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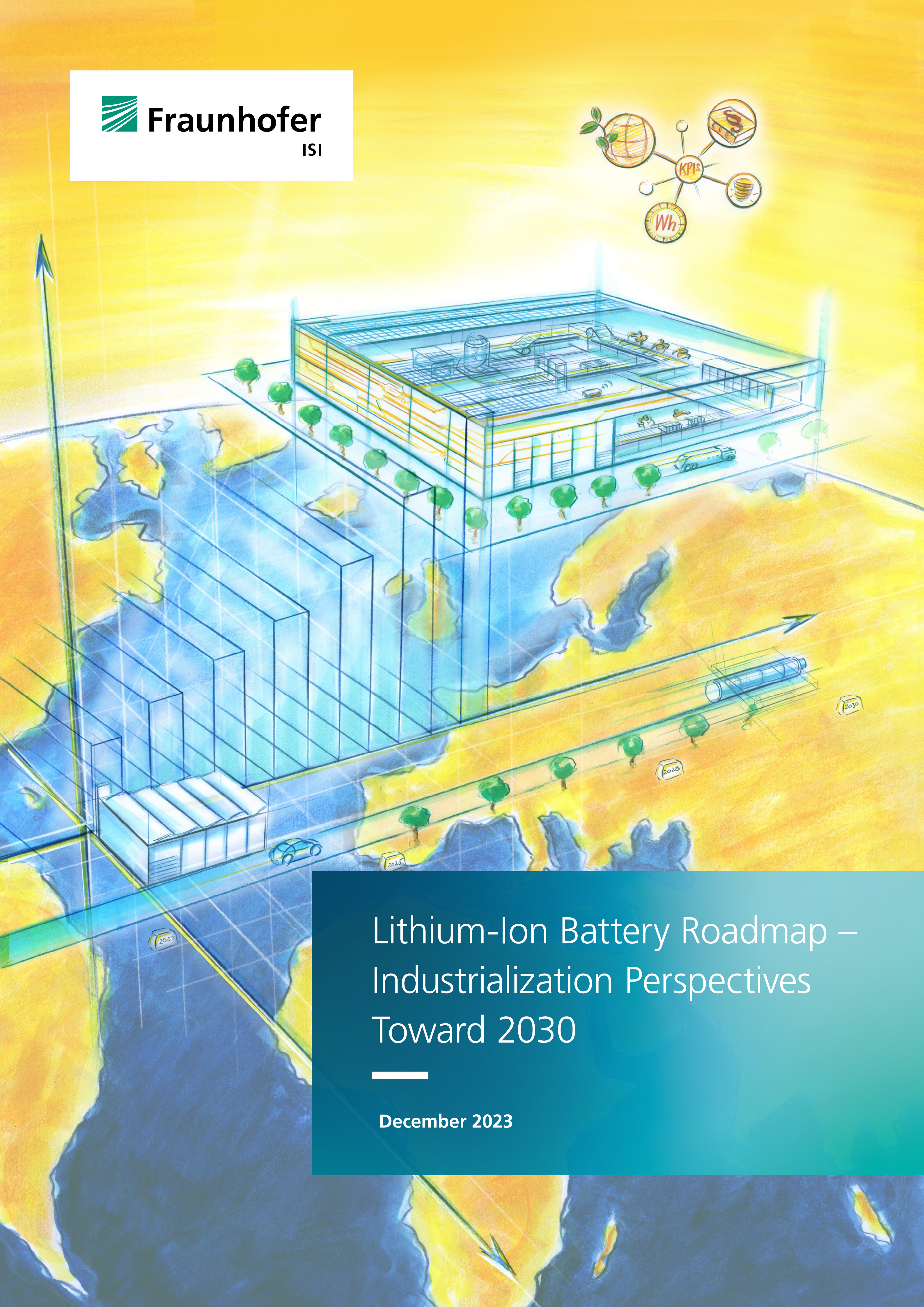

Lithium-Ion Battery Roadmap – Industrialization Perspectives Toward 2030

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The market for lithium-ion batteries (LIB) continues to expand, across borders and despite crises. In 2023, sales could exceed the 1 TWh mark for the first time. By 2030, demand is expected to more than triple to over 3 TWh. The high growth rates of recent years are set to continue.

The transition from gigawatt hours to terawatt hours in demand and production has many implications for the industry, but also for technology development and the requirements for batteries. For example, recent regulatory requirements mandate battery sustainability. The mass use of LIBs in electric vehicles has pushed the issue of battery price to the fore and more technical factors such as energy density and range into the background, at least in the smaller vehicle and mass segments. As the market continues to grow, questions of production localization and the share of value creation that stakeholders and nations will have in the future will become more important.

This study "Lithium-Ion Battery Roadmap - Industrialization Perspectives Toward 2030" attempts to take into account the status of LIB as an established technology by focusing on the scaling activities of the industry, while still considerung the numerous technological challenges that range from materials to the final treatment of end-of-life batteries. The result is a quantification of this industry until 2030 and an evaluation of approaches in the areas of materials, cells, production, systems and recycling, not only according to their performance but also according to their significance for three key trends: The production of performance-optimized batteries, the production of particularly low-cost batteries and the production of particularly sustainable batteries.

LIB target system and industrial implementation

There are ambitious development goals for performance-optimized batteries. Over the next few years, the aim is to significantly increase the parameters of energy density and fast-charging capability in particular. It is not uncommon to see targets of more than 800 Wh/l and more than 350 Wh/kg in industry roadmaps. For some flagship vehicles, charging rates will be accelerated to 4C and thus into the range of 10 to 20 minutes. To achieve these goals, the industry is turning to high-nickel cathodes, silicon anodes and new cell and pack designs that change space requirements, thermal coupling and safety characteristics. The goals sound impressive, and the technological approaches are very promising. However, it is increasingly being asked whether such “best of class” approaches are suitable for mass production, and whether they are compatible with a second major and maybe even more important development goal of reducing battery costs. The cost target at the battery pack level is still well below 100 EUR/kWh. Compared to today's costs, this could mean a reduction of 30 to 50 %. The industry aims to achieve this by using both cobalt-free and nickel-free materials, standardizing cells and integrating them directly into the battery pack. New manufacturing processes could also contribute to reducing costs, both by leveraging energy and equipment costs and by standardizing the factory itself. Costs also show that technologies are not necessarily location-neutral. Achieving the lowest battery cost could be linked to siting factories at the most advantageous production location.

Very similar considerations apply to the production of sustainable batteries as required by the EU Battery Directive, among others, but also by an increasing number of car manufacturers. Specifically, sustainability can affect many factors, from raw material extraction to production and use scenarios. In the coming years, industrial developments are likely to focus on cell technologies and production technologies, some of which even combine sustainability, e.g., a low CO_2 footprint with low cost. These include iron- and manganese-based cathodes, water-based or dry electrode processing, and using recycling to recover materials at the end of the battery's life. The location of production also plays an important role in sustainability, influenced by factors such as the available energy mix and the distance to upstream and downstream production sites.

The three key trends and target systems discussed in the study are partly contradictory. High performance is sometimes expensive and at the limits of what is technically feasible. The high priority of a low environmental footprint may limit the use of some technologies and must also take into account end-of-life treatment in the design phase. While there are some compromise technologies that combine several of these objectives, the current trend in the industry seems to be more in the direction of diversification and the production of batteries with clear profiles and use cases.

The development of batteries tailored to specific application requirements goes hand in hand with scaling up production. In recent years, there has been a strong focus on cell production. There are plans to build more than 10 TWh of annual production capacity by 2028. Even if this figure is adjusted to take into account the likelihood of implementation and typical delays, up to 5 TWh of cell production capacity could still be available in 2028.

Looking at the upstream value chain, it is clear that this figure is high and reflects a kind of gold rush. Here, scaling projects have been announced that would enable the production of around 3 TWh of anode and cathode active materials in 2028, which is closer to the projected battery demand of the application markets of 2 to 3.5 TWh. These figures suggest that there could be a consolidation of cell production projects in the coming years. At the same time, it is likely that there will soon be a greater focus on materials production, as joint ventures with automotive OEMs increasingly enter this segment of the value chain.

How battery recycling capacity will develop is still unclear. By 2030, the recycling of production waste in particular will play an important role for the industry. It is not yet known how scaling will work with the EoL batteries that will then be returned.

Europe on the way to self-sufficiency?

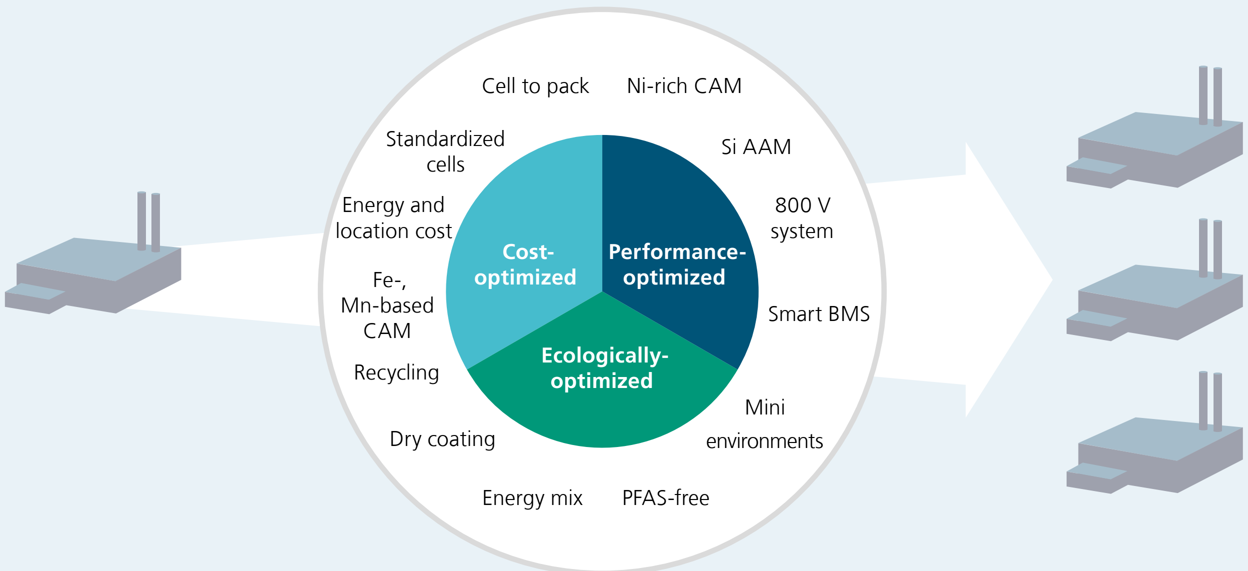
In In Europe, too, there is still a large imbalance between supply and demand. The latter is expected to be around 550 GWh in 2028 due to increased electric vehicle production. This contrasts with announcements of plans to build cell production capacities of 1.7 TWh, or more realistically around 1 TWh after adjustments for the likelihood of implementation and delays. These figures for Europe therefore confirm the global trend of a strong focus on projects and investments in cell production. The goal of locating 30 % of global cell production on European soil could be achieved.

However, Europe is likely to remain weak in the production of anode materials and will have to rely on imports. There are plans in place to build production capacities of around 200 GWh, mainly for graphite, by 2028. The figure for cathode materials is expected to range from 400 to more than 600 GWh, which is roughly in line with the projected demand for batteries.

At first glance, therefore, Europe appears to be well on the way to becoming self-sufficient in the value creation steps examined in this study from material to battery system. However, gaps still exist and not just in terms of the anode materials, e.g., in passive cell components or the key technology of lithium iron phosphate, which is extremely important for low-cost batteries. So far, there have been no substantial announcements regarding the expansion of production capacities for this material. It also remains unclear which manufacturers intend to cover this technology in cell production. Similarly, no material manufacturer has yet committed to building significant capacity for silicon materials, which are considered to be the next generation of LIB technology.

To fill in these gaps and create a competitive, self-sufficient and sustainable European battery ecosystem, a number of challenges still need to be overcome. These include investments and investment conditions, energy costs, the training of qualified workers and the creation of a continuous local value chain. Streamlining bureaucratic processes and reducing time-consuming procedures, as well as improving government subsidies and financing mechanisms could help to attract more industrial players and ensure a level playing field with non-European countries.

Figure 1: Schematic representation of the three LIB target systems under consideration: (1) performance-optimized, (2) cost-optimized and (3) ecologically-optimized and available technologies.



Zusammenfassung

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Der Markt für Lithium-Ionen Batterien (LIB) wächst, über Grenzen und auch über Krisen hinweg. Im Jahr 2023 könnte der Absatz zum ersten Mal die Marke von 1 TWh Batteriekapazität überschreiten. Bis 2030 soll sich die Nachfrage sogar auf über 3 TWh mehr als verdreifachen. Die hohen Wachstumsraten der letzten Jahre setzen sich fort. Der Übergang von der Nachfrage und Produktion im Gigawattstundenbereich in den Terawattstundenbereich hat zahlreiche Implikationen für die Industrie, aber auch für die Technologieentwicklung und die Anforderungen an Batterien. Unlängst sind regulatorische Anforderungen entstanden, die z. B. Vorgaben zur Nachhaltigkeit von Batterien machen. Der Masseneinsatz von LIB in Elektrofahrzeugen hat das Thema Batteriepreis in den Vordergrund und technischere Faktoren wie Energiedichte und Reichweite, zumindest im Kleinwagen- und Massensegment, in den Hintergrund treten lassen. Und je weiter der Markt wächst, desto gewichtiger wird auch die Frage nach der Produktionslokalisierung und dem Anteil an der Wertschöpfung, den Akteure und Nationen in Zukunft haben werden.

Die Studie „Lithium-Ion Battery Roadmap – Industrialization Perspectives Toward 2030“ versucht dem Status der LIB als kommerzialisierte Technologie Rechnung zu tragen, indem ein klarer Fokus auf die Skalierungsaktivitäten der Industrie gelegt wird, ohne die vielen technologischen Herausforderungen von den Materialien bis zum Endverbleib ausgedienter Batterien zu vernachlässigen. Im Ergebnis steht eine Quantifizierung dieser Industrieaktivitäten bis 2030 und eine Bewertung technologischer Ansätze in den Bereichen Material, Zelle, Produktion, System und Recycling nicht nur nach ihrer Leistungsfähigkeit sondern nach ihrer Bedeutung für drei Schlüsseltrends der Industrie und Anwendung: Die Herstellung von leistungsoptimierten Batterien, die Herstellung von besonders günstigen Batterien und die Herstellung von besonders nachhaltigen Batterien.

Zielsystem LIB und industrielle Umsetzung

Die Entwicklungsziele für leistungsoptimierte Batterien sind ambitioniert. In den nächsten Jahren sollen insbesondere die Parameter Energiedichte und Schnellladefähigkeit nochmal deutlich erhöht werden. Auf den Industrieroadmaps sind nicht selten Ziele von über 800 Wh/l und über 350 Wh/kg zu lesen. In einigen Flagschifffahrzeugen sollen die Laderaten auf 4C und damit in den Bereich zwischen 10 und 20 Minuten beschleunigt werden. Zur Erreichung dieser Ziele setzt die Industrie auf Kathoden mit höchstem Nickelgehalt, Silziumanoden und neuen Zell- und Packdesigns, die sowohl den Platzbedarf als auch die thermische Ankopplung und Sicherheitseigenschaften verändern. Auf der Systemebene steht z. B. mit der 800 V Technologie eine neue Option zur Performanceverbesserung zur Verfügung und auch softwareseitig soll, z. B. durch intelligente Managementsysteme, nochmal mehr aus der Batterie herausgeholt werden können.

Diese Entwicklungsziele klingen eindrucksvoll und die technologischen Ansätze sind vielversprechend. Dennoch stellt sich immer mehr die Frage, wie massentauglich solche „best of class“ Ansätze sein können und inwiefern ein Konflikt mit einem zweiten großen und vielleicht sogar bedeutsamerem Entwicklungsziel besteht: der Redukion von Batteriekosten. Nach wie vor liegt das Kostenziel auf Batteriepackebene bei sehr deutlich unter 100 EUR/kWh. Gegenüber heutigen Kosten kann dies durchaus die Reduktion um 30 bis 50 % bedeuten. Die Industrie will dieses Ziel durch die Nutzung sowohl cobalt- als auch nickelfreier Materialien, die Standardisierung von Zellen und die Direktintegration ins Batteriepack erreichen. Auch neue Produktionsprozesse könnten beitragen, sowohl durch den Hebel der Energie- und Anlagenkosten als auch über eine Standardisierung der Fabrik selbst. Auch zeigt sich bei den Kosten, dass Technologien eben doch nicht unbedingt standortneutral sind. Die Erreichung niedrigster Batteriekosten könnte an die Nutzung des günstigsten Produktionsstandorts gekoppelt sein.

Ganz ähnliche Überlegungen gelten für die Herstellung nachhaltiger Batterien, wie sie u.a. von der EU Batterieverordnung aber auch von immer mehr Automobilherstellern gefordert werden. Konkret kann Nachhaltigkeit viele Faktoren vom Rohstoffabbau bis zur Produktion und zu Nutzungsszenarien betreffen. Im Fokus industrieller Entwicklungen dürften in den nächsten Jahren Zelltechnologien und Produktionstechnologien stehen, die teilweise sogar Nachhaltigkeit, z. B. im Sinne eines geringen CO_2-Fußabdrucks, und niedrige Kosten kombinieren. Dazu zählen eisen- und manganbasierte Kathoden, eine wasserbasierte oder trockene Elektrodenprozessierung und die Rückgewinnung von Materialien am Batterielebensende durch Recycling. Auch in Punkto Nachhaltigkeit spielt der Produktionsstandort eine große Rolle und wirkt sich beispielsweise durch den zur Verfügung stehenden Energiemix oder die Entfernung zu vor- und nachgelagerten Produktionsorten aus.

Die drei in der Studie diskutierten Schlüsseltrends bzw. Zielsysteme stehen teilweise im Widerspruch. Hohe Performance ist häufig teuer und bewegt sich an der Grenze des technisch machbaren. Die hohe Priorisierung eines ökologisch niedrigen Fußabdrucks kann die Nutzung einiger Technologien einschränken und muss auch die Behandlung nach dem Lebensende berücksichtigen. Teilweise existieren zwar Kompromisstechnologien, die mehrere dieser Ziele vereinen können, jedoch scheint der Trend in der Industrie zur Diversifizierung und Herstellung von Batterien mit klarem Profil und Anwendungsfall zu führen.

Hand in Hand mit der Entwicklung spezifischerer und anforderungsgerechter Batterien geht die Skalierung der Produktion. In den letzten Jahren lag ein starker Fokus auf der Zellproduktion. Mittlerweile häufen sich bis 2028 die Ankündigungen von Zellherstellern, Automobil OEM, Start-Ups und Joint Ventures derselben zum Aufbau von mehr als 10 TWh jährlicher Produktionskapazität. Korrigiert man diesen Wert unter Berücksichtigung der Umsetzungswahrscheinlichkeit und mittlerweile typischer Verzögerungen, so stünden im Jahr 2028 dennoch bis zu 5 TWh an Zellproduktionskapazitäten zur Verfügung.

Dass dieser Wert hoch ist und eine Art Goldgräberstimmung ausdrückt, verdeutlicht der Blick auf die vorgelagerte Wertschöpfungskette. Hier wurden Skalierungsprojekte angekündigt, die eine Herstellung von etwa 3 TWh an Anoden- und Kathodenaktivmaterialien in 2028 ermöglichen würden, was näher an der prognostizierten Batterienachfrage der Anwendungsmärkte von 2 bis 3,5 TWh liegt. Die Zahlen legen nahe, dass es in den nächsten Jahren eine Konsolidierung bei den Zellproduktionsprojekten geben könnte. Gleichzeitig ist es wahrscheinlich, dass die Materialherstellung demnächst stärker in den Fokus gerät, z. B. indem zunehmend Joint Ventures mit Automobil OEM auch in diesen Wertschöpfungsschritt einsteigen.

Unklar ist aktuell noch der Kapazitätsaufbau für das Batterierecycling. Bis 2030 wird insbesondere die Verwertung von Produktionsabfällen eine große Rolle für die Industrie spielen. Wie sich die Skalierung mit den dann zurückkommenden EoL Batterien gestaltet, ist aktuell noch unbekannt.

Europa auf dem Weg zur Selbstversorgung?

Auch in Europa besteht noch ein hohes Ungleichgewicht zwischen Angebot und Nachfrage. Letztere dürfte 2028 aufgrund der starken Elektrofahrzeugproduktion bei etwa 550 GWh liegen. Demgegenüber stehen Ankündigungen für den Aufbau von Zellproduktionskapazitäten von 1,7 TWh, bzw. nach Korrektur hinsichtlich Umsetzungswahrscheinlichkeit und Verzögerung von realistisch etwa 1 TWh. Diese Zahlen für Europa bestätigen also den globalen Trend einer starken Fokussierung von Projekten und Investitionen auf die Zellfertigung. Das Ziel, 30 % der globalen Zellfertigung auf europäischem Boden anzusiedeln, könnte erreicht werden.

Bei der Herstellung von Anodenmaterialien dürfte Europa derweil weiterhin schwächeln und auf Importe angewiesen sein. Bis 2028 sollen Produktionskapazitäten, vornehmlich für Graphit, von etwa 200 GWh aufgebaut werden. Bei den Kathodenmaterialien sollen es 400 bis über 600 GWh sein, was in etwa der prognostizierten Batterienachfrage entspricht.

Europa scheint damit bei den im Rahmen der Studie untersuchten Wertschöpfungsschritten vom Material bis zum Batteriesystem auf den ersten Blick auf einem guten Pfad in Richtung Selbstversorgung zu sein. Im Detail bestehen jedoch noch Lücken, auch abseits der Anodenmaterialien, z. B. bei den passiven Zellkomponenten oder auch bei der für niedrige Kosten wichtigen Schlüsseltechnologie Lithiumeisenphosphat. Bislang wurden keine nennenswerten Ankündigungen für den Aufbau von Materialproduktionskapazitäten gemacht. Auch bei der Zellherstellung erscheint weiterhin unklar, welche Produzenten diese Technologie abdecken wollen. Ebenfalls hat sich noch kein Materialproduzent zum Aufbau größerer Kapazitäten für Siliziummaterialien, die als LIB Technologie der nächsten Generation gelten, bekannt.

Um die Lücken zu schließen und ein wettbewerbsfähiges, souveränes und nachhaltiges europäisches Batterie-Ökosystem zu schaffen sind noch einige Herausforderungen zu meistern. Zu diesen gehören Investitionen und Investitionsbedingungen, hohe Energiekosten, die Ausbildung qualifizierter Fachkräfte und die Schaffung einer durchgängigen lokalen Wertschöpfungskette. Die Straffung bürokratischer Prozesse und die Verringerung zeitaufwändiger Verfahren sowie staatliche Subventionen und Finanzierungsmechanismen können weitere industrielle Akteure anlocken und für gleiche Wettbewerbsbedingungen mit dem außereuropäischen Ausland sorgen.

1. Introduction

1.1. Introduction and Motivation

Lithium-ion batteries (LIBs) have emerged as indispensable and widely adopted energy storage solutions in electric vehicles, especially in high-energy configurations. Nonetheless, their application also extends beyond electric mobility and is rapidly diversifying across other industries, including aerospace, the energy sector, and consumer electronics.

Scope and function of roadmaps.

Roadmaps are intended to be used as a strategic guideline for the further development and optimization of the respective technologies. They facilitate continuous improvement and can help to overcome current performance limitations through targeted research and development, driving innovation. Roadmaps support industry players by providing overviews of planned production capacities, investments, and supply chain expansion. A roadmap focusing on improvements to and applications for high-energy LIBs is crucial to promote sustainable battery technologies and contribute to the energy transition. This can help to empower the industry to address challenges, prepare for future developments, and fully harness the potential of this technology.

This roadmap focusing on high-energy LIBs was compiled to describe the technological development, availability, and cost optimization of lithium-ion batteries. Technologically, there is still potential to improve performance, sustainability, and optimize costs. This roadmap is even more important given the debate on climate change and the need to decarbonize the economy, current geopolitical tensions, and countries' attempts to achieve technological sovereignty.

There are substantial investments dedicated to advancing LIB technology and production. Forecasts anticipate a tenfold increase in these investments in the short term. In addition, there is a growing global trend toward establishing circular battery ecosystems, aiming to promote sustainability through efficient battery recycling and resource conservation.

In the near future, LIBs are the only giga-scale battery technology suitable for automotive applications, with lead-acid batteries (PbA) remaining the sole alternative at GWh production levels. Hence, the roadmap represents a strategic initiative focused on optimizing and advancing Li-ion technology.

What does the roadmap mean in this context?

A technology roadmap strategically monitors and projects the evolution of a particular technology, with progress embodied in continuous optimization rather than sudden breakthroughs. For LIBs, the emphasis has shifted from discovering entirely novel materials to enhancing the performance of existing ones. The escalating public discourse on climate change and the necessity for sustainable energy sources has amplified the significance of this roadmap. Current developments show that optimization is no longer solely confined to research endeavors but primarily enabled by industry-driven efforts and initiatives. Hence, this LIB technology roadmap is oriented toward monitoring the technology choices and advancements anticipated by industry players rather than just documenting (public) research.

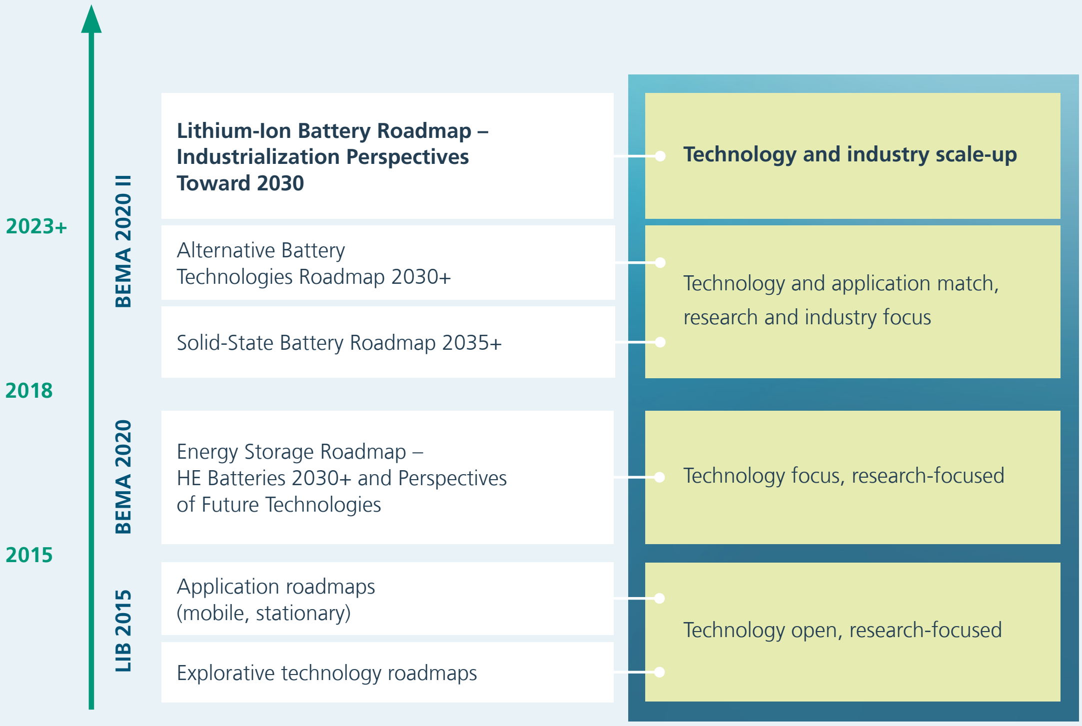
Focus on market ramp-up

LIBs have solidified their presence as a versatile solution across various applications. Technological advancements primarily stem from competitive dynamics among manufacturers, emphasizing improvements in performance and cost efficiency. The focus has shifted from basic technology developments needed for applications to mass production and scaling up lithium-ion battery production to meet the rising demand. This is also true for the principles of the circular economy. As a result, the pivotal Key Performance Indicators (KPIs) outlined in this and competing roadmaps have transitioned from solely material or cell-level metrics to system-level considerations. They now encompass larger scale issues, including (raw) material availability and procurement in kilotons or soon in megatons, meeting demand at GWh-scale or soon at TWh-scale, and investment volumes in billions of euros.

What does this mean for the Fraunhofer ISI roadmap?

This roadmap complements and expands the existing Fraunhofer ISI roadmaps, adapting and enlarging their methodology and objectives in parallel with the technological maturity and market evolution of LIBs. Earlier iterations like the "LIB2015 Roadmaps" concentrated on diverse applications, employing various technology approaches to meet distinct requirements. Conversely, the "BEMA 2020 Roadmaps" emphasized different battery technologies and their potential advancements, particularly in performance enhancement. In contrast, this roadmap is tailored to address the industry's strategies for meeting the growing demand for LIBs and determining the extent to which individual stakeholders can add value.

Figure 2: Further development of the research focus of BMBF-funded ISI battery roadmaps in parallel to the industry's progress in scaling up.



Does the roadmap focus only on market share and value creation?

Alongside economic considerations, environmental aspects are also becoming more important. Although batteries aim to address societal challenges like climate change and decarbonization, their production involves critical raw materials and leaves a substantial ecological footprint. Thus, effective recycling processes are essential at the end of their life cycle.

The discourse surrounding battery origin and global supply chains, both closely tied to technological sovereignty, is gaining significance in Europe. This roadmap was compiled in the context of diverse legal and political regulations, such as the EU Battery Regulation, the EU Critical Raw Materials Act, the US Inflation Reduction Act, and notable trade policy dynamics between major global centers like China, North America, and Europe. Public discourse and political advancements have further underscored the relevance of this roadmap concerning sustainable battery technology and technology sovereignty. There are also links to other Fraunhofer ISI studies focusing on technological sovereignty and overarching political meta-roadmaps.

What insights does this roadmap offer?

This roadmap explores advanced and mature LIB technologies, focusing on industrial scale-up (When?) and industrial stakeholders (Who?) rather than technical specifics (How?) (chapter 3). It offers a structured analysis of planned LIB material and cell production capacities, and discusses regional market shares, key players, and scale-up potentials. Additionally, it evaluates trends in technology, production, and key areas like performance improvement, sustainability, cost-effective manufacturing (chapter 4.1), and meeting the growing demand in the automotive sector (chapter 4.2).

This roadmap closes with a focus on Germany and Europe, analyzing the strengths of the domestic industry and interpreting the presence of Asian companies in Europe as an indicator of the location's viability (chapter 4.3). Accordingly, it includes discussions about European LIBs or what share of Europe's own demand can be met by domestic production. It also provides an outlook to further developments in the public debate and policy developments.

1.2. Methodology

This roadmap focuses primarily on the further development of LIB technology from an industrial production perspective. The roadmap is global, technology-neutral and limited to the period up to 2030, although many of the activities discussed relate to the next few years, e.g., up to 2025. In this respect, this LIB roadmap differs from other Fraunhofer ISI roadmap studies [1, 2], which look at a much longer development period and therefore also place a much greater focus on research activities.

Battery technology and KPI targets

Research is being done on a variety of technologies in the areas of materials, cells, production and recycling. Only a small proportion of these make it into industrial application. In this roadmap, we limit ourselves to technologies for LIBs that have either already been adopted by the industry or for which the industry has clearly positioned itself for future use.

The analyses are therefore based in particular on industry roadmaps and other announcements concerning the production or use of specific technologies. As many of the technologies are still under development, concrete timetables for their implementation must be treated with caution.

The planned implementation dates of various companies are presented in the technology chapters. We do not evaluate these in the context of this roadmap. However, the technology chapters also include a description of the key development challenges associated with these technologies. These are based on the evaluation of scientific literature and therefore mostly on information that does not come from the players who want to use the technologies industrially.

In In some cases, we provide KPIs for these technologies, either based on information provided by industry or our own evaluation, e.g., using the Fraunhofer ISI cell design tool (see also [3]).

Material and cell production capacities

Current and future production capacities were compiled based on producer information, either directly from the producers themselves, e.g., in the form of press releases, annual reports or company presentations, or indirectly, e.g., from studies and newspaper reports. The various data sources are not homogeneous in terms of format and information and range from speculative statements to validated data. The data basis for the evaluation only includes communicated producer information. If manufacturers do not communicate their capacities or expansion plans, these could not be included in the study.

To use the information in this roadmap, over 600 data sets on past, present or future production capacities of cell manufacturers and around 250 data sets on material manufacturers were collected and integrated into an overall database. The database contains information on the location, operator and, if applicable, financer of a production plant, the status of production announcements and the products themselves (e.g., material type, cell type).

In order to be able to combine and use different sources of information and different levels of detail, all the data sets were evaluated in terms of their validity, feasibility and accuracy.

This is particularly important for the evaluation and comparison of announcements concerning the expansion of production capacities. Companies sometimes communicate very differently here, both in terms of the timing of the announcement and its specifics. Four parameters were therefore documented to evaluate announcements:

1. Experience of company: new cell manufacturer, established cell manufacturer

2. Background of company: car manufacturer, joint venture of car manufacturer/cell manufacturer

3. Type of announcement: new site, expansion of an existing site

4. Progress of construction: existing production site, production site specified, financing available, construction started

For the analyses and forecasts, the individual announcements were weighted and totaled using these parameters. If the production site was specified and the investment expected to be secured, the announcement was classified as "expected". If the plans were optional expansions of existing plants, or the production site was not concretely specified (e.g., only on country level) or the decision to invest did not seem final, the announcement was classified as "potential". Plans that lack convincing indications that they will be realized (e.g., lack of financing or only rough plans on a global level) were classified as "doubtful". Additionally, cell manufacturers were classified into established and new based on their experience with large-scale battery cell manufacturing. Three alternative classifications were used to account for the additional uncertainties in the choice of cell format. Announced production capacities with reliable information about the cell formats and which are assumed to have a high likelihood of realization were denoted as "certain"; announcements with either reliable information about the cell format or a high realization likelihood were denoted as "expected"; announcements with neither reliable information nor a high realization likelihood were denoted as "potential".

In addition to this project-specific "likelihood of implementation", two other factors can influence actual future production capacities: (1) delays in setting up production compared to the SoP communicated by the companies; (2) production rejects or set-up times that reduce the stated production capacity. We have long observed that companies tend to communicate the commissioning of new production facilities with optimistic time assumptions. For our scenarios, we therefore took into account the possibility of a delay until the actual SoP in sales-ready quality. We also considered tooling times, production waste and factors that can reduce annual production capacity in long-term operations.

Within this study, the production capacities for Europe also include countries who are not part of the European Union (the UK, Norway, Switzerland and Serbia).

Demand forecast

The forecast of the demand for batteries is based on a market model developed by Fraunhofer ISI, which describes different battery submarkets (passenger and commercial EV, stationary storage, consumer, communication, computing, two- and three-wheeler, others). The model can be evaluated regionally (e.g., globally, Europe) and uses various forecasting approaches:

The battery demand of vehicle markets is described on the basis of segment-specific registration figures in the Bass Diffusion Model [4]. For this purpose, a distinction is made between seven submarkets (A,B-segment cars, C-segment cars, D,E,F- and SUV-segment cars, light commercial vehicles, heavy commercial vehicles buses, motorcycles) and four drive technologies (BEV, PHEV, HEV, ICE), each with different assumptions for the development of typical battery capacities. The drive technologies are not modeled independently of each other, so displacement effects between the technologies can also be modeled, which is relevant in the case of high market penetration of EVs [5].

Demand in other submarkets (ESS, 3C, others) is described by decaying exponential functions. The development of previous sales figures for the respective applications (home and large-scale storage systems, electronics, power tools, etc.) is also used as a basis for this. Industrial demand for batteries is based on OICA production data for motor vehicles [6].

Recycling capacities

To estimate future recycling capacities and identify the relevant actors, announcements of capacity additions were collected in a database and analyzed. Similar to the approach taken for material and cell producers, direct information, e.g., in the form of press releases, annual reports or company presentations, or indirect information, e.g., from studies and newspaper reports, was used. This search resulted in a total of 163 announcements. The findings were supplemented by literature searches where applicable. The data quality of non-European manufacturers, particularly those from Asia, is limited due to poor accessibility. This is especially valid for the current status. New and larger recycling plants, on the other hand, are often announced publicly.

Patent analyses

The patent analyses were performed using IPC classes (International Patent Classification) under the classification H01M for chemical energy storage (e.g., batteries). We used the Derwent Worlds Patents Index (WPI) database hosted by the Scientific & Technical Information Network. The searches were limited to transnational patent applications to the European Patent Office (EPO) or the World Intellectual Property Organization (WIPO), as these require a high level of investment in the patent application process and enable a fair comparison between countries.

The IPC classes with highest number of patent applications in the most recent year (2021) were compared to the applications in 2016 (five years earlier) in order to identify the IPC classes with the highest dynamics. The cut-off criteria were more than 50 applications in 2021 and, when comparing 2016 with 2021, a dynamic development larger than 200 percent (factor > 2).

Compilation of a roadmap

This study yielded three very target-specific roadmaps for (1) particularly high-performance, (2) particularly low-cost and (3) particularly sustainable batteries. The wide range of individual technologies from the areas of materials, cells, systems and recycling were evaluated and combined for this purpose. Both the evaluation with regard to (1) to (3) and the discussion of the advantages and disadvantages of technology combinations were carried out qualitatively by experts. It is precisely the trade-offs between different technology characteristics: energy versus power density, costs versus flexibility, and many others that can lead to a slower implementation of technologies in the overall battery system than may be implied when looking at the roadmaps of the individual technology providers.

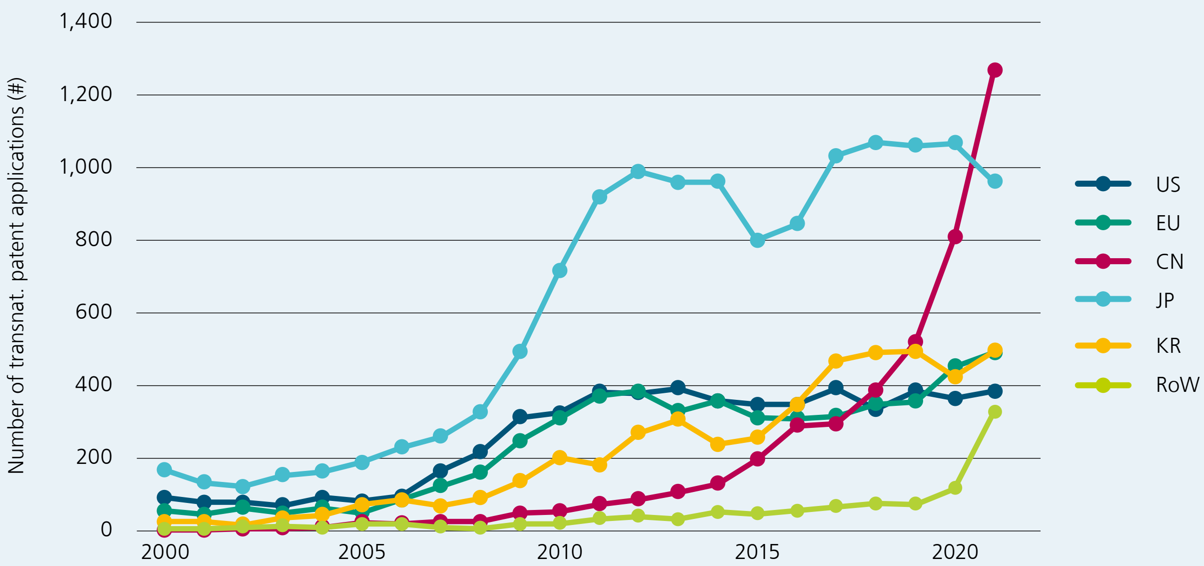
1.3. LIB Patent Analysis

Global transnational lithium-ion battery patent applications have increased more than tenfold in the past 20 years, from more than 300 per year around 2000 to almost 4,000 per year in 2021. Japan used to dominate patent activities with a global share of around 50 %, but its applications have stagnated at around 1,000 each year for several years, causing its global share to decline to below 30 %. Recently, other major players like the USA, South Korea, and the EU27 + the United Kingdom have had shares between 10-15 %. In contrast, China has become the leading country in patent applications with a recent share of more than 30 % share. Other countries and world regions have also increased their activities, with patent application shares reaching 9 % in 2021 compared to 2-4 % in previous years.

In terms of R&D and patent activities, the largest and most dynamic fields are Li-accumulators (secondary cells) with over 2,700 patent applications in 2021 and a 156 % increase since 2016. This is used as a benchmark for further patent analyses. Among the IPC sub-classes analyzed, the classes for electrodes were mentioned in 85 % of all LIB applications. IPC classes on cells are the second biggest group with a 168 % increase in patent dynamics over the past five years (number of patents in 2021 relative to number of patents in 2016). European patent applicants have lower dynamics compared to global activities.

The IPC classes with the highest application dynamics in the past five years (more than 200 % increase from 2016 to 2021) were grouped by topics, resulting in seven groups, each of

Figure 3: Transnational patent applications for electrochemical energy storage (Batteries, IPCH01M).



which had more than 100 applications in 2021. These show a shift of activities toward optimizing battery cells and system parts.

This indicates that purely materials-based applications are no longer the main R&D trend, and areas such as *electrode connections, casing sealing, jackets* and *heating and cooling control* are emerging trends in the battery patent landscape.

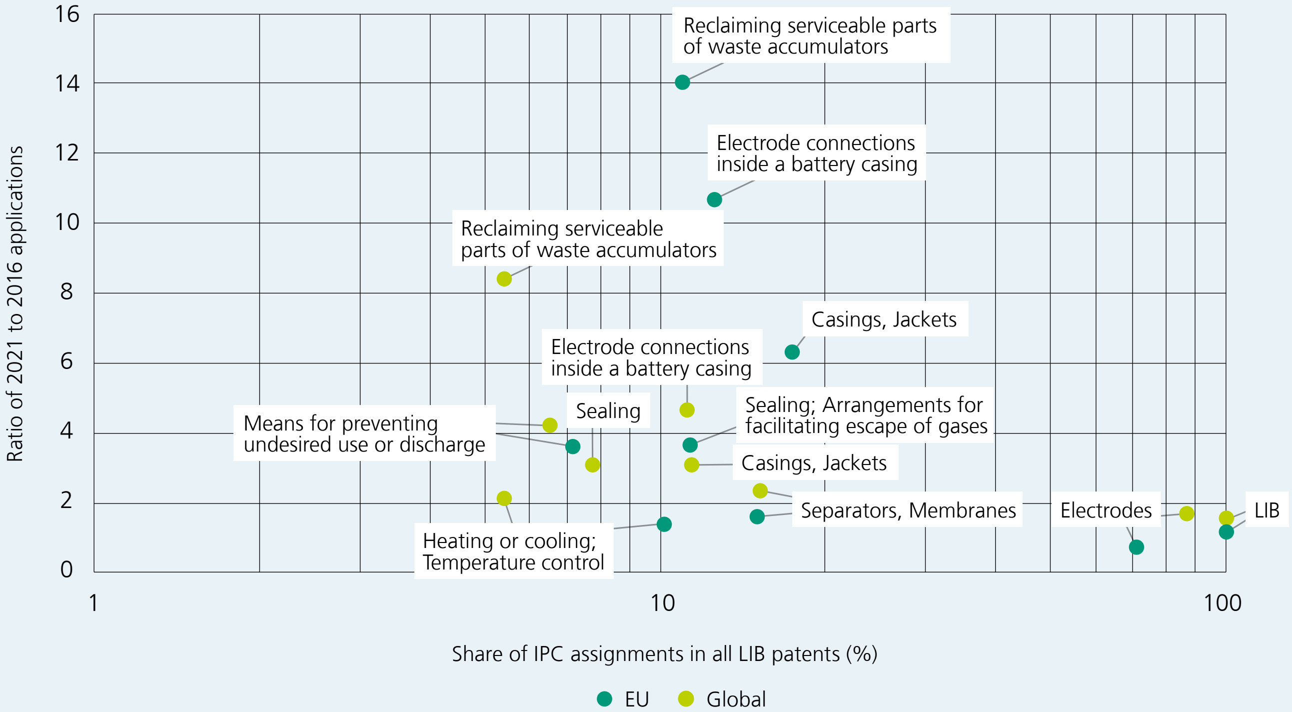
Additionally, there are considerable dynamics and high shares for activities focused on *reclaiming serviceable parts of waste accumulators,* particularly in EU activities, accounting for about 11 % compared to LIB cell applications. This suggests an increasing focus on sustainability issues alongside performance optimization.

As the analysis of leading countries already suggests, the new battery applicants driving these activities are mainly from China. CATL (CN) is the absolute leader among patent applicants across all fields with high dynamics. Even for activities related to *reclaiming serviceable parts of waste accumulators,* the company Hunan Brunp (Recycling Technology Co., Ltd.), a subsidiary of CATL, is a leading player. Hunan Brunp was founded in 2008 and is a giant enterprise in the lithium battery industry and a private enterprise that specializes in the green recycling of waste batteries.

Other major applicants include LG Energy Solutions, Samsung SDI, SK On (KR), Panasonic/PPES (JP), and various other Asian companies. Active Japanese and Korean companies include Murata, GS Yuasa, Sanyo, Toyota. Chinese companies include SVOLT, ATL, BTR, Shenzhen Capchem. Non-Chinese companies were major applicants in 2016 but have since been overtaken in all subfields of activities.

European applicants active in the identified fields with high dynamics include BMW, VW, BASF, Umicore, Northvolt, and VARTA. US and Canadian companies, such as the Global Graphene Group and Li-Cycle, are also involved in these activities.

Figure 4: IPC H01M sub-fields with the highest application numbers and dynamics (2021 vs 2016).



2. Applications and Requirements

2.1. Technical Requirements

This subchapter discusses different requirements and specialties focusing on battery electric vehicles (BEVs). These mainly comprise techno-economic aspects such as the required energy or power levels, costs, as well as cyclic and calendar aging. We also discuss sustainable, technologically sovereign, and competitive battery production and value chains, as well as battery production scales compared to BEV production numbers. In addition, we extend and discuss these aspects by including other applications such as PHEVs, stationary storage as well as e-bikes and drones.

BEV pack size, energy and range requirements

Pack capacities and the resulting electric driving range depend heavily on the vehicle purpose and segment. Vehicle segments range from mini and small vehicles (AB segment) through compact cars and multi-purpose vehicles (CM segment) up to large and premium-type vehicles (DEF segment), and SUVs. Moreover, manufacturers typically offer short-range and long-range model versions and country-specific model portfolios, complicating the pack capacity assessment. The associated pack capacities have evolved differently over time, but have typically increased due to larger pack sizes accompanied by increasing energy density at the cell and pack level. Thus, the average net pack capacities currently range from around 30 kWh for AB vehicles, to 50-60 kWh for CM vehicles and small SUVs, 70-80 kWh for DEF vehicles, and 70-90 kWh for large SUVs. Certain large SUVs and premium-type vehicles have also crossed the 100 kWh threshold and are even approaching 150 kWh. Overall, the average cross-segment pack capacity is around 50-65 kWh [8, 9]. This is equivalent to an average electric range of roughly 200 km for small or low-range vehicles and around 450 km or even 650 km for large SUVs, long-range models, and premium-type vehicles under normed conditions and certification standards (Worldwide Harmonized Light Vehicle Test Procedure – WLTP). Despite these improvements and considerable ranges, range anxiety and the perceived real-world range are still two major concerns for drivers when considering the purchase of a BEV [10, 11]. Therefore, the following section addresses real-world performance and outlines future OEM targets.

Battery performance and thus the effective BEV range is heavily affected by the ambient conditions, with real-world conditions being very different to and more volatile than WLTP standards. The focus here is usually on drivers and their driving style as well as ambient temperatures, with the ideal operating temperatures for batteries between 20 and 30 °C. Empirical data and studies [12-14] suggest that while both cold and hot temperatures lower the effective range, colder climates have a larger impact. Cold climates may halve the effective BEV range for several reasons. First, electrochemical processes inside the battery cells slow down and increase internal battery resistance, meaning it can neither take nor deliver its charge as quickly as under ideal conditions. Thus, on-board battery and thermal management systems (BTMS) are designed to draw energy to warm or cool the battery cells as needed in order to maximize the effective range and prevent excessive battery degradation. Second, additional energy is required for heating and driver comfort as well as other auxiliary systems. Third, unfavorable road and weather conditions may increase driving resistance and consequently energy usage. As a result, manufacturers aim to maximize the effective range over the entire service life and a wider range of ambient conditions to remain closer to WLTP specifications.

Most manufacturers are aiming at up to 1,000 km range for their lead models and balance their remaining model portfolio by lower range targets to avoid unnecessary battery mass, which impairs performance, vehicle dynamics and efficiency, and increases costs. Several OEMs such as Tesla [15], BMW [16], Volvo [17], Toyota [18] and VW [19] have announced targets around but not exceeding 1,000 km of range within this decade when using high-energy LIBs. Accordingly, the European Council for Automotive R&D (EUCAR) specifies around 400 km of range for average low-range models and more than 600 km of range for average long-range models by 2030 [20]. In contrast, Toyota announced BEVs with up to 1,500 km by the end of this decade when introducing all-solid-state batteries [21]. These range improvements are based on three correlated strategies: (1) larger pack capacities; (2) batteries with higher energy density; (3) improved vehicle energy efficiency. The potential for larger packs is restricted by space and weight constraints, although optimized platforms and a higher degree of battery integration into the chassis may offer some scope for improvement. Therefore, higher energy densities are key. Several OEMs such as VW, Tesla, PSA, Mercedes, Renault and BYD are targeting around 700-800 Wh/l and 300-350 Wh/kg at the cell level by 2025. 800-1,000 Wh/l and 350-400 Wh/kg are targeted by 2030. These are roughly in line with the EUCAR's cell-level targets of 450 Wh/kg and 1,000 Wh/l by 2030 [20]. Additionally, the EUCAR specifies pack-level capabilities of 360 Wh/kg (80 % compared to the cell level) and 750 Wh/l (75 % compared to the cell level). The Mercedes Benz EQXX showcased the effect of optimizing vehicle energy efficiency to maximize range and indicated that it is feasible for a moderately sized EQS battery pack (108 kWh) to achieve 1,000-1,200 km in real-world tests [22]. Similarly, the Lucid Air reaches nearly 900 km of WLTP range with its 118 kWh battery pack [23]. To conclude, we highlight that these BEV range strategies crucially rely on the associated fast-charging capability to enable the respective daily or long-distance ranges.

Figure 5: Roadmap on current and future BEV capabilities, including the electric range in km (WLTP), energy density in Wh/l, and specific energy in Wh/kg [9, 17, 20, 24-27].

Required energy density for other applications

In contrast to BEVs, battery requirements for future Plug-in Hybrid Electric Vehicle (PHEVs) are likely to focus more on specific power and power density, with the EUCAR stating 350 Wh/kg and 800 Wh/l as energy-level targets [20]. These are achieved using substantially smaller batteries compared to BEVs, yet the electric range of PHEVs is still expected to increase to lower their CO_2 footprint.

Aerospace applications have significantly increased power- and energy-level requirements compared to BEVs, particularly concerning gravimetric capabilities. For longer flight distances of several 100 km, cells with a specific energy of well over 300 Wh/kg are required. There are also high demands on the power density of batteries of over 400 W/kg in continuous operation [28, 29].

The requirements for stationary storage systems diverge from mobile applications, although a compact system footprint remains a priority. In industrial and domestic applications, the energy density requirements of stationary storage systems can often be met by current LIB.

Fast charging capability for BEVs

Fast charging may be crucial to enable long-distance trips beyond the single charge BEV range, but this places several demands on the battery and battery thermal management system BTMS. Among others, fast charging is suspected of accelerating battery aging, especially at low temperatures. Thus, the BTMS must warm or cool the battery cells as needed to optimize the charging process and prevent excessive battery degradation. Likewise, it is equally important that older batteries still maintain their initial fast charging performance or at least offer an acceptable charging rate.

Current 800 V platform models - mostly premium-type vehicles – such as the Porsche Taycan GTS ST, Audi e-tron GT, KIA EV6 or Hyundai Ioniq5 have average charge rates of around 2.5-2.7C (20-25 min, SOC 10-80 %) at moderate temperatures [30, 31]. This is equivalent to more than 300 km of recharged range within 20 min for large battery packs (90 kWh). Maximum peak charge power is around 270 kW, while the Combined Charging System (CCS) standard is currently certified up to 350 kW. Standard and volume models – mostly with 400 V platform architectures – are around 1.4-1.7C (40 min, SOC 10-80 %) [30, 31]. The EUCAR targets charging rates of 3.5C (17 min, SOC 0-80 %) by 2030, which represent around 350 km of recharged range within 20 min. Most OEM targets are less than 20 min to reach the 80 % SOC level, equivalent to 250 to more than 400 km of charged range depending on battery size [32]. Toyota announced around 10 min of charging time for future solid-state batteries [33].

Figure 6: Roadmap on range requirements and fast charge capabilities. Differentiation between recharged range (10 min, SOC 10-80 %) and C-rate [20, 30-32].

	2023	2030
Standard recharged range (10min)	100-150 km	250-300 km
Top-class recharged range (10min)	200 km	350-450 km
Standard charge C-rate	1.5C	2-2.5C
Top-class charge C-rate	2.5-3C	3.5-4C

Battery swapping

In addition to increased battery capacity and fast charging capability, battery swapping is prominently discussed as another option to enhance the range of an electric vehicle. Technical requirements for battery swapping vary depending on the application and vehicle type. Battery swapping for electric vehicles is a concept whereby an empty battery is swapped for a fully charged one instead of recharging it. The empty battery can then be fully recharged under optimized conditions (e.g., Nio [34]: <1C at 40 kW and ambient temperature of 20 °C), which help to prolong battery lifetime. Battery swapping requires special infrastructure called battery swapping stations. These stations must have a sufficient number of fully charged batteries and have automated, robotic systems or human operators to swap the batteries.

Battery swapping is viewed quite positively in emerging markets, particularly in Asia, ASEAN and African countries that focus on 2-wheel (2Ws) and 3-wheel (3Ws) electric vehicles [35]. It is particularly attractive for these segments due to the low initial vehicle costs, costs for infrastructure and its suitability for fleet and commercial vehicle applications, especially due to the small size and light weight of the battery, which can be manually handled, and given the lack of charging infrastructure in these markets [36]. These factors enable quick battery swaps and minimize downtimes in vehicle operation [37]. For power tools such as cordless screwdrivers or hedge trimmers, small and removable lithium-ion battery packs have been state-of-the-art for some years now, although customers still complain about the lack of interoperability in some cases. Forklift trucks, on the other hand, have had a standardized swapping system in place for decades in order to increase vehicle availability, especially with the predominant lead-acid battery technology.

There are still some systemic challenges, such as the further development of standardization and the interoperability of batteries, establishing dedicated infrastructure, dealing with damaged and defective batteries as well as the issue of ownership responsibility [38]. In particular, the latter addresses requirements to indicate the battery's state of health (SoH), predict its remaining useful life and battery aging management control. However, strong efforts are currently being made to address these challenges and some progress has been made by the Swappable Battery Motorcycle Consortium founded in 2021 [39] to standardize a swappable battery system for 2Ws/3Ws with regard to general & safety requirements, mechanical parts, connectors, BMS, electrical parts and test specifications.

EV battery lifetime requirements

Real-world empirical data on battery lifetimes are scarce. However, BEV batteries – with an end-of-life limit of 70-80 % SoH – are projected to last between 160,000 and 320,000 km. This is equivalent to less than 1,500 cycles or about 15 to 20 years, which is sufficient for most vehicles. Empirical data from Tesla [40] and recent studies [41] underline these capabilities. The EUCAR specifies that the battery life must correspond to that of the vehicle and must last for at least 150,000 km. Most BEV manufacturers offer around 8-10 years warranty on their battery pack.

If future BEVs are integrated into the energy system (Vehicle-to-Grid, V2G), meaning that electrical energy from the batteries can be fed back into the energy system or the local household with a photovoltaic or home storage system, the cycle life requirements may increase accordingly. However, V2G with narrow SoC windows and low C-rates will likely not lead to excessive ageing.

ESS and other applications battery lifetime requirements

Set targets and announcements for BEVs also cover various mobile applications like two- and three-wheelers and micro-mobility, but there are distinct demands for aviation applications that emphasize high energy density while operating with lower cycle numbers. There are more stringent criteria for industrial mobile applications and stationary storage systems. For instance, heavy-duty trucks can have service lives spanning 1.2 to 1.6 million km over 5 to 15 years [42-44]. This is equivalent to 3,000 to 7,000 cycles, which is beyond the scope of standard LIBs. The requirements for ESS are also significantly higher depending on the application. Daily cycles may be used for load shifting, so that a service life of 10 years corresponds to a cycle life of 3,000. Frequency regulation or other grid-supporting applications could require significantly higher usage rates, so that requirements increase to 10,000 cycles and more. In general, most ESS systems should be designed for around 20 years (80 % nominal capacity), with standard warranty periods of around 10 years.

Battery safety requirements

Electric vehicles and traction batteries must be approved by the authorities (homologation) before their market entrance. The UNECE Regulation No. 100 (ECE R 100-Part II) is the European standard for the rechargeable energy storage systems used in xEVs [45]. To obtain EU approval, several thermal, mechanical and electrical tests at pack level are necessary, e.g., mechanical integrity, vibration, shock and cycling tests as well as safety measures. The regulations and certification requirements differ in different regions and consequently in different markets all over the world [46]. The international standard for the transportation of lithium-ion batteries is covered by section 38.3 in the 7th revised edition of the UN Manual of Tests and Criteria with a total of 8 tests for internal and external influences [47].

Battery safety is a critical aspect that begins at cell level. There are different approaches to ensuring safety at this level, but not all safety features are suitable for every type of battery. For instance, hard-case housing can withstand internal pressure better than pouch foil housing [3]. To ensure comprehensive safety, cell-level safety features are used in conjunction with module-level safety features to prevent thermal runaway in a single cell developing into thermal propagation in the whole pack. Thermal runaway prevention is the most prominent safety requirement for batteries, as the stored electrical and chemical energy can generate intense heat and leak gases during thermal runaway thus endangering people and the environment. Triggers include, e.g., overloading (BMS malfunction), physical damage (loss of separator integrity), heat exposure or internal short circuits due to manufacturing defects [48]. The maximum (ambient) temperature as well as a rise in temperature affect the probability of thermal runaway, which is why a dangerous goods transport regulation sets a maximum external temperature of 100 °C [49]. Thermal barrier materials (e.g., ceramic coatings) or heat transfer spaces as well as gas venting/routing and electrical isolation - especially in high voltage (800 V) systems - are of great interest for system-level safety [48]. There are additional protective mechanisms for batteries installed in a vehicle, such as insulation of the HV components and automatic shutdown of the HV system in the event of an accident.

2.2. Volume Requirements

The vehicle market will continue to grow in the coming years. For example, the market for light vehicles (< 6 t), which currently dominates the EV market and thus global battery demand, is expected to grow from around 79 million units in 2022 to 110 million by 2040 [50]. In 2023, it is likely that most electric vehicles will be built by Tesla and BYD, with around 1.8-2 million cars each [51, 52]. However, future demand for BEV is expected to increase sharply in parallel with the respective OEMs' need for battery cells. Tesla has one of the most ambitious goals for the future. By 2030, the manufacturer wants to produce 20 million vehicles annually [53]. Today's largest vehicle producers in terms of number of vehicles produced (regardless of drive type) also have strategies for electrifying their units in the future. The number of vehicles produced by some large manufacturers today is significantly higher than the figures for Tesla and BYD and these manufacturers have the potential to retain their market position in a future dominated by electric mobility. In 2022, Toyota had the largest market share with nearly 10 million vehicles sold, followed by Volkswagen (about 8 million) and Hyundai/Kia (6.5 million). GM and Stellantis ranked 4th and 5th, respectively (6 and 5.7 million).

Supply volumes for individual vehicles

Due to rising market demand, sales of individual models are currently at more than a million annually (e.g., Honda RAV4 in 2022) [54]. With sales suspected to reach more than one million vehicles, the Model Y could become the best-selling vehicle in 2023 [55, 56], something no EV has achieved before.

The corresponding battery demand is already huge for just one vehicle model today. The one million Model Y correspond to a battery cell demand of around 60 to 70 GWh. The VW Tiguan, which was VW's best-selling model in 2022 with 458,000 vehicles [57], would require 25-28 GWh of battery capacity if fully electrified.

Consequently, if an automobile manufacturer aims to deploy identical battery cells across all versions of just one vehicle model, with the objective of streamlining design and reducing manufacturing expenses, this would require battery cell suppliers to scale up their production capacities significantly. This could imply future production capabilities ranging from more than 10 GWh (for low-selling models) to potentially exceeding 100 GWh (for top-selling models) for this respective cell type.

Standardized cell formats

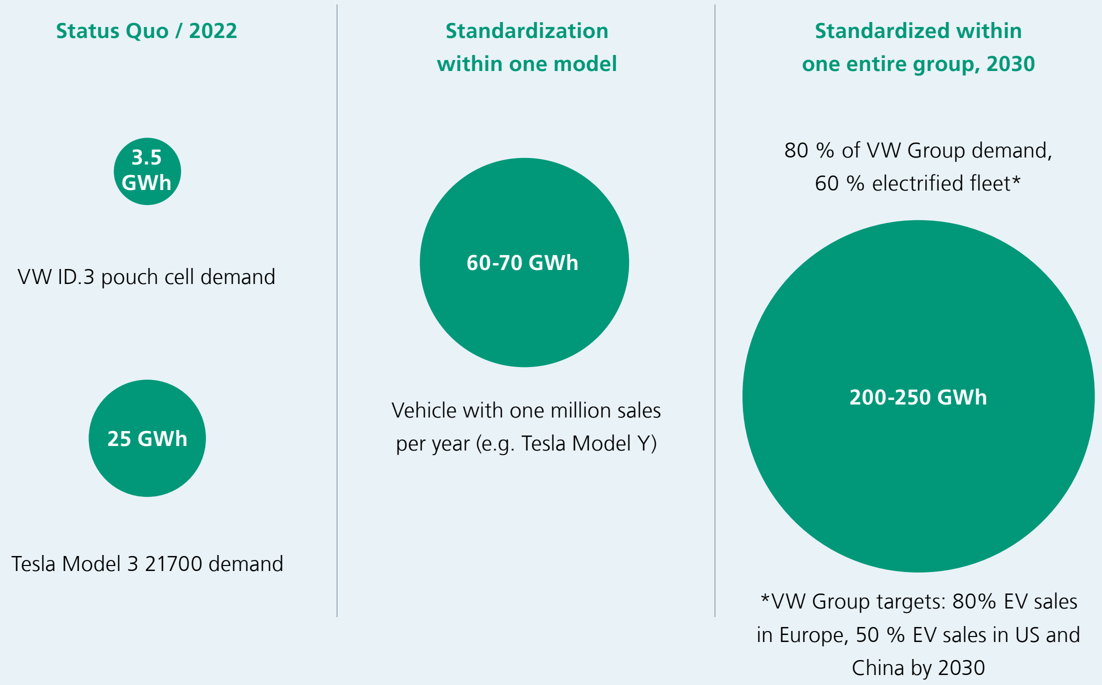
OEM and cell manufacturers are already working on standardized cell designs. This approach facilitates production scalability and streamlines battery procurement across diverse cell suppliers. So far, Volkswagen (VW) has predominantly utilized prismatic and pouch cells. By 2022, the deployment of pouch cells increased notably across most VW Group vehicles, totaling 17 GWh. Around 3.5 GWh of these pouch cells were integrated into the VW ID.3 model. In the future, VW aims to focus on prismatic cell design. Tesla employs both cylindrical and prismatic cell formats in standardized configurations. In 2022, Tesla's 18650 and 21700 cylindrical cell formats contributed 5 GWh and 40 GWh, respectively. Around 25 GWh of the 21700 cells were integrated into the Tesla Model 3, while the prismatic cell format in two Tesla models accounted for a cumulative 35 GWh. Besides CATL, prismatic cells from BYD, also known as blade cells, were installed. BYD uses these standardized cells in many of its own vehicles (approx. 30 GWh in 2022) [58]. In the future, Tesla wants to use 4680 format round cells on a large scale. Other car manufacturers such as GM and NIO also intend to use the same cell format and BMW wants to supply the new generation BEVs with standardized 4695 or 49120 cells in the future [59]. GM currently employs a standardized Ultium pouch cell format across various vehicles [60].

With increasing sales figures for individual models of up to one million vehicles per model, the demand for standardized cells for individual models could continue to rise sharply (50-100 GWh). Demand will escalate if the largest worldwide global OEMs (see above) electrify most of their model portfolio and deploy standardized cells. As an example, a battery requirement of up to 300 GWh could result for the VW Group's 2030 target (80 % BEV in Europe and more than 50 % in North America and China). Installing standardized cells in 80 % of all VW vehicles would mean a demand of 200 to 250 GWh for just this one cell type and only this one OEM [60].

Cell manufacturers can produce around four to five GWh of cells per production line per year. While, for example, around four lines are required today for VW's pouch cells, the demand for standardized prismatic cells could increase to up to 40-60 production lines by 2030. Approximately four to six production lines are operated in parallel at one production site, so around ten production facilities will be required to manufacture VW's standardized cells in 2030.

The number of cells and production sites poses various challenges in terms of security of supply, logistics and maintaining consistent quality in all plants. It is already apparent that OEMs often pursue so-called multi-sourcing strategies to secure supply. Tesla, for example, sources its round cells from LGES and Panasonic. BMW recently announced its intention to purchase 46 format round cells from CATL, AESC and EVE Energy. GM also intends to have the current Ultium cells manufactured by SDI in addition to LG [60]. Besides boosting supply

Figure 7: Standardization and possible sourcing strategies of OEMs and resulting demand scenarios for cells of one type [51, 61].



security and competition, this also reduces the dependency on one manufacturer. Even if, for example, three manufacturers are considered for the supply of standardized cells for one big OEM group, the demand for cells from each supplier can still amount to 100 GWh or up to four production sites.

The large quantities of cells make single-sourcing strategies unlikely, particularly in Europe and America. In contrast, some large Chinese cell manufacturers might be able to supply cells on such a large scale. Reasons for pursuing such a single-source strategy could be in-house cell production at BYD for their own EVs, for example, or to be able to offer a unique technological selling point (e.g., new and innovative cell chemistries).

The high demand for standardized cells also impacts the upstream production steps in battery manufacturing triggering a corresponding demand for cell materials and raw materials. Here, again, we can see that cell manufacturers purchase active materials from different manufacturers.

ESS industry battery demand

So far, the market for stationary energy storage systems (ESS) has been rather small compared to the EV battery market. In 2023, ESS battery demand could exceed that of the electronics and consumer market (3C) for the first time, but still lags well behind EV battery demand.

Therefore, the issues of line sizing and cell standardization do not apply to ESS to the same extent as for EVs. Apart from a few large manufacturers, the ESS industry is characterized by many smaller producers with manageable purchase volumes. It is therefore unlikely that there will be cell production lines designed specifically for individual customers. On the contrary, cells that were actually designed for other applications (EV) are still frequently used in the ESS sector today. The aforementioned 4-5 GWh per year and production line is therefore also a critical threshold for the demand of an individual ESS customer who can enforce the design of customer-specific cells. Tesla achieved a comparable volume of ESS installations in 2022 [62].

ESS industry customers are therefore unlikely to place high volume demands on cell manufacturers in the medium term. Instead, it is more likely that the standardization of ESS cells will come from the cell manufacturers themselves and that they will aim to supply several customers with the same ESS cell.

2.3. Ecological, Economic and other Requirements

BEV battery cost

BNEF specified 115 USD/kWh as volume-weighted average cell-level costs in 2022. Accordingly, the pack-level value was 138 USD/kWh (+20 %) [63]. Future battery costs are associated with high uncertainty due to potential non-negligible disruptions caused by raw material shortages, supply chain disruptions, higher inflation levels, or increased energy costs. In addition, costs depend on the chosen chemistry and format. Renault has announced pack-level target costs of around 100 USD_{2019}/kWh by 2024 and less than 80 USD_{2019}/kWh by 2030 [27]. Tesla already confirmed cell-level cost targets for its 4680 cylindrical cells of around 70 USD/kWh at their Q3 Earning Call in 2022 - even before accounting for US incentives such as the Inflation Reduction Act (IRA). The EUCAR specifies cell-level target costs of 70 EUR_{2019}/kWh and a 15 % surcharge for pack integration (80 EUR_{2019}/kWh) by 2030. The BATT4EU Strategic Research and Innovation Agenda (SRIA) targets pack-level costs of less than 100 EUR/kWh by around 2025 and less than 75 EUR/kWh by 2030 for mobile applications [64]. Recent studies and assessments [65] indicate that pack-level costs of 100 USD/kWh may facilitate large-scale BEV breakthrough, which would then unlock further cost reduction potentials.

Sustainability

While the project calls of German and European funding agencies highlight ecological and economic sustainability, the term sustainability extends well beyond these aspects. In the public discourse on creating a sustainable battery value chain, social aspects are prominent as a third sustainability dimension.

Since electric mobility and other applications using high-energy battery systems are usually motivated by the desired transition toward a carbon-neutral economy, the ecological sustainability of the battery value chain - and its carbon footprint in particular - is a crucial aspect. This is expected to become a major selling point and could be a way to improve the competitiveness of the European battery industry. The carbon footprint of a battery throughout its life depends heavily on the application it is used in, as well as on external factors, such as the energy mix of the energy stored in it. The sphere of influence for cell manufacturers includes the sourcing of the battery materials and the energy used in cell production.

The environmental balance of a battery is determined on the one hand by the materials and components used in it and, on the other hand, by cell production. Depending on the type of battery and the place of manufacture, the share of cell production in total greenhouse gas emissions varies between 20 and 50 %. Various studies have identified the optimization of thermal processes (e.g., dry room, electrode drying), which account for about 80 % of energy consumption, as a central lever for improving the CO_2 footprint. Process innovations in this area could reduce emissions by approx. 25 % up to 2030. An electricity mix more oriented toward renewable energies could enhance this effect [66, 67].

Material production is responsible for a large proportion of the emissions. Due to the different value chain steps and options

Figure 8: Roadmap on future cell- or pack-level costs in EUR_{2020}/kWh. [27, 63-65]

	2023	2025	2030
Av. cell costs in EUR_{2020}/kWh	~120 €/kWh	~90 €/kWh	~70 €/kWh
Av. pack costs in EUR_{2020}/kWh	~150 €/kWh	~110 €/kWh	~80 €/kWh

for the various cell chemistries, it is difficult to make a general statement here, but mining and processing play an important role in terms of the GHG balance [67, 68]. The source of the lithium used, whether this is extracted from brine or ore, also has a significant impact on the GHG balance: A recent study [69] concludes that the different lithium sources can make a difference of up to 20 % in GHGs for NMC811 cathodes and up to 45 % in GHGs for NMC622 cathodes. At the battery cell level, this means a difference of up to 9 % for NMC811 batteries and a difference of 20 % for NMC622 batteries.

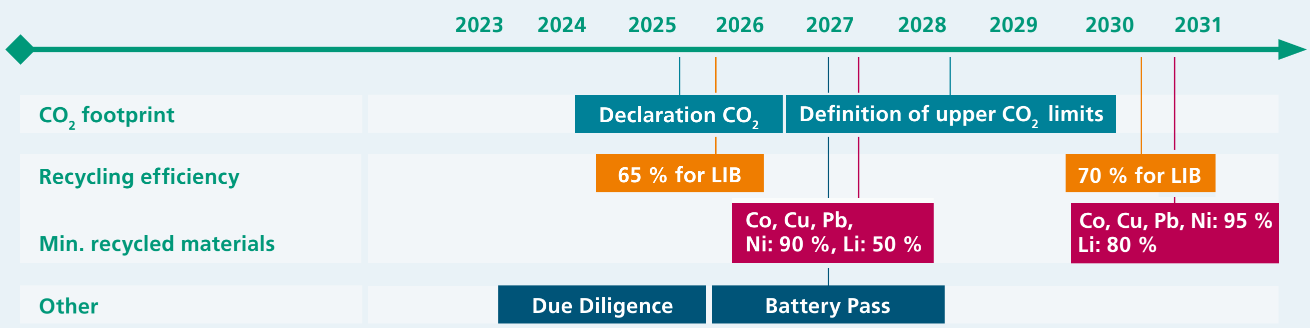
In Europe, battery recycling is being strongly driven by the new Batteries Regulation (Regulation (EU) 2023/1542) [70], which entered into force in August 2023. The new regulation applies to all batteries including waste batteries and strengthens their sustainability, safety and circularity.

Under the new Batteries Regulation, a carbon footprint declaration will become mandatory for each battery model (>2 kWh and batteries for light means of transport (LMT), such as e-scooters) and each manufacturing plant. This will be introduced from February 2025 for EV batteries, from February 2026 for industrial batteries, from August 2028 for LMT batteries and from August 2030 for industrial batteries with external storage. Starting from August 2026, batteries for electric vehicles must carry a label showing their carbon footprint over their life cycle (and at a later date for the other types). A maximum threshold for the carbon footprint will be stipulated (for EV batteries) from February 2028, but this will not be defined until August 2026. To further improve battery handling in terms of dismantling and safety measures, the relevant information is to be saved in a digital battery passport, which can be accessed using a QR code. This will become mandatory in 2027.

The new Batteries Regulation sets clear collection targets for end-of-life portable and LMT batteries, starting at 45 % for portable batteries by the end of 2023 (LMT: 51 % by end of 2028) and increasing to 73 % by the end of 2030 (LMT: 61 % by the end of 2031). No collection rate targets are defined for larger batteries, such as those needed for electric vehicles, but it will be mandatory to set up a take-back and collection system for these types of batteries. Additionally, the removability and replaceability of portable batteries and LMT batteries will become mandatory by 2027 (known as "Design for Recycling"). Furthermore, a recycling efficiency is defined for different battery types. For lithium-ion batteries, this efficiency ought to reach at least 65 % (in respect to battery weight) by the end of 2025 and 70 % by the end of 2030. For battery materials, the recycling quota must reach 50 % for lithium and 90 % for cobalt, copper, lead and nickel by the end of 2027. By the end of 2031, this value must have increased to at least 95 % (Co, Cu, Pb, Ni) or 80 % (Li), respectively. Finally, by 2031, electric vehicle batteries are supposed to contain at least 16 % recycled cobalt, 85 % recycled lead, 6 % recycled lithium and 6 % recycled nickel. These values are set to increase in 2036 to 26 % (Co), 12 % (Li) and 15 % (Ni), while also applying to other battery types, such as those used in light transport.

While the European Union provides a clear goal for the transition toward a sustainable and circular battery economy, OEM have started to formulate their own sustainability goals to address potential customer requirements. The five largest European car manufacturers have committed to reaching net carbon neutrality within the next decades (2038 - 2050) (Stellantis 2038, BMW 2050, Renault 2040 in Europe/2050 global, Mercedes-Benz 2039, Volkswagen 2050 [71-75]).

Figure 9: Implementation roadmap for the EU battery regulation and its sub-aspects [70].



Further commitments concern environmental and social sustainability aspects, including Design for Recycling (e. g., [76]) and due diligence in the supply chain (e. g., [77]). The latter incorporates taking responsibility for the conditions of raw material extraction, which is a controversial issue for example for cobalt mining in the DRC due to the poor conditions for the workers [78, 79], and for lithium mining in Chile due to the high consumption of water in comparatively dry regions [80].

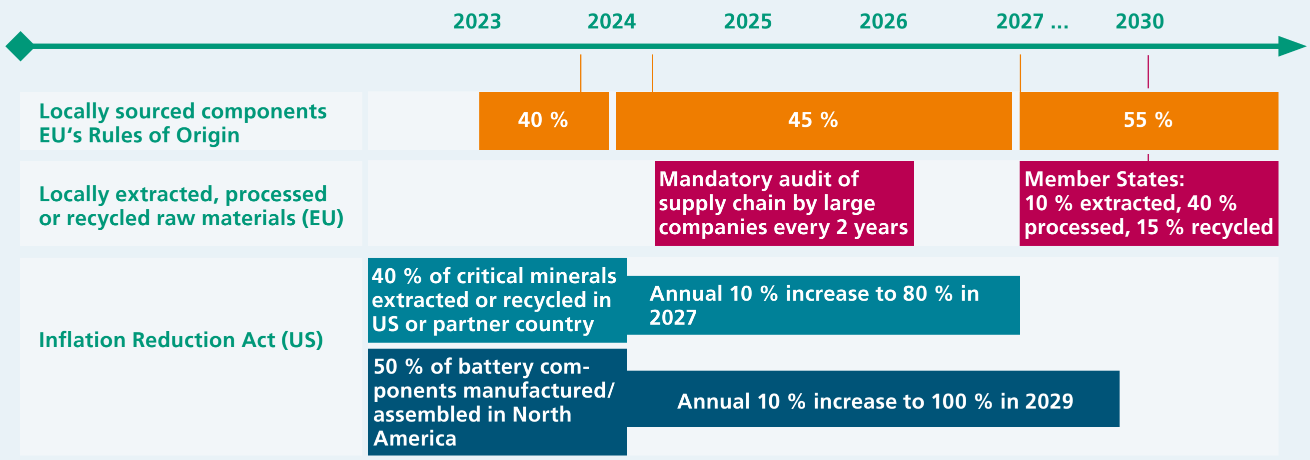
Many other sustainability aspects are discussed that concern battery production. These include the use of potentially toxic materials in manufacturing, such as solvents like NMP and the discussed ban of PFAS in Europe, due to their potential toxicity and long durability.

Technological sovereignty, supply chain and sourcing

Since the emerging battery economy is critical for enabling transformation in numerous industrial sectors, many actors have called for Europe to achieve and safeguard its technological sovereignty in this field. However, this term is interpreted in many different ways. The widely accepted definition of technology sovereignty [81] is the ability of a state or an association of states to provide the technologies considered crucial for its welfare, competitiveness and ability to act, and to be able to develop them itself or obtain them from other economic areas without unilateral structural dependence. Establishing large-scale domestic manufacturing of such technology in order to safeguard value creation in the EU and its member states is often demanded on top of this. Several politicians have formulated goals in this direction, such as meeting a third of the global battery cell demand with European production by 2030 [82]. Geopolitical aspects are becoming more and more important, as indicated by the different strategies and activities of many nations and regions that affect electric mobility. Examples include the Inflation Reduction Act, which specifically aims to advance and deploy American-made clean energy technologies in the US [83], the Critical Raw Materials Act of the EU or the ban on nickel ore exports of Indonesia [84].

Within the Inflation Reduction Act, incentives and credits were announced for the purchase of "clean vehicles". Vehicles purchased since April 2023 only qualify for this credit of up to 7,500 USD if they match the requirements. These include final assembly of the vehicle in North America as well as requirements for the critical minerals and battery components [85]. The latter specify that the critical minerals contained in the battery have to be either extracted in the US or any country with which the US has a free trade agreement, or recycled in North America with a percentage greater than 40-80 % with

Figure 10: Regulations influencing Europe's battery technology sovereignty.



respect to the year in which the vehicle was placed in service (increasing yearly in steps of 10 % from 2023 to 2027) [86]. Similarly, a certain (value)percentage of the battery components must be manufactured or assembled in North America. This percentage starts at 50 % for vehicles put into service before 2024, increases to 60 % in 2024/2025 and subsequently in annual steps of 10 %, reaching to 100 % in 2029.

In the EU, the Critical Raw Materials Act was passed in 2023 to lower the supply risk for certain raw materials [87, 88]. While setting goals for the Member States on the amount of materials that are extracted (10 %), processed (40 %) or recycled (15 %) by 2030 within the EU, it also holds large companies (>500 employees, or >150 million EUR turnover) in the battery value chain responsible for addressing the risks associated with dependencies along the value chain. The companies identified by the Member States must perform an audit of their supply chain every two years. This includes mapping where strategic raw materials are extracted, processed or recycled, as well as a stress test of their supply chain by assessing its vulnerability to the impact of different scenarios. The critical raw materials potentially needed for crucial battery cell components include cobalt, nickel, manganese and phosphate for the cathode, fluorspar for the electrolyte, copper and bauxite (aluminum) for the respective current collectors, as well as graphite and potentially silicon or germanium for the anode.

Furthermore, the Critical Raw Materials Act has set the goal of not importing more than 65 % of the European Union's annual consumption from any single third country for any strategic raw material at any stage of processing. This value is put into perspective when considering that more than 70 % of the global extraction of cobalt takes place in the DRC, while around two-thirds of the global extraction of natural graphite takes place in China. Diversifying the supply of these materials is therefore a major challenge. Not being dependent on suppliers from single countries becomes even more relevant for European cell manufacturers, given the recent geopolitical tensions and conflicts, which can trigger trade restrictions and embargoes, as already demonstrated in the past.

The EU Battery Regulation, which was enforced in July 2023, includes several Articles that indirectly address the localization of the value chain. The Battery Regulation announces that CO_2-footprints will be defined in the future, and thus indirectly incentivizes a localization of the value chain to shorten transport routes. It also obliges distributors and OEM to carry out due diligence measures and risk assessment, which includes the volatility of the supply chain, in particular considering raw materials and metals.

Furthermore, various free trade agreements between the EU and other countries introduce favorable conditions, such as reduced custom duties, for products that are recognized as domestically produced. For example, the Trade and Cooperation Agreement between the UK and the EU [89] set the required locally sourced components for electric vehicles in these "Rules of Origin" at 40 % before 2024, rising to 45 % afterwards and finally to 55 % by the beginning of 2027. For batteries, 30 % of both the cell and pack need to be local, increasing to 50 % (65 %) for the battery cell and 60 % (70 %) for the battery pack until the end of 2026 (beginning of 2027), respectively. This requires siting the manufacturing of the most important battery components within the EU in the next few years.

3. Industry and Technology Roadmaps

3. Industry and Technology Roadmaps

Battery materials

The selection of active and passive battery materials is a key factor in determining the performance characteristics of the battery cells and packs. The storage capacity and kinetics of the materials, voltage level and behavior during cyclization translate directly into properties such as energy and power density, but also robustness and service life. At the same time, the materials in the overall battery system also represent the largest share of the costs, which is not least due to the expensive materials Li, Co and Ni contained in the cathode.

Among the cathode materials, three main strands have now emerged which are likely to continue to play a major role in the future: (1) low-cost Fe- and Mn-based materials such as $LiFePO_4$ (LFP) or future Li- and Mn-rich so-called LMRs; (2) high-Ni materials with the highest specific capacitance such as $LiNi_{0.8}Mn_{0.1}Co_{0.1}O_2$ (NMC811) and further developments up to almost Co-free materials with a Ni content well above 90 %; and (3) further ternary $Li(Ni,Mn,Co)O_2$-based materials (NMC) with high stability, good capacity and mod-erate cost, e.g. with single-crystal morphology and high cell voltage. On the anode side, Si-based materials with high specific capacity and advantageous fast-charge properties are increasingly joining the well-established graphites. The material class shows a high range from composites of Si or SiO_x nanoparticles and graphite, which can rather be described as "graphite-like", to Si-dominated anodes, which bring completely new properties to the battery cell.

Industry is preparing to scale up and implement these new materials. Often these are aimed at the EV market, but in some cases they are clearly aimed at other applications. In the area of Si anodes, many innovations are being introduced by start-ups.

Battery cells

The battery cell design involves several aspects which together lead to the level of energy or power density, these include electrode thickness, coating porosity, assembly techniques, and choice of cell format. In order to achieve maximum energy or power density in LIBs, certain trade-offs must be made. Electrode coatings in automotive LIBs typically range from 50 to 80 µm, although the trend is toward over 100 µm which goes hand in hand with lower coating porosities (around 20 %), thinner current collectors, and thinner separators. Electrode assembly techniques range from winding continuous electrodes to stacking pre-cut ones, progressing to single-sheet stacking for prismatic and pouch cells.

The automotive industry navigates between single and multi-format strategies (see chapter 3.2), with most players opting for multi-format strategies and aim for standardized cell formats with customised dimensions. Noteworthy trends include the resurgence of prismatic cells (including cell-to-pack designs), advancements in larger cylindrical cells such as 4680, and evolving pouch cells with increased capacity and customized designs. Forecasts anticipate format-independent higher energy densities driven by material improvements and design innovations. More specifically, it is assumed that nearly 1,000 Wh/l and 400 Wh/kg will be achieved by around 2030, with pouch cells being the leading format.

Battery packs and systems

At the battery system level, a number of promising new trends are emerging. The Cell2Pack (C2P) approach integrates battery cells directly into the battery pack, eliminating the need for individual modules. This concept allows for optimal use of space. As a result, C2P batteries can offer an increased specific energy and driving range. The Cell2Chassis (C2C) design goes a step further by integrating battery cells into the vehicle body, serving as a structural support for the chassis. This reduces vehicle weight, maximizes interior space utilization, and offers cost savings in comparison to module-based batteries. However, the challenges include protecting the exposed battery and ensuring ease of recycling and replacement. Another trend is the 800 V technology, which offers advantages over 400 V systems, such as doubling the power or halving the current. The higher voltage enables faster charging, but the challenges include a lack of standardization and increased safety requirements. Battery swapping involves replacing empty batteries with fully charged ones, eliminating the charging time. In terms of cooling methods, air cooling, indirect cooling, and immersion cooling are used for the thermal management of batteries. Indirect cooling with a water-glycol mixture is widely used in current vehicle models, offering improved efficiency but at higher complexity and cost. Immersion cooling provides even better cooling performance, reduced complexity, and weight but poses a challenge in the selection of suitable cooling fluids. With regard to the battery management system (BMS), it is becoming increasingly interconnected and sophisticated in order to optimize battery control and thus increase its performance and service life.

Up-scaling and production

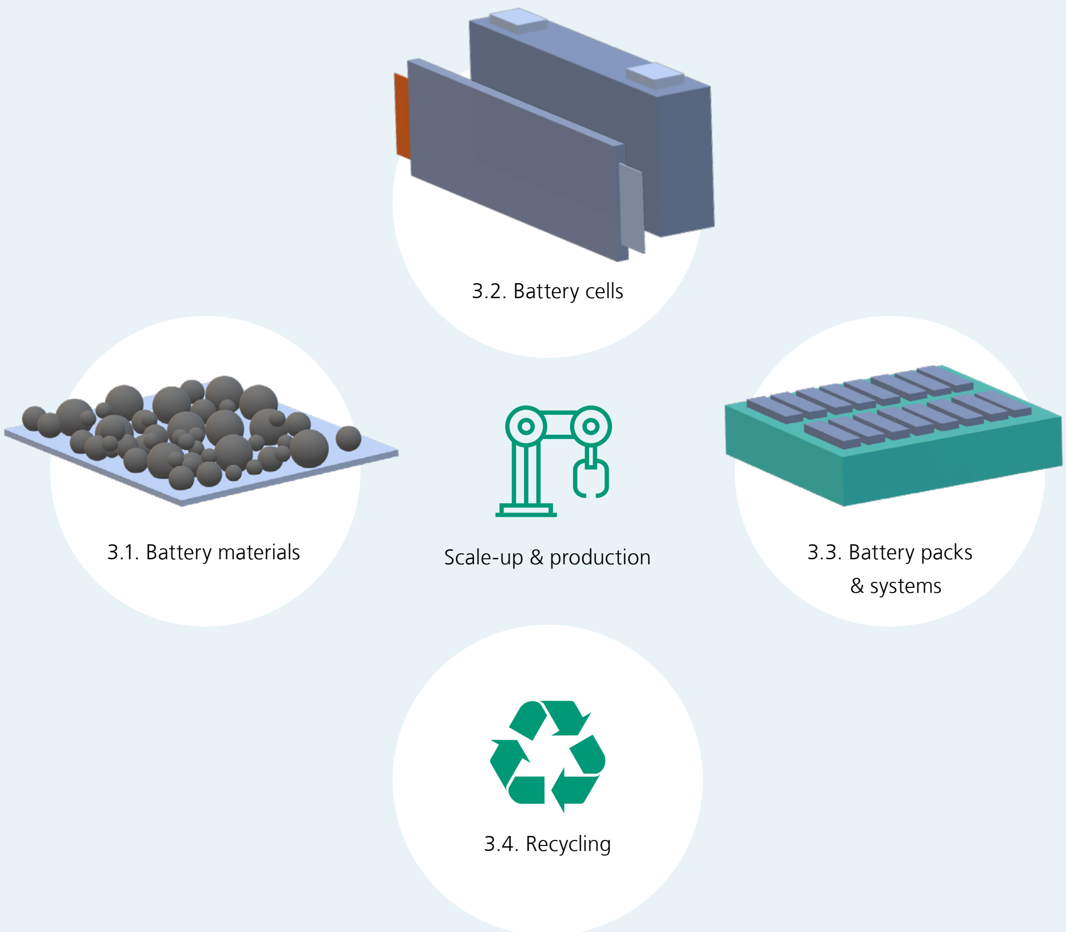
In addition to improvements on the product side, there are also various improvement measures on the production side, in particular to produce batteries more cost-effectively, but also more sustainably. Driven, among other things, by investments of various OEMs the production lines are currently still growing in size and individual production sites are planning to produce up to 100 GWh of battery cells. As increases in the throughput of individual production lines are limited, several production lines are being used in parallel in large-scale production facilities. Through overhead savings on the infrastructure and buildings required, for example, as they grow in size larger production facilities become more competitive.

On the other hand, there are various optimization approaches along the entire production process that affect not only costs and sustainability but also throughput and quality. The most frequently mentioned product innovations that could significantly change cell production in the future are dry coating and the use of mini environments instead of large drying rooms. However, there are also other process innovations such as laser technology or inline monitoring, which bring improvements at various points in the process. If throughputs increase, particularly in cell assembly, higher throughputs of an entire production line could be achieved and additional process steps such as pre-lithiation can have a positive impact on the product itself.

Recycling

According to recent company announcements there is a growing interest in LIB recycling. Recycling facilities differ in their processes, which can include the processing of production scrap, the pre-treatment of EoL batteries or the use of metallurgical methods for material recovery. Ongoing acitivities focus on improving metallurgical efficiency and its industrial scale-up. The dominant source of material to be recycled is expected to shift from production scrap to EV batteries by the 2030s. LIB recycling corresponds to the goals of sustainability, resource conservation and reduced environmental impact, and is important in the context of a circular economy. In addition to recycling, second-life applications are also of increasing interest.

Figure 11: Structure of the chapter and investigation levels for LIB.



3.1. Battery Materials

3.1.1. Cathode Materials

Cathode materials represent not only the largest cost component in LIBs, but their further development has also had the greatest influence on the performance of LIBs in the past. Efforts to optimize materials and develop new materials are correspondingly high. In the following, we distinguish between the categories (1) iron- and manganese-based cathode active materials (CAM) and (2) nickel-based CAM.

Lithium Iron Phosphate (LFP)

Lithium iron phosphate ($LiFePO_4$ - LFP) belongs to the class of polyanion materials and crystallizes in an olivine structure [90, 91]. Due to its higher temperature stability LFP is inherently safer than layered oxide materials [92]. Additionally, Li is the only critical or expensive material that it contains, as it does not contain Ni or Co, which results in a lower price for this material compared to NMC/NCA.

The olivine crystal structure with one-dimensional diffusion pathways for the Li-ions results in a relatively slow diffusion of Li-ions. Moreover, LFP has a limited electrical conductivity [92]. To compensate for these limitations, a successful approach is to reduce the particle size and to use conductive carbon coatings [93]. LFP exhibits a discharge potential of 3.2 V [94] and a medium specific capacity of 150-160 mAh/g (Table 1), which results in a medium energy density and specific energy of the battery (lower than NMC/NCA). LFP shows flat voltage characteristics in the middle SOC range, which makes it difficult to determine the exact SOC. However, advanced approaches incl. AI and machine learning algorithms might help to solve the issue [90].

LFP is a well-established CAM and currently one of the most widely used cathode active materials for LIB with an estimated 37 % market share (by volume) among CAMs [95]. Trends in cell-to-pack concepts have increased the attractiveness for LFP batteries, as the energy density of the LFP packs could approach that of NMC packs due to the inherently higher safety of LFP cells as compared to NMC cells. Although the energy density is lower, so is the price, which, especially for the small EV sector, is one of the most important KPIs. LFP is particularly popular in China (in 2023, more than two thirds of power battery installations in China involve LFP) [96]. An increasing number of car manufacturers outside China are also considering or already using LFP batteries for their EV [97-100]. Hence, it can be assumed that LFP will continue to play a major role in the near to medium term (see also below). As a result of the huge commercial interest in this material, continuous progress is being made in R&D on this material (e.g., using nanocrystalline LFP) and LFP batteries in general (e.g., cell-to-pack concepts), leading to an improved performance of LFP batteries (e.g., fast-charging up to 4C in CATL's Shenxing battery) [101, 102].

Lithium manganese iron phosphate (LMFP)

The advantage of lithium manganese iron phosphate ($LiMn_xFe_{1-x}PO_4$ - LMFP) over LFP is the higher operating potential and thus higher energy density and specific energy compared to LFP. At the same time, still no expensive materials are needed (except for Li), so that costs similar to those for LFP can be expected [103]. The charge and discharge curve of LMFP shows two voltage plateaus, corresponding to the Fe^{3+}/Fe^{2+} (at ~ 3.6 V vs. Li/Li^+) and Mn^{3+}/Mn^{2+} (at ~ 4.1 V vs. Li/Li^+) transitions [104]. Hence, high Mn-contents are desired for achieving a high energy density. However, high Mn-contents lead to slow kinetics (Li-ion diffusion) and thus the Mn content should typically not be above x=0.8 [105]. Most state-of-the-art LMFPs have a Mn-content of about x=0.6.

One of the challenges for LMFP is its poor rate performance, caused by even lower electronic and ionic conductivity compared to LFP [105]. This limitation could be partially compensated through carbon coatings and small (nano-) particle sizes. Further challenges include a lower cycle life than LFP (due to Mn dissolution) and higher sensitivity to moisture and water [104].

BYD carried out research on LMFP already in 2013 but terminated the development in 2016 due to limitations of the materials in terms of cycle life and high internal resistance [103]. Today, industry seems to have solved these issues to a satisfactory degree and consequently various battery companies are actively working on the development of LMFP cells. However, the timing of volume production is uncertain for most companies (incl. CALB, JEVE, REPT BATTERO) [106].

The Chinese cell manufacturer Gotion has announced its "Astroinno L600" LMFP cell that, according to Gotion, achieves a specific energy of 240 Wh/kg and a volumetric energy density of 525 Wh/l and cycle life of 4,000 cycles at room temperature and 1,800 cycles at high temperature [107, 108]. Mass production is planned for 2024 [109]. SVolt announced the production of LMFP batteries with a specific energy of 220 Wh/kg and a volumetric density of 503 Wh/l 2024 [110]. According to reports, Nio will start small-scale production of LMFP battery packs that are expected to hit the market in 2024 [111]. According to their announcements, CATL already started to mass produce so-called M3P batteries in 2023 [112].

Their material has probably a more complex chemical structure containing additional metals to Mn and Fe [103, 113].

Lithium Manganese Oxide (LMO)

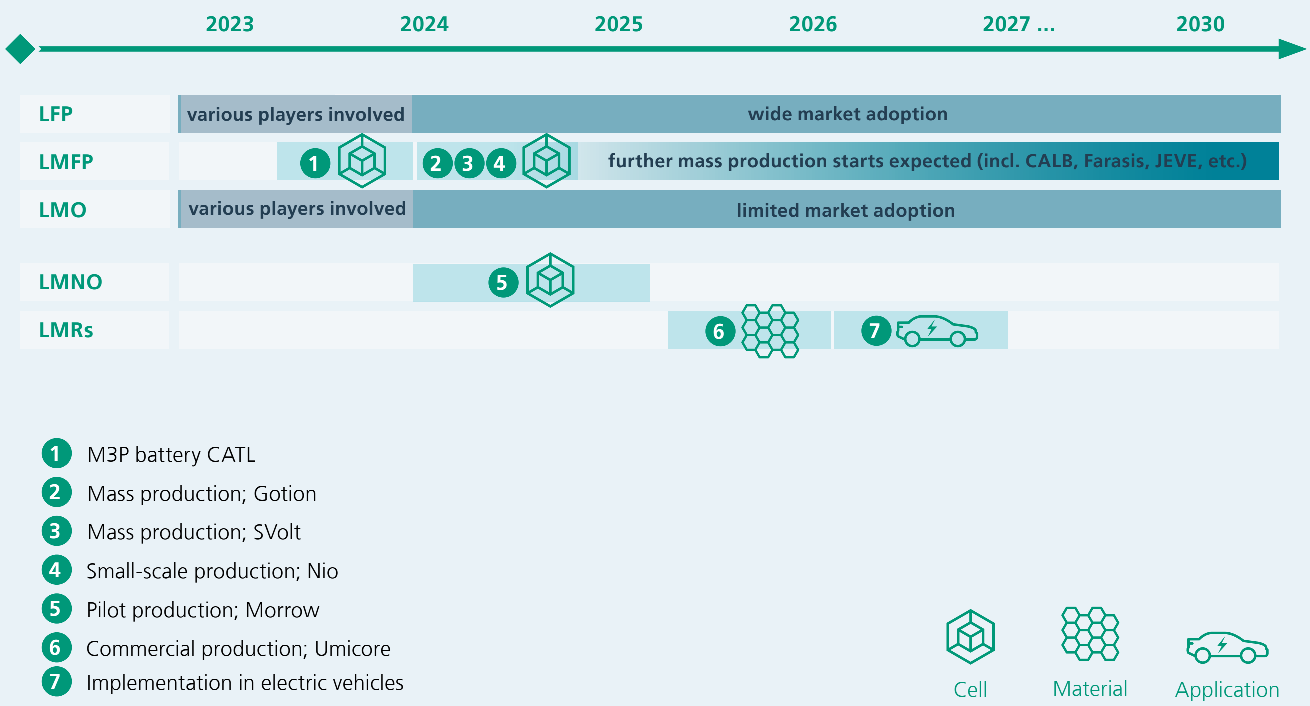
Lithium manganese oxide ($LiMn_2O_4$ - LMO) crystallizes in a spinel structure that allows for Li-ion diffusion in all three dimensions. As a consequence, LMO batteries exhibit a relatively high power capability [93]. Additionally, LMO offers greater safety than layered oxides, as less energy is released at high temperatures (thermal runaway), and no critical or costly metals other than Li are required. On the other hand, LMO has a lower specific energy and energy density compared to LFP and NMC/NCA CAM (Tables 1 and 2). A strategy to increase the energy density is to replace part of the Mn with Ni (see LMNO paragraph below).

LMO was used as a CAM in the first successful mass market BEV (Nissan Leaf) [93]. Today, however, it is mostly used in small devices such as electric bikes, e-scooters, or power tools, as well as low-capacity EVs and in logistics where the focus is on low-cost [95]. China remains the major market for LMO, and Chinese cathode material manufacturers are the major LMO manufacturers [95, 114].

Lithium manganese nickel oxide (LMNO)

Lithium manganese nickel oxide ($LiMn_{1.5}Ni_{0.5}O_4$ - LMNO; also called lithium nickel manganese oxide - LNMO) has structural and chemical similarities with LMO [114]. While the ratio between Ni and Mn can be varied, the material $LiMn_{1.5}Ni_{0.5}O_4$ is of particular interest [115]. This material uses the Ni^{2+}/Ni^{4+} redox reaction at 4.7-4.75 V vs. Li/Li^+. The Mn^{3+}/Mn^{4+} redox couple could also be used, however, at a significantly lower potential and in a less reproducible manner. Therefore, in practice only the Ni^{2+}/Ni^{4+} redox reaction is used and the Mn remains in a stable oxidation state [115]. The benefits of this material are the high reversible potential, the avoidance of Co and

Figure 12: Industrial activities on next generation Fe- and Mn-rich cathode active materials. The illustration is not exhaustive. References can be found in the text above.



the requirement of only medium quantities of Ni (compared to high-Ni NMC/NCA) and the improved energy density and cycling stability compared to LMO.

The challenges facing LMNO include the dissolution of Mn (Mn^{3+} ions in disordered LMNO (spinel) disproportionate into Mn^{4+} and Mn^{2+} ions) [116-118] and severe interfacial side reactions between LMNO and the electrolyte at high voltage or high temperature [116], which leads to capacity fading during cycling and a limited cycle life [115]. Specific electrolytes are needed with high chemical stability, even at the high potentials, to enable long cycle and calendar life (oxidation potentials of electrolytes >5 V vs. Li/Li^+). Other strategies to overcome these challenges include reducing particle size, optimizing the particle morphology, doping and surface modifications to reduce interfacial side reactions between the LMNO surface and liquid electrolytes [115, 118].

As of 2023, LMNO-based LIB are not yet on the market. Morrow Batteries is planning to start pilot production of prismatic LMNO cells at their Customer Qualification Line in Q1 2024 [119]. Greater market penetration is expected to take some time. Nevertheless, the market intelligence firm Benchmark Mineral Intelligence expects LMNO battery chemistries to be commercialized soon and to achieve a market share of six percent by 2030 [120].

Lithium- and manganese-rich layered oxides (LMRs)

Lithium- and manganese-rich oxides (LMRs, e.g. $Li_{1.1}(Ni_{0.21}Mn_{0.65}Al_{0.04})O_2$ [121]) can be considered a composite of the two oxides Li_2MnO_3 and $LiMO_2$ (with M = Mn, Ni, Co, Fe, etc.) and can be written as $xLi_2MnO_3 \cdot (1\text{-}x)LiMO_2$ [122]. Various combinations of transition metals are possible in LMRs, such as $Li_{1.2}Ni_{0.13}Mn_{0.54}Co_{0.13}O_2$ [123] or $Li_{1.1}(Ni_{0.21}Mn_{0.65}Al_{0.04})O_2$ [121]. The advantage of these materials is the high operating potential combined with the high specific capacity, leading to batteries with high energy density and specific energy (Table 1).

Some of the challenges include a significant voltage and capacity fading during cycling, which is attributed to strain-induced structural instabilities in the composite structure during (de-)lithiation [123]. Furthermore, LMRs exhibit a limited rate performance due to the poor electronic conductivity of the manganese-based oxide [122]. These challenges could be overcome with optimized morphology design and bulk design, as well as by a possible surface modification [123].

Table 1: Typical value ranges for relevant parameters of Fe- and Mn-rich cathode active materials [104, 121, 123, 125-129]:

	LFP	LMFP	LMO	LMNO	LMRs
Theoretical specific capacity (mAh/g)	170	170	148	146	>300
Practical specific capacity (mAh/g)	150-160	135-160	90-120	115-125	>200
Operating potential (V vs Li/Li^+)	3.2-3.5	3-5-4.1; 3.8	4.0	4.7	<4.4
Material cost (EUR/kg)	8-15	10-16 (estimate)	8-15	12-20 (estimate)	20-30 (estimate)
Comment	Mass market material used widely in EV	Improved energy density compared to LFP; market adoption planned shortly	Limited market adoption, mostly in small-scale applications	Not on the market yet, but pilot production planned; capacity fading represents biggest challenge	Currently still low TRL; capacity fading represents biggest challenge

In 2023, the technology readiness level of LMR is currently still rather low and batteries using these CAM are not yet on the market. Umicore has announced that it is aiming for the commercial production of a so-called HLM (high lithium, manganese) CAM and its implementation in electric vehicles by 2026 [124].

Lithium nickel manganese cobalt oxides (NMC) and lithium nickel oxide (LNO)

Lithium nickel manganese cobalt oxides ($LiNi_{1-x-y}Mn_xCo_yO_2$ - NMC) and lithium nickel oxide ($LiNO_2$ – LNO) belong to the class of layered transition metal oxides, as does lithium cobalt oxide ($LiCoO_2$ - LCO) which is frequently used in consumer devices. In NMC, the Ni- ions are the dominant redox-active species. The Co^{3+} ions increase the electronic and ionic conductivity and the Mn^{4+} ions help to maintain thermal and structural stability [122, 130, 131]. The first commercially relevant NMC material $LiNi_{1/3}Mn_{1/3}Co_{1/3}O_2$ (NMC111) exhibits high electrochemical performance and safety and was used in some of the early battery electric vehicles [131]. Apart from NMC111, various compositions are possible. In an effort to increase the energy density of the batteries and reduce the amount of the expensive and critical Co, the Ni-content has been increased in NMC materials. NMCs with low to medium Ni-content (relative content of 30 % to <70 % Ni in relation to Mn and Co) have been and are increasingly being replaced by NMCs with high Ni-content (e.g. NMC811). The current trend is toward ultra-high Ni layered oxides with relative Ni-contents of more than 90 % (e.g. NMC9.5.5) [132].

The advantage of NMC over most other CAM lies in its good performance in the most relevant parameters, such as energy density and specific energy, rate performance, calendar and cycle life and costs. Because of this balance of good performance indicators, NMC materials have become the most widely used CAM in electric vehicles [93, 95].

The challenges facing NMC materials are the limited thermal stability and their thermal runaway behavior that makes a tight BMS control necessary [133]. Furthermore, Mn-ion dissolution and surface structural reconstruction, as well as structural instabilities during cycling limit the cycle life [134]. These challenges intensify with increasing Ni-content resulting in lower capacity retention and lower thermal stability of NMCs with high-Ni content [132]. The ultimate goal of achieving 100 % Ni-content (LNO), which gives the highest theoretical capacity, faces similar challenges such as mechanical instability during cycling leading to cracks in the particles, limited thermal stability, (electro-)chemical instability as well as the synthesis with a perfect layered structure and stoichiometry [135].

Strategies to overcome challenges include surface coatings to suppress side reactions, gradient particles, doping (various elements are possible, incl. Al which then leads to NMCA, see below), and morphology optimization, such as using single-crystal CAM particles for layered oxide CAM with the highest Ni-content, to increase high-voltage stability and to prevent the formation of cracks thus mitigating degradation [132].

Lithium nickel cobalt aluminum oxides (NCA) and Lithium nickel manganese cobalt aluminum oxides (NMCA)

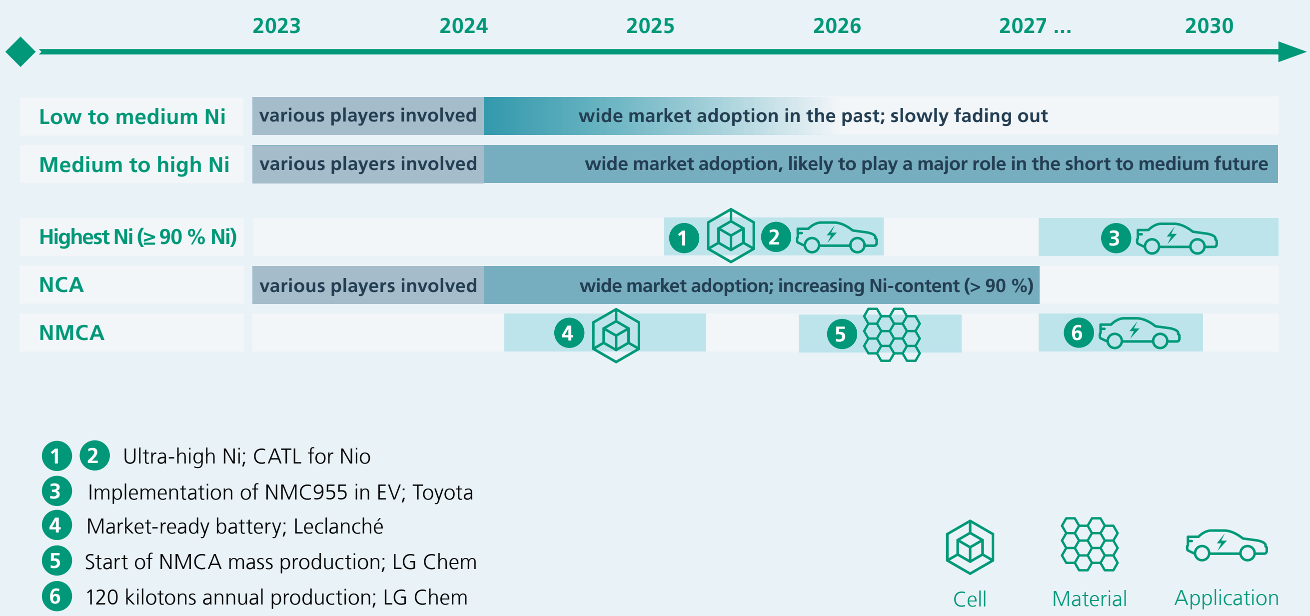
Like NMC materials, lithium nickel cobalt aluminum oxides ($LiNi_{1-x-y}Co_xAl_yO_2$ - NCA) belong to the class of layered transition metal oxides. Also, in NCA, the Ni-ions are the redox-active species; Co and Al are not actively participating in the electrochemical reaction. The Co^{3+} ions increase the electronic and ionic conductivity and the Al^{3+} ions are stabilizing the system. Similar to NMC materials, NCAs exhibit good performance at a reasonable cost in all relevant parameters, such as energy density and specific energy, rate performance, calendar and cycle life. At the same time, similar challenges exist, including structural instabilities during cycling leading to capacity fading and limiting the cycle life, as well as limited thermal stability [133]. An increase in Ni content, which is aimed at increasing the energy density, increases these structural instabilities and leads to capacity fade, which reduces cycle life. Strategies to overcome these challenges include surface coatings to suppress side reactions and doping [133].

The move to lithium nickel manganese cobalt aluminum oxides ($LiNi_{1-x-y-z}Mn_xCo_yAl_zO_2$ - NMCA) by adding small amounts of Mn results in better cycling stability, lower intrinsic volume variation and higher mechanical strength compared to NMC and NCA with a similarly high Ni-content [134, 136].

Table 2: Typical value ranges for relevant parameters of Ni-based cathode active materials [125, 136, 147, 148].

	Low to medium Ni (30 to <70 % Ni)	High Ni (70 to <90 % Ni)	Ultra-high Ni (≥90 % Ni)	NCA (>80 % Ni)
Theoretical specific capacity (mAh/g)	275-280			
Practical specific capacity (mAh/g)	150-190	170 to >200	>200	190- >200
Operating potential (V vs Li/Li⁺)	190 to >200			
Material cost (EUR/kg)	22-30	23-30	25-32 (estimate)	23-30
Comment	General comment: cost depends on Ni-/Co-content and particle morphology	Increasing energy density and decreasing stability with increasing Ni-content		

Figure 13: Industrial activities on next generation Ni-rich cathode active materials. The illustration is not exhaustive. References can be found in the text above.



Industrialization of high-Ni CAM

NMC CAM are currently the most widely used CAM in EV application, if the different types of NMC are combined [9, 93]. Whereas early EVs used NMC111, in recent years there has been a shift to NMC532, NMC622 and NMC811, and medium to high Ni-content are currently the most commonly used NMCs chemistries [9, 93]. NCA-based batteries are being produced mainly by Panasonic and Samsung SDI [95]. These batteries are used for electric vehicles (Tesla is using NCA batteries from Panasonic for their long-range models) and power tools.

The industry is moving towards even higher Ni-contents, both for NMC and NCA (e.g. Ni > 90 %) to increase the energy density and thus range of the EVs. Such ultrahigh-Ni NMCs and NCAs are expected to gain significant market shares by the end of this decade [132]. Major cell producers such as SK On and Samsung SDI are already producing cells with ultra-high-Ni content [137]. CATL has announced the production of batteries with an ultra-high nickel technology that was initially planned to go into mass production in 2025 [138]. Leclanché announced that it will manufacture NMCA-based batteries with a Ni-content of around 90 percent using a water-based production process. They are planning for these batteries to be available on the market in 2024 [139]. LG Chem announced the construction of a cathode manufacturing plant in the USA that is supposed to mass produce NMCA material starting in 2025 [140]. However, LG Chem is likely to produce NMCA earlier through its joint venture with Huayou Cobalt in South Korea [141]. Both, Tesla and GM are expected to be using NMCA cells from LG ES (that is likely to use the NMCA from LG Chem) for automotive applications [142]. BMW, GM and Toyota plan to implement ultra-high-Ni technology in 2025, 2026 and 2028 respectively [143-145]. Other industry efforts are moving in the direction of completely eliminating Co in the NMC chemistry, such as SVOLT's cobalt-free cathode material NMX [146].

Blends of different CAM

The cathode active materials discussed above can also be used as blends, i.e. mixtures of different CAM. The goal is to combine the advantages of the different materials, while mitigating their limitations [149]. An example of such a CAM blend is the low-capacity EV "Hongguang MINI" that uses a blend of LMO and NMC which can provide a good energy density (NMC) and high power and safety (LMO) at the same time [95]. Other combinations may involve LFP (low cost, safety) and NMC (high specific energy) or blends of CAM of similar stoichiometry (e.g. NMC) but with different particle properties such as particle size or single-crystal and poly-crystal morphology. This can improve the volume utilization in the cathode (higher compaction) or compensate for the loss of stability and performance at different temperatures or high charge states.

With the transition to Si-based anodes (see section 3.1.3), other blends of CAM and Li-containing materials may also become relevant. The loss of Li due to SEI build-up in high-capacity anode materials such as Si in the first cycle can be considerable and reduces the Li available for the reversible reaction and thus the cell capacity. Blends of CAM and Li sacrificial salts in the cathode can counteract this. The Li sacrificial salts do not provide a reversible capacity and only act during formation or in the first cycles.

3.1.2. Cathode Material Production Capacities

Cathode active material production is mainly focused on Asian countries, especially on the three largest players: China, Korea, and Japan. However, an increasing number of large companies and start-ups have announced plans to establish or expand CAM production capacity in Europe and North America [95]. Production facilities are mainly for lithium iron phosphate (LFP) and nickel-manganese-cobalt (NMC) (see Figure 14) [150].

The largest CAM producers worldwide are primarily located in China. The biggest of these are Shenzen Dynanonic, Hunan Yuneng and LOPAL. Those three mainly focus on LFP production and had a cumulative CAM production capacity of more than 1,000 kilotons per year (see Table 3). They plan to expand their CAM production capacity over the next few years. Dynanonic and Hunan Yuneng each plan to reach an annual capacity of almost 900 kilotons per year by 2028 [95, 106]. The only companies outside China with similar capacities are South Korean. L&F, Posco, and Ecopro have a combined annual CAM production capacity of more than 400 kilotons, part of which is located in China [95]. In 2028, they are expected to have an annual production capacity of almost 1,000 kilotons, partly produced in new production facilities in Europe and North America. Overall, the worldwide annual CAM production capacity is currently 3,700 kilotons, of which 78 % is produced in China. The CAM producers are preparing to face the significant increase in demand that is expected over the next few years. Until 2028 the worldwide capacity will grow to about 8,350 kilotons, 59 % of which will be produced in China (see Figure 14).

The situation in Europe and North America

A few companies have announced their plans to establish CAM production capacity in Europe. Apart from large companies like BASF, Ecopro, and Umicore, there are also some smaller companies and start-ups like Freyr Battery and Northvolt.

The increasing demand from car manufacturers is driving the expansion of CAM capacity forward. Freyr Battery is a company that specializes in clean battery solutions. The company has started the construction of its first factory in Norway and has announced its further expansion plans in Finland and the US. They plan to have a CAM production capacity of 90 kilotons per year by 2025 and 173 kilotons per year by 2030 [151]. Northvolt has similar ambitions, with the construction of two production facilities in Sweden and one in Canada. They plan to have a CAM production capacity of 312 kilotons per year in 2028 [152] (see Table 3). The establishment of a total capacity of 980 kilotons per year of CAM production in Europe by 2028 has been announced.

Similar to Europe, the CAM production capacity in North America is currently low, but some companies plan to increase it. For example, there are BASF, Ecopro, Posco, and Umicore; additionally, there are smaller start-ups like Reedwood Materials and Mitra Chem. Redwood Materials specializes in recycling and expects a CAM production capacity of around 71 kilotons per year by 2025 and 430 kilotons annually by 2030 [153]. Based on announcements, we expect a total production capacity of about 700 kilotons per year by 2028 in North America.

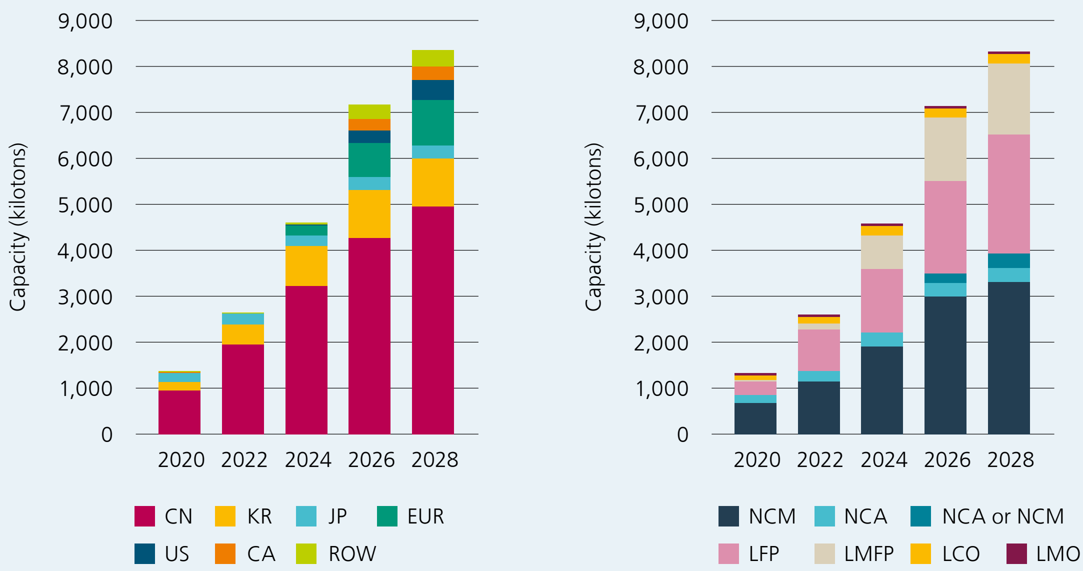
The Situation in the rest of the world

A few more countries are active or plan to become active in CAM production, mainly India and Indonesia. India wants to become independent in terms of CAM production [154]. Until recently, there was no CAM production in India, but they plan to have an annual production of 75 kilotons in 2028. Indonesia is one of the largest nickel producers worldwide. Until recently, however, they mainly exported the nickel, a fact which the Indonesian government wants to change. They are therefore restricting the export of nickel, so that large companies now have to look into establishing CAM production facilities in Indonesia [155]. They are expected to have an annual CAM production capacity of 160 kilotons by 2028 [156].

Table 3: Major cathode material producers and production capacities in 2023 and 2028 (announcements). *: including parts of BTR (LOPAL bought everything LFP-related from BTR); **: announced/future.

Company	HQ	Locations	Materials	Production capacity 2023 (kilotons per year)	Production capacity 2028 (kilotons per year)
Northvolt	SE	SE**, CA**	NMC**	0	312
Posco	KR	CN, KR, CA**	NMC, LMO	128	264
L&F	KR	KR	NMC, LMO	131	281
Umicore	BE	KR, CN, PL, BE, CA**	NMC, LCO	149	648
Ecopro	KR	KR, HU, CA**	NMC, NCA	179	422
Easpring	CN	CN, FI**, IN**	LCO, NMC, LMFP	246	566
Ningbo Ronbay	CN	CN, KR	NMC, NCA, LFP	253	348
LOPAL*	CN	CN, ID**	LFP	270	440
Hunan Yuneng	CN	CN	LFP	317	900
Shenzhen Dynanonic	CN	CN	LFP, LMFP	540	870

Figure 14: Planned (announced) cathode material production capacities based on plant location (left) and type (right).



3.1.3. Anode Materials

Graphite is still the state of the art as anode material for LIB and will probably retain this position for the foreseeable future. Despite the advantages of the material, which are its low cost and high storage capacity, there is an increasing demand for higher energy density and fast charging capability, which cannot be achieved with graphite or only at great expense. A major focus of industrial development is therefore on the use of silicon-based materials.

Natural and synthetic graphite

Although graphite has been used as anode material in LIB for more than 30 years, the material and its production have not reached their final stage of development. In principle, natural graphites (NG) can be extracted in mines and synthetic graphites (SG or AG) can be produced in high-temperature processes from organic precursors such as tar. Both types of material are used in batteries, although the use of synthetic graphites for electric mobility has gained ground in recent years. In synthetic production, the properties of the material can be much better tailored to the application requirements. However, with increasing demands for materials with the lowest possible CO_2 footprint, natural graphites could also regain importance: Depending on the process, mining method or starting material and energy mix, the CO_2 emissions of synthetically produced graphite can be significantly higher than those of natural graphite obtained under favorable conditions [157-160]. However, the production of natural graphite in battery quality also has a strong environmental impact. The purification process in particular, which mostly requires hydrofluoric acid or extremely high temperatures, can have strong local impacts on air and water pollution [161]. Therefore, one of the biggest challenges in using graphite in both cases will be the reduction of production-related environmental impacts. Among other things, the new EU battery regulation, as well as the strict environmental regulations in China, the main manufacturing country, are likely to act as motivating factors for the industry [70, 161].

In industry, this topic is also being addressed in part through the development of new processes. The Estonian start-up "Up Catalyst", for example, is working on the conversion of CO_2 from industrial processes into graphite and other carbon products and claims to want to scale up the process by 2030 [162]. Other actors such as Carbonscape from New Zealand or Kibaran Resources from Tanzania are working on graphitization processes for biomass [163] and the use of less hazardous chemicals in the purification of natural graphites [164].

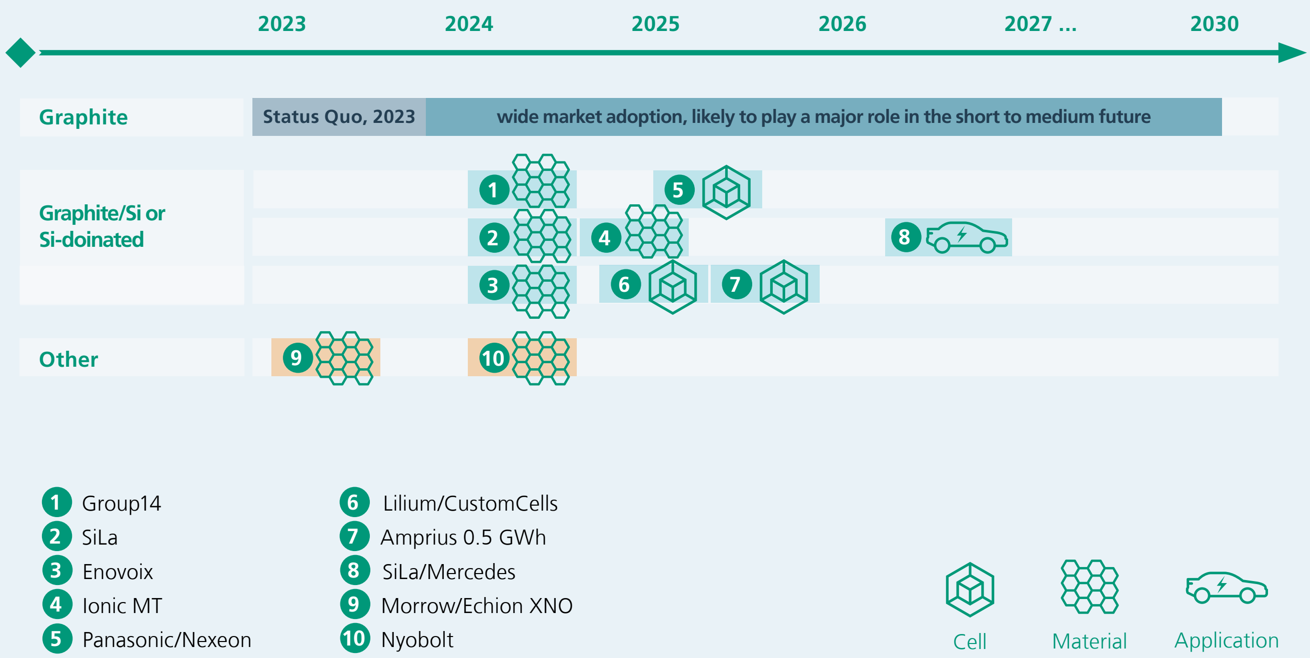
In addition to the adaptation of starting materials and production processes, graphites are also being further developed at the material level. Although commercially available graphites already almost reach the theoretically possible storage capacity, challenges still exist in the areas of service life, fast-charging capability and the irreversible losses during cell formation that are associated with the build-up of a solid electrolyte interphase (SEI).

One of the main approaches to change the material properties is to tune the particle size and morphology. NGs often occur as flake graphite, sometimes as microcrystalline graphite. Typically, the materials are spheroidized for use in batteries, which improves performance characteristics and lifetime. The right choice of size determines, among other things, the Li kinetic of the anode. Small graphite particles have fast Li intercalation kinetics and a long service life, but cause low initial coulomb

Table 4: Properties of anode active materials.

	Graphite	Graphite-silicon composites	Silicon dominated	Lithium	Titanates and Niobates
Theoretical specific capacity (mAh/g)	360	>360	3,579	3,842 (charged cell)	175, 400
Operating potential (V vs Li/Li$^+$)	0.1	0.1-0.22	0.22	0	~1.5
Material cost (EUR/kg)	5-9	>10	>30	80-200 (metal cost)	>15
Practical performance on cell level	<280 Wh/kg, <750 Wh/l	~300 Wh/kg, ~800 Wh/l	>300-500 Wh/kg, >900 Wh/l [171-174]	>300-400 Wh/kg, 1,000 Wh/l [169, 170]	70-150* Wh/kg, 150-250* Wh/l
Comment	demonstrated	demonstrated / claims	claims	claims	demonstrated, *claims

Figure 15: Industrial activities on next generation Si-based anode materials and other anode materials [180, 181, 183, 184, 193-196]. The illustration is not exhaustive.



efficiency (CE) due to their high surface area [165]. Most graphites used in batteries are therefore additionally coated. A carbon coating is usually used, which influences the SEI formation and thus increases the initial CE and improves the cycle life and thermal behavior. Other surface modifications such as targeted oxidation can also improve properties.

These measures however do not affect the bulk properties of graphite. Other strategies, especially for increasing the fast-charging capability of the material, use etching processes, for example, to create pores in the graphite and thus create new Li transport channels, or aim at producing so-called "mildly exfoliated graphites", i.e. chemically modified graph-ites with slightly increased spacing between graphene layers, which can significantly improve Li kinetics and storage capability [167, 168].

Silicon in composites and as a stand-alone material

Silicon is used as an anode material in high energy LIB due to its high capacity and favora-ble voltage compared to Li/Li^+. Currently, it is being used as an additive to improve graphite-based anodes, but in the future the importance of Si is expected to increase. The range of possible Si materials is very wide, ranging from 2D or 3D Si structures to carbon/silicon composites, which can consist of a wide variety of carbon materials such as graphite, CNTs and amorphous carbons, as well as a wide variety of Si materials such as spherical particles or fibers. Accordingly, the composites can consist of carbon matrices with embedded Si, mixtures of Si and carbon particles, carbon coatings for Si particles, or other configurations [165].

The main challenges in using Si are related to its high chemical reactivity in contact with common electrolytes and the large volume change when forming an alloy with Li. The reactivity with the electrolyte leads to high irreversible losses during cell formation and a thick SEI, which can break due to the large change in volume during cyclization. In the particle bulk, the volume changes also lead to high stresses, which can cause particle breakage or loss of contact.

Possible solutions involve coating or surface modification of the Si particles. SiO_x materials, for example, offer a Li-Si oxide matrix surrounding the Si domains which is much less reactive [175]. Other approaches use coatings with carbon or conductive, flexible or "self-healing" polymers [176, 177]. Si-based prelithiated anode materials are increasingly being developed precisely to compensate for the Li loss associated with irreversible reactions. Full cell level capacity and cycling stability can be significantly increased by using such concepts, but the method requires new and additional process steps in material production [178, 179].

Similarly to the multitude of possible Si anodes (e.g., with different Si to carbon ratio, particle size and morphology, manufacturing process, etc.), a variety of players have addressed the topic. Established manufacturers, especially from China, Japan and South Korea, are scaling their productions for already commercialized or near-market concepts like SiO_x [95]. Specific capacities of over 1,400 mAh/g are achieved with the material.

A number of start-ups, especially from the USA, are working on very new materials, some of which require new manufacturing processes. For example, Group14 plans to start industrial production of its silicon-carbon nano-composite material in 2024 [180]. The technology of SiLa Nanotechnologies seems to be based on multi-layer Si materials and is also expected to be brought to industrial production in 2024. By 2026, the material is expected to be used in EVs, specifically in the electric G-Class from Mercedes Benz [181]. The company Amprius Technologies develops composite materials containing nanowires and has presented cell data with high specific energy of 350 Wh/kg and wants to start giga-scale production in 2025 [182, 183]. The UK's Nexeon is also working on needle-like silicon. Together with SKC from South Korea, mass production is to be realized by 2026 [184]. Panasonic is one customer already waiting in the wings [185]. Neo Battery from Canada is an-other example for a Si start-up. They claim to achieve >2,500 mAh/g with their material [186]. So far, there is no information on scale-up plans of the company. In Europe, Umicore, a major player, is also working on this topic. The company relies on Si/C materials, which achieve a capacity of >1,000 mAh/g [187]. Plans for scaling up have, however, not yet been announced.

Other anode materials

Even though these mostly do not have the high energy densities of graphite and silicon, other anode materials are still being developed, some with excellent performance characteristics and stability. A material with high structural and chemical stability is lithium titanate (LTO, $Li_xTi_5O_{12}$) which has been in use for a long time [188]. In the insertion reaction, a specific capacity of 175 mAh/g, and a volume change of less than 1 % can be realized. The company Echion from the UK is working on the commercialization of niobium-based anode materials which are also expected to have very good kinetics and lifetime. By 2024, material production is to be scaled up to the kiloton scale [189]. Morrow Batteries is already a potential European customer that would like to integrate the material into special battery cells [190]. The UK company Nyobolt is working on a similar class of material. Production is to be established by 2024 [191]. Toshiba, a large and established company in the battery sector, is also pursuing this topic [192].

3.1.4. Anode Material Production Capacities

Global production capacities for anode active materials, especially graphite, are strongly focused on China. China has one of the largest deposits of natural graphite, with the main deposits located in Inner Mongolia and Heilongjiang Province [197]. Compared to many other deposits, certain deposits in China can be considered "super-large", making their development economically very advantageous. Although the production of artificial graphite is not so strongly linked to having local access to raw materials, production capacities are still heavily concentrated in China.

Some of the largest producers for both types of graphite in China are BTR with large plants in Shenzhen, Tianjin and Huizhou and Jixi Shanshan and Shanghai Putailai with production bases in Jiangxi. Chinese manufacturers are planning to massively expand their production capacities in the next few years. BTR is building a plant in Yunnan with a capacity of 200 kilotons per year [198] and in Heilongjiang with a capacity of up to 600 kilotons per year, mainly for NG [199]. Shanshan is building production facilities of up to 200 and 300 kilotons per year for both AG and NG, in Sichuan and Yunnan respectively [200]. Shanghai Putailai (Zichen) is building another 100 kilotons per year in Sichuan [201].

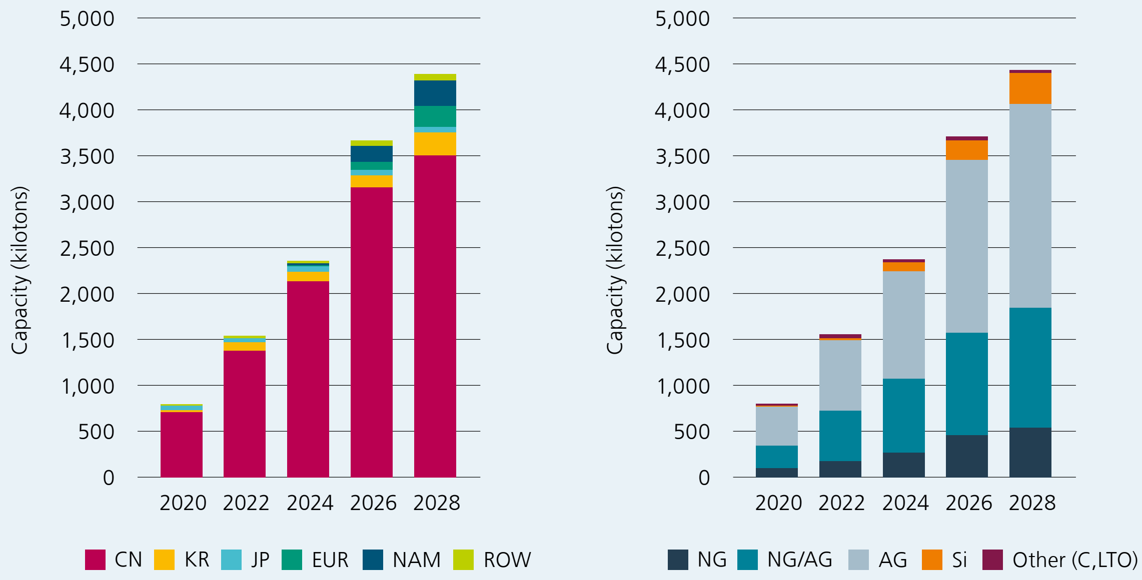
Based on these announcements, China could even expand its market share in global production capacity from more than 80 % at present to almost 90 % in the medium term.

The only heavyweight producer of graphite anode material outside China is the South Korean company Posco which operates plants in Sejong and Pohang. There are expansion plans for the Pohang plants in particular, but these are smaller than those of the Chinese competitors [202, 203]. Starting from today's share of about 4 % of global production capacities, this value should nevertheless increase slightly by 2030 due to Posco's expansion plans.

Situation in Europe and the US

IIn Europe, too, some producers have announced the establishment of production capacities, especially for graphite.

Figure 16: Planned (announced) anode material production capacity based on plant location (left) and type (right). NG: Natural graphite, AG: artificial Graphite, NG/AG: unknown type of graphite, Si: Si-based materials, Other: Other carbons and LTO.



These include Talga, which operates in Sweden, Vianode/Elkem and Mineral Commodities in Norway, and Grafintec in Finland. In addition, the Chinese giant Shanghai Putailai has also targeted Europe as a production site and is planning a plant in Sweden. The announcements are mainly related to NG and are quite sizeable. Both Putailai and Vianode are planning production capacities of around 100 kilotons per year by 2030 [204, 205]. The other manufacturers plan several tens of kilotons per year [206-208].

In the USA, there are also major efforts to increase production capacities for battery anodes, even though, as in Europe, there is still only a small scale industry in this area. A number of new but also established players, including Novonix, Epsilon, Anovion, Graphite One and Syrah, have positioned themselves to build plants for graphite production [209-216]. Most of the announcements regarding capacity are for several tens of kilotons per year. Due to the pressure to localize supply chains triggered by the IRA, some already have customer relationships with cell manufacturers who want to use the materials in the US [211, 217].

Based on these announcements global production capacity market shares of <1 % today for both Europe and the U.S. could increase significantly in the future. By 2030, both regions could reach global shares of 5-6 %. In total, the announcements for the development of production capacities for graphite as an anode material amount to about 4 million tons by 2027/2028. At least 50 % of this is attributable to the capacities of AG. The total graphite quantity corresponds to just under 4.5 TWh of battery storage capacity.

Silicon production capacities

Compared to the graphite production plants currently in operation and those announced for the future, the development of Si production as an anode material is taking place on a smaller scale. The largest plants producing a few kilotons per year are currently operated by BTR, Shanshan and Chengdu Guibao from China and Daejoo from South Korea. These and other producers such as Shida Shenghua plan to expand their capacities to several tens of kilotons per year in the next few years [95]. This means that from about 2027 onwards up to 300 kilotons per year of SiO_x-based and other Si-based materials should be available worldwide. With 70 to 80 %, China is also likely to account for the majority of the market share in terms of production capacity. The South Korean manufacturers Daejoo, Posco, SK Materials and others [95] could account for a future market share in this country 15 to 20 %. The announcements of the US manufacturers SiLa, Amprius, Group14 and others correspond to a share of 6 to 8 % [180, 181, 183].

3.1.5. Other Cell Components

Electrolytes

Common electrolytes for LIB all consist of a mixture of organic solvents and Li salts. However, the exact composition varies greatly depending on the cell type and can be regarded as the core IP of the cell and electrolyte manufacturers. Various fluoridated salts such as LiFSI or $LiPO_2F_2$ play a major role in the current developments, which, in addition to the common $LiPF_6$, can decisively influence the behaviour of the electrolytes at high and low temperatures [218]. Current and future developments also concern the stability at high cell voltages >4.2 V, which is already state of the art in smartphones (e.g. 4.45 V) and could become so in the EV sector in the future. Another topic in electrolyte development is compatibility with Si anodes. Here, too, there are approaches involving the use of additives, e.g. LiDFBOP or FEC, which lead to a more robust SEI on the particle surface [219, 220].

The largest production plants for electrolytes are in China, whereby the companies Tinci, Guotai-Huarong and Shenzhen Capchem currently have the largest production capacities. Outside China, only Japan and South Korea have other producers with relevant global market shares. Here, too, the map of producers is likely to shift in the next few years as a result of the US IRA and the further development of the battery industry in Europe.

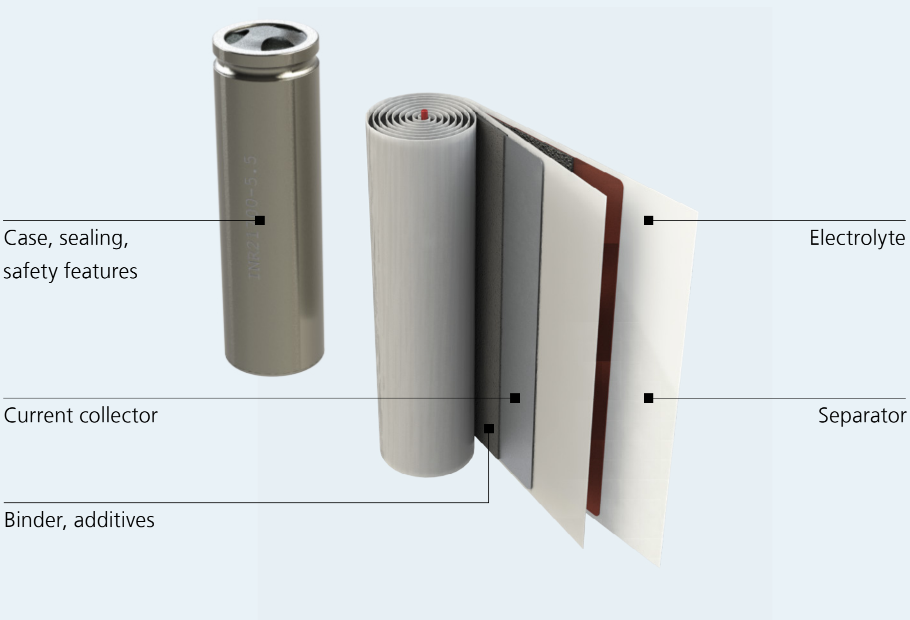
The company Lanxess, for example, has announced its intention to produce electrolytes in Germany based on Tinci's technology [221]. The South Korean company Enchem already runs a factory in Poland and has announced the construction of a second electrolyte production plant capable of producing 20 kiloton per year electrolyte in Hungary [222]. Similarly Dongwha also runs a factory in Hungary capable of 20 kilotons per year [223]. There are also major expansion plans for the USA. The manufacturers Enchem and Dongwha are planning to build factories in a total of five states with a combined capacity of over 300 kilotons per year [224, 225]. Other Asian suppliers such as Soulbrain and Shenzhen Capchem also seem to be following this trend [225].

Separators

Industrially used separators often consist of a porous, polyolefin-based polymer layer and a ceramic coating. While these systems have good mechanical properties, they offer limited stability at high temperatures. When cells are thermally overloaded, the polymer layer begins to shrink, which can lead to short circuits in the cell.

The state of the art for polymer separators, including a potential ceramic coating, is 10 to 12 µm. Recent findings [9] indicate that the separators are slightly thicker for pouch-type cells (~15 µm) and thinner for prismatic or cylindrical cells, most likely due to the solid housing of cylindrical and prismatic cells. Separator foils with around 8 µm are commercially available.

Figure 17: Components of LIB cells.



Current research activities concern the use of other polymers, for instance those based on polyimides, PEEK or polyacrylonitrile, which in some cases can significantly improve the critical thermal load as well as properties such as electrolyte wetability [226, 227]. In the industry, developments in recent years have focused on reducing production costs and further reducing separator layer thicknesses. Ceramic coating has now become the standard in the automotive sector, with separators coated on one or both sides depending on the cell design. Different materials, e.g. Al_2O_3 or AlO(OH) (Boehmite), are used for the inorganic coating.

The largest manufacturers and production capacities for separators are currently located in China. SemCorp, currently the largest manufacturer, is planning capacity expansions in China and potentially in the US. With its plant in Hungary, the company now also has a European production capacity of 350 million m² [228]. Similar plans have also been implemented by the South Korean supplier SK IE Technologies. In Poland, an annual capacity of more than 1,000 million m² of separator will be created in several expansion stages by the end of 2024 [229]. The Japanese company Asahi Kasei is also planning expansion to the US [230]. Overall, the share of production capacities outside the established countries of origin China, South Korea and Japan is likely to increase significantly in the coming years.

Current collectors

In addition to their function as current conductors, the Al and Cu foils used in LIB also function as a thermal bridge between the electrode and the cell and ensure the mechanical stability of the electrode stack or winding. In recent years, there has been a clear trend towards reducing the thickness of the foils, which has essentially been implemented to increase the energy density of the cells. Around 15 µm is the state of the art for aluminum foils on the cathode, with 10 to 12 µm being expected for future generations. Certain material suppliers already offer aluminum foils with 10 µm [231]. For copper foils on the anode, 8 to 10 µm are state of the art. While LG Chem announced the mass production of EV pouch-type batteries with 6 µm copper foils in 2020 [232], some studies refer to this thickness as practicable limit due to mechanical strength or processability. However, some market analysts anticipate that around 4 µm will be feasible, and certain material suppliers are already offering those foils for future battery generations [233]. A further development to reduce film weight and volume is the use of multilayer systems, e.g. of a polymer film thinly coated on both sides with Cu [234-236]. Sputtering, electroplating and densification processes are used for this purpose. Films with a total thickness of 6 µm (1 µm Cu per side) have already been presented by the industry. The future use of such thin foils is conceivablein high-energy batteries with low power requirements.

Binders and conductive Additives

Polymer-based binders and conductive carbons are used to produce mechanical and structural stability as well as electronic conductivity in the battery electrodes. The choice of either type of additive type depends on the requirements for power density, the manufacturing process and the active materials. In the aqueous processing of graphite anodes and LFP cathodes, mixtures of styrene-butadiene rubber and cellulose derivatives have become established as binders. Polyvinylidene fluoride (PVDF) is used in NMP-based processing. For the establishment of electronic conductivity, nano-scale conductive blacks are still predominantly used. More and more, special nanomaterials such as carbon nanotubes (CNTs) are being used in commercial LIBs. The high conductivity of CNTs and their 1D morphology can increase the robustness of the electrode composite, especially for active materials with high volume expansion such as Si, and thus increase the service life of cells [237]. The use of Si in the anode also increases the demands on the binders, as conventional binders often do not have sufficient elasticity. Possible approaches include the use of propylene-based binders [238] or supramolecular binders, and in some cases bio-based materials [239]. Work is also being done on combining binders and conductive additives in the form of electronically conductive polymer binders [240]. One of the main criteria for their usability is the compatibility of the materials with widely used mixing, coating and drying processes used in electrode production.

3.1.6. Cell Production Capacities by Chemistry

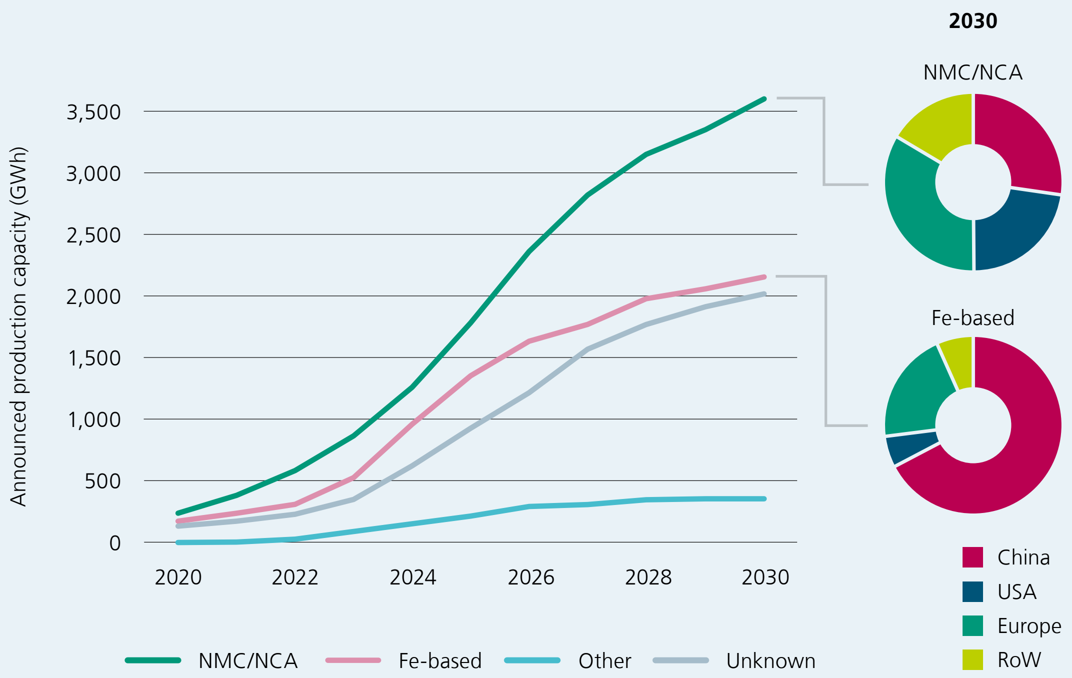
The main trends in the choice of cathode materials can be derived by analyzing the production capacities planned (announced) for LIB cells. Even if in many cases the cathode material used is not specified, it can be inferred based on information about the cell manufacturer or the potential customer. Assumptions were made reagrding the most likely cathode materials used to generate the forecasts shown in Figure 18. The announcements were categorized on the one hand by LFP and other iron-based cathode materials and on the other hand by nickel-based materials, such as NMC and NCA. The two additional categories are "other cathode materials", including Mn-based cathode materials (e.g. LNMO), and "unknown", for production where no reasonable assumptions were possible.

According to this assessment, 44 % of the global cell production capacity will be for Ni-based and 26 % for Fe-based cell chemistries by 2030. While less than 5 % are expected to have an alternative cathode chemistry, such as those which are Mn-based, the remaining 25 % couldn't be allocated due to insufficient information. Although the share of these cathode chemistries in the predicted global cell production seems to be relatively stable in the coming years, absolute capacities will increase rapidly.

The regional differences are well-pronounced, whereas cell production for LFP plays a major role in China, the trend is the opposite in Europe. In the US cell production announcements there is a clear dominance of nickel-based cathode materials, which, in addition to NMC include a large share of cells with NCA chemistry.

However, the regional dynamics within this decade reveal a more complex picture: The share of LFP-based cell production in Europe is set to increase over the coming years, indicating that low-cost battery cells are becoming increasingly important here. A similar effect can be observed in the US, even if the share of LFP cell production capacity is only predicted to reach a minimum of 8 %. (It should be noted that the proportion of production capacity with unknown cell chemistry is higher).

Figure 18: Planned (announced) cell production by CAM and region.



This situation can easily be transferred to the countries/regions with the largest planned (announced) capacities for cells using the different cathode active materials: The production of LFP battery cells will be heavily dominated by China, where around 90 % of production capacities will be located by 2025. However, this share will decrease to around two thirds by the end of the decade, mainly due to the increase in activity within Europe. In the case of NMC and NCA, the predicted shares of cell production capacities in the different countries/regions are more diverse, whereby Europe has a share of around one third and China a share of around one quarter.

The cell manufacturers with the largest production capacities for battery cells with an LFP or another iron-based CAM all come from China. By 2030 CATL could potentially establish production capacities for cells based on LFP cathodes of more than 500 GWh. Together with EVE, BYD and CALB, they make up nearly half of the expected production capacities for LFP battery cells.

In the case of battery cells with NMC cathodes, an Asian manufacturer is also expected to be the largest producer by 2030. Nearly 500 GWh of LG ES's planned cell production is estimated to use an NMC cathode. In addition to them, CATL, SK On and CALB are expected to be the most important players by the end of the decade. Together they make up around half of the expected production capacities of NMC battery cells by then. Northvolt could become the most important European cell manufacturer in this field, followed by PowerCo and ACC, according to their respective announcements and Panasonic is likely to become the most significant manufacturer relying on NCA cathodes.

3.2. Battery Cells

3.2.1. Battery Cell Design Trends

Battery cell design concerns the electrode level and covers component thicknesses, electrode porosity, and the assembly from single sheets to stacked or wound electrodes up to the choice of cell format and size.

HE electrodes - an engineering trade-off between energy density and power density

The LIB engineering process requires several design choices from electrode composition to coating weights and thicknesses, electrode porosities, current collectors and connection tags, the separator and the electrolyte. These choices are complicated by the fact that maximum energy density and high power density often have opposing requirements. Optimizing power density, for example, requires minimizing any cell component's electronic, ionic, and thermal resistance. Suitable measures here comprise lower coating weights and thicknesses, higher electrode coating porosities, thicker current collectors, thicker and wider tags, or increased shares of highly conductive carbon. In contrast, optimizing energy density requires maximizing the ratio of active material to the total electrode volume. Suitable measures here are the opposite of those mentioned above to optimize power density and include increased coating weights and thickness, lower electrode coating porosities, thinner current collectors, thinner and smaller tags, or minimal shares of conductive carbons. OEMs and cell suppliers must find the right trade-off between vehicle range given the limited installation space (energy density) and fast-charging capability (power density).

Automotive HE-LIBs have a typical coating thickness (single-sided) of 50 to 80 µm for both cathodes and anodes [9, 241-243]. For HE cathode chemistries, graphite anodes may be close to 100 µm to sustain an appropriate anode to cathode balancing ratio (N/P). Increasing coating thickness promises higher energy densities and cost savings [244], but is currently unexploited. Between 100 and 150 µm are considered to be practical, achievable limits for single-sided coating thicknesses [242, 245]. Recent findings [9] suggest that LFP-type cells tend to be thicker than their Nickel-rich counterparts and at the upper end of the spectrum, and are most likely to compensate the lower capacity, probably facilitated by their higher intrinsic safety. For these reasons, it is likely that future HE-LIBs will be equipped with slightly thicker electrodes. Final coating porosities for automotive HE-LIBs tend to decrease slightly toward 20 % [9], with 10 to 40 % referenced as a typical LIB optimization corridor [246]. Several concepts aim to increase the active electrode surface and shorten the lithium-ion transport pathways (low tortuosity) to facilitate very thick electrodes capable of high C-rates. On the other hand, it is crucial to maintain the mechanical integrity of the electrode. Adjusted slurry casting with new solvents or added nanoparticles are the most mature technologies, while template-based concepts (such as salt or ice), additive manufacturing concepts, or laser ablation may become more relevant in the future [247].

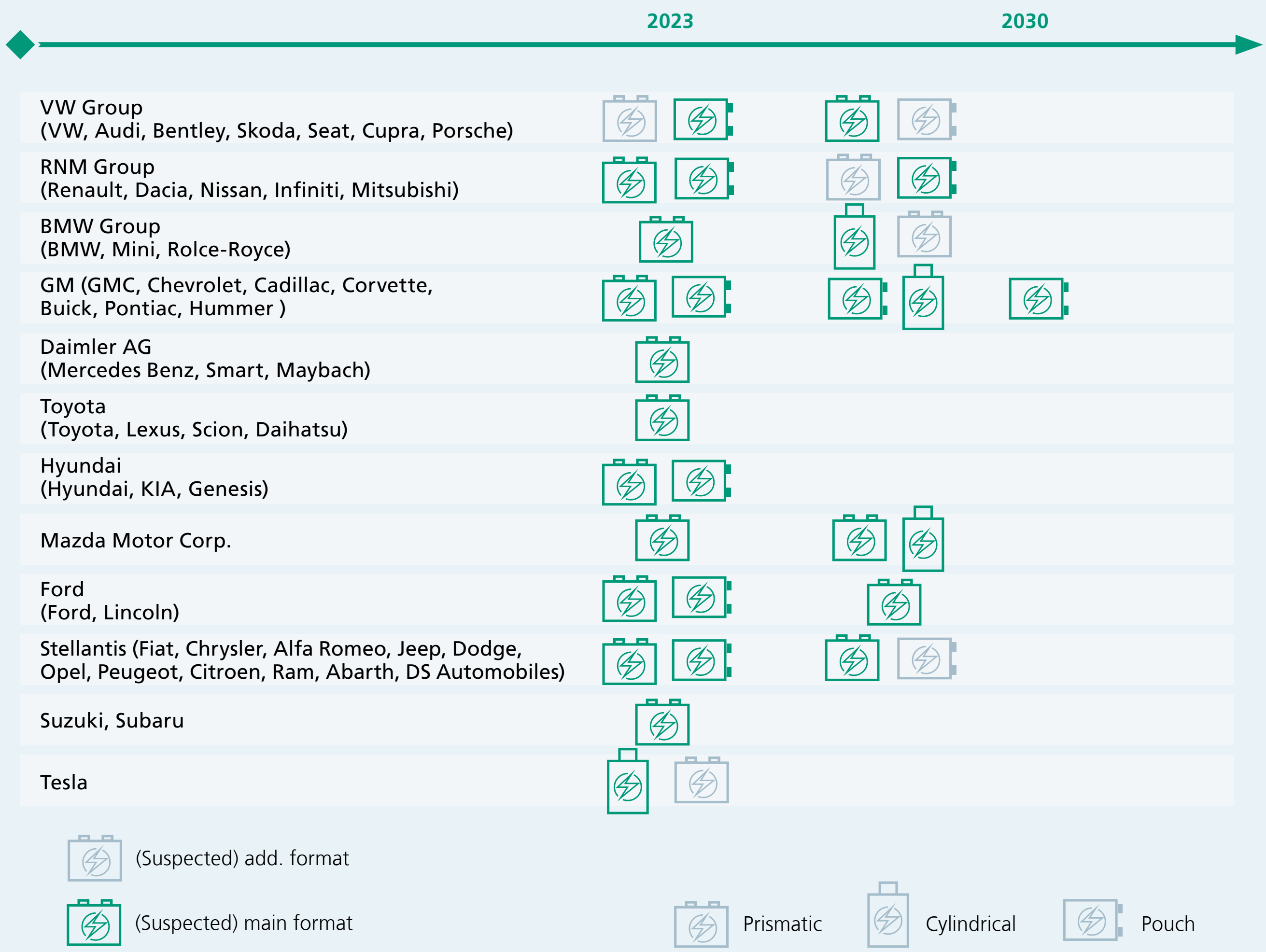
Electrode assembly

The type of electrode assembly used in the cell housing has a strong influence on overall cell performance, and the final electrode geometry should be as close as possible to the cell housing to avoid any dead volume. While there are two principal techniques, namely (1) winding of continuous electrodes and (2) stacking of pre-cut electrodes, in practice, there are several combinations such as Z-folding or stack-winding. The first technique, electrode winding, is most common among prismatic and cylindrical cells. The winding process and the equipment used are highly optimized, well established, very accurate and fast. The second technique, stacking and Z-folding, is used in pouch cells. The biggest challenge here is to combine fully automated handling and positioning accuracy at high process speeds. Industry announcements imply that future generations of prismatic and pouch cells will be assembled using single-sheet stacking or stack-winding while winding concepts will continue to be used in cylindrical cells [248].

Balancing single- and multi-format strategies

Cylindrical cells, hard case prismatic cells and pouch bag cells are the three formats used in large LIBs. Consolidating cell formats and developing common standards are well-established approaches in the automotive industry to leverage economies of scale or facilitate multi-sourcing strategies. Early on, the German Association of the Automotive Industry (VDA) and the German Institute for Standardization (DIN) proposed several industry-wide standards. These include prismatic cells with the HEV1, PHEV2, HEV1, HEV2, or BEV1 to BEV4 format and pouch cells with the HEV, PHEV1, PHEV2, or BEV format (DIN 91252:2016-11). However, manufacturers and alliance groups have also started developing and using modified formats that are tailored to their specific requirements and targets. Most OEMs combine single and multi-format strategies (cf. Figure 19), and most have selected a main format. While some manufacturers aim to establish their own cell production (own companies, joint ventures, start-up investments), others are seeking cooperation with established cell suppliers. There are high expectations and obvious trends toward cells with hard

Figure 19: Roadmap on current and planned cell formats per alliance group / OEM [249-257]. The illustration is not exhaustive.



housing, i.e., prismatic or cylindrical cells. Despite this, the announcements made indicate that all three cell formats are likely to retain substantial market shares.

Tailored prismatic cells and blade-type cells

Large prismatic cells feature high single-cell capacities, good mechanical stability and durability due to the solid aluminum housing, easy installation and high packing density, but challenging cooling characteristics. There is a wide range of utilized cell geometries within the global automotive industry. Overall, very large prismatic cells from 2,000 to 3,500 ml have mostly disappeared, while a new corridor has recently formed between 500 and 1,500 ml [9]. Thus, single prismatic cells have not grown in volume but have rather been tailored to the space available in the vehicle. We highlight two market trends and a true renaissance of prismatic cells in the last few years. On the one hand, there are thinner (12-36 mm) and smaller cells (up to around 400 mm) that primarily feature high-energy nickel-rich cathodes (mainly NMC). This results in average single-cell capacities of up to 100 Ah due to higher energy active materials and optimization. On the other hand, there are larger (400-900 mm) and thicker cells (up to 80 mm) with average single-cell capacities of around 150 Ah that primarily feature LFP cathodes, especially since 2019. In particular, there is a transition toward cell-to-pack (C2P) concepts with counter-tab designs and, thus, greater integration of cells into the vehicle chassis (see also chapter 3.3). This C2P concept is typically associated with either high volume or very long cells (up to around 900 mm) and promises cost advantages due to higher process efficiency and fewer components, and performance advantages due to higher achievable specific energy and energy density at pack level. As of 2023, many OEMs such as VW, Ford, Honda, Toyota, BMW, Mercedes, or BYD have announced their intention to keep using or shifting toward prismatic cells for future vehicle generations [259-262]. Even Tesla introduced prismatic LFP cells (276x80x62 mm³, ~3,200 g, 1,370 ml, 183 Ah) into their portfolio for their entry-level Model 3 and Model Y variants in 2020. In parallel, leading suppliers such as CATL, Samsung SDI, Gotion, Northvolt, SVOLT, or PPES have also committed to this format. As an example, we highlight the unified cell approach of VW, whose prismatic one-cell design (approx. 320x120x30 mm³, ~2,200 g, ~1,150 ml) should work across nearly 80 % of its product portfolio, with differentiations achieved by varying the active material from LFP to LMNO and NMC [263]. In addition, we highlight the BYD LFP blade battery (960x90x13.5 mm³, 3,900 g, 1,200 ml, ~200 Ah) with a potential stacked-electrode NMC-variant expected to reach over 280 Ah, and the SVOLT product portfolio with its L300 (220x102.5x33.4 mm³, ~1,800 g, ~750 ml, 115 Ah) to L600 (574x118x21.5 mm³, ~3,500 g, ~1,400 ml, 226 Ah) cells.

Larger cylindrical cells

Cylindrical cells have numerous advantages. They are robust, vibration- and shock-resistant, can withstand elevated internal pressure as well as mechanical stress making it feasible to integrate them structurally into the vehicle, and are inexpensive to manufacture. Tesla started with their 18650 cells early on, making them the only automotive OEM to rely on this cell format. Those cells had around 40 g of cell mass, 16 ml of cell volume and <34 Ah of cell capacity. The subsequent update to larger 21700 cells increased those properties to around >60 g, 23 ml, and 5 Ah [9]. In 2020, Tesla announced their 4680 cell format (diameter: 46 mm, height: 80 mm) with potentially even higher energy and power density, featuring 120 ml of cell volume and 24-27 Ah capacity. The new tabless design solved the potentially higher internal resistance problem. Since then, cylindrical cells have experienced a boom and a more diverse product portfolio is expected. Several OEMs such as BMW and GM as well as start-ups like Nio, Rivian and Lucid Motor have announced their intention to use large cylindrical cells for future vehicle generations. More precisely, BMW plans to use 4695 (420-450 g, ~140 ml, 32-36 Ah) and 46120 (530-560 g, ~180 ml, 40-46 Ah) cells in its upcoming next-generation "Neue Klasse" electric cars, expected by 2025 [264, 265], with higher cells more likely in larger van-type cars and SUVs. Nio [266] and GM [267] have announced plans to adopt the 4680 format from 2024/25 onwards, with other major OEMs such as Mazda [268] and Subaru [269] also showing interest in using this format. Likewise, many large cell manufacturers such as LG Energy Solutions, Samsung SDI, BAK, CATL, Panasonic, SVOLT, and EVE Energy are developing the respective product portfolios and production capacities. These also include shorter 46-millimeter diameter battery cells such as 4640 (170-180 g, ~60 ml, ~11 Ah) and 4660 [270] to allow lower floor height in a finished car or other large cylindrical formats, such as 4080 battery cells.

Tailored pouch cells and blade-type cells

Pouch cells have flexible designs enabling high packaging efficiency and energy densities, but suffer from relatively poor mechanical stability and durability due to their non-solid foil housing. Thus, single pouch cells need extra module- or pack-level protection against battery damage and thermal runaway. Before 2018, most automotive pouch cells were typically up to 300 mm long. Since then, more elongated and blade-type pouch cells with a length of more than 500 mm have entered the market [9]. For example, the VW MEB pouch cells with around 530 mm or the AESC pouch cells with around 590 mm. However, these cell dimensions are still compatible with typical battery module sizes. Pouch cells have also become substantially thicker from around 7 mm between 2012 and 2016 to around 11-12 mm in the 2020s, with up to 15-16 mm now being possible due to the manufacturability of thermoformed foils and improved cell stability. Despite these elongated and thicker pouch cells, total cell volume increased only slightly between 2010 and 2021 and remained between 400 and 500 ml. This indicates that single pouch bags have not become larger, but have been better tailored to the space available in the vehicle. However, average single-cell capacities have doubled to around 70 Ah due to new active materials [9]. As of 2023, many of the latest vehicle platforms from several OEMs such as VW, Mercedes, Renault, Hyundai, Kia use pouch cells, ensuring high demand in the coming years. Renault has made future commitments to pouch cells [271] as have Hyundai and Kia [272] and leading suppliers such as LG Energy Solutions, SK Innovation, VERKOR, or Envision AESC.
In the future, experts are talking about the end of this decade for early com-mercialization, pouch cells are expected to garner further attention, as this may be the preferred technology for solid-state batteries (SSB) [1].

Energy densities – toward 1,000 Wh/l and 400 Wh/kg

Historical data and the announced properties of future cells indicate a steady increase in energy density across all three formats as well as a head-to-head race between cylindrical and pouch cells.

For cylindrical cells, average values have plateaued around 250 Wh/kg and 700 Wh/l since 2021. With the introduction of 46-millimeter diameter battery cells, similar levels for early NMC/Gr or NCA/Gr variants are expected while next-generation cylindrical cells with high-energy cathode material (such as NMCA) and silicon-enhanced (10-20 %) graphite anodes may achieve 300 Wh/kg and 800-850 Wh/l [49].

For pouch cells, performance improved greatly between 2015 and 2018, reaching average values over 260 Wh/kg and around 600 Wh/l in the early 2020s, with around 300 Wh/kg and 670 Wh/l as the market-leading values. These values are very similar to those of cylindrical cells. Next-generation pouch cells are expected to surpass this level and reach 350 Wh/kg by 2025 and up to 400 Wh/kg by 2030, corresponding to 800-850 Wh/l by the mid-2020s and potentially close to 1000 Wh/l near the end of this decade [17].

Prismatic cells had a clear deficit in cell-level energy density to start with but have since improved significantly. Average values for HE prismatic cells with nickel-rich cathodes plateaued at around 210-220 Wh/kg in 2018, but surpassed 500 Wh/l in 2020 and reached 550 Wh/l in 2022. Maximum energy densities have even surpassed the 650 Wh/l, 250 Wh/kg threshold, meaning that prismatic cells are closing the gap to the other formats [273]. Recently announced targets suggest that >280 Wh/kg and 700 Wh/l could be reached within this decade when using high-energy cathodes (NMC, NCA, and NMCA) and silicon-enhanced (10-20 %) graphite anodes as well as stacked electrodes [3]. If almost solid-state electrolytes are used, >300 Wh/kg may be feasible [274]. In contrast, prismatic LFP cells currently feature >160 Wh/kg and > 400 Wh/l [273, 275]. Using stacked electrodes, manganese-doped LMFP, and silicon-enhanced (~5 %) graphite anodes could achieve the targets of >200 Wh/kg and >500 Wh/l within this decade, e.g., Gotion High-Tech's Astro-inno [3, 276]. Thus, it is considered likely that future prismatic LMFP cells will reach the level of their current HE counterparts.

Figure 20: Roadmap on energy density development by cell format and chemistry type [9, 26, 107, 277-281]. The illustration is not exhaustive.

3.2.2. Battery Production Trends

Due to the increasing demand for batteries, a corresponding upstream ramp-up of production capacities must take place. As a result, many so-called gigafactories are being built worldwide, which produce cells on large and mostly fully automated production lines. In 2023, the cells produced in such gigafactories will achieve a market volume of approximately 120 billion USD [282].

Cell production can be divided into three main steps. First, the electrodes of the battery have to be manufactured. These are then assembled into complete cells in a process known as cell assembly. During cell finalization, the cells are activated and tested [243, 283].

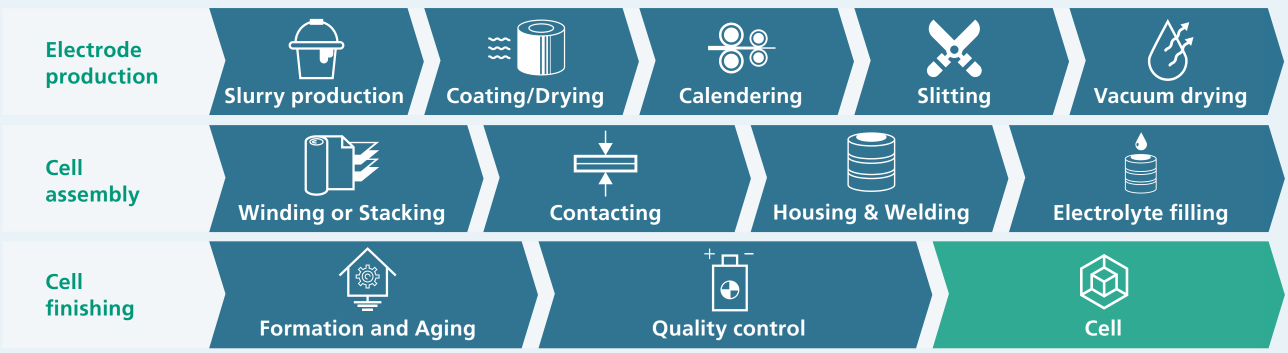
Electrode production
In the first step of electrode production, the starting materials of the anode and cathode are mixed with a solvent, additives and binder in a batch process to form a slurry. The slurry is then applied to a metal foil (made of copper on the anode side and aluminum on the cathode side) in a coating step. In a drying step directly downstream, a large proportion of the solvent is removed from the coated slurry. This is followed by a calendering step in which the coating layer is rolled under a certain pressure and thus post-compacted. Afterwards, the electrode foils, some of which are up to two meters wide, are cut into narrower pieces (slitting) and then usually the last moisture is removed from the coated layer in a vacuum oven. The process sequence from coating to slitting takes place in a clean room atmosphere to prevent contamination.

Cell assembly
The finished electrode foils from the vacuum dryer can then be layered in cell assembly together with a separator foil to form a cell stack or, depending on the cell format, a cell coil (jelly role). This is followed by appropriate contacting and insertion as well as welding in a cell housing. The next and final step of cell assembly is electrolyte filling. All the process steps of cell assembly have to take place in a dry room.

Cell finishing
The cell, which is now structurally complete, must then be electrochemically activated. To do so, it is first alternately charged and discharged during the forming process, which can take up to 24 hours, and then stored for a certain period of time (up to 3 weeks), known as aging. The final step is quality control.

Process innovations
The cost and sustainability requirements of the battery mentioned in chapter 2.3 can be transferred to battery production and indicate what needs to be optimized here as well. Since cell production accounts for approximately 15 to 25 percent of the total cost of a battery, there is an incentive to keep production costs as low as possible and to further reduce them [284, 285]. In addition, a relevant proportion of the CO_2 emissions from the life cycle assessment of a battery can be traced back to its production (in addition to the production and processing of the raw materials and recycling) [67]. Besides the costs and sustainability, however, the other two important criteria for production are the achievable throughput of the individual machines and the production quality.

Figure 21: Overview of the battery manufacturing process.



These criteria mutually influence each other. For example, if energy savings reduce costs, this is also beneficial for sustainability. Better quality control and less scrap also help to reduce costs and, in turn, have a positive effect on throughput and sustainability. Because these four criteria are so influential, it is vital for new technology trends to offer advantages in at least one of the them.

Approaches to reduce costs

Total cell costs are made up of similar shares of investment costs (and the associated depreciation) and OPEX (labor, energy, other) [284]. The highest investment costs for the battery production facility are the dry rooms for cell assembly and the large automated infrastructure for cell formation and finishing. After the investment costs, the most expensive processes are those with the highest energy consumption. In battery production, these are primarily the dry rooms and the drying process in electrode production. Cell formation also requires high energy input. Dry coating (1) can save the energy needed for the actual drying process or solvent recovery [67, 286]. Micro and mini environments (2) can replace the dry room and require less energy due to the smaller volume that has to be conditioned [67, 287] as well as lower investment costs for the infrastructure. Laser processing (3) can also be used at various steps in the production process to replace other state-of-the-art processes (e.g., in welding but possibly also in drying) in a cost-optimized manner.

Approaches to increase throughput

In order to meet the high demand for batteries and reduce overhead and investment costs at the same time, each production step has to be optimized to achieve the highest possible throughput. This is what enables efficient production (resulting in cost and sustainability benefits). The throughputs of the individual production steps differ significantly. For example, cell assembly and cell finishing have disadvantages compared to electrode production. Round cells and prismatic cells (winding) have cell assembly advantages over pouch cells (stacking). In cell assembly, many machines have to be used in parallel in current state-of-the-art production systems in order to achieve the throughput of upstream electrode production. Formation (due to slow charging and discharging cycles) and aging also require a significant amount of time. For this reason, very large, fully automated plants must be able to process many cells simultaneously.

Besides optimizing formation protocols, there are also approaches to increase the throughput of cell assembly (4), e.g., accelerate the electrolyte filling or to shorten and accelerate the stacking process.

Quality improvement

The reduction of scrap through inline monitoring of production is essential for cost-optimized and sustainable battery production. There is usually a very high scrap rate, especially during the ramp-up of new production sites. This must be reduced as quickly as possible after production commences. High-quality production systems, sensor technology and process expertise can help to ensure this.

Production scrap occurs throughout the entire process. However, reject rates are particularly high during (batch) mixing as well as coating and drying. There are fewer product failures in cell assembly and cell finishing, but the contacting and weld spots must be checked in cell finishing, for example. It is preferable if faults are detected immediately before cell testing and have not passed through the entire production process.

Early detection of scrap through inline measurements (5) can help to optimize quality. Pre-lithiation (6) is a process for anode treatment during or prior to cell manufacturing. It is still rarely used in battery cells, but could play a role for new high-energy materials. Integrating it into the production process could make a significant contribution to improving battery production.

Sustainability of cell production

Sustainability depends heavily on the type and amount of energy used. In battery production, electricity or natural gas can be used as an energy source. Electricity can have a lower environmental footprint than natural gas depending on the electricity mix used. It is important for production to be as energy-efficient as possible, but also to use low-carbon electricity processes wherever possible (especially in Europe, where policy measures focus on sustainability). Both the drying process and the dry rooms are usually operated with heat or cooling energy obtained, e.g., from natural gas. Formation, on the other hand, requires electrical energy to charge and discharge the cells. Energy-efficient drying and dry room operation in particular are therefore critical for battery sustainability. It is also desirable to avoid the use of toxic solvents in the production process, particularly during electrode coating. If toxic solvents are used, they have to be recovered, which also requires high energy use.

As mentioned above, technologies that lead to cost savings due to lower energy demand (1-3) or that produce less waste (5) contribute to improving the sustainability of the production process.

Technologies	Description
Dry Coating [288-290] **Impact:** Costs Sustainability Quality Throughput	In order to make the electrode production process more effective, an attempt is made to work without or with only a small amount of solvent. There are different types of processing (extrusion, direct calendering process, powder application and single layer application). Dry coating has **advantages** in terms of energy consumption. No or only a reduced amount of toxic solvents is used and the plant's environmental footprint is much smaller. Dry coating still faces **challenges** because of the impact on up-stream and downstream processes, the adhesion of active material to the current collector foil, and binder processing. **Outlook:** Because of the positive impact on energy savings and the efforts of major companies such as Tesla and VW, it is likely that this technology will make its way into series production over the next few years. **Industrial Players:** Direct calendering: Tesla / Maxwell (US) | Extrusion: Liten (FR), EAS (DE) | Unknown: VW (DE), Targay (CA)
Laser Processing [291-297] **Impact:** Costs Sustainability Quality Throughput	Laser systems can be used at many points in the process chain for cutting, drying, structuring, contacting and packaging or improving quality. Laser applications can offer **advantages** over other state-of-the-art processes, e.g., reducing energy demand (drying), reducing operational expenditures (cutting), increasing power density (structuring) or increasing throughput and flexibility. Laser processing faces **challenges** concerning contamination in cutting processes, material damage due to high energy input (cutting or drying) or scaling the application speed to serial production with the required quality (drying, structuring, cutting of coated electrodes). **Outlook:** Due to the wide range of applications, a large number of players are active in laser processing. Technical solutions are already in series production in welding, and cutting. **Industrial Players:** Welding: e.g. Trumpf (DE), Manz (DE), Vitronics (DE), IPG Photonics (US), Coherent (US), Cutting: e.g. Trumpf (DE), IPG Photonics (US), Rofin-Sinar (DE/US), Han's Laser (CN) | Cleaning: Laser Photonics (US) Drying: Laserline (DE), Trumpf (DE) | Marking: Trumpf (DE), Rofin-Sinar (DE/US), Lumentum (US) Structuring: edgewave (DE), IPG Photonics (US)
Cell Assambly [298, 299] **Impact:** Costs Sustainability Quality Throughput	In cell assembly, optimizing the production steps is primarily about increasing throughput. This is especially necessary for stacking (e.g., high-speed single-sheet stacking or working with rotating tools) and electrolyte filling (monitoring of the wetting process or acceleration of wetting). Accelerated cell assembly has **advantages** because fewer synchronized machines are necessary, reducing the costs for investments and dry rooms. Increased throughput is **challenging** because of precision requirements with faster processes and process automation. **Outlook:** In the field of cell assembly, many already established manufacturers are continuously improving their machines. Major breakthroughs such as those made by rotating tools in stacking or by structured electrodes in electrolyte filling are still at the research stage. **Industrial Players:** Stacking: SVolt (CN), Manz (DE), Mühlbauer (DE), Sovema (IT), Hitachi Power Solutions (JP) Z-folding: e.g. Manz (DE), Mühlbauer (DE), Jonas & Redmann (DE), Sovema (IT), Wuxi Lead (CN) Electrolyte Filling: e.g. Mercedes Benz (DE), SK On (KR), BMW (DE), Industrie-Partner (DE)

Technologies	Description
Inline Monitoring [299-306] **Impact:** Costs Sustainability Quality Throughput	There are many points over the entire production process where different parameters can be checked using various measurement techniques: detection of defects or contamination in the coating (e.g., with cameras), measurement of the compressive load during calendering, monitoring of electrolyte filling and especially wetting (e.g., with weighting or ultrasound) or monitoring of contacting in cell assembly (e.g., with X-rays). Inline monitoring has **advantages** because it can improve trans-parency (traceability), increase throughput (electrolyte wetting) and reduce scrap. Inline monitoring faces **challenges** because of the need for fast and contactless measurement as well as the evaluation and in-terpretation of the data. The additional sensors and analytics required are also expensive. **Outlook:** Due to increased automation, inline measurement options are also becoming more important. Digitalization of production is a general trend that can accelerate the use of in-line measurement technology. **Industrial Players:** X-Ray: Viscom (DE), Waygate (DE), Nikon (JP), Dürr (DE), VisiConsult (DE) | Ultrasound: Liminal Insights (US) Optic: e.g. Ametek (US), Isra Vision (DE), Xiris (CA), Koh Young (KR), Dr. Schenk (DE), BST (DE) Weighing: Metter-Toledo (CH)
Mini environments [287] **Impact:** Costs Sustainability Quality Throughput	Mini environments encapsulate individual production lines, so that only a small volume needs to be main-tained in a clean or dry room atmosphere. There is a differentiation between mini environments (e.g., single production machines are separated) and macro environments (several machines are in the same enclosure). The main **advantages** of mini and macro environments are the reduced energy demand and thus lower CO_2 footprints and energy costs. The **challenges** for mini and macro environments relate to managing the intralogistics between different machines and determining the optimal process conditions. **Outlook:** Due to the many advantages that mini and macro environments can offer, many dry room manufacturers are already busy with the technical development of product solutions. At present, however, this is still at the research stage. Concrete systems (especially on a large scale) could go into series production by 2030. **Industrial Players:** Wuxi Lead (CN), FISAIR (ES), Weiss Klimatechnik (DE), ULT Dry-Tec (DE), Munters (DE)
Pre-Lithiation [299, 307] **Impact:** Costs Sustainability Quality Throughput	In pre-lithiation, introducing lithium into the anode is intended to compensate for lithium losses over the battery lifetime. The two processing routes are electrochemical pre-lithiation (anode is passed through an electrolysis bath with a lithium source) and contact pre-lithiation (lithium is first applied to a carrier foil, e.g., by PVD, and then brought into contact with the electrode). Pre-lithiation has **advantages** because it increases the energy density through full utilization of the cathode capacity. There are also improvements to the SEI and a reduction of the formation cycles is possible. Pre-lithiation faces **challenges** due to the necessity of working with pure lithium (highly reactive and complex material handling for contact pre-lithiation), the homogenization of the lithiation (electrochemical pre-lithiation), complex production machinery, and monitoring the degree of lithiation and scaling. **Outlook:** While the technology represents an additional process in electrode manufacturing, it can reduce formation time and provide longer battery life. Although the technology is still at the research stage, some industry players are trying to commercialize it. **Industrial Players:** Electrochemical: Musashi Energy Solution (JP), Rena (DE), Nanoscale (US), Mercedes-Benz (DE) Contact: Applied Materials (US), Livent (US), LG Chem (KR)

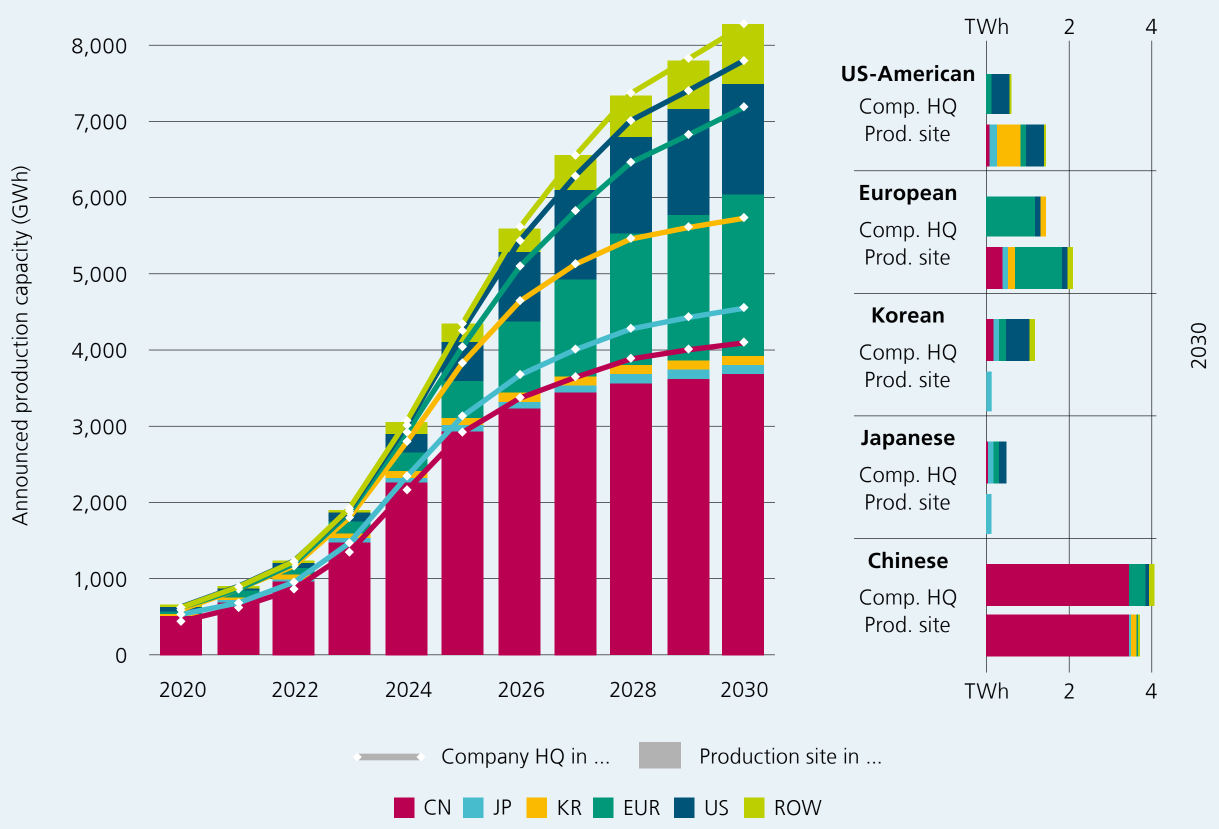
3.2.3. Cell Production Capacities by Location and Origin of Manufacturer

Within this decade, a strong increase in high-energy battery cell production capacities is expected to take place worldwide, driven by the diffusion of electric mobility and renewable energies. Battery plants have been announced by established and potential future cell manufacturers with production capacities of more than 8 TWh, which exceeds the expected demand considerably. However, it is unlikely that these capacities will be fully realized and utilized within the announced schedules, due to the high economic risk related to the large-scale investments. This is expected to lead to the failure of some projects, delays and limited utilization due to high scrap rates and downtimes, as well as technological challenges during production ramp-up. Despite this, the analysis of the announced production capacities provides extensive insights into the emerging global battery cell industry.

The most striking feature in today's global battery cell manufacturing is the dominance of Asian companies and the localization of production in China. More than half of the announced production capacities are located in Asia. Nevertheless, by 2030, around one quarter of cell production could be sited in Europe, and around one fifth in the United States (see Figure 22). Similarly, half of the announced capacities are by Chinese companies (with CATL the largest cell manufacturer according to these announcements). Furthermore, the announcements of Korean companies are similar to the sum of all the potential European battery cell manufacturers.

Korean and Japanese manufacturers, in particular, plan to scale up their production capacities outside their home countries. Chinese, US-American and European companies, on the other hand, mostly plan to establish facilities within their home regions. It is remarkable that more than 80 % of the announced production capacities of European companies will be located in Europe and nearly 10 % in the US, which is therefore the

Figure 22: Planned (announced) global battery cell production capacities until 2030. On the left the bars represent locations, the lines represent capacities at headquarters. Planned production in 2030 according to region, subdivided into company HQ and production site in shown on the right.



country with the largest cell production of European companies outside Europe. However, this value is still relatively small, indicating that the Inflation Reduction Act has not yet led to extensive relocation plans of European companies, as feared by some actors (e.g., [308]).

While joint ventures between local and foreign companies only play a small role in China and Europe, these seem to be a dedicated strategy of large US-American car manufacturers planning to enter battery cell production. These joint ventures could make up more than a quarter of US cell production capacities by 2030. Examples include Ford and CATL, or GM and LG ES. In the medium term, foreign companies will drive domestic production in the US and in Europe. Cell production in China is mostly in the hands of Chinese companies. While non-European companies are expected to dominate cell production within Europe until around the mid-2020s, this trend will be evened out by the end of the decade. However, it should also be noted that the plans of European companies, nearly all of which concern completely new or large-scale battery production, are expected to have a higher likelihood to fail than those of established Asian companies, such as LG Energy Solutions, CATL, Samsung SDI, SK On, and so on.

The announced cell production in Europe is spread over many countries and many players. LG ES in Poland, Samsung SDI and SK On in Hungary and Northvolt in Sweden currently have the largest production capacities in Europe, making these countries the largest LIB cell producers. Until 2030, most of the announced production capacities for battery cells are for Germany, Hungary, UK, and France. Eight different countries have announced plans for more than 100 GWh, indicating the intensive ramp-up taking place all over the continent. Until 2025, the announcements add up to 500 GWh, and capacities are expected to quadruple between 2025 and 2030. The largest number of companies are active in Germany (14), while UK and France are in second joint place with six companies in each country. Additional production capacities of 175 GWh have been announced for Europe in general without specifying a particular country.

3.2.4. Cell Production Capacities by Format

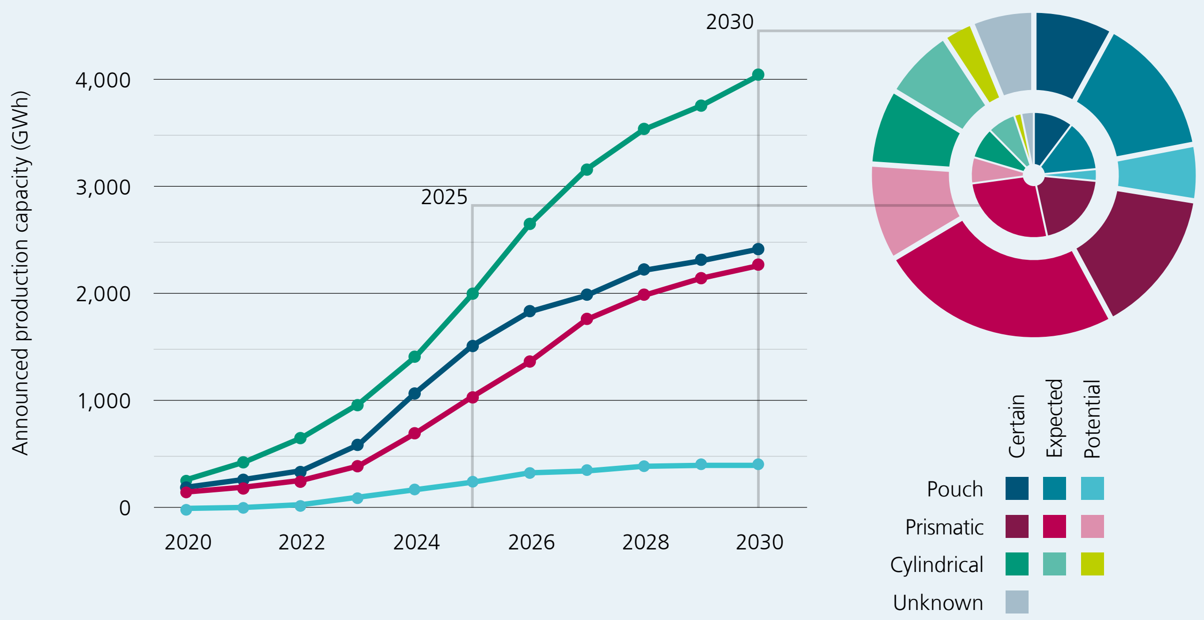
As previously mentioned (section 3.2.1), different cell formats are used for different rea-sons. Recent trends include larger formats in terms of size and energy capacity (e.g., the BYD blade cell or Tesla's cylindrical 4680 format), and some OEM pushing a standardized format for all their products (e.g., Volkswagen). Therefore, categorizing the formats into pouch, prismatic and cylindrical cells is the best way to gain insights on a general level.

The announced production capacities do not indicate any consolidation of formats so far. All formats will continue to be used. However, in terms of the announced production capacity until 2030, prismatic cells dominate with up to 4 TWh, equivalent to approx. half of global cell production. This is mainly due to the activities of large Chinese cell manufacturers, such as CATL, CALB and BYD. Until 2030, production capacities of 2.3 TWh for pouch cells and 1.5 TWh for cylindrical cells have

been announced (Figure 23). Excluding Chinese companies from this calculation results in very similar production capacities (1.1 TWh cylindrical, 1.3 TWh prismatic and 1.4 TWh pouch cells). It was not possible to allocate around 0.5 TWh to any of the three main format categories due to the lack of specification in some announcements.

However, as this forecast depends on the realization of the announcements and estimations made, it comes with significant uncertainties, as visualized in the respective Figures 23 and 24. It was assumed that most manufacturers will stick to their original format choice in future plants, if no contrary announcements have been made. Furthermore, estimations

Figure 23: Planned (announced) maximal production capacities by cell formats for the upcoming decade. The pie chart indicates the relative share of formats in 2025 and 2030.

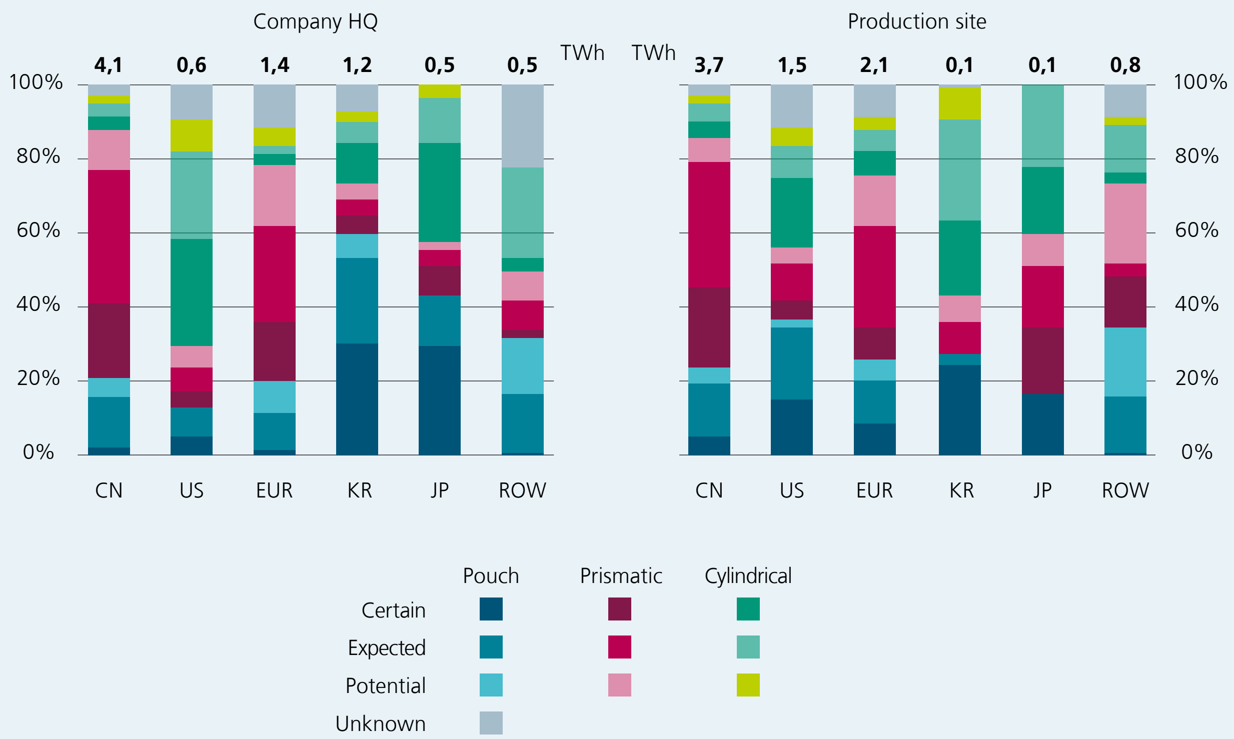


for the share of formats were made for manufacturers who are known to already produce them (e.g., in some cases 50/50 distribution was assumed). A more indepth discussion of the assessed probability of realization is included in chapter 1.2.

Some companies are known to push for one cell format, while others try to diversify their portfolio. The production of prismatic cells could be dominated by the Chinese companies CATL (potentially more than 800 GWh), CALB (around 600 GWh), and BYD (around 400 GWh). The production of pouch-type cells could be dominated by SK On (more than 300 GWh), followed by LG ES and AESC Envision. Tesla could become the largest manufacturer of cylindrical cells with production capacities of up to 350 GWh by 2030. LG ES is another large player for cylindrical cells.

As shown in Figure 24, prismatic cells are the dominant format for China and Europe in terms of production site as well as the origin of the cell manufacturers. The picture is more diverse for production capacities in the US, when including non-US manufacturers as well, with around one-third cylindrical and one-third pouch-type cells. The large share of cylindrical cells in US companies is explained by US-American OEM that often build battery cell plants as joint ventures with Asian companies (Tesla and Panasonic, GM and LG ES, Ford and CATL). Korean companies (e.g., SK On and LG ES) have a strong focus on pouch cells, while Japanese companies (e.g., Panasonic and AESC) have announced production capacities mostly for pouch and cylindrical cells (40 % each). Figure 24 shows the relative share of production of the three formats by companies from different countries/regions as well as by production site.

Figure 24: Estimated share of formats for the planned cell production in 2030 in respect to the origin of cell manufacturer (left) and production site (right).



3.2.5. Plausibility of Production Implementation and Industry Structure

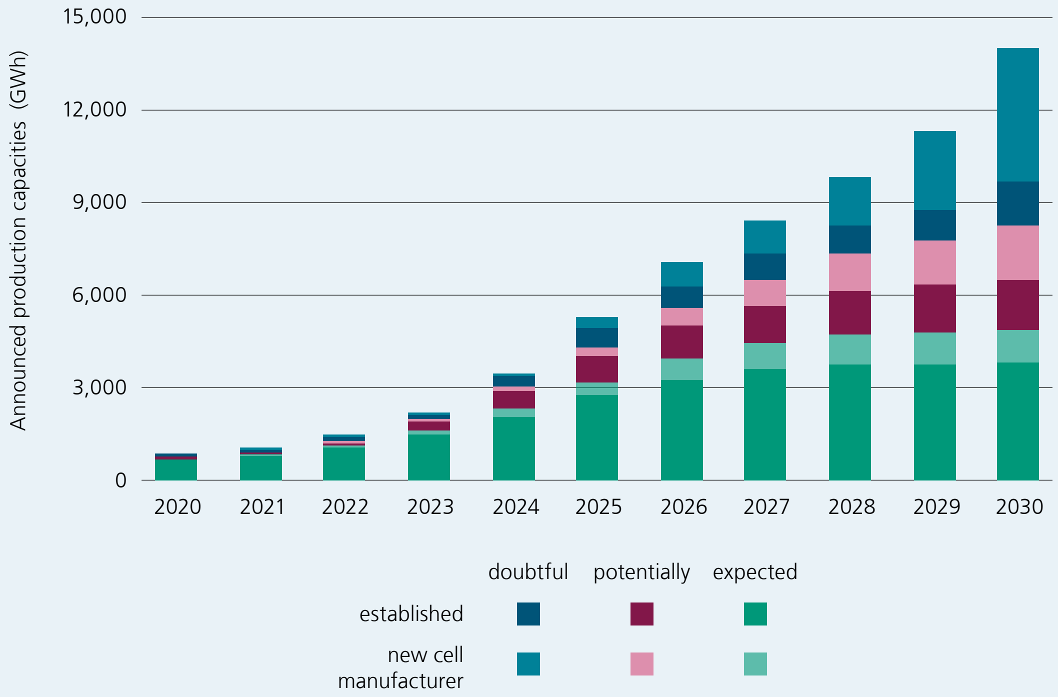
The discussions above are based solely on the announced production capacities or information gathered from market reports or comparable sources. These numbers do not indicate realistic production capacities that can be expected within this decade. However, we want to give more detailed insights into the quality of these announcements, which might help to indicate the feasibility of the respective projects being realized.

As shown in Figure 25, around 8.3 TWh of the announced production capacities can be classified as expected or potential – this value forms the basis for the analysis in chapters 4.2 and 4.3. The announcements classified as “expected” until 2030 are dominated by established manufacturers, while those classified as “potential” have roughly equal shares of established and new manufacturers. In addition to these announcements, another 5.7 TWh of capacity announcements were classified as “doubtful”.

Cell production will be strongly dominated by a few large cell manufacturers. CATL alone has announced more than 1 TWh production capacities by the end of the decade with plants all over the world. LG ES, CALB and BYD have all announced more than 400 GWh, followed by 15 other companies that have announced more than 100 GWh by the end of the decade. As indicated by Figure 26, the five companies with the largest scale-up announcements make up around half of the globally announced total production capacities in 2025, while the top ten companies account for around two-thirds. Even though their market share may decrease due to the activities of emerging cell manufacturers, the ten largest cell manufacturers are still expected to retain half of the market by the end of the decade.

Many car manufacturers plan to get involved in battery manufacturing as part of their strategy to electrify their portfolio. Some intend to invest in existing cell manufacturers, while others want to set up their own production lines.

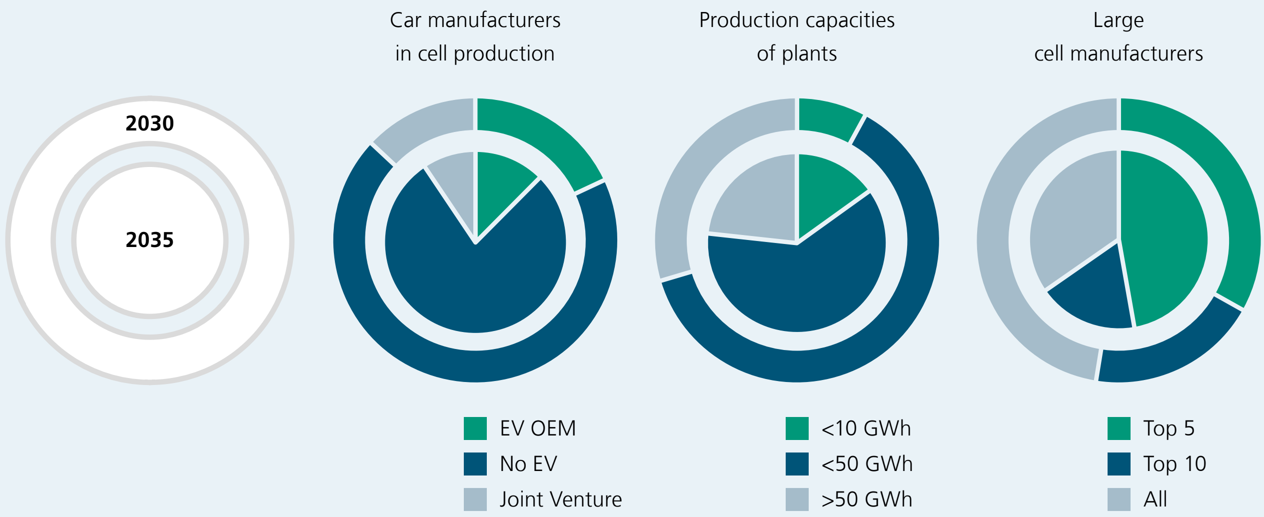
Figure 25: Announced global production capacities classified by their feasibility of realization and the experience of the potential cell manufacturer.



Cell manufacturing by EV OEM could account for around 18 % of global battery production capacities by 2030, while joint ventures between car manufacturers and cell manufacturers could make up 13 %.

Within this decade, the production capacities per production site are set to increase. By 2030, around 30 % of global production capacity will be at plants producing more than 50 GWh, and less than 8 % will be at plants with capacities of less than 10 GWh, according to the announcements.

Figure 26: Share of planned global cell production capacities according to different types of manufacturer, magnitude and production capacities.



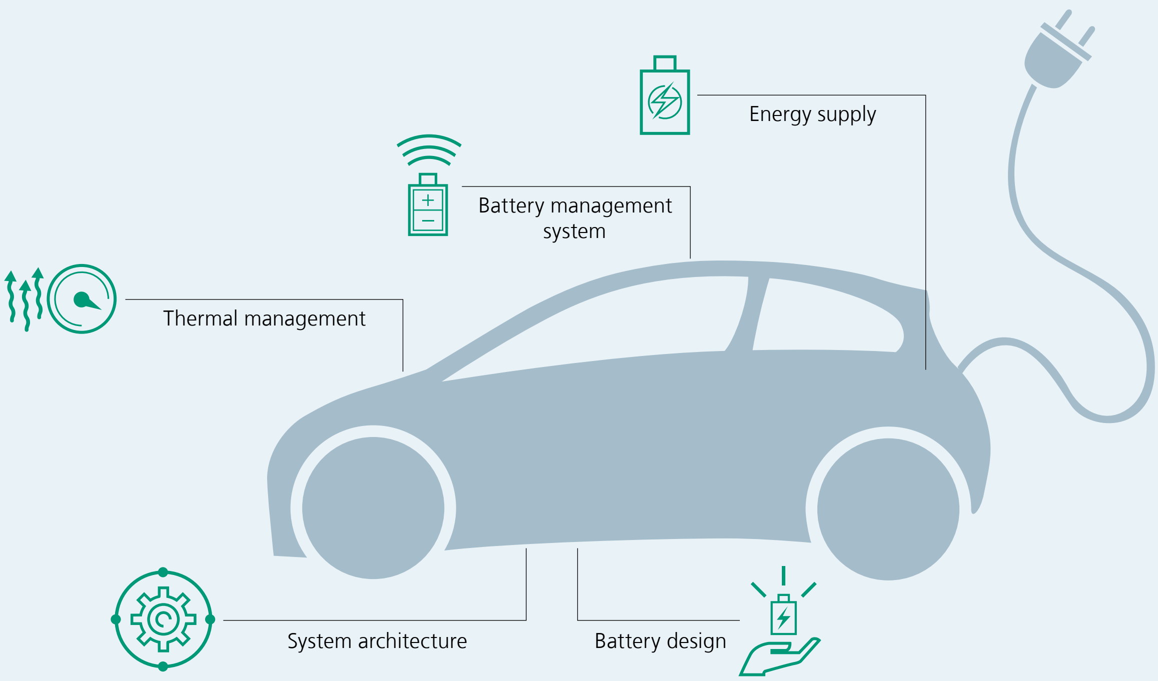
3.3. Battery Packs and Systems

Battery pack performance is influenced by various design aspects. It is necessary to optimize the design and configuration of the battery pack in order to achieve the best possible cell performance at system level. In terms of battery design, Cell2Pack and Cell2Chassis concepts, for example, are gaining the attention of different OEMs. Battery swapping solutions have also been recently reintroduced. With regard to cooling the battery system, immersion cooling is seen as an alternative to indirect cooling. Another major trend concerns the connectivity and digitalization of the battery system, with digital twins of the battery system considered particularly important. Of course there are numerous other possibilities for improvement, but those mentioned above are explained in more detail below.

Structural Battery – Cell to Pack (C2P)

A Cell2Pack system utilizes the cells as structural elements by installing them directly into the battery pack without assembling them first into individual modules. A Cell2Pack concept therefore avoids the (passive) components at module level and makes optimal use of the available installation space. A prominent application example is the Blade LFP cell by BYD, which entered the market in 2020. The Blade battery consists of several individual cells with a length of up to 96 cm. BYD is using the concept in their Han models and others. Other examples include CATL's Qilin battery, which was announced in 2022 [309], and SVOLT's Dragon Armor battery [310]. The specific energy of the Qilin battery at pack level is claimed to be 255 Wh/kg for NMC cells and 160 Wh/kg for LFP cells. The Dragon Armor battery was announced to achieve a driving range of between 800 kilometers (LFP) and over 1,000 kilometers (NMC). C2P concepts are also possible with other cell formats such as the hard case cylindrical cells used in the C2P battery packs of Tesla’s Model Y. Many OEM including BMW, Mercedes, Volkswagen and others have announced their intention to use C2P concepts in future models [311-313].

Figure 27: Illustration of battery system components.



Structural battery – Cell to Chassis (C2C)

The C2C design represents a further evolution of the C2P design, in which battery cells are integrated directly into the vehicle chassis. This allows the installation space to be used even more efficiently. The battery explicitly serves as a structural support for the chassis, which means that the overall weight of the vehicle can be reduced at the same battery capacity thus also saving costs. Another advantage is the lower interior floor, which permits more efficient use of the vehicle's interior space [314]. Volume utilization can be increased by about 50 % compared to conventional module-based designs. C2C concepts can also achieve cost savings of around 35 % compared to conventional module-based batteries [315].

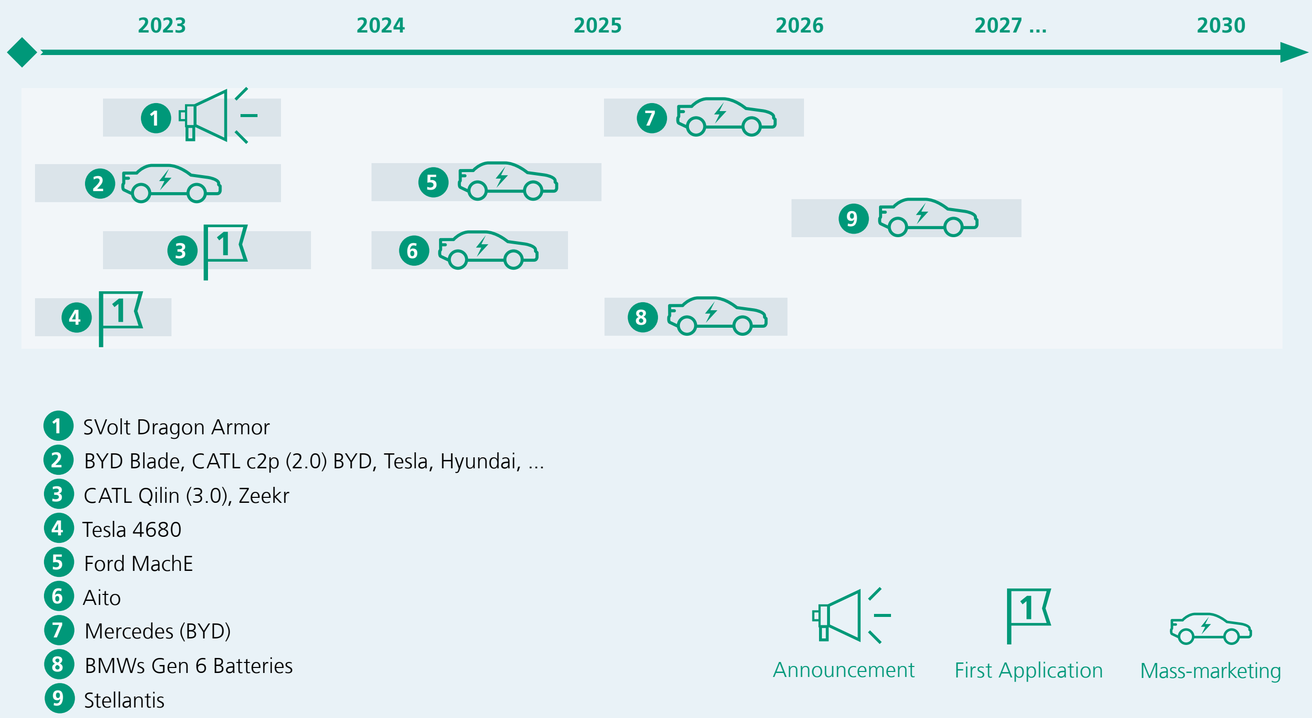
However, due to its more exposed position, the battery must be protected from external impacts or corrosion. In addition, integrated designs can make it more difficult to recycle or replace a battery. This must be addressed by the corresponding chassis design [316]. In addition to C2C, there are already approaches that go even further. The company 24M announced an electrode-to-pack system at the Japan Mobility Show in 2023. Such an approach would further optimize the use of passive materials and thus energy density as well as costs [317].

Swappable battery

In contrast to charging an electric vehicle by plugging it in to a power source, battery swapping remove the empty battery from the vehicle and replaces it with an already charged battery fully automatically. The advantage of this solution is the elimination of charging time, although swapping the battery also takes several minutes [325]. In addition, using exchangeable batteries permits different business models for car sales, as the battery can be considered a rental good which reduces the purchasing costs of an electric vehicle. In addition to the direct use of the battery as a traction battery, there is also an additional business model for the exchange station operator, where the batteries can also be used for grid regulation, for example. In addition, battery swapping means it is easy to change the size of battery in the vehicle and appropriately sized, application-dependent batteries can be rented.

Since swappable batteries are not standardized in terms of interoperability between different OEMs, the exchange stations are usually brand-specific and not available to other manufacturers. The infrastructure available so far has been built mainly in China, where individual OEMs play a leading role.

Figure 28: Industry announcements on the manufacture and implementation of C2P concepts [309, 310, 318-324]. The illustration is not exhaustive.



The battery swapping idea is not a new one. As early as 2013, the Israeli company Better Place wanted to set up a nationwide infrastructure for battery exchange in cooperation with Renault-Nissan. A decade ago, Tesla was working on battery swapping in order to make the charging time of its cars comparable to refueling at a filling station [326]. Since then, however, Tesla now relies primarily on its Supercharger network. In Asia, especially in China, battery swapping has been offered by several manufacturers for some years now. The Chinese company Nio has adopted this concept and currently operates around seven "Power Swap Stations" in Germany and around 27 across Europe. Worldwide, Nio has more than 2,000 swap stations, the vast majority of which are located in China (approx. 1,975 stations) [327]. Nio's current swap stations can store 21 batteries (at present only suitable for Nio EVs) and the company claims swaps are performed in about 3 minutes [327]. It is worth mentioning that the standardization of batteries in China was propelled by Nio and Geely, who now offer the first cross-manufacturer battery swaps in China. Nio is not the only manufacturer active in this field. Contemporary Amperex Energy Service Technology Ltd. (CAES), a subsidiary of CATL, also launched the battery-swapping brand EVOGO in 2022, and is currently setting up a battery-swapping infrastructure in China. Several Chinese companies have announced more than 20,000 swap stations for BEVs by 2025, mainly focused on Chinese cities [328].

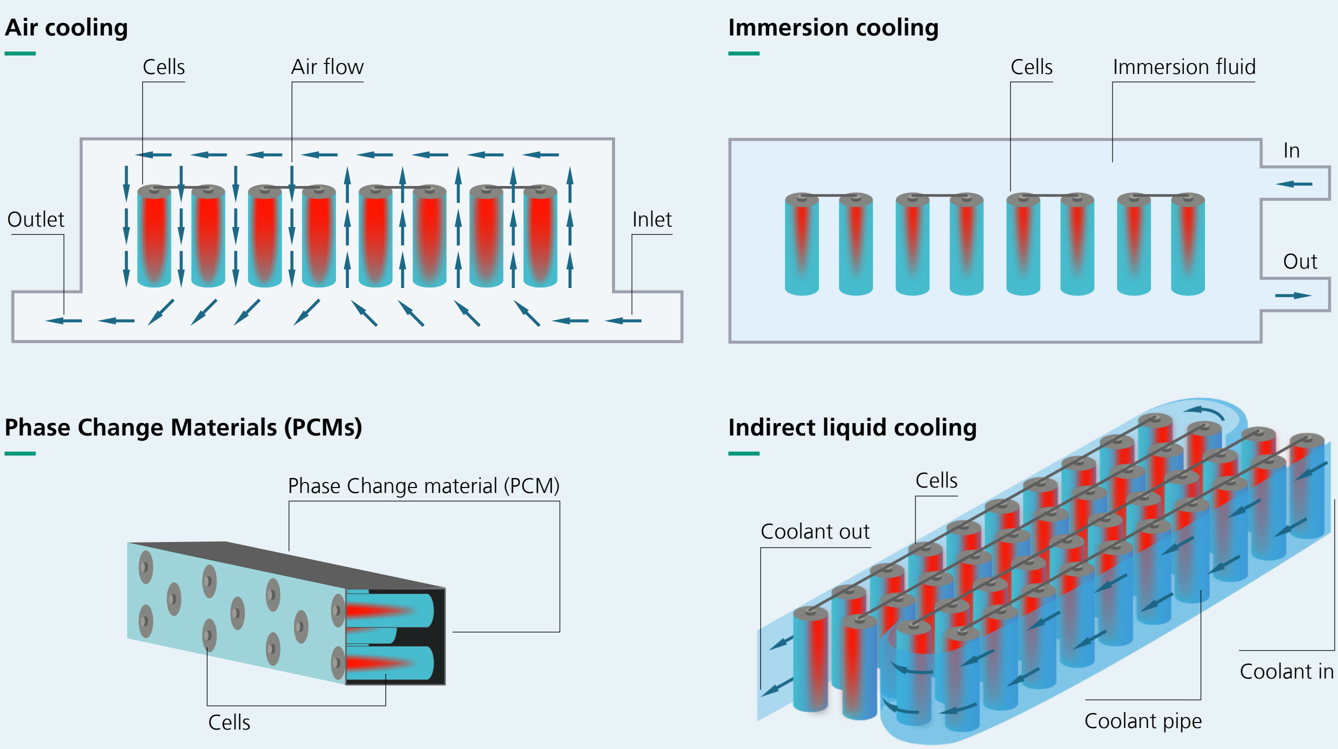
Cooling concepts

Cooling is necessary to keep the battery cells within an optimal thermal window. Typically, three different types of cooling methods are used: (1) air cooling, (2) indirect cooling and (3) immersion cooling. Air cooling dissipates heat via an airflow, but this method has a low cooling capacity and is therefore not really suitable for automotive applications [329], even though it was used in an older version of the Nissan Leaf, for example [330].

Today's vehicle models predominantly use indirect cooling systems based on a water-glycol mixture. Here, there is no direct contact between coolant and battery cells, and heat is transferred indirectly via cooling plates. Compared to air cooling, indirect cooling is more efficient, but associated with higher complexity and costs.

Direct cooling or liquid immersion cooling is even more efficient. As the name suggests, battery cells are cooled in direct contact with the coolant. This cools better than indirect or even air

Figure 29: Illustration of cooling concepts for battery packs [338].



cooling [331]. In addition, this cooling variant is less complex than indirect cooling, which is also reflected in the reduced total weight for cooling [331]. Even though the coolant is in direct contact with the cells, fire protection can be ensured by mixing in appropriate flame-retardant additives. The risk of short circuiting is even lower here due to the use of dielectric materials. Despite these advantages, direct cooling still faces certain challenges. For example, selecting an electrically non-conductive base fluid and heat-resistant additives is hard to do and impurities can be formed in the fluid during operation [329].

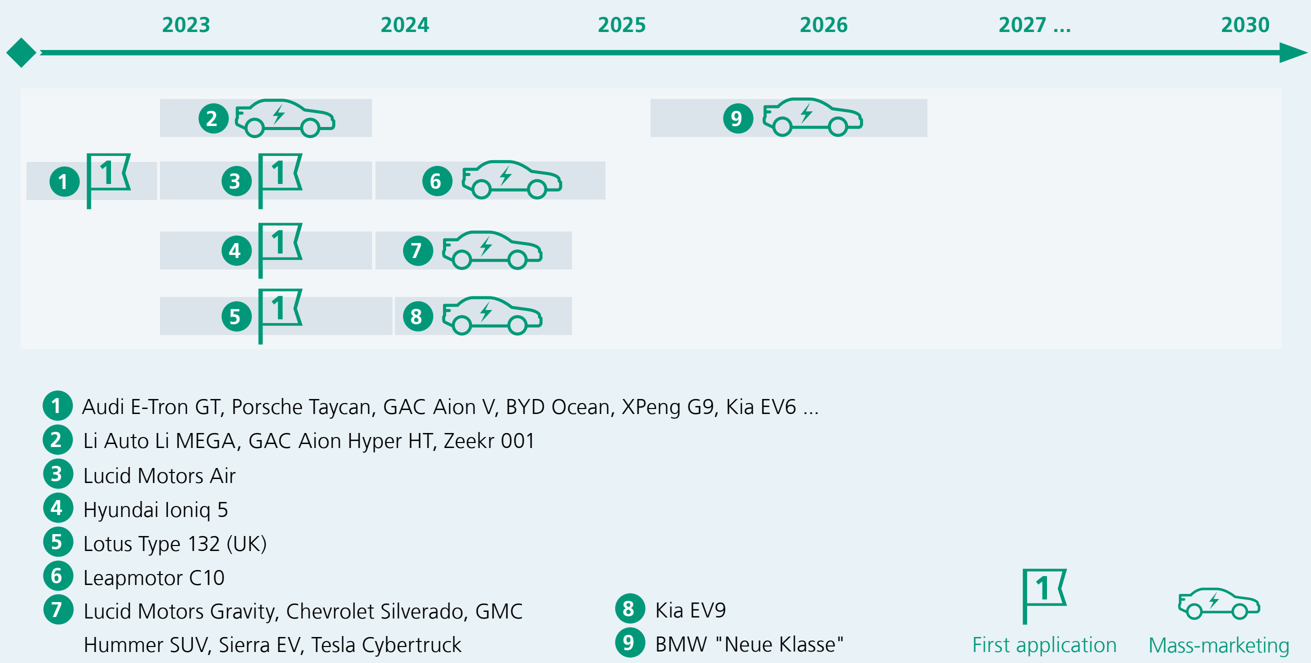
One application example for this technology is Xing Mobility's Immersion CTP, announced in August 2023 [332]. The BYD's Seal will also have direct cooling [333]. Other manufacturers have also upped their efforts in this area. In 2020, Kreisel Electric and Shell announced a battery solution that combines Kreisel's Li-ion module technology with Shell's thermal management fluid [334]. The two companies claim that their solution increases efficiency, enables fast charging and offers improvements in safety and stability. In 2021, automotive supplier Mahle developed a novel battery cooling system that uses immersion cooling as a key technology to enable faster charging of electric cars [335].

The use of phase change materials (PCMs) is a passive cooling alternative for thermal management. Taking advantage of the high latent heat, PCMs can absorb the enormous amounts of heat and thus reduce both the maximum temperature and the temperature difference in the battery pack. PCMs undergo a phase change from solid to liquid when heated. Organic PCMs (e.g., paraffin) or inorganic PCMs (e.g., hydrated salts) can be used. PCMs are relatively inexpensive and, due to their passive mode of operation, relatively energy-efficient. However, since heat is normally only stored and not dissipated, it is important to avoid exhausting this storage capacity at higher ambient temperatures or charging rates. Combining this with an active cooling system is an option. Unfortunately, the active cooling system counteracts the advantages of PCMs. For this reason, PCMs are still the subject of research and not yet used in EVs [336, 337].

800 V battery systems

In 2019, Porsche launched its Taycan. This was the first series vehicle based on 800 V technology, even though most electric vehicles on the market today are still equipped with a 400 V system [339]. Switching from a 400 V system to an 800 V system offers several ad-vantages, e.g., doubling the power at the same current or, conversely, halving the current at the same power. This can directly increase performance.

Figure 30: Industry announcements on the use of 800 V systems [343-350]. The illustration is not exhaustive.



The resistance losses in the cables, which scale with the current squared, are minimized. In addition to increasing the efficiency of the battery system, this also means that external cooling can sometimes be avoided during charging. One of the greatest advantages of the 800 V system is particularly evident during charging. While a 400 V system, for example, is only able to charge at 200 kW, a similar 800 V architecture allows a theoretical charging power of 400 kW. This means, in theory, that charging time can be halved.

Its novelty and the associated lack of standardization are drawbacks associated with the 800 V concept. The 400 V system represents the international standard and charging stations etc. are predominantly equipped for this technology. Additionally, the higher voltage places additional demands on safety. For example, components such as switches, fuses or cables might have to be replaced by components with a higher voltage resistance, and additional safety elements might have to be added.

Despite these drawbacks, many other manufacturers such as Audi, BYD or KIA have already launched their own 800 V models or have announced their intention to do so (e.g., VW, BMW) [340-342]. The current and announced vehicles are mainly high-performance and in upper middle-class or luxury segments.

Smart Battery Management Systems

The task of the Battery Management System (BMS) is to control and protect the battery. The BMS monitors charge status (SoC), battery health (SoH) and optimizes battery performance. The BMS usually consists of a BMS slave, which is responsible for signal reception and filtering, and a BMS master, which diagnoses the battery. These are connected to each other. Current trends in BMS include making the system more intelligent and advancing its digitalization. A major step toward making the BMS more intelligent is to link it directly to the power electronics. Traditional battery management systems are separate from the power electronics. BMS controls the power converter, while the power electronics is responsible for charging, discharging and motor control. With the development of broad-band semiconductors, future power electronics could be used for battery management without a separate BMS. When combined with cloud computing technology, intelligent power electronics could also offer the diagnostic support [351, 352].

Data from the battery could then be stored in a cloud BMS, and analyzed via cloud computing, e.g., using machine learning. The use of a cloud-based BMS reduces the burden on the onboard BMS. A digital twin of the battery, which is the digital image of the physical battery, also plays an important role. The combination of cloud computing and the Internet of Things (IoT) makes it possible to determine the SoC and SoH of the battery and to control them in the most effective way. Using machine learning, the data stored in the cloud can be analyzed and the system can be optimized to increase battery life. The wireless linking of slave and master also makes it possible to reduce component costs and the system's physical susceptibility to errors. Furthermore, the digital twin offers the possibility of documenting and transparently displaying the relevant vehicle data over the vehicle's service life. This is important, for example, if the vehicle is resold. With the Battery Regulation and the planned introduction of a Digital Product Passport (DPP), this possibility to document and transparently display battery properties will be highly relevant and is set to play an important role in the introduction of a circular economy for batteries [351-354].

Hybrid battery packs

The performance requirements for electric vehicles can be very diverse and sometimes contradictory in terms of the demands on the cells. A mixture of cells can be used to fulfil the requirements of an application. The best-known example of this is the combination of high-energy and high-performance cells. The application can then benefit from the advantages of both cell types, although compromises have to be made, for example in terms of absolute power or energy capacity [355]. Combining NMC cells with LTO cells enables high total energy and, at the same time, the LTO cells enable high charging rates and increase the lifetime of the high-energy cells by relieving them from power peaks. The combination of LFP and NMC is a variant that combines the high safety and service life of the more cost-effective LFP cells with the superior performance of the NMC cells. In 2021, the manufacturer Nio announced the introduction of such a mixed battery in combination with their C2P architecture [356]. CATL also presented a combination of lithium-ion and sodium-ion cells in a ratio of 2:1 and in a certain arrangement through series and/or parallel integration. In addition to lower costs, this results in further advantages in terms of the battery's low temperature behavior, increased safety with regard to thermal runaway and reduced cooling requirements [357]. Although these hybrid concepts increase the demands on the BMS and power electronics, they also allow a high degree of flexibility when adapting battery systems to specific application requirements.

3.4. Battery Recycling

Battery recycling at the end of a battery's life cycle specifically includes the recovery of battery components and materials. Various different recycling processes exist that can be categorized into three groups: pyrometallurgical recycling, hydrometallurgical recycling and mechanical recycling. Processes from these groups are typically combined in order to achieve the most efficient material recovery in terms of quantity and quality. The first steps before the actual recycling processes are the testing, discharging, sorting and disassembly of the EoL battery packs into modules and cells. After this, many process routes start with mechanical processing steps, e.g. shredding and mechanical sorting in order to obtain the black mass. Some components such as housings can be extracted in this step. The black mass is then recycled via hydro- or pyrometallurgical processes to recover the valuable battery materials. Different recycling routes are possible, many of which are currently being developed or are already at pilot or industrial scale [7, 358].

One main area of focus in the industry is the automation of the sorting and dismantling process, which can significantly increase the speed of pre-treatment and thus reduce the costs of the upstream recycling process. One of the biggest challenges for the disassembly itself is the wide variety of LIBs, or packs, cell formats and chemistries. Because of this diversity, semi-automatic disassembly is proving to be a good option for the time being [359]. In the longer term, recycling-friendly design could contribute to the introduction of more automated dissassembly processes [360].

In the pyrometallurgical process [7], battery cells or modules are heated in a series of temperature ranges directly after the dismanteling process of larger battery packs, for example, in order to first utilize the organic components energetically and then, depending on the temperature stage, reduce the metal compounds. The resulting liquid metal alloy consists of Co, Ni, Cu, Fe, with Li, Mn and Al ending up in form of oxide compounds in the slag. Both the separation of the metals from the alloy and the recovery of lithium from the slag are usually carried out by hydrometallurgy post-treatment. Industrial operations that utilise pyrometallurgy as a core process include Umicore [361] Nickelhütte Aue [362], Nippon Recycle Center Corp [363] or Glencore [364].

The hydrometallurgical process [7] uses (acid-based) dissolution and precipitation, filtration or solvent extraction processes to separate and recover the metals. This process can also be used without pyrometallurgical pretreatment. In this case, the metal compounds in the black mass from the mechanical pretreatment are chemically dissolved, and high-purity raw materials are recovered by the above-mentioned extraction processes. Industrial operations that utilize the hydrometallurgical as a core process include BASF [365], SungEel HiTech [366], ACE Green Recycling [367], Neometals [368] or Northvolt [369]. Other industrial operations are for example Duesenfeld [370], TES [371], Mercedes-Benz [372] or Volkswagen [373].

Both the very high temperatures required for pyrometallurgy and the waste water treat-ment of the hydrometallurgical process are critical in terms of sustainability. New processes, such as mechanochemical [374] or froth flotation [375], are under investigation to improve material separation and recovery rates while reducing the environmental impact. The recycling of the graphite anode has also been investigated recently [376-378]. Although it is still of less economic interest, it might be of strategic interest since it is a critical raw material which is highly dependent on the Chinese supply chain [379]. The recycled graphite can be reused in batteries, but also in other areas such as in supercapacitors or for catalysis [380].

Material recovery is not only important at the battery EoL but also during cell production. In this context and in addition to the rather complex, costly and environmentally harmful (established) processes, research is also being carried out into the direct recycling of production waste for immediate reuse of the active materials for new electrodes. In this approach, the defective electrode is crushed and the cathode or anode material is separated from the electrode, whereby the separated black mass can be returned to the electrode production. Direct recycling is still in the research phase and represents a relatively new technique (there is some first industrial activity, e.g. by PNE [381]) but it has the potential to optimize material utilization in the production and reduce environmental impact in terms of production waste handling and circular economy discussions [382]. In addition to the direct recycling of manufacturing scrap, there is also discussion of its potential for recycling traction batteries.

The approaches of reusing (i.e. an already used traction battery is used in (another) mobile application with less demanding requirements), repurposing (i.e. a second life ESS built with used traction batteries) or remanufacturing (refurbishing and restoring the battery for an extended lifetime) are also being discussed as crucial for a more sustainable battery lifecycle. For example, second-life results in cost and environmental benefits by extending the batteries' lifetime [383, 384]. In particular, used batteries from electric vehicles with a sufficient capacity of typically 70-80 % SoH might serve in a second life in a less demanding stationary application and thus cover the increasing demand for stationary battery storage. Because of the high potential of second life, several major automotive OEMs have started to investigate second-life applications for used electric vehicle batteries [385-387]. However, second-life applications still face challenges before becoming widely adopted. These challenges relate to aspects such as the additional processes required, a mismatch of first and second life requirements, battery health and advanced battery diagnostics, missing open standards for the exchange of design and status information, or warranties and liability issues [384].

Capacity developments

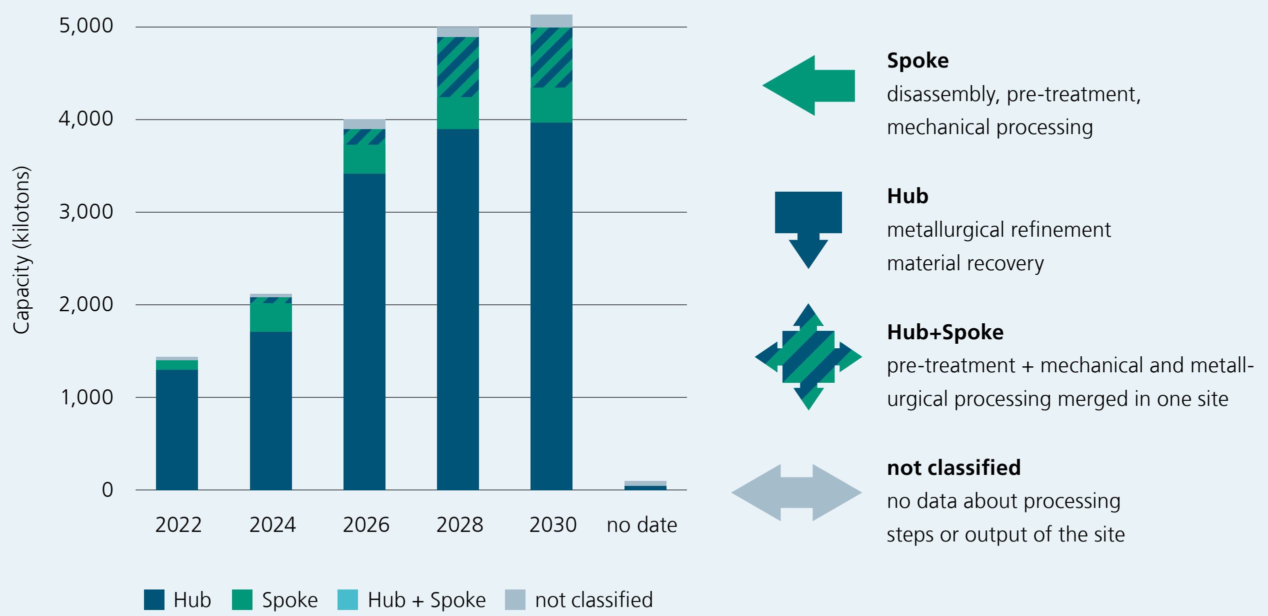
While currently reycycling activity centers around used batteries from consumer electronic applications (i.e., mobile phones, laptops) and scrap from cell production, end-of-life batteries from electric vehicles are expected to represent the highest share from 2035 onwards [7]. Due to the high demand for batteries and the small number of returning batteries, recyclates will only be able to provide a small proportion of the battery materials required in the medium term. Yet, in the long term they can reduce the dependence on battery raw materials to a significant extent [7].

Together with the increasing quantities returned, this increases the attractiveness of recycling also from an economic perspective, so that intial market activity has started to emerge. In addition, the LIBs used today contain numerous valuable and, in some cases, critical materials that make recycling particularly attractive from an economic perspective. These include cobalt, nickel, lithium, copper and aluminum. In terms of quantity, aluminum, nickel and copper make up the largest share. In terms of value, cobalt and lithium are the most important.

Recycling sites can be classified according to recycling depth into so-called spokes and hubs. Spokes are capable of performing the first steps of the battery recycling process to the so-called black mass, containing the cathode and anode active materials (which in-clude most of the valuable metals). Hubs can perform the second step of battery recycling: The black mass is refined using the (electro-)chemical, hydrometallurgical or pyrometallurgical processes mentioned above, allowing valuable substances such as cobalt, nickel and lithium to be recovered.

Figure 31 shows the globally announced LIB recycling capacity for hubs, spokes, fully integrated recycling plants (hub+spoke) and for sites that cannot be classified. Cumulative global battery recycling announcements for 2030 indicate a capacity

Figure 31: Planned cumulative global recycling capacities in kilotons per year according to facility type and planned (announced) construction date.



of approx. 4,000 kilotons per year of processing capacity for material recovery and approx. 400 kilotons per year if only the pre-treatment processes and black mass production are considered. From 2024, China is expected to dominate the ramp-up of hub capacities, whereas European industrial activities in particular will dominate the ramp-up of spoke capacities in relative terms. Note that based on these data, a forecast of battery recycling processing capacities up to 2030 is only possible to a limited extent: The in- and outputs of the recycling facitilites are often not exactly clear and data availability is limited, especially where Asia is concerned. Hence, it can be assumed that collection, sorting and mechanical pre-treatment, especially in the so-called spokes, is rather informal [388] and therefore difficult to identify. Whereas in Europe, the existing capacity and announcements are based on a very large number of companies and start-ups in battery recycling, in Asia there are numerous announcements regarding significant capacities by large and established companies.

Globally, approx. 89 % (59 % in Europe) of the announced recycling capacity can be categorized as hubs, 7 % (35 % in Europe) as spokes, and 4 % (13 % in Europe) of the announced sites could not be categorized, i.e., it is unclear whether the announcements refer to hub or spoke capacity. Together with the generally low availability of data (e.g., construction years or capacities for the announced sites), and a high share of unclassified sites (of which approx. 25 % of the capacity is located in China) this results in a high degree of uncertainty regarding overall recycling capacity.

Currently, and presumably in the future, most of the capacity is located in China, but substantial capacities have also been announced for Europe, amounting to more than 400 kilotons per year (spokes and unclassified sites) and 470 kilotons per year (hubs) by 2030. The particularly high number of recycling sites in Germany is striking. The existing current capacity in Germany is approx. 100 kilotons per year in 2023 [389]. Announcements indicate additional capacity of approx. kiltons per year (hubs) and 130 kilotons per year (spokes) by 2030. In the coming years, however, countries such as Spain, and the UK as well as Eastern European countries such as Romania, Poland and Hungary will also increase their capacities and thus diversify the project situation in Europe.

The highest capacity announcements come from the Chinese company Brunp, a subsidiary of CATL. Another Chinese company, GEM, has already built substantial battery recycling capacities. Other companies with announcements of large capacities are Camel (China), Gotion (China), Gravita (India), SungEel HiTech (South Korea), Li-Cycle (US), Redwood Mate-rials (US), Guanghua Sci-Tech (China), Eramet (France). Each of these companies is expected to have a capacity share lower than 15 % in 2030. The European companies with the big-gest capacity announcements by 2030 are Umicore (Belgium), Eramet (France), InoBat Auto (Slovakia), Avesta Battery and Energy Engineering (Belgium), Altillium Metals (United Kingdom), Librec (Switzerland), BASF (Germany) and Northvolt (Sweden).

Sites are often planned in close proximity to battery material producers, battery cell manufacturers or automotive manufacturers. During the ramp-up phase of cell production, but also during ongoing operations, relevant quantities of production scrap have to be recycled. For example, the high density of recycling facilities in the eastern region of Germany can, for example, be explained by the battery cell production facilities of Tesla and CATL. SungEel HighTech, for example, has installed its new recycling plant for production scrap not far from the LG ES cell manufacturing facility Wroclaw in Poland. Hence, market dynamics for recycling in the European region are driven, among other things, by the establishment of battery cell production sites.

4. Implementation Outlook

4.1. Technology Roadmaps

Many product and manufacturing innovations have the potential to improve LIB. The specific type of improvement depends largely on the application's or target system's requirements.

Here, we chose three objectives for the implementation of new technologies: (1) to optimize the performance of LIBs, e.g., in terms of energy density and fast charging capability; (2) to optimize the cost of LIBs; and (3) to minimize the environmental footprint of LIBs. While these three objectives sound desirable overall, the individual KPIs of a LIB often have conflicting objectives, making it impossible to optimize all the characteristics at the same time. For example, there is cross-talk between components: new active materials require adjustments to the electrolytes; in addition, changes in battery design affect several levels of the battery hierarchy: new active materials affect the way cells can be built and require adjustments to the system-level BMS. All these interactions must be taken into account when optimizing LIB.

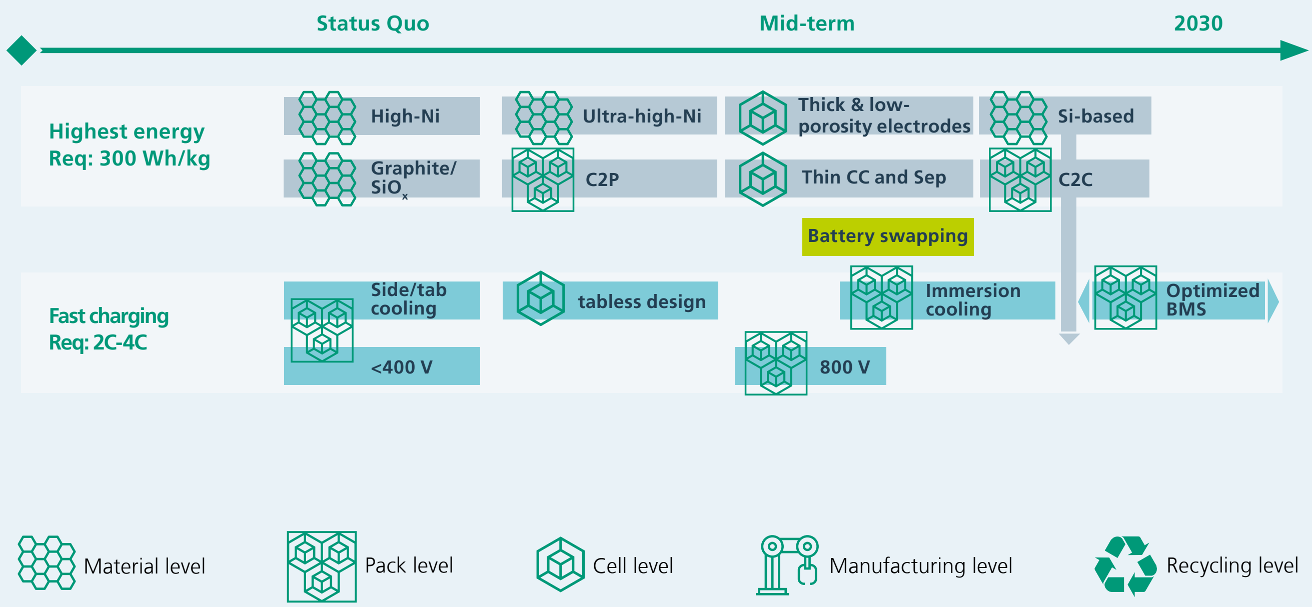
The target system of LIB is very complex and cannot be summarized using only the three chosen parameters: performance, cost and environmental footprint. In the following, we assume that the other non-mentioned parameters, such as safety, lifetime, temperature stability, manufacturability and others, can be maintained at least at the level required for the respective applications. As an example, there is a trade-off between increasing the energy density and implementing passive safety components in the battery (cell) design.

4.1.1. Performance-Optimized LIB

High performance in LIB often means high energy density and fast charging. However, in many cases these two parameters conflict. There are opposing designs of materials, electrodes, cells and systems for high energy and for high power / fast charging (see section 3.2.1), since energy increases in proportion to the volume of active materials, while power increases in proportion to their surface area.

High energy LIB can best be achieved using Si-dominated anodes and high capacity cathodes, namely high-Ni CAM. A further increase in energy, independent of the active materials used, can be achieved by increasing electrode thickness and decreasing electrode porosity. The downside of this approach is the challenges associated with the stability of both anode and cathode, which affects both cycle stability and safety. Possible solutions are the use of stabilizing blends (CAM) and advanced Si-compatible binders and electrolytes.

Figure 32: Technological approaches and implementation perspective for the performance optimization of LIB.



If the announcements of the major cell manufacturers are anything to go by, ultra-high Ni CAM can be taken for granted. Cells with more than 90 % Ni and well over 200 mAh/g at material level will soon be on the market. The situation with Si-dominated AAM is more cautious. Most of the announcements about production and use are not coming from the large cell manufacturers, but from smaller players and start-ups. The commercialization of Si-AAM with capacities above 1,000 mAh/g on a large scale could take until after 2025.

The arrangement of the cells in the battery pack also has a major impact on the real energy density at the application level. The absence of modules in C2P concepts can significantly increase energy density. However, because of the omitted level, safety must be established at the cell and pack level. This can be challenging, particularly for high-energy materials. Battery analytics, using data from the BMS in predictive diagnostics for ageing prediction, performance monitoring or failure prevention, is one way to prevent thermal runaway. To this end, the monitoring of voltage, current and temperature is crucial and differ for the range of cell formats and chemistries.

Industry roadmaps are however clear on the point of direct cell integration. With the exception of some sport and premium segments, the announcements of almost all major OEMs indicate that future battery concepts will allow direct C2P, even for cells with high-energy materials such as Ni-rich CAM.

In electrode and cell design, higher fast-charging requirements might mean that electrode layer thicknesses are not increased any further and porosities and current collector thicknesses are not reduced any further. This additional lever for increasing energy density would therefore remain unused. In some cases, however, increasing energy density and improving fast charging capability go hand in hand, or are at least not mutually exclusive. Si as an AAM is one example, as the alloying kinetics with Li appear to be significantly faster than the intercalation kinetics of Li in graphite. This high-energy material would therefore also increase power density. Other approaches to fast charging affect the higher levels of cell and system design. The "tabless" design of current collectors in large cylindrical cells can already be considered a standard for all future developments in this area. At the system level, approaches such as immersion cooling, software-based optimization of the charging process by the BMS or increasing the cell voltage to 800 V should further contribute to fast charging capability. The latter approach, in particular, is being pursued by many OEMs and is likely to become increasingly common in the premium segments over the next few years. The extent to which more expensive power electronics will lead to differentiation in mid-range and entry-level vehicles is still unclear.

A completely different solution is offered by battery swap concepts that could achieve very short refueling times for EVs without fast-charging capability. So far, this option is only widely used in China.

Manufacturing processes and recycling approaches are not explicitly considered in the concepts aiming to optimize LIB performance. In fact, the best performance can often be achieved by using established manufacturing methods such as NMP-based coating with PVDF-based binders for the cathode and solvent-based processes with specialized binders for the anode. Recycling design is also often not consistent with achieving maximum performance and is made more difficult by the use of material blends.

4.1.2. Cost-Optimized LIB

Material and component costs continue to represent the largest proportion of LIB costs. To reduce raw material costs, the industry is focusing on Ni-free and Co-free LFP. Lithium remains the main cost driver in this system, but significantly lower material costs are possible compared to NMC-based cathodes. At the cell level, however, the advantage of LFP cathodes is offset by their lower energy density. For the same storage capacity, LFP cells require more anode material, current collector, separator, electrolyte, and other passive components than NMC cells. Although the lower cell voltage of LFP means that fewer expensive additives need to be used in electrolytes, cost optimization still requires further reductions in passive components, such as reducing the thickness of the current collector and separator.

A second lever to optimize costs that is increasingly being used is the transition to larger cell volumes. Cost savings can be achieved in cell manufacturing and system-level integration. This is where the characteristics of low-cost LFP go hand in hand with the ability to be integrated. C2P approaches are based on ensuring a high level of safety at the cell level, so the majority of C2P packages in use today actually use prismatic LFP cells, which can also be classified as comparatively safe.

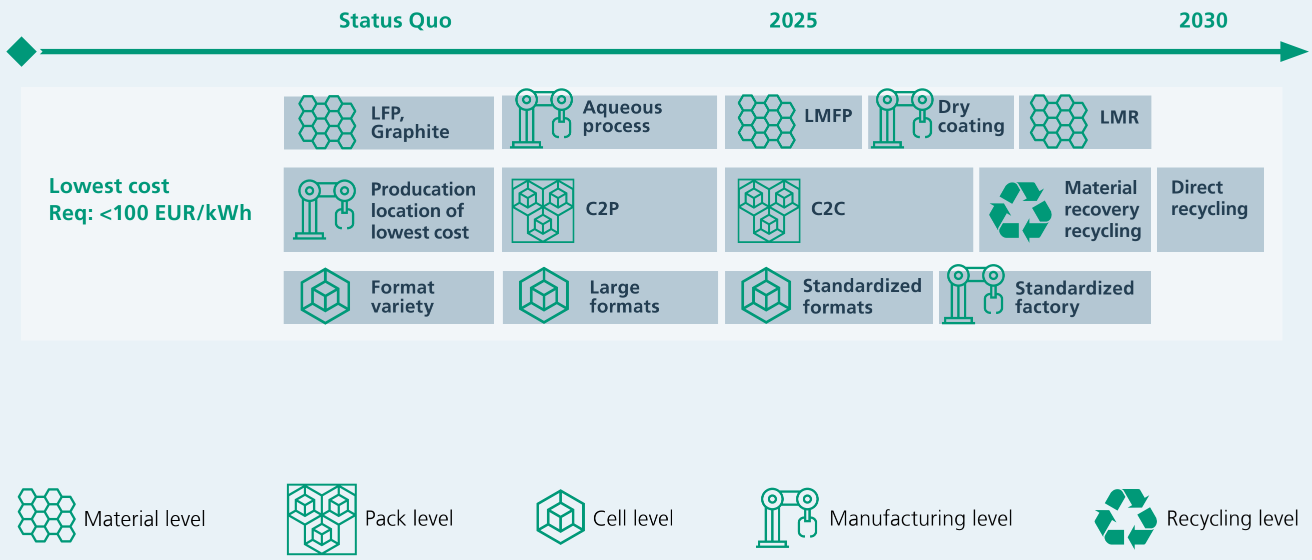
The use of these approaches (large format LFP cells with reduced passive components) also has disadvantages. Due to the limited voltage and capacity, LFP will not reach the energy density of the more expensive Ni-based cells. The transition to LMFP, and in the long-term to LMRs, as a CAM could decrease this difference, but it is unclear whether the low cost of LFP cells can be maintained when transitioning to LMFP or LMRs. At the system level, large cell sizes also impose limitations. The greater the energy in a single cell, the greater the damage in the event of an accident. In addition, concepts such as 800 V system voltage become impossible due to the rather small number of cells in the pack.

Many international OEMs have committed to LFP as a low-cost option, at least for their entry-level models. Chinese OEMs have been using the technology for some time, while US and European OEMs either already have models with LFP batteries or plan to introduce them by 2025. This trend also continues in the supplier industry. According to announcements, Chinese LFP cell manufacturers will soon be joined by some of their South Korean and Japanese counterparts. Some European cell manufacturers or joint ventures between US OEMs and Asian cell manufacturers are also planning to enter the LFP market. While the technology itself is of course location-neutral, at present, not only cell production but also material production is essentially limited to China. This is the result of the strategy adopted by the Chinese government a few years ago, as well as the fact that LFP is a low-cost technology. China currently offers the most favorable location conditions in terms of labor, energy, materials, and other costs. Whether competition from other players and regions will be successful, or whether low-cost optimization of LIB will continue to be synonymous with manufacturing in China, remains to be seen.

New production technologies could bring fresh impetus to the competition for low-cost cells by changing the cost structure of cell production. Although cell production does not affect material costs, it does affect important cost components such as energy and equipment. This is where many new process technologies come into play: Drying time and energy consumption can be reduced by further decreasing the solvent content in the electrode coating. The use of aqueous pastes can eliminate the need for expensive and time-consuming NMP recovery. New drying methods (infra-red, laser) make it possible to reduce the size of the production line. The ultimate goal here is dry coating and thus significant cost savings in electrode production. In cell assembly, mini-environments, for example, are designed to reduce the operating costs of drying rooms.

To date, all of these technologies have only been used in isolated industrial cases. A holistic machinery concept is not yet commercially available, so that only gradual diffusion can be expected by 2030. The applicability of some of the above mentioned processes also depends strongly on the active materials and cell design used. Fortunately, most of the new process technologies seem to be compatible with the low-cost materials LFP and graphite. This is promising for the lowest

Figure 33: Technological approaches and implementation perspective for the cost optimization of LIB.



conceivable cost cell, but it also means that many of the high-energy technologies will not benefit from these process innovations for the time being and will still be expensive.

In addition to the use of specific manufacturing processes, production scaling is one of the most important levers for reducing costs. The high proportion of materials in LIB costs is also the result of extensive optimization in cell production costs. So far, economies of scale have been achieved primarily by increasing the throughput of individual LIB lines. A second lever is the standardization of cell formats across models and OEMs, whereby the production volume of a single cell type becomes so large that it can be produced not only on the same lines in one factory, but in several standardized factories. This saves costs in factory design and construction, equipment procurement, and possibly even regulatory approvals.

The fact that the industry is moving in this direction is evident not only from the openly communicated medium-term strategies of the OEMs (46 mm cylindrical cell, "Einheitszelle", etc.), but also the "incidental" appearance of the same cell types in vehicles from different OEMs.

The impact of LIB recycling on LIB costs is still controversial. However, it is often assumed that the recovery of important metals from waste LIBs should be cheaper than primary production once a critical market volume of EoL batteries becomes available. As a future option, direct recycling of active materials could help to reduce costs, as the processing costs might be lower than new synthesis.

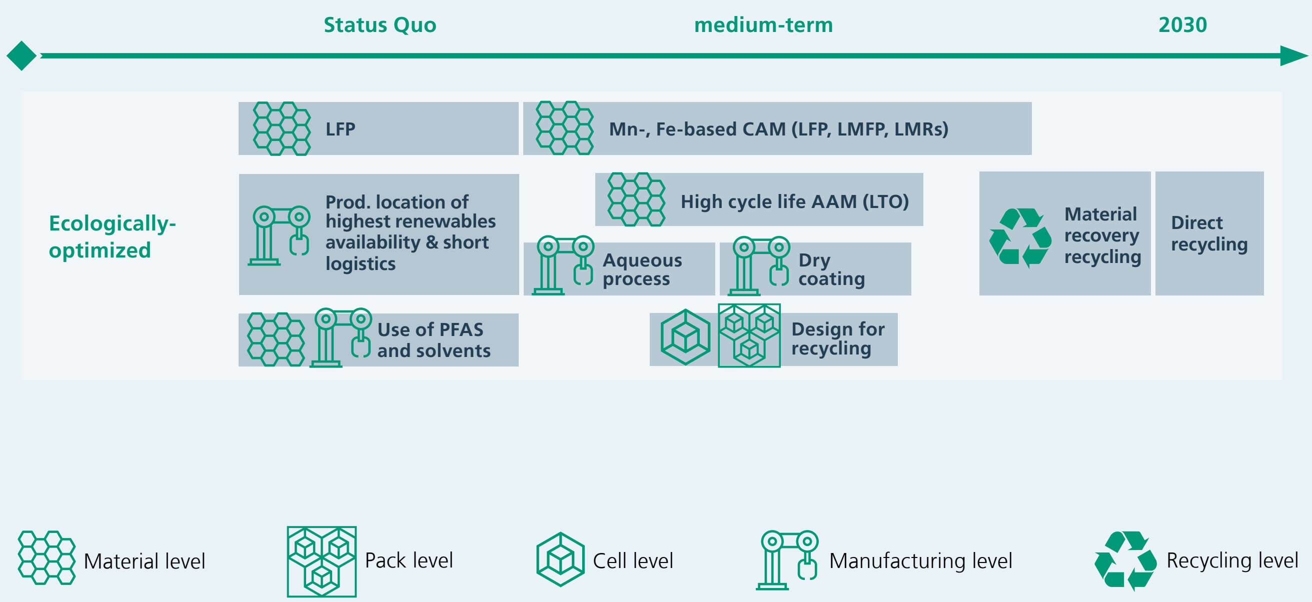
4.1.3. Ecologically-Optimized LIB

LIBs have a high ecological footprint because of the materials used and the complex manufacturing process. The advantages of LIB-powered applications such as EV often only become apparent during their use phase. This is why the ecological evaluation should be based on a life cycle assessment (LCA), which includes the manufacturing and use phase as well as post-EoL recycling. For the use phase in particular, factors such as the round-trip efficiency of batteries as well as their cycle life and calendar life can play a major role.

The technologies used to optimize the ecological footprint of LIBs are, in many cases, the same as those used to optimize costs. This makes sense, as cost drivers such as energy and resource consumption are often also linked to the generation of CO_2 or other environmental impacts. The implementation period therefore largely corresponds to the roadmap described in the previous section (see 4.1.2).

The environmental impact of resource extraction results from the sometimes extremely high quantities of material that have

Figure 34: Technological approaches and implementation perspective for the ecological optimization of LIB.



to be moved and processed in order to extract metals such as lithium, cobalt and nickel. In addition, chemicals, water and high amounts of energy are used during extraction. There are corresponding advantages to using iron- and manganese-based materials, as both raw materials are easier to extract than nickel and cobalt. Graphite can be mined and produced synthetically. The environmental impact of mining results from the movement of earth and rock, and that of synthesis from the high temperatures involved requiring high energy input. In terms of the CO_2 footprint of manufacturing, LFP and natural graphite-based cells in particular are likely to perform well. However, if the service life is also taken into account, synthetic graphites could perform better overall (higher cycle life), even if the initial CO_2 budget is higher. This may also apply to other anode materials, such as titanates, which have an extremely long cycle life and lead to low LCA results in applications with correspondingly high requirements.

Recently, ecological assessment has focused on another group of materials, the so-called per- and polyfluorinated substances (PFAS). These include the electrolyte salts used in LIBs and the binder material PVDF. There are no alternatives to the salts in the foreseeable future. However, the possibilities for aqueous processing of many cathode materials and graphite and their small volume changes during cyclization allow the use of non-PFAS (e.g., rubber and cellulose-based) binders.

In cell production itself, energy consumption probably has the biggest influence on the environmental footprint. All approaches to reduce this (low-solvent coating, dry coating, mini-environments) have a direct impact on both costs and the carbon footprint. In addition to the amount of energy required, production location is also an important lever. In Europe in particular, new production sites with good access to renewable energy are being targeted, e.g., in Northern Europe, which should have very low CO_2 emissions. Other locations also promise this. So far, however, the location of cell factories seems to be based solely on energy costs and not on the available electricity mix. In Europe, for example, many location decisions favor Poland and Hungary, which still have a comparatively high share of fossil fuels in their electricity generation mix.

The choice of location affects not only the carbon footprint of production, but also the emissions associated with the length of the supply chain. LIB production today is extremely global, not least due to the sites of raw material deposits. An ecologically sound production site shortens the supply chain or aims to process raw materials "on site". Even though economic motivations are likely to have played a major role, the efforts of many resource rich countries, such as Indonesia (nickel), to increase the value share of battery production at home also have environmental benefits, provided that renewable electricity and other key factors are available.

The end-of-life of LIBs also has an impact on their environmental footprint. Compared to the primary extraction of raw materials, recycled materials can massively reduce local environmental impacts such as energy consumption, earth and rock movement, and water consumption, especially if recycling is highly efficient and the batteries are designed accordingly. However, even this approach does not seem to play a major role at present, as reflected for example in the use of adhesives and foams in pack construction or the continuing difficulties in accessing SoH data for used batteries. “Design for Recycling” therefore remains a long-term vision and is not incorporated into industry roadmaps.

4.2. Battery Demand and Production

The global demand for batteries has risen rapidly in recent years, particularly due to the shift in the mobility sector from internal combustion engine vehicles to electrically-powered ones. However, in addition to the mobility sector (xEV), batteries are also used in electronic communication and household appliances (3C) as well as in stationary energy storage (ESS). Additional mobility applications are emerging such as electrified two-wheelers (micromobility). Overall, the battery market has recently seen annual growth rates of between 30 and 40 %. According to optimistic estimates, total demand for LIB could exceed 1 TWh for the first time in 2023 and surpass 3 TWh in 2030 (2.5 to 4.5 TWh according to our minimum and maximum scenarios).

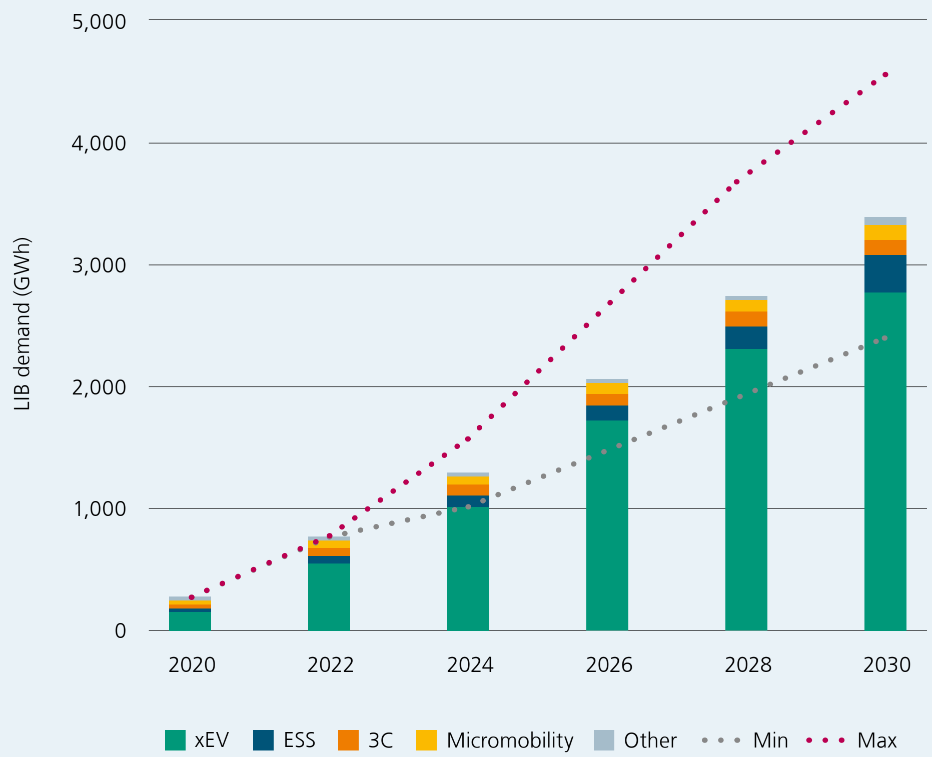
4.2.1. Battery Markets and Demand Forecast

The mobility sector dominates overall battery demand. In 2022, approximately 75 % of lithium-ion batteries were installed in vehicles and the majority of these (>90 %) were installed in passenger cars. This ratio was different until the mid-2010s. In 2015, for example, just under 40 % of LIB in the mobility sector were installed in passenger cars and the majority were installed in e-buses. The very high growth rates of recent years are now slowing down. In 2030, the battery demand in this sector could be just under 3 TWh.

3C applications constitute the second largest market for LIB. In fact, until 2015, they were the largest market. The growth rate in this market has been consistently below that of xEV and ESS (approx. 5-10 %).

The ESS market could expand the most in the next few years and achieve growth rates above 20 %. This market is essential for global power supply due to the expansion of renewable energy and could overtake the 3C market for the first time in 2023. The projected market size in 2030 is around 300 GWh. Micromobility (e.g., two-wheelers like motorcycles or scooters and three-wheelers like tuk-tuks) plays a major role here, especially in emerging markets. India and China are the largest demand regions for these applications. By 2030, the ESS market could be similar in size to the 3C market (approximately 130 GWh). In addition to the examples given, there are other LIB applications in trains, ships or aircraft. However, battery

Figure 35: Forecast of the demand for lithium-ion batteries in various applications.



electrification is not expected to play a major role in these sectors (especially in aviation) until after 2030.

Over the past few years, the demand forecast for LIB has increased steadily. However, some factors could now slow this growth. On the one hand, subsidy programs for electric mobility are coming to an end [390], and on the other, demand for BEVs, for example, is falling due to the current economic situation [391, 392].

4.2.2. Battery Material and Cell Production

If the current capacities of material and cell manufacturers (production) are compared with current demand, there seems to be a slight oversupply. In order to analyze the supply situation in the future, we reviewed and compared the announced production capacities of active material manufacturers discussed in chapter 3.1 and the production capacity of cell manufacturers (chapter 3.2). To do so, the production volumes need to be corrected by scrap rates and capacity utilization of individual production facilities.

Due to the announcement-based approach, no meaningful capacity forecasts can be made until after 2028. Manufacturers usually announce the construction of new factories with a shorter timeline.

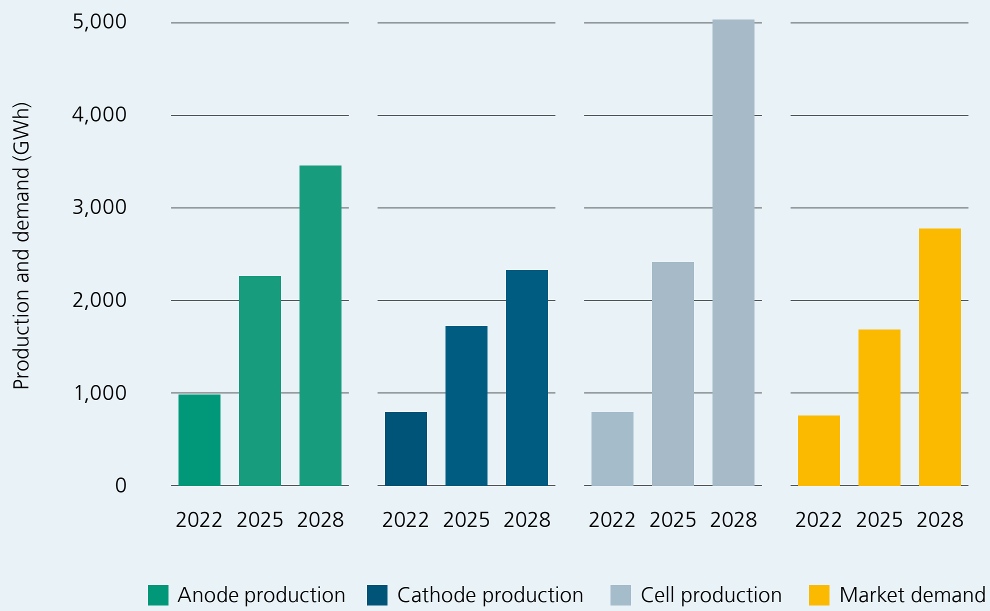
Forecast anode material

Graphite will remain the most widely used anode material until 2030. Accordingly, there are large global production capacities and individual production sites, particularly for artificial graphite. Up to 4 megatons of production capacity could be installed by 2028, mainly in Asia. In full cells, graphite can deliver a specific energy of 1,100 to 1,300 Wh/kg. Taking into account scrap rates, utilization and general losses, 4 megatons of production capacity yields approx. 2.8 TWh of cell capacity. Graphite is also required for the production of some silicon composite anodes. Compared to graphite anodes, silicon (composite) anodes can achieve significantly higher specific energy densities of 2,500 Wh/kg and, depending on the Si content, up to 10,000 Wh/kg for full silicon utilization. Together with smaller quantities of LTO as well as hard and soft carbons, anode material for almost 3.5 TWh of LIB could be produced in 2028.

Forecast cathode material

While there was three times more NMC production capacity in 2020 compared to LFP production capacity, by 2028, the difference will only amount to 30 % by weight according to industry announcements. NMC cathodes (depending on the exact composition) achieve an average of 600 Wh/kg, whereas LFP cathodes can only achieve around 500 Wh/kg.

Figure 36: Base scenario of the planned (announced) global production capacities for active materials and cells as well as demand forecast.



Based on the conversion factors, around 1.2 TWh could be produced from the 3.4 megatons of announced NMC cathode production capacity in 2028, and around 800 GWh from the 2.6 megatons LFP production capacity. NCA production capacities could account for 250 GWh of battery capacity (approx. 600 kilotons). LCO and LMO only account for smaller quantities. In total and corrected by scrap rates and plant utilization, approx. 2.4 TWh of cells could be produced with the materials from the announced CAM production facilities in 2028.

Forecast cell production

Whether or not global battery demand in 2030 can be met will depend heavily on how many of the globally announced production facilities can be implemented and operated in time. Three scenarios (maximum, base and minimum) were developed to estimate realistic production capacities:

