to the electrode foil as a solid instead of a solvent-based slurry.

PATENTS IN BATTERY CELL PRODUCTION

According to a study conducted in 2022, Asia accounts for 70% of all international patent families submitted in the last few years (see figure 18). However, the number of co-inventions by European and American companies has increased. Since most innovation activities in Asia are carried out by large companies, the contribution of SMEs and universities is much higher in the US and Europe.[40] This underlines the great potential of joint R&D projects for the European market.

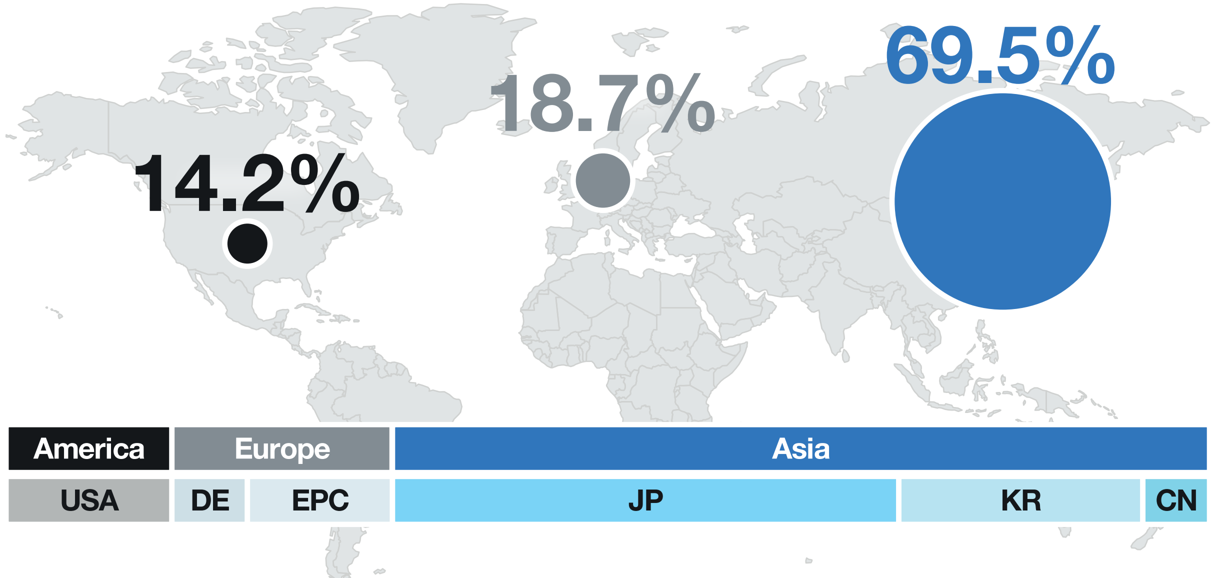


Figure 18: Overview of international patent families covering battery cell manufacturing technology, 2000-2018[39]; *Source: Degen, F.; Krätzig, O. 2022*

INNOVATION CYCLE – TIME-TO-MARKET

In order to push new technologies from the first idea to patent application and final integration, various innovation cycles have to be completed. In fast-moving areas such as the battery industry, time-to-market as an indicator of the time that passes until a product idea has reached market maturity is an essential factor. Furthermore, to better understand the battery system as the core element of most products and to lessen dependency on suppliers, a trend in end users setting up their own research manufacturing lines can be observed.

Depending on prior experience and planned changes of the products, the development process of new battery systems can take from months to several years. While innovation in Asia is driven by radical investments, the American innovation culture is characterized by agility and a vast network of start-ups. European equipment manufacturers are following this example by focusing more on collaborations.

> “New product and process innovations form the foundation for affordable and at the same time CO_2-neutral battery cell production of the future.”

Daniel Neb

Moritz Frieges, Jonas Gorsch, Benedikt Späth, Christian Offermanns, Nikolaus Lackner, Niklas Kisseler

PRODUCT PERFORMANCE

Battery technology is applied in several use cases, ranging from smaller applications such as entertainment devices, electric light vehicles (scooters & bikes), or electric tools to larger applications like industrial and logistics solutions, electric cars, electric utility vehicles, and electric aircrafts. The possibilities are open to the imagination, and the steady development of those battery cells is the key enabler for the electrification of those solutions, enabling a more sustainable transportation sector. Also, stationary energy storage is key for the transition to more sustainable energy production, and there are huge investments being made to store the energy produced by wind turbines and solar farms.

STRATEGIC IMPLICATIONS

For policymakers

Battery technology requires further future-proofing. A regulatory framework that encourages sustainability, recyclability and safety but also addresses energy density, power density and costs is essential to ensure the acceptance of electrified transportation and thus raise buyer numbers. To meet these goals, investment should be made in research and development projects and collaboration between industry and academia should be encouraged.

Policymakers in Europe should focus on fostering a competitive environment for battery technology development within the region. North America's great success with the IRA shows that providing incentives for the battery industry can attract massive investments. Similar subsidies can be explored to incentivize local developments and drive advancements in materials, safety and energy density.

For battery manufacturers

The use of sustainable and eco-friendly materials in battery production should be prioritized. Further developing new cell chemistries like sodium-ion battery technology and exploring other alternatives can mitigate potential supply chain shortages, especially for materials like lithium. This can be supported by innovation in cell design. One main goal should be the maximization of energy content. Continuous investments in research and development to improve energy density while reducing the use of non-active materials are key to future competitiveness. Energy content can be raised by exploring innovative cell designs, such as larger cylindrical and prismatic cells. In combination with integration options like Cell-to-Pack (CTP) and Cell-to-Chassis, weight can be reduced and overall efficiency improved. These approaches can lead to cost savings and competitive advantages.

Besides performance optimizations, safety should be a key concern. Better separators, venting, and innovative insulating materials are viable options for optimization on cell level. Developing advanced thermal management systems can further ensure safe and efficient operation.

SUSTAINABILITY

Sustainability in batteries is largely influenced by three main performance indicators: material, lifetime and efficiency. On system and cell level, battery engineers aim to maximize power and energy output while keeping the cell within lifetime-acceptable conditions regarding temperature and lithium plating behavior. Trends in this area include using more stable cell chemistries like lithium iron phosphate (LFP). On the other hand, it is predicted that there could be a supply shortage in the coming years, especially for lithium. This leads to a need for new, more sustainable raw materials. One key enabler as a more sustainable cell chemistry is the sodium-ion battery. This cell chemistry won't compete with high-performance batteries but could be a suitable alternative for low-cost vehicles or stationary storage. Its key characteristics are high C-rate capabilities, a high thermal stability, and the possibility to discharge the batteries to 0 V. These characteristics increase safety during usage and transportation of the cells, e.g. the logistics of cells without charge. Also, there is a lower risk of thermal runaway in the event of a mechanical cell impact.

Another method of battery life improvement is thermal or electrical management. Examples of thermal management improvements include emerging cooling technologies such as immersion cooling and improved battery models for fast charging. Besides improving first lives as traction batteries, a possible second life also needs to be considered in the development process. In a second-life approach, batteries from electric vehicles are reused in other applications such as stationary energy storages. This leads to an increased usage time for a battery while decreasing its total lifetime cost.[41]

Competition among car manufacturers is growing in the category of electric drivetrain efficiency. Improved efficiency of the battery system can help minimize losses in the powertrain. Improved efficiency of electric vehicles reduces the equivalent carbon footprint of the energy used per kilometer, and the OEMs' implementation success still varies significantly. Reducing the battery's weight while maintaining all other performance parameters increases the efficiency of the overall material used.

The biggest levers to reduce weight are increased integration from cell to system level as well as improved cell designs. Conventional battery packs consist of battery modules and battery cells inside them. New system architecture approaches skip module level and integrate the cells directly into the pack. Examples of this are BYD Han and CATL Qilin. In terms of sustainability, a parameter for comparison is the different architectures' gravimetric and volumetric efficiency. There is always a loss of gravimetric and volumetric energy from cell level to pack level due to additional components on system level. Cell-to-Pack approaches have the advantage of requiring fewer components, e.g. the module housing, which leads to better overall efficiency. Figure 19 a comparison between different vehicles. It is evident that there is a significant increase of efficiency. Apart from Cell-to-Pack approaches, there are other architectures where the conventional design is adapted to more structural integrations into the vehicles, for example Cell-to-Chassis approach, with even higher efficiencies possible.

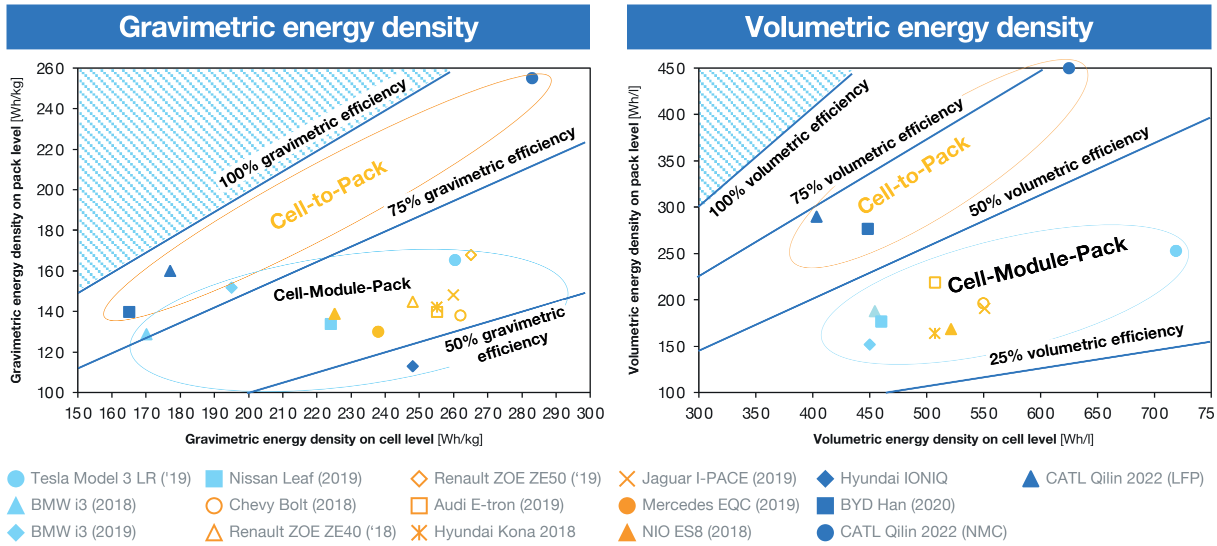


Figure 19: Packaging efficiency of battery cells; *Source: PEM RWTH Aachen University*

TECHNOLOGY PERFORMANCE

The performance of a battery system is defined by optimizing the key engineering dilemma of cost, power capabilities (vehicle charging times), and energy density (vehicle range) (see figure 20). Finding this optimum while simultaneously optimizing lifetime and safety is crucial. These two requirements have direct tradeoffs with the above-mentioned key requirements. This optimization space can be addressed on cell chemistry level, cell design level, and system design level while keeping the integration from level to level in mind.

The choice of cell chemistry is the key factor influencing battery performance. A key trend for increasing performance is the optimization of the respective material systems and additives with regard to the aforementioned capabilities. These optimizations are carried out on material and electrode design level. On the anode side, natural graphite, synthetic graphite and silicon are used as composite anode materials for high-energy and high-power designs. Silicon is added to graphite to enhance the energy density. The use of pure silicon anodes is not yet feasible in automotive quality. Lithium titanate oxide (LTO) is used purely in high-power applications such as power tools or hybrid electric vehicles. On the cathode side, the trend is going towards using lithium iron phosphate (LFP), lithium-nickel-manganese-cobalt (NMC), or LFP and NMC compound systems). Recently, the focus on NCA has diminished due to its safety challenges, while LFP's market share has increased significantly due its cost and material availability advantages.

On cell level, three established formats – pouch, prismatic and cylindrical – each influence pack design and battery performance. Recently, cell size has increased across all formats, although there is a maximum (capacity) due to the trend in higher-voltage packs. High-voltage systems limit cell size by requiring a high number of cells in serial connection while keeping the pack at a realistic capacity/energy level. For example, to reach a 100kWh, 800V pack architecture, the maximum capacity of an NMC cell would be around 125Ah. Typically, prismatic cells and pouch cells have a lower energy density than cylindrical cells, but they make up for this disadvantage on system level with higher integration efficiencies.[42]

Pack level performance of batteries has seen a significant development over the last few years. On range level (energy density), average Cell-to-Pack ranges and pack efficiencies have increased overall from 2017 to 2021 (see figure 21). Unfortunately, the curve for pack costs has plateaued from 2022 to 2023. One reason for this is the increasing price of battery materials (see Battery Materials chapter). In terms of performance, there are still major differences between OEM products in all vehicle categories.

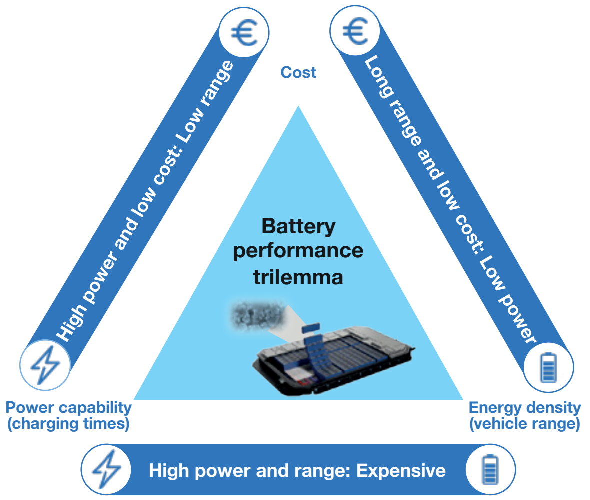


Figure 20: The battery performance optimization challenge;
Source: PEM RWTH Aachen University

COMPETITIVENESS

Analyzing the industries in which batteries are used shows that the automotive sector is the strongest catalyst for the battery industry's development, as most of the investment comes from there. Planned investments in the battery production sector surpass $0.5 trillion through 2030, which is comparable to the investments into the electric vehicle production sector in the period through 2030.[43] As of 2019, more than half of all lithium-ion battery cells were used in the automotive industry. In the year of 2030, more than 80% of the produced lithium-ion battery cells will be used in this sector[44] (see figure 22).

Focusing on the competitiveness in this field, the ability to compete successfully with other companies, countries and organizations must be analyzed. To evaluate the area of electric mobility and battery technology especially in this regard, we must take into account the history of combustion engine vehicles and battery-electric vehicles. Europe and the US have a long history in developing combustion engine vehicles and built their whole industry on this technology. The Asian region, specifically China, was not able to catch up with the technology advantage of European and American car companies to be competitive with them. Instead, Asia built an industry for batteries – used in smartphones and entertainment electronics. Based on this knowledge advantage, China invested heavily in the electrification of their car industry and developed themselves into a technology leader in the field of batteries as a whole. Contemporary Amperex Technology (CATL), a Chinese company, is the biggest and leading company for producing battery cells worldwide. On a yearly basis, they release groundbreaking battery advances on cell, module and pack level, steadily moving up the value chain from a battery cell manufacturer to a battery pack producer. Also, BYD, a Chinese company as well, sells the most electric vehicles worldwide, having the most integrated value chain inhouse – going from material production to battery cell, module and pack production to vehicle integration. Comparing the sales figures of the major car brands worldwide, it is evident that BYD has the largest share, alongside Tesla, mainly because most electric vehicles are sold in the Asian region (see figure 23). The steady advancement of battery technology can therefore be traced back to both the continued growth in interest in electric mobility and additional regulatory incentives coming from the US. As a result, demand for improved batteries is increasing. Further developments are expected in this area as research and development continue to advance.

Apart from the technology advancements themselves, supply chain resilience is becoming an increasingly important factor. Securing the whole supply chain gives a company a major cost advantage due to the highly volatile battery material prices. Considering that China managed to secure most of the raw material processing, this represents a significant advantage for the material supply chain, even though raw materials are often mined in other regions in the global south, like Australia, Africa and South America. Due to the major intercontinental dependencies, automotive manufacturers are increasingly trying to rely on regionally available technologies, which strongly influence system design as well.

Looking at the battery cell suppliers, nearly all car manufacturers are relying on dual-sourcing or multi-sourcing strategies to secure the cells needed for their battery-electric cars to be built. In contrast, product characteristics are fundamentally influenced by the supply chain and must be shaped by the materials' cost and availability. Figure 24 presents an abstract view of the sourcing relationships between car manufacturers and battery manufacturers.

To strengthen the European market and to increase the sustainability of the technology, regulators are pushing regulatory framework conditions, specifying requirements for sustainability, recyclability and safety in order to future-proof battery systems, besides customer requirements like product safety, energy density, power density, efficiency, service life, material cost and manufacturing cost. Based on this, the key factors for differentiation can be concluded, as per figure 25.

Considering the key performance indicators of newly registered electric vehicles, as well as research papers, China is clearly ahead. The pioneering role China is currently taking must be addressed by the European and American companies to be competitive in the long run.

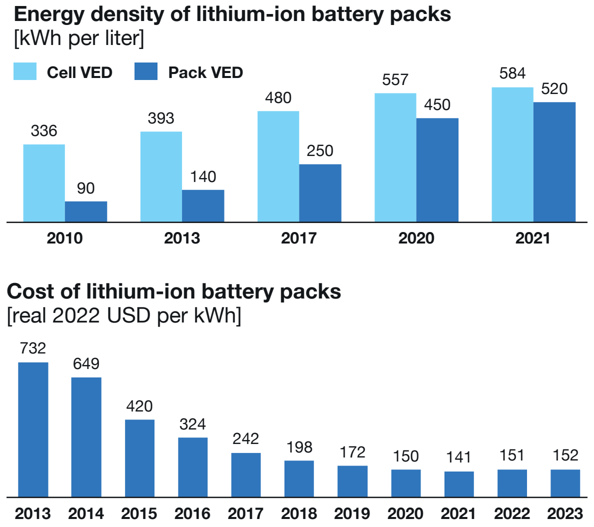


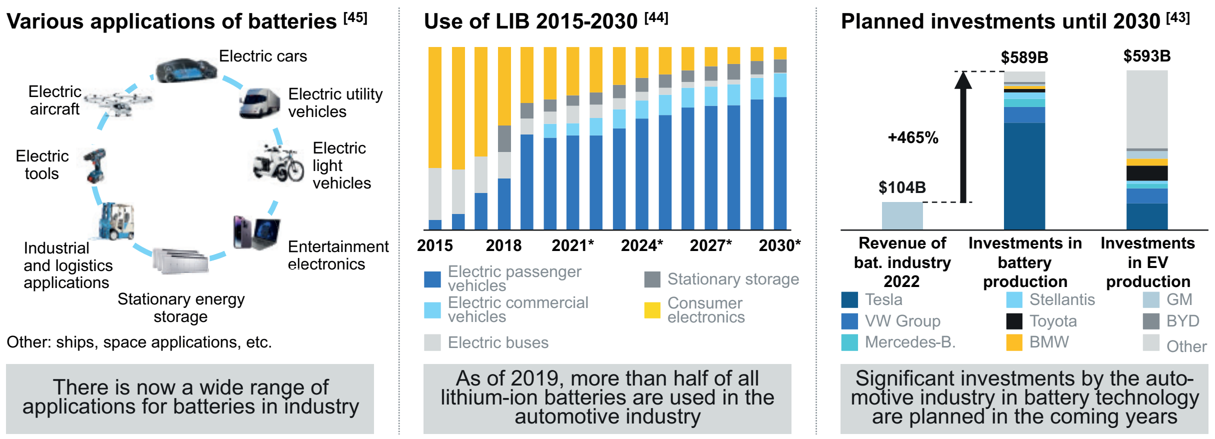
Figure 21: Cost and energy density of automotive batteries;
Source: PEM RWTH Aachen University

INNOVATION

In future battery cells and battery system architectures, significant changes will be visible in comparison to the products known today. This has two main goals: One is to increase energy density by improving the cell design and reducing the materials that are not actively involved in energy storage, and the second aim is to reduce assembly costs by making systems simpler, more uniform, and made up of fewer components. This also leads overall to larger and fewer cells in a battery system. As a result, production volumes can be increased and costs reduced.

The technical implementation of these goals results in several trends that are emerging in battery system design. The best-known one is the design of Cell-to-X (CTX) battery systems. Whereas in the past the structure of a battery system was standard in the three levels of battery cell, battery module, and battery system or battery pack, this architecture is increasingly being replaced by the elimination of these clear boundaries. Three approaches can be distinguished. In this context, Cell-to-Pack refers to the direct integration of the battery cells into the battery pack. For assembly reasons, the cells are often first pre-assembled into groups. The Cell-to-Chassis approach is similar, in which the battery pack is fused with the chassis and the battery cells are installed directly in the underbody of the vehicle. The third approach, Module-to-Chassis, is particularly feasible for pouch cells since those do not have a stable housing. Here, pre-assembled modules are installed in the underbody of the vehicle.

Along with this approach of simplification and high integration, battery systems will also make much greater use of adhesives. This trend peaks in battery system designs that are completely filled with a curing resin that adds to the structural integrity. However, those designs cause unresolved challenges for repair and recycling of vehicle batteries. With current regulations and customer demands, car manufacturers seem to prioritize the factor of cheaper production costs over the sustainability of their products.



Deployment in the automotive sector is proving to be the largest source of investment and thus the strongest catalyst for the technology

Figure 22: Battery use cases and investments; *Source: Reuters Graphics (2022)[43], UN DESA (2021)[44], Brandt (2022)[45]*

What all approaches have in common is that both the individual battery cells and the battery modules or cell clusters will become larger in the future. This is another reason for avoiding inactive masses and thus improving energy density. In addition, a trend towards simplifying the structure and reducing the number of components can be seen in all systems. The elimination and simplification of numerous components also increases the degree of integration of the battery system into the overall vehicle. In the future, battery systems with prismatic battery cells will also increasingly feature side contacting.

For cylindrical battery cells, the future trend will be a new standard diameter of 46 millimeters instead of the current 21 millimeters, which is equivalent to a fivefold increase in volume and thus in energy content. For prismatic battery cells, the average energy content will more than double from 100 to over 200 ampere-hours. For pouch cells, the energy content will also increase significantly, although here, the increase

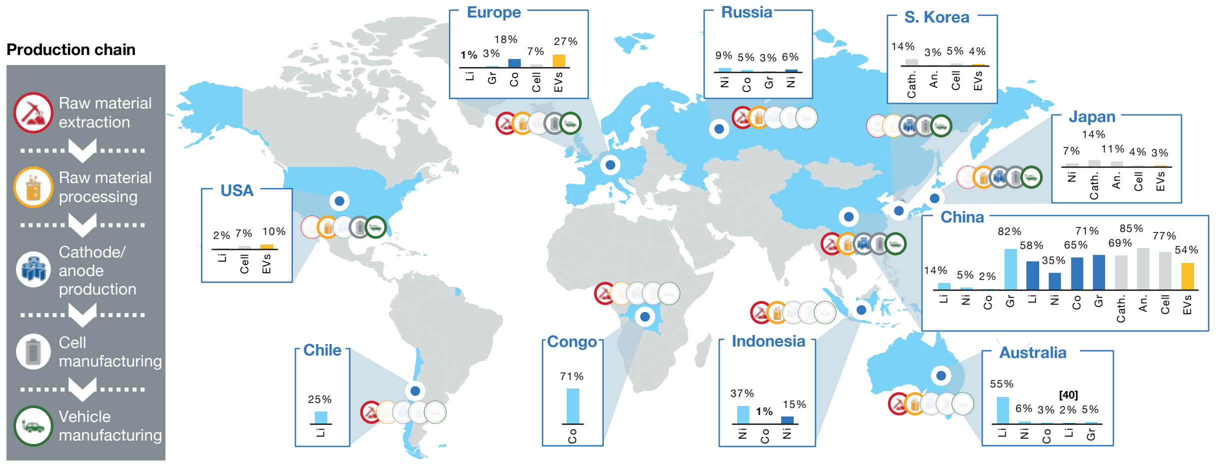
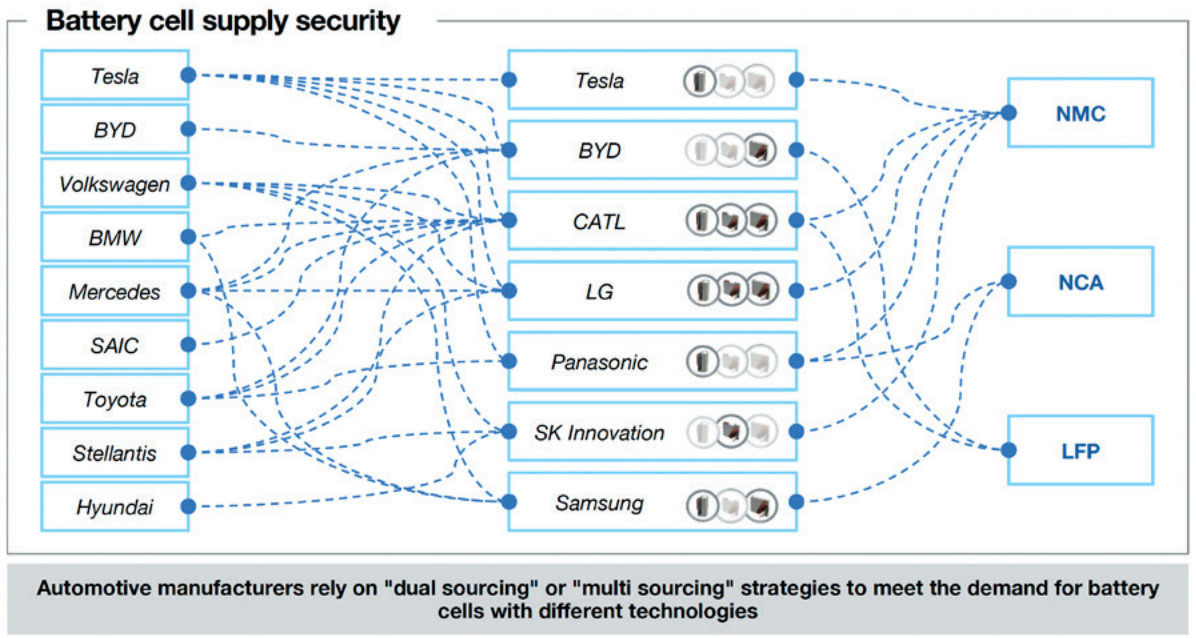


Figure 23: Due to major intercontinental dependencies, automotive manufacturers are increasingly relying on regionally available technologies; *Source: IEA (2022)[46]*



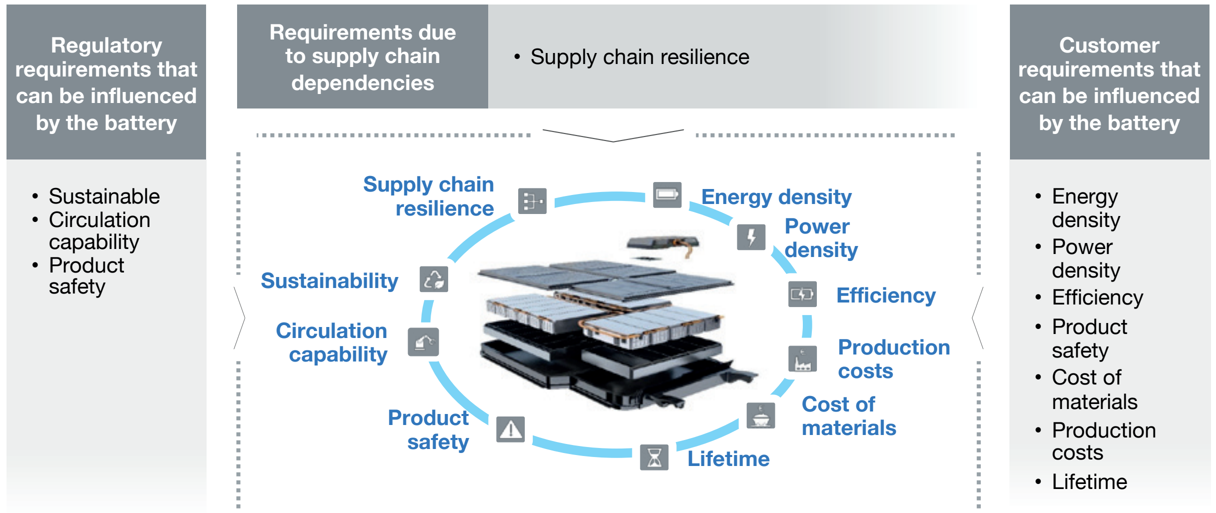
Automotive manufacturers rely on "dual sourcing" or "multi sourcing" strategies to meet the demand for battery cells with different technologies

Figure 24: Automotive manufacturers' sourcing strategies; *Source: Volta Foundation (2023)[47]*

is more difficult to quantify. When it comes to battery modules or cell groups, the trend is also clearly towards a single-digit number of assemblies in a battery system.

As far as the market share development of the various battery cell formats is concerned, no clear trend is discernible – all three cell formats will remain relevant in the future market. However, it is becoming apparent that prismatic and cylindrical battery cells will achieve higher market shares than pouch cells by 2030.

Current examples of CTX approaches include the Tesla Model Y and Tesla Model 3, where the chassis underbody is also the battery system/pack. At the same time, this system uses larger battery cells than before. These are installed in the 4680 format (46-millimeter diameter, 80-millimeter height) instead of 2170 (21-millimeter diameter, 70-millimeter height) and thus have a significantly higher energy content. Another example is BYD's 'Blade' battery systems. These are based on the battery cell of


Regulatory requirements that can be influenced by the battery

- Sustainable
- Circulation capability
- Product safety

Requirements due to supply chain dependencies

- Supply chain resilience

Customer requirements that can be influenced by the battery

- Energy density
- Power density
- Efficiency
- Product safety
- Cost of materials
- Production costs
- Lifetime

Figure 25: Radar for key performance indicators (KPI-radar) for the evaluation of battery innovations; *Source: PEM RWTH Aachen University*

the same name, which has a width of 900 millimeters and thus advances into new dimensions. Depending on the model, one row or two rows above each other are stacked in the vehicle underbody.

Besides higher energy density, the thermal design of the battery cell and battery system as well as the improvement of the overall safety are central questions in developing battery systems. Safety is mainly improved by better separators, electrolyte additives, venting, and degassing behavior of the battery cell as well as by innovative insulating and flame retarding materials on battery system level, which aim to prevent a thermal runaway of one cell from causing the same in the whole battery system. There are many more innovations that are depicted in the following figure, together with when they are expected to appear in the market.

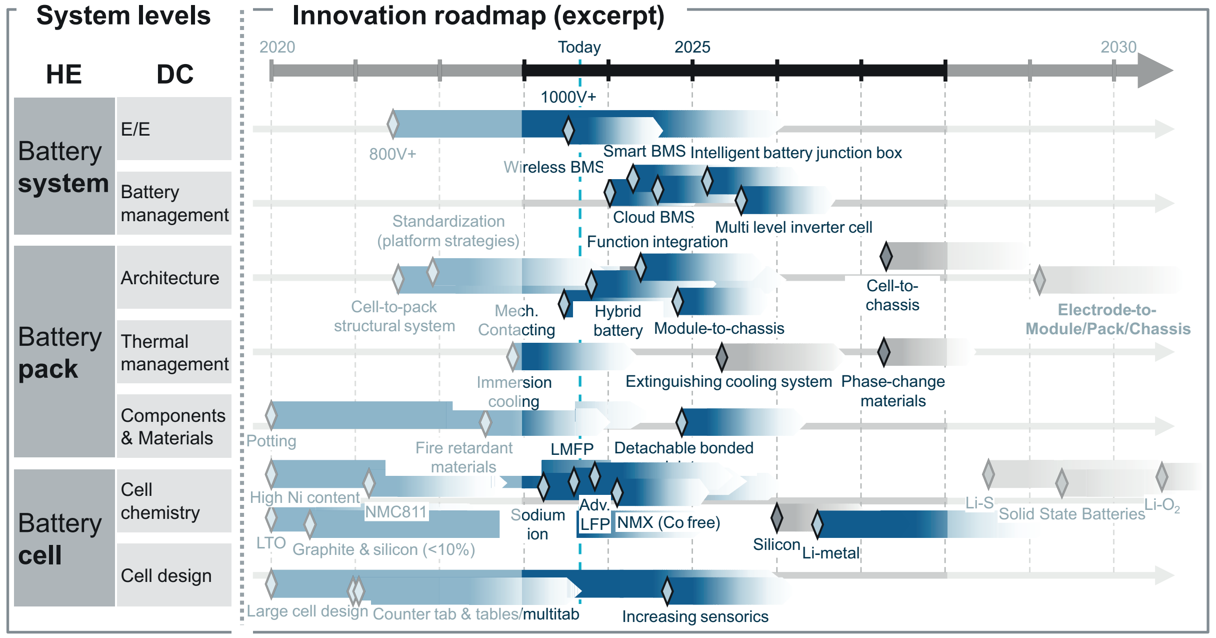
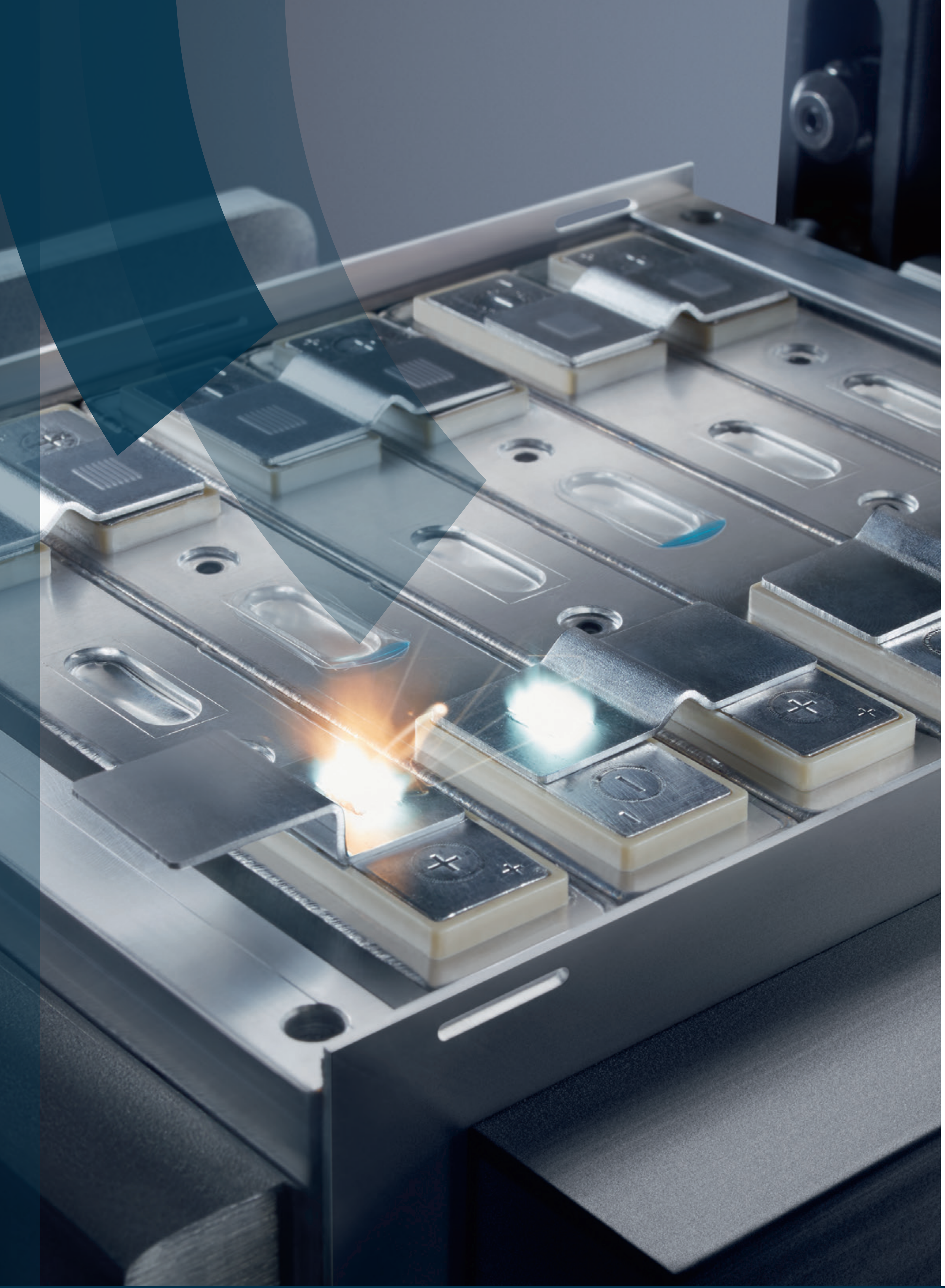


Figure 26: Upcoming innovations in battery cells, packs and systems;
Source: PEM RWTH Aachen University



Jan-Philipp Hasenberg, Konstantin Knoche, Timur Achmadeev

BATTERY USAGE

ELECTRIC VEHICLES ARE THE PRIMARY USERS OF LI-ION BATTERIES. BATTERY USAGE IS THEREFORE STRONGLY INFLUENCED BY THE EV MARKET, EV SUSTAINABILITY AND EV CHARGING.

Electric vehicles are expected to account for around 80% of Li-ion battery demand over the upcoming decades, making the EV market critical to battery usage.

Sustainability: The share of renewable energy used to charge EVs will be a key determinant of battery sustainability. While in most markets carbon intensity in the grid decreased, Germany's emissions have increased.

Technology performance: High upfront costs are now the main concern of EV owners, while fears over residual/sales values are increasing. Fast-charging technology continues to improve and grow.

Competitiveness: Ease and speed of charging is a major factor in the competitiveness of a battery in the usage phase. The EV charging market is buoyant, with satisfaction levels on the rise.

Innovation: Battery swapping is becoming a viable alternative to charging, with several new companies entering the market.

STRATEGIC IMPLICATIONS

For regulators

The sustainability of EVs can be achieved only through a decrease in the carbon footprint of electricity. Decarbonization of the grid is therefore essential. While most countries are addressing this, Germany's grid mix is currently increasing due to the nuclear phase-out.

For OEMs

OEMs need to protect against price fluctuations, for example through direct investments or LTAs, to lower customer concerns about high upfront costs, and develop cost-effective technology like LFP.

With range anxiety declining, development focus should switch from energy density to fast charging and competitiveness.

Battery swapping can enable technologies that are not capable of high charging rates. Depending on the market, customer perception and potential adoption may change, however.

For ESS manufacturers

Most ESS use cases can already be covered by LFP technology. Sodium-ion will most likely also provide sufficient power for ESS. High power applications can be covered using bigger batteries.

SUSTAINABILITY

Electric vehicles are only as sustainable as the power used to charge them. This means a country's energy mix determines the long-term sustainability of its EV fleet – a higher share of renewables results in lower CO_2 emissions per kilometer and over an EV's lifetime. In this subchapter, we give an update on how the grid mixes of the countries with the highest EV sales penetration compare, and look at the sustainability potential of energy storage systems.

NORWAY AND SWEDEN LEAD THE WAY IN EV SALES AND SHARE OF RENEWABLES, BUT CHINA IS CATCHING UP

Norway and Sweden again lead the way in terms of sales penetration and sustainability. The Nordic countries have the highest rate of pure EV sales penetration in the world, at 83% (Norway) and 37% (Sweden) so far in 2023. The rate is growing in both, with neither expected to be affected by the EU's ban on the sale of new

fossil-fuel vehicles in 2035. The two states also have the lowest carbon intensities in their electricity mixes. In the case of Norway, these two factors make it the country with the lowest vehicle CO_2 emissions in the world.
Western Europe is faring less well. Germany, the Netherlands and France have medium levels of sales penetration but are still highly reliant on fossil fuel-based power sources. In particular, Germany's carbon footprint has increased markedly since Russia's invasion of Ukraine in 2022. It had to diversify quickly away from Russian gas at the same time as it was phasing out nuclear power, which led to an increase in the use of high-CO_2-intensity coal. The country now needs to step up its emission-reduction efforts, which are impeded by the high level of red tape involved in building, for example, new solar capacities. France has a comparatively lower carbon footprint due to its high reliance on nuclear power (40% share). However, the sustainability of nuclear power is at least questionable, despite it being labeled as green by the European Commission in 2022.

The EV sales penetration rate in the US is still very low, at around 7%.[48] However, the IRA, which includes tax credits of up to USD 7,500 on many EVs, as well as many other incentives for the EV industry, is expected to have a big impact on this figure. In addition, the carbon intensity of the US's energy mix continues to fall, unlike in Germany and France. However, emission levels vary widely by state; for example, 84 g CO_2/kWh in Washington compared to 883 g CO_2/kWh in West Virginia.[50]
China, while still largely powered by coal and continuously building new coal power plants, has also seen considerable growth in solar and wind power in recent years. Installed solar and wind capacity is set to double to 1,200 GW in 2025[51], and the country plans to be carbon neutral by 2060.[52]

ENERGY STORAGE SYSTEMS CAN INCREASE SUSTAINABILITY IN MULTIPLE AREAS

At around 850 GWh per annum, global ESS demand is the second-largest driver for Li-ion and Na-ion batteries and is a key enabler for the transition towards renewable energy. The main factor in the choice of technology used is the cost per cycle, which is determined by usage per use case, upfront cost and cycle life. C-rate (charging rate) is also a consideration, although power requirements can also be achieved by increasing the capacity of the storage system. Energy density is of lower priority, which makes this segment a good fit for LFP and Na-ion technology, as discussed earlier. Applications can be clustered into behind-the-meter (BTM) use cases, such as backup power and demand response, which cover the electricity generation, transmission and distribution side, and front-of-meter (FTM) use cases, such as energy arbitrage and frequency regulation, on the consumption side.

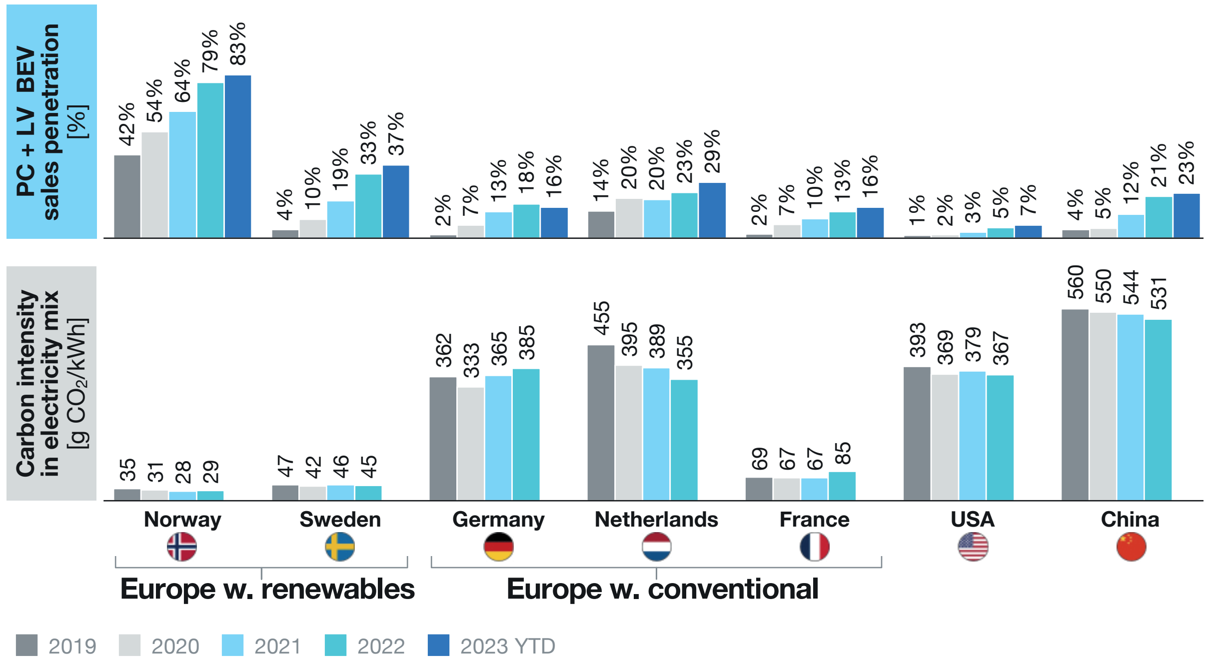


Figure 27: Electric vehicle sales penetration and carbon intensity of electricity mix in major EV markets; *Source: EV Volumes[48], Ember climate[49]*

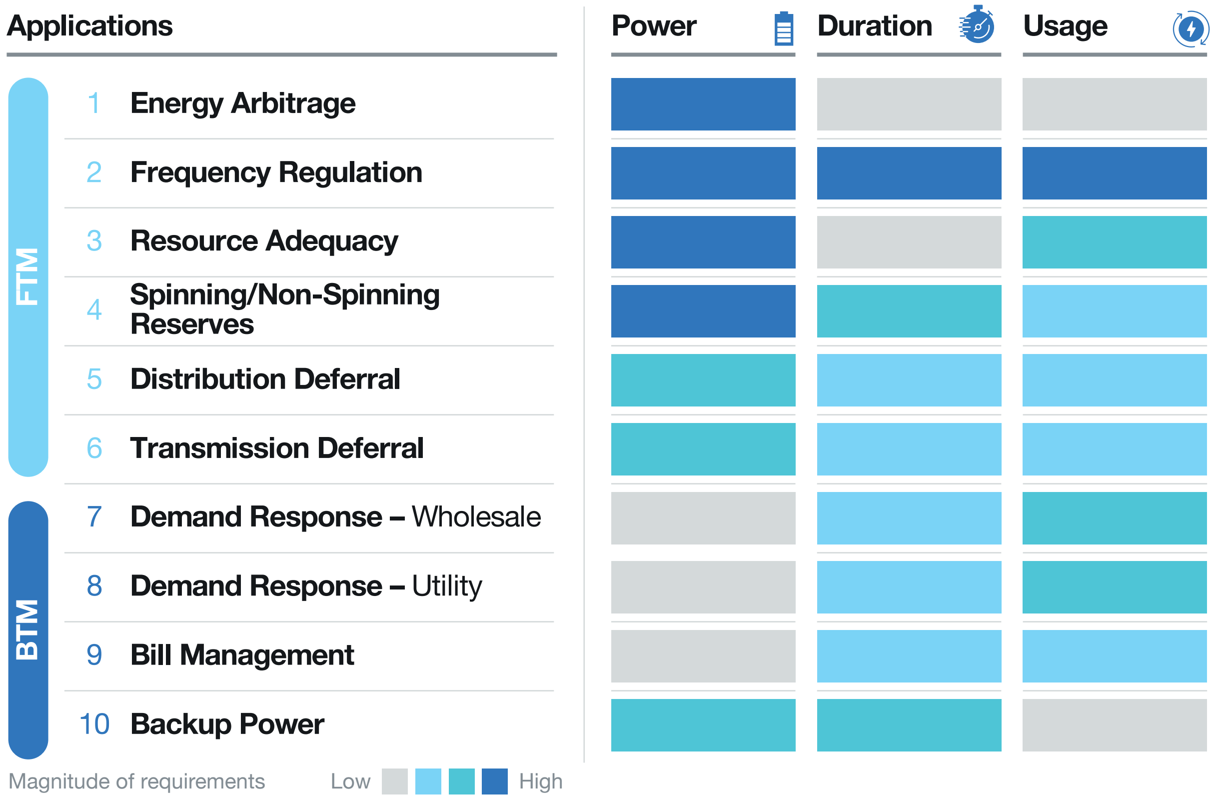


Figure 28: Overview of potential ESS applications and characteristics; *Source: Lazard and Roland Berger (LCOS 7.0)[53], IEA[54], Avicienne*

TECHNOLOGY PERFORMANCE

The decision to buy an EV is usually dependent on several factors, in particular costs, range and access to charging stations. To assess these areas, we used the latest edition (July 2023) of Roland Berger's EV Charging Index, which includes a comprehensive survey on perceptions of technology performance. The main findings were that high upfront costs are now the main concern, and that residual/sales values are becoming a major worry for EV owners. In this subchapter we also look again at the development of fast-charging infrastructure.

HIGH UPFRONT COSTS, LACK OF CHARGERS AND FALLING RESIDUAL VALUES ARE NOW TOP 3 EV CONCERNS

Roland Berger publishes the EV Charging Index on a six-monthly basis, with the July 2023 edition the fourth in the series.[55] The Index covers 30 markets in five regions – Europe, China, Americas, Middle East and Asia (other) – using 31 indicators. It is based on industry interviews, primary research and a survey of 16,000 participants from all regions conducted in the first half of 2023.
The starkest finding in the survey is that 'high upfront costs' has replaced 'lack of charging infrastructure' as the primary concern among potential EV buyers. 'High upfront costs' jumped 18 percentage points between H2 2021 and H2 2022, driven by the recent strong

rise in inflation, raw material prices and global supply chain disruption.

These factors have had a direct impact on EV purchase prices. Tesla, for example, increased its prices by as much as USD 6,000 per car in the US in summer 2022 to mitigate soaring inflation and the cost of raw materials, especially lithium. However, the US giant did start discounting again in some markets in summer 2023. For example, it dropped the price of its Model 3 and Model Y in Australia to the cheapest price they have ever been.

Despite the discounting, our survey shows that such price fluctuations are clearly not increasing confidence levels in the purchase of an EV.

While still a significant factor, concerns about a lack of charging infrastructure fell back markedly between H2 2021 and H2 2022. This is likely because the continuous expansion of both AC (standard) and DC (fast) charging networks by a growing number of stakeholders (energy suppliers, OEMs, start-ups etc.) has considerably improved perceptions among EV owners and potential buyers.

Fears about the range of EVs, so-called range anxiety, were once the primary concern of potential owners. But such worries have been easing off in recent years as battery pack sizes have increased and charging times have fallen. Now range anxiety is the joint-lowest of the five main concerns, suggesting the problem has been alleviated.

The biggest change in the survey was the rise in concern about 'residual/sales values' of EVs. It rose 22 percentage points to 37% between H2 2021 and H2 2022, raising it from the lowest-rated concern to the third highest. A possible reason for the jump could be that the first Tesla vehicles (2013 models) are now reaching the end of their battery lifespan, meaning a generation of EV owners are beginning to think about how old batteries will affect their vehicle's resale value.

CHARGING NETWORKS CONTINUE TO GROW, WITH FAST DC CHARGING GAINING AN INCREASING SHARE

The number of installed charging points continues to grow significantly in major EV markets. In China, for example, the total number of stations has risen by around 50% compared to the figures in Battery Monitor 2022, and in Germany by around 60%. But while AC charging continues to dominate the market due to its safety and low investment cost, new fast-charging DC technology (150 kW+) is having a huge effect and driving growth. Penetration levels in Norway have increased from 27% to 36%, for example, while China is nearing a 50/50 split.

Already, fast charging has become a base requirement for EVs with at least 150 kW. Hyundai Kia's 800V E-GMP platform, Porsche and Audi's J1 platform and the Tesla Model 3 lead the way with peak charging above 200 kW. Recently, CATL has announced an LFP battery pack capable of charging from 20% to 80% in 10 minutes, giving a C-rate of nearly 4C.[56] Taking this as an example, a scaled battery pack of 100 kWh would then require a charging point capable of 400 kW. While this is hypothetical, we see the need for charging powers to increase far beyond 150 kW.

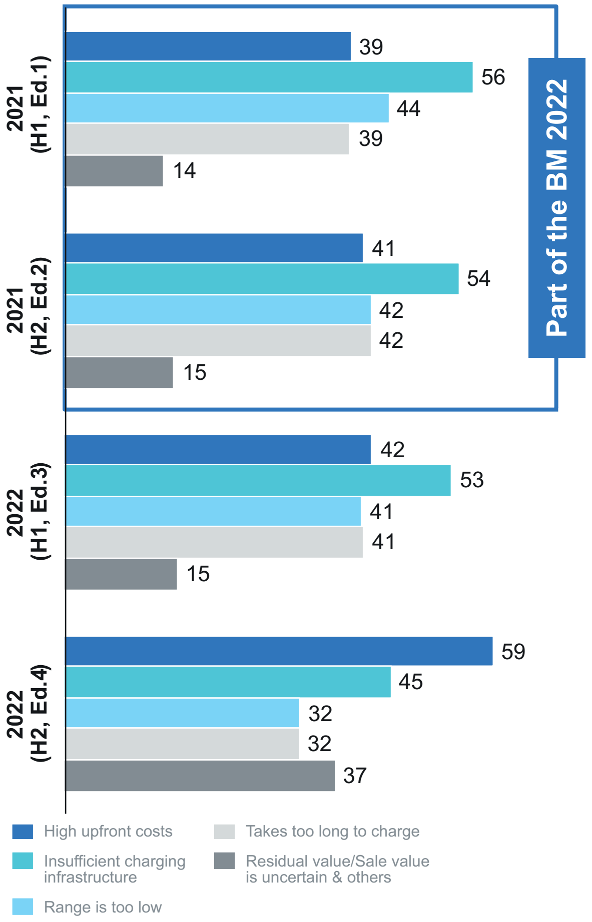


Figure 29: Respondent concerns about owning an EV; *Source: Roland Berger Charging Index, Ed. 4*[55]

Charging speeds, which have not increased in the past year at most OEMs, are unlikely to rise unless new platforms are developed. This is because it is not only the cell itself that is limiting, but also the cell pack and charging components. These must be designed to withstand fast charging, meaning completely new packs and platforms are the only way forward. With work on several new OEM platforms due to start in the next two years, this gives the charging infrastructure until about 2028 to adapt.

COMPETITIVENESS

Alongside components and quality, ease and speed of charging is a major factor in the competitiveness of a battery in the usage phase. Those markets with the largest and fastest networks will have a competitive advantage. Here, we use the key findings of the latest edition of Roland Berger's EV Charging Index to gauge charging competitiveness in leading EV markets.

INDEX SCORES SUGGEST THE GLOBAL EV CHARGING MARKET IS BUOYANT, WITH USERS LARGELY SATISFIED

The Index revealed that the top five performers reached new record-breaking highs in terms of overall scores. China led with a score of 82, followed closely by Germany (74), the United States (73), the Netherlands (69), and Norway (65). The gaps between these countries narrowed, with Germany and the US making notable progress in catching up with China.

Positive news also emerged from the lower ranks, with Malaysia, Indonesia and Saudi Arabia seeing significant score increases. The improved performance in the Middle East and Southeast Asia raised the average country score from 45 to 51, indicating a thriving global EV charging market.

In particular, the Index highlights a growing global trend in public DC chargers, as well as DC charger density more widely. China is

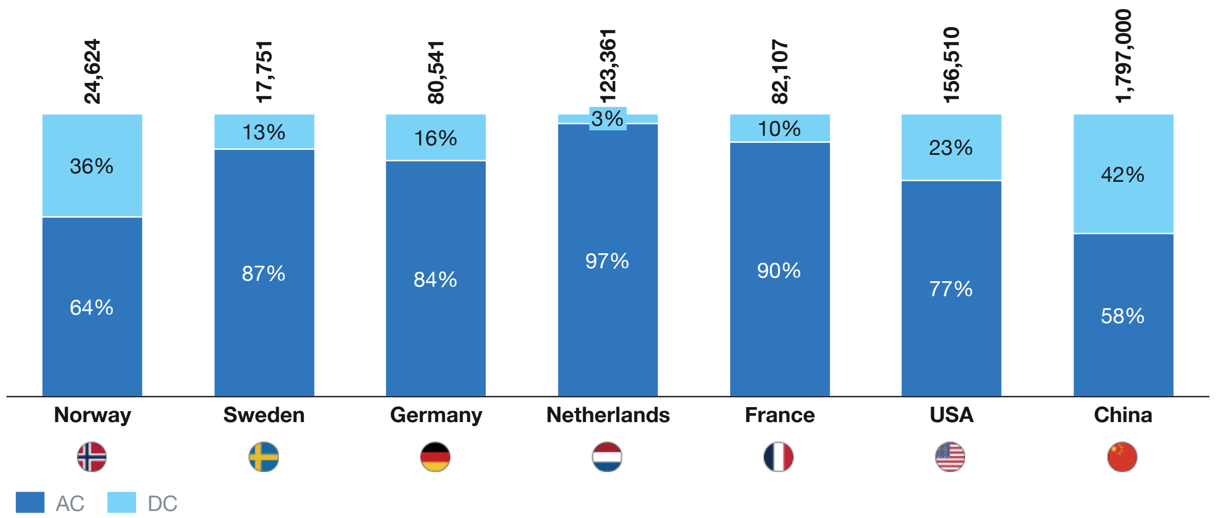


Figure 30: Split between number of AC and DC charging stations in major EV markets; *Source: EV Volumes*[48]*, Ember Climate*[49]

leading the way in the rollout, with a 42% share of DC chargers in public networks, while the Middle East increased its charging density by 125% in 2022 to 1.3 DC chargers per 100 km of road.

Global satisfaction with public charging networks is also on the rise. A total of 83% of the Index survey respondents said that public charging networks were easier to access in H2 2022, compared with 67% in H1 2022. More than half (55%) think charging speeds are sufficient. The situation is more mixed regarding vehicle-to-charger ratios. The global average vehicle-to-public-charger ratio rose in 2022 from 14.6 to 15.9, with China and other Asian countries dragging down performance. However, the global vehicle-to-DC-charger ratio fell about 20% to 105.7, driven by growth in Europe and the Americas.

The Index showed that EV sales are driving the charging market. Global EV sales penetration rates reached record highs in the second half of 2022, hitting 15% at the global level. In particular, EV sales in major European countries rebounded strongly in late 2022 after a downswing in the first half of 2022. The underlying reason behind this dip was the energy crisis and EV drivers' high level of price sensitivity.

INNOVATION

As outlined in Battery Monitor 2022, battery swapping has become the main rival to conventional EV charging. While the technology is still in an early phase of development, its rollout continues to gather pace.

CHINA REMAINS THE BATTERY SWAP LEADER, BUT OTHER MARKETS ARE NOW DEVELOPING THE TECHNOLOGY

Battery swapping, whereby a compatible EV's entire battery is exchanged for a fully charged one at a swapping station whenever it runs low, has a checkered history. It has been tried by several companies over the years, including Mercedes Benz in the 1970s and the Israeli start-up Better Place between 2007 and 2013. None had much success, with Better Place going bankrupt. But now the EV market is more mature, and Chinese companies, in particular are resurrecting the idea. The country dominates the swapping market – the number of swapping stations in China has risen by almost 700 to 1,973 since the publication of Battery Monitor 2022. But the technology is now starting to penetrate in other countries too, especially Asian countries such as India, Indonesia and Japan. Like China, their rapid adoption is attributable to a strong emphasis on prioritizing robust public charging infrastructure over home charging.

The deployment of this alternative charging method in Asia has led to its rising significance in other markets, which are now looking to develop the technology or use it to expand their own charging networks. In Europe, the Chinese EV manufacturer NIO is actively working on expanding its own-brand battery swap network. For example, it has confirmed plans to beef up its presence in Germany, where it already has three stations, with the addition of seven new swapping stations and three new showrooms (NIO Houses) in 2023. NIO's six models all have the same battery, helping to standardize the process.

In North America, the focus is on enhancing the technology. Ample, a Californian start-up dedicated to battery swapping, has developed a platform that can be made compatible with any EV. It claims swap times of around five minutes, which is comparable to the time it takes to refuel fossil-fuel-powered vehicles, and considerably shorter than the typical 30-minute or longer charging times at public fast-charging stations. The company has been given a grant of USD 15 million by the California Energy Commission to develop its network, and recently signed a deal with the US EV maker Fisker. Fisker plans to offer its debut Ocean model with replaceable batteries in the first quarter of 2024, primarily targeting customers in the US and Europe.

The commercial vehicle segment also presents opportunities for battery swapping systems. For example, CATL has developed a battery-swapping solution for heavy-duty electric trucks called Qiji Energy, consisting of exchange stations, battery packs and a cloud platform. According to CATL, the swapping process takes just a few minutes.

In addition to shorter charging times, battery swapping has another significant advantage – because charging times are far less relevant in battery swapping, it can enable technologies that have difficulties in supporting fast charging. These include semi-solid-state and solid-state batteries. For example, NIO's new 150 kWh battery pack is expected to use semi-solid-state cells made by Prologium. As the fast charging capabilities of this technology are not yet clear, battery swapping could serve as a workaround as the batteries can be charged according to their capability. As well as enabling such technologies, swapping could potentially increase the lifetime of batteries as slower charging is, generally speaking, gentler on the battery.

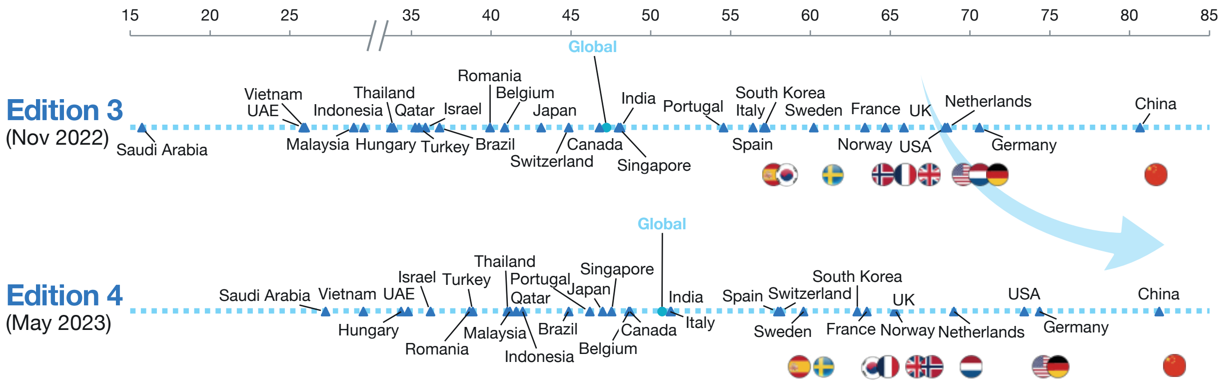


Figure 31: Evolution of Roland Berger Charging Index scores [points out of 100];
Source: EV Volumes[48]; Roland Berger EV Charging Index 4[55]

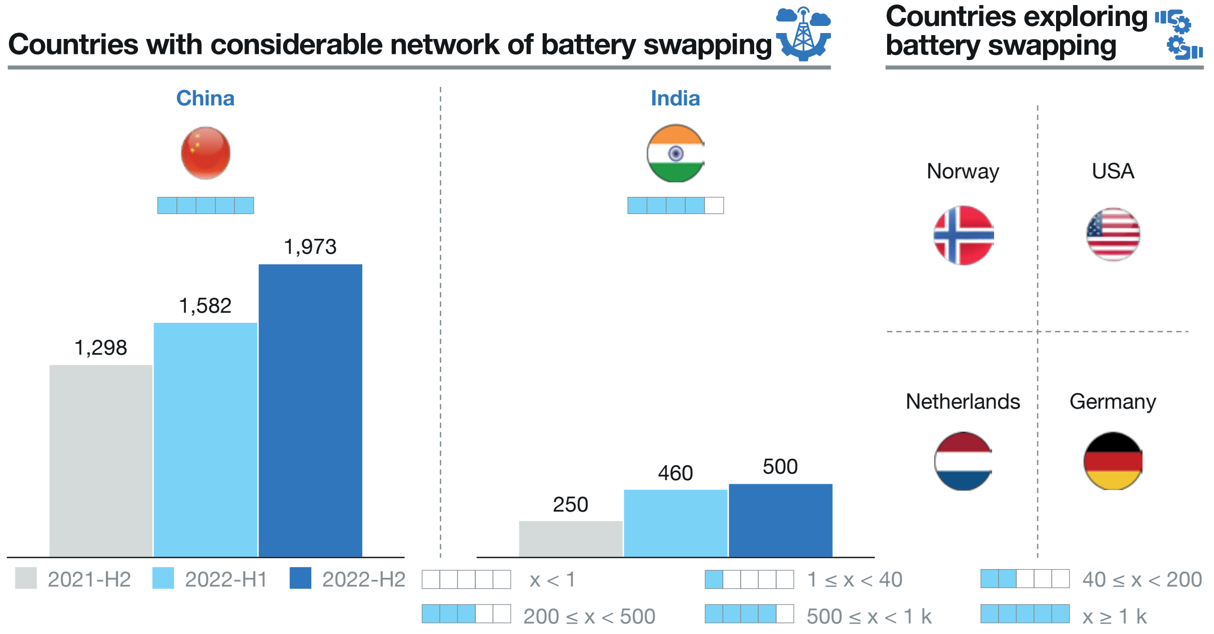


Figure 32: Current status of established and developing battery swap markets;
Source: Roland Berger EV Charging Index 4[55]

Nikolaus Lackner

RE-X

LIBs, vital as they are, come with a significant environmental cost due to resource-intensive production. Embracing a circular economy approach by reducing, reusing, recycling, recovering, and removing materials can substantially mitigate this impact. As vehicle batteries lose capacity for their original use, they can be repurposed for stationary energy storage, reducing CO_2 emissions by up to 31% and lowering the levelized cost of energy (LCOE) compared to single-use batteries. The growing demand for battery-electric vehicles (BEVs) presents an opportunity for closed-loop recycling, reducing material demand for lithium, cobalt, and nickel by over 20%. Projections show recycling can meet battery material needs through 2035.

Pyrometallurgy, hydrometallurgy, and direct recycling are key methods. Hydrometallurgical processes, especially with mechanical pre-treatment, are favored due to lower energy consumption and higher efficiency. Recycling efficiency varies globally, with European companies achieving 60 to 95%, and Asian counterparts reaching 80%. A global shift towards a 90% recycling rate is expected. The EU Battery Regulation sets targets for recycling efficiency.

Recycling plant capital expenditure (CapEx) ranges from USD 156.5 million to USD 165 million, while operating expenses (OpEx) vary from USD 1,560 to USD 4,000 per ton. Europe hosts 139 kilotons per year recycling capacity, expected to expand to 400 kilotons by 2030. Asia currently leads in LIB recycling, with Europe and North America rapidly catching up. Innovation is vital to meet rising electric vehicle demand and improve recycling. Direct recycling holds promise for a lower carbon footprint and resource conservation.

STRATEGIC IMPLICATIONS

For battery manufacturers

Efficiency in materials use and recycling will be a competitive advantage. Investments in research and development can create more sustainable and easily recyclable battery designs. The exploration of circular economy models, including second-life batteries and closed-loop recycling partnerships, is favorable to reduce the environmental footprint and meet regulatory requirements.

Due to the growing consumer demand for environmentally responsible products, sustainability is considered a strategic selling point.

For policymakers

The implementation and enforcement of regulations that incentivize sustainable practices, recycling, and closed-loop systems for battery manufacturing and disposal is very important. At the same time, the economic interests in the global context must always be considered, as otherwise overregulation would result in a loss of competitiveness. Collaboration with other nations to establish global standards for battery recycling ensures a level playing field for manufacturers and recyclers.

For investors

A company's commitment to sustainability and recycling should be considered in investment decisions. Companies with robust recycling strategies may offer more long-term value. Investors should evaluate investments in the context of evolving regulatory and environmental risks associated with unsustainable battery practices. Interesting investment opportunities are currently emerging in the field of battery recycling, with many technology start-ups and sustainable battery ventures.

For recycling companies

Investments in expanding recycling capacity to meet the growing demand for battery recycling are crucial, particularly in regions where electric vehicles are being rapidly adopted. Close collaboration with other specialists in the technical environment can leverage additional efficiencies.

SUSTAINABILITY

IMPACT OF REUSE/SECOND LIFE/REMANUFACTURING (RE-X) IN TERMS OF THE LIFE CYCLE EMISSIONS OF BATTERIES

Sustainability has become an increasingly important issue in recent years, including the mobility sector and lithium-ion batteries (LIBs). LIBs require rare raw materials and a lot of energy to produce. However, the environmental footprint can be reduced by making the batteries multifunctional and long-lasting. One approach is to follow the five-step ‘waste hierarchy’ in a circular economy: reduce, reuse, recycle, recover, remove.

Due to range requirements, vehicle batteries are used on average up to 80% of their original capacity. After that, these batteries can be reused in various other applications that do not require such a high energy density. Typical applications for these so-called second-life batteries as stationary energy storage are photovoltaic systems and energy buffers for fast-charging stations or households. This has a positive impact on CO_2 emissions and the levelized cost of energy (LCOE). Compared to single-life batteries, CO_2 emissions are reduced by up to 31% and LCOE by up to 57%.[57]

POTENTIAL OF A FULLY CLOSED LOOP CYCLE FOR BATTERY MATERIALS

At some point, all batteries must be recycled, and the materials need to be recovered. If those recovered materials are used to produce new batteries, they are in a closed loop. The rapidly growing global demand for battery-electric vehicles (BEV) provides a unique opportunity to integrate closed-loop recycling into production processes right from the beginning. Recycling of vehicle batteries has the potential to reduce material demand for lithium, cobalt, and nickel by more than 20% on average over the upcoming years. Figure 33 shows in detail how much recovered material can be used in new batteries in the years up to 2035. The projections show that a steadily rising amount of battery materials can be covered by recycling.[58]

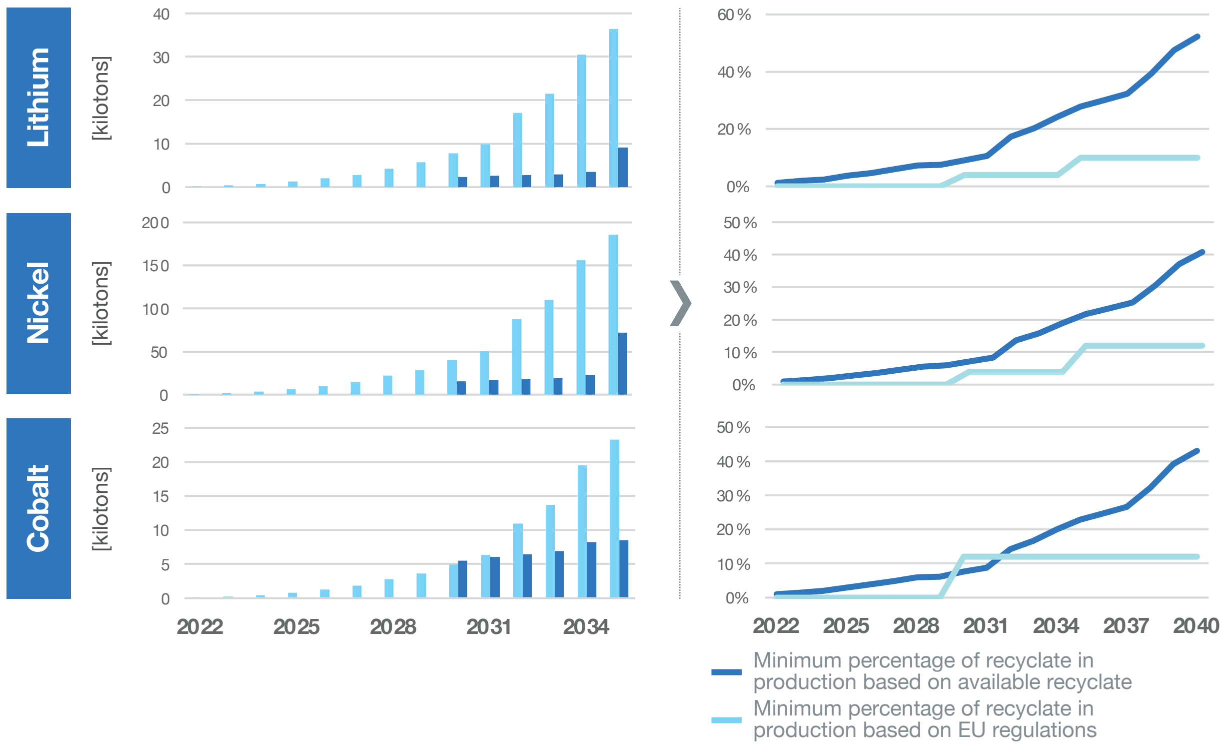


Figure 33: Percentage of recyclate in production based on EU regulations; *Source: PEM RWTH Aachen University*

TECHNOLOGY PERFORMANCE

(CHALLENGES IN) RECYCLING PATHS FOR LIBS

The recycling methods currently used are pyrometallurgy, hydrometallurgy, and direct recycling.

Pyrometallurgical processes use high temperatures to treat lithium-ion batteries (LIB) and melt the materials for later recovery. Advantages include the absence of pre-treatment of battery components, a short process chain, easy scalability, and the ability to deal with different battery types. However, the process is energy-intensive and produces waste that is difficult or impossible to recycle. Achievable recovery rates are as high as 60% for nickel and cobalt and very low for lithium.[59]

Hydrometallurgical processes dissolve metals from pre-treated battery waste by leaching. The resulting aqueous solution containing metal ions and impurities is then treated and purified. Eventually, the metal ions are gradually extracted from the solution. Hydrometallurgical processes require pre-treatment of the components to be recycled, such as mechanical crushing, but operate at lower temperatures than pyrometallurgical processes and are therefore less energy-intensive. Recovery rates of more than 90% can be achieved. The hydrometallurgical process with mechanical pre-treatment is likely to prevail due to its lower energy requirements and higher recycling efficiency.[59, 60, 61, 62] Direct recycling is the process by which materials are recovered without first being reduced to elementary size. However, this process is still

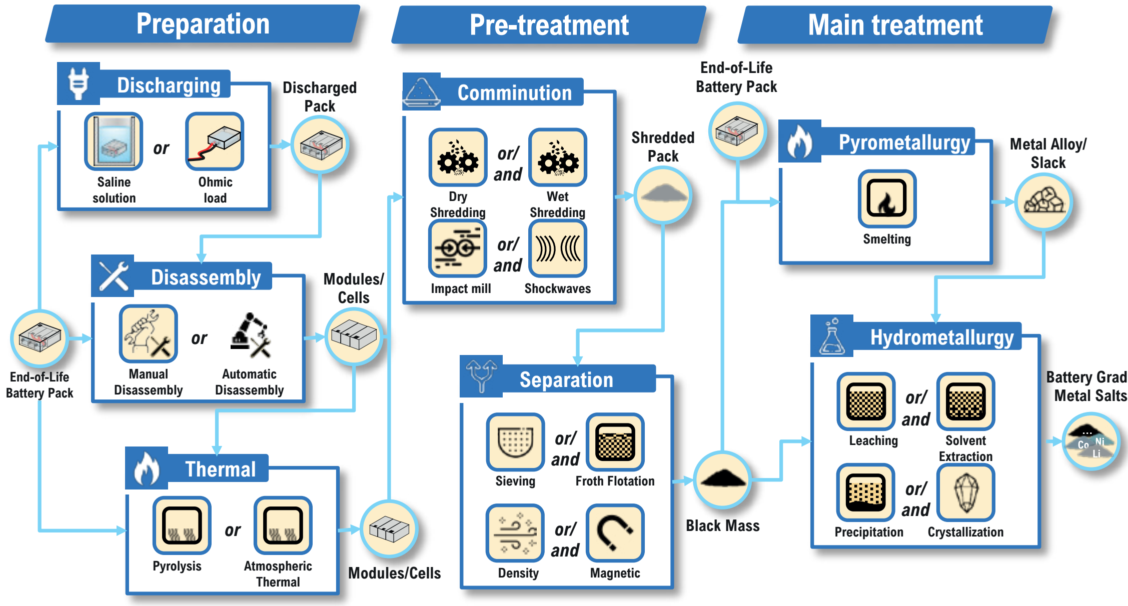


Figure 34: General steps and possibilities in recycling routes for lithium-ion-batteries; *Source: PEM RWTH Aachen University*

in the development stage prior to being suitable for large-scale use.[62]

To make this process as efficient as possible, hub-and-spoke networks are being established. First, the batteries are pre-treated in spokes. The resulting black mass is then delivered to the hubs – larger chemical companies – for recycling. One of the main reasons for this is that the hydrometallurgical processes are only economically feasible when conducted at large scale.[63]

Many companies take different approaches to recycling, depending on their background and existing expertise. This results in a variety of recycling routes as a lot of process variations and combinations can achieve the same goal with different advantages and disadvantages. This poses a challenge for new market players as well as established companies, and no standardized process chain has yet been established. An overview of general options in recycling routes is shown in figure 34.

STATE-OF-THE-ART RECOVERY, RECOVERY RATES, AND RECYCLING EFFICIENCIES OF BATTERY MATERIALS

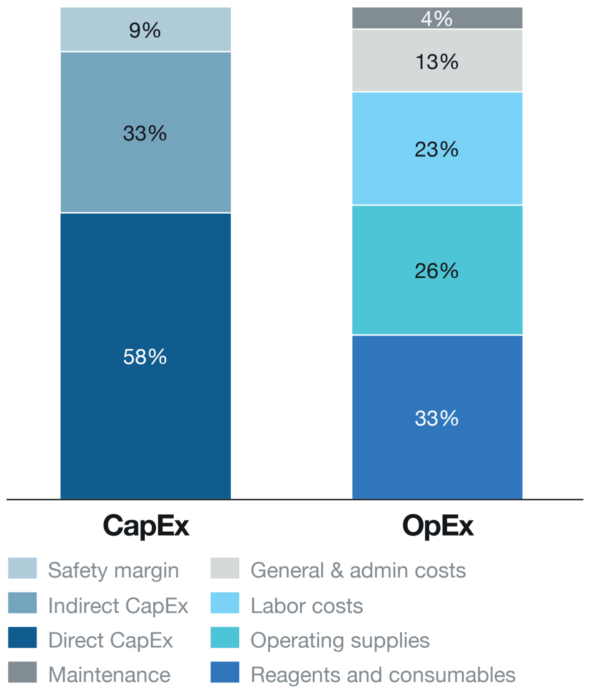


Figure 35: Cost structure of a recycling plant; *Source: PEM RWTH Aachen University*

Current recycling efficiencies vary widely. European companies achieve recycling efficiencies between 60 and 95%. In Asia, the recovery rate is 80%. However, it is expected that recovery rates worldwide will increase to around 90% in the next few years with the help of established and mature process chains and technologies. American companies report efficiencies of 65 to 80%, depending on the cell type. Overall, the data on recycling efficiencies must currently be viewed with caution, as the companies often do not provide the calculation basis and technological details.[64, 65, 66, 67]

INFLUENCES AND OUTLOOK ON RECOVERY RATES AND RECYCLING EFFICIENCIES OF BATTERY MATERIALS

Recycling rates and recycling efficiency depend on both technical and legal requirements. With the publication of the EU Battery Regulation, as discussed in chapter 3, legal requirements for battery recycling have been established. The regulation states that the recycling efficiency of batteries has to increase from 50 to 65% by 2025. By 2030, this rate is to be increased to 70%. It also sets material-specific recycling targets for recyclable materials. These regulations provide European companies with planning reliability and clear targets for battery recycling. Other important countries such as China and the US plan to launch similar regulations.

The technical requirements for recovery rates are closely linked to the recycling process used. It is expected that as recycling capacity increases, know-how, technology, and recovery rates will improve. One important factor is the quality and purity of the black mass containing the battery active materials such as nickel, cobalt, and lithium. This is the intermediate product after the mechanical pre-treatment. The process steps of the mechanical recycling greatly influence its quality. Downstream hydrometallurgical processes greatly depend on a consistent quality of the black mass as an input material but can also be highly optimized in chemical and process engineering aspects. Many recycling companies see this process optimization as one of their key differentiating factors.

PROFITABILITY/COMPETITIVENESS

CAPEX OF RECYCLING PLANTS

The capital expenditure (CapEx) for an LIB recycling plant varies depending on the recycling process used. Neometals has provided a detailed capital cost estimate for a hydrometallurgical recycling plant in Germany with an annual throughput of 18.25 kilotons. Based on these analyses, the total investment cost is approximately USD 165 million, including a contingency of USD 15 million. The majority of USD 96 million is linked to direct CapEx for aspects such as hydrometallurgy, site development, and buildings. The remaining USD 54 million is linked to indirect CapEx, which include expenses such as engineering, project management, and operating costs.[68]

A comparable study determined a price of USD 156.5 million for a recycling plant in Canada with an annual throughput of 16.56 kilotons. This results in a price of USD 9.45 million per kiloton. The percentage cost distribution between direct and indirect investment costs is identical to that of Neometals.[69]

Due to the minor differences among the individual cost predictions, the figures outlined are believed to provide a realistic approximation of the investment costs for a recycling facility. Nonetheless, the final expenditure will depend on the chosen location and potential financial assistance. Therefore, making a well-informed decision regarding where to locate can significantly influence CapEx.

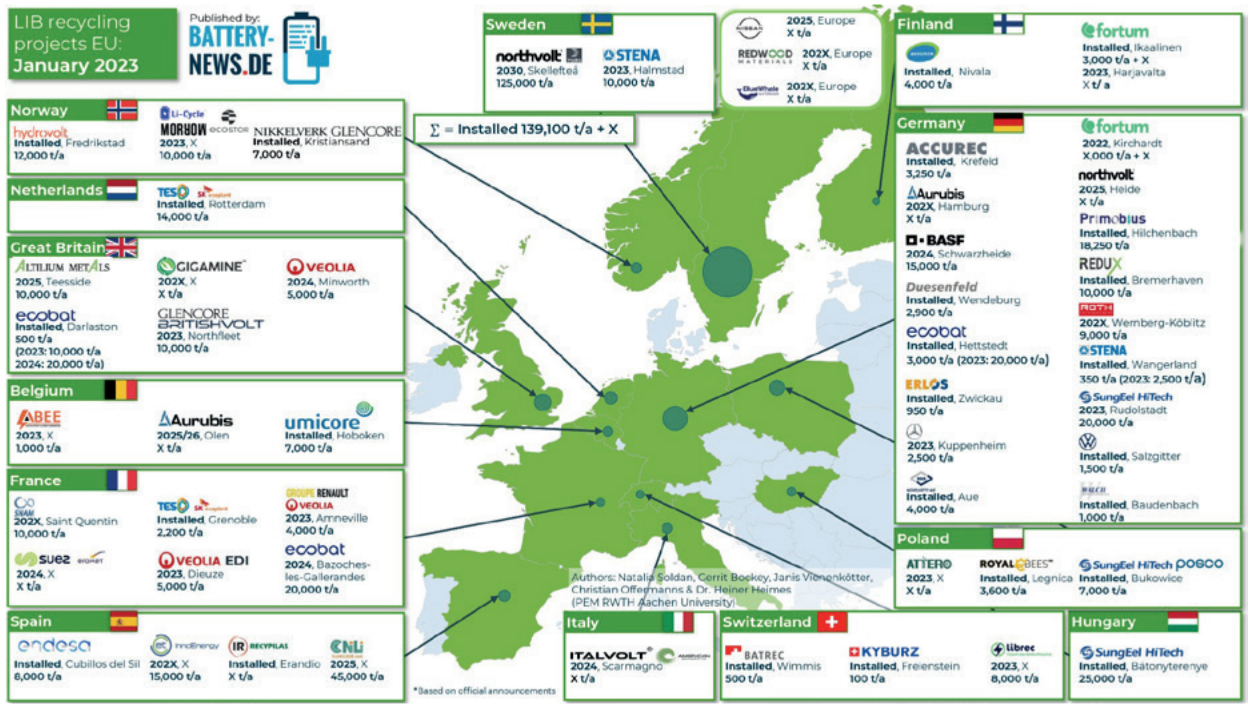


Figure 36: Development of the recycling landscape in Europe; *Source: PEM RWTH Aachen University*

OPEX OF RECYCLING PLANTS

In addition to the recycling method utilized, the operating expenses (OpEx) for recycling primarily depend on location. Neometals has determined that the cost for their hydrometallurgical recycling plant in Germany is approximately USD 1,560 per ton.[68]

A study of a recycling plant in Canada estimated that the cost per ton can be as high as USD 4,000.[69] However, comparing these values can be challenging due to the varied factors that affect operating costs, including wages, transportation, energy costs, and raw material prices.

In Neometals' cost structure, reagents and consumables make up the largest portion at 33.4%, followed by operating supplies accounting for 26.4% and labor costs accounting for 22.9%. General and administrative expenses account for 12.8% of total costs, while maintenance costs for the recycling facility are only 4.5%.[68] Successful integration into a hub-and-spoke network, as discussed in the Technology Performance section, could help to provide strategic and economic benefits by reducing the operating expenses of a recycling facility.

ANNOUNCED RECYCLING CAPACITIES IN EUROPE

Recycling plants with a capacity of approximately 139 kilotons per year are installed in Europe as of January 2023. The number of companies looking to enter the LIB recycling market continues to grow. It is predicted that total recycling capacity in Europe will increase to approximately 400 kilotons per year by 2030. In addition, some companies have announced capacity expansions but not yet published exact figures. This could lead to an even higher total capacity.[70]

WORLDWIDE MARKET DEVELOPMENT

Asia has the largest capacity for LIB recycling. In fact, more than half of the world's recycling capacity is located in China. Currently, several new recycling projects have been announced and started in Europe as well as in North America. This indicates strong capacity growth in the European market.[71]

INNOVATION

UPCOMING KEY INNOVATIONS IN LIB RECYCLING

The increase in global electric car production is a challenge for the entire automotive sector. At present, Asian countries have a lead over the EU in research, supply chain, and LIB recycling. Significant investments will be needed to bring the competition to a level playing field. The EU Battery Regulation establishes clear goals for companies. Additionally, the recycling sector has experienced a considerable increase in start-ups, and direct recycling could play a major role in the future. So far, this method has not been applied on a large scale because of the various cell designs and chemistries. Nonetheless, this recycling method could provide several benefits, such as a lower carbon footprint and resource minimization, due to reduced energy requirements, emissions, and recycling steps.[62]

PUBLICATIONS IN THE FIELD OF LIB RECYCLING

The number of publications concerning LIB recycling and circular economy displays a significantly favorable trend. From 2018 to 2022, the number of annual publications increased more than tenfold reaching over 48 per year. This number is projected to continue rising in forthcoming years. The majority of the publications mainly centered on recovery, followed by recycling that aimed to enhance the material recovery rate. This highlights the increasing significance of LIB recycling and the creation of scientific principles to encourage and enhance LIB recycling.[62]

PATENTS IN THE FIELD OF LIB RECYCLING

Patent applications play an important role in the early LIB recycling market. 74% of the literature on this subject consists of patent applications. China, Japan, and France are leading in this category, with China filing the most patent applications. This highlights China's important role in the development of LIB recycling technologies. These patents are critical to the advancement of sustainable approaches to LIB recycling.[72]

Nikolaus Lackner

> “In the current decade, strong market growth in battery recycling can be expected, following the growth of battery production with several years distance.”

Tim Hotz, Konstantin Knoche

KEY TAKEAWAYS

Regulations
Regulations are getting more and more complex and having growing implications for players in the battery value chain. The IRA significantly raises the attractiveness of the US to investors, while the new EU Battery Regulation and proposals for a ban on PFAS increase necessary efforts for battery producers – the EU regulation is firmly focused on the shift to sustainability.

Investors
The battery market, especially in Europe and China, is becoming overheated and getting more and more difficult for new entrants. Investments and further expansions should be based largely on secured sales volumes.
Announced overcapacity in China might lead to significant exports into the European market (the US market being largely closed to Chinese imports). This puts more competitive pressure on European newcomers to compete with Chinese imports, though that might be eased by the EU's EV subsidy probe in case it comes into place.
Advances in Li-ion cell technology and a resilient supply chain are now differentiating factors. In-depth due diligence is thus essential, both on the market and customers and on technology and the supply chain.

CAM and AAM manufacturers
As last year, there was a growing number of hedging strategies and approaches. However, advancements in LFP and sodium-ion technology mean that a more flexible approach is now required. In particular, the supply/demand balance and the costs for nickel are expected to vary drastically based on the market penetration of other materials. We forecast that the balance will settle at a lower level than we predicted in 2022.
Industrialization of high-silicon-anode technology is yet to occur, but fast charging for graphite anodes is improving. Silicon players thus need to be cost competitive, as only a small portion of the market is likely to accept a price premium.
Upstream technologies with highly differentiated production routes have varying carbon footprints and cash costs. The right supply chain strategy and level of vertical integration are more important than ever – IRA compliance and ESG are the key sourcing criteria for cell manufacturers, besides price, when choosing CAM and AAM suppliers.

OEMs and battery manufacturers
The new EU Battery Regulation means strategic supply chain management and the integration of recycling will be key. In the US, intensive value chain analysis is required to utilize IRA-based tax credits. China is increasingly moving away from CO$_2$-intense production, especially as domestic battery producers are adapting to European customers' emission requirements by developing carbon-neutral facilities. This places more pressure on new European battery cell producers, who advertise sustainability as their key USP.

Equipment providers
As in last year's report, the cost of equipment is vital in attracting battery producers. The advantage in cost and experience of Chinese equipment is reflected in European OEMs' announcements around equipping their gigafactories primarily with Chinese equipment. Thus, besides focusing on next-gen equipment with advanced specs such as energy efficiency, Western equipment providers also need to find a solution for cost effectiveness. Numbers of Western turnkey solution providers are also lacking.

Recyclers
The increasingly important sustainability of products is also evident in the area of lithium-ion batteries. Driven on the one hand by regulations, but also by economic and strategic interests, work is underway to establish a closed loop for batteries. Research and industry are increasingly addressing this topic in order to overcome technological hurdles and secure a leading position in this rapidly growing market.

Wolfgang Bernhart, Tim Hotz, Konstantin Knoche

CLOSING WORDS & OUTLOOK

In this year's second edition of the Battery Monitor as a collaboration between PEM at RWTH Aachen University and Roland Berger, we see the continuation of predicted trends from the first edition within the battery industry. Ongoing political tensions, new regulations affecting the market and new free trade agreements are moving the figures on the global chess board of geopolitical powerplay. Over the next year, it will be interesting to see how the balance between the four big battery regions, North America, Europe, China and Korea/Japan, will evolve. The EU probe against Chinese EVs (announced after the editorial deadline) may be just a glimpse of what lies ahead. In respect of the raw material activities in countries like Indonesia and Australia, it will further drive complexity in supply chain handling.
Besides regulation, we see one of the biggest challenges in scaling up operations and industrializing from pilot scale to mass production. Several major players have made their strategic decisions and are now facing challenges in building and industrializing the facilities. A number of SOPs are planned for the next two years – if they actually happen is another story. Acquiring talent, solving ramp-up problems and finding the right suppliers that will supply at low cost, reliably and with low political risks are just some of the challenges to be resolved.
Last but not least, one question still remains open: What will drive the market – technological leadership or cost-effective solutions? While Western and Korean/Japanese players seem to focus on technological leadership and innovative cell technology with, for example, even higher nickel shares or silicon-anode technology, Chinese players appear to focus on cost-effective solutions such as LFP, sodium-ion and cell-to-pack designs. That said, a cost-effective solution in the battery space often also requires technical advantages. While the race is still anyone's game, it will require a sound strategy, significant innovation efforts and capital from Western players if they are to be in the winner's circle.

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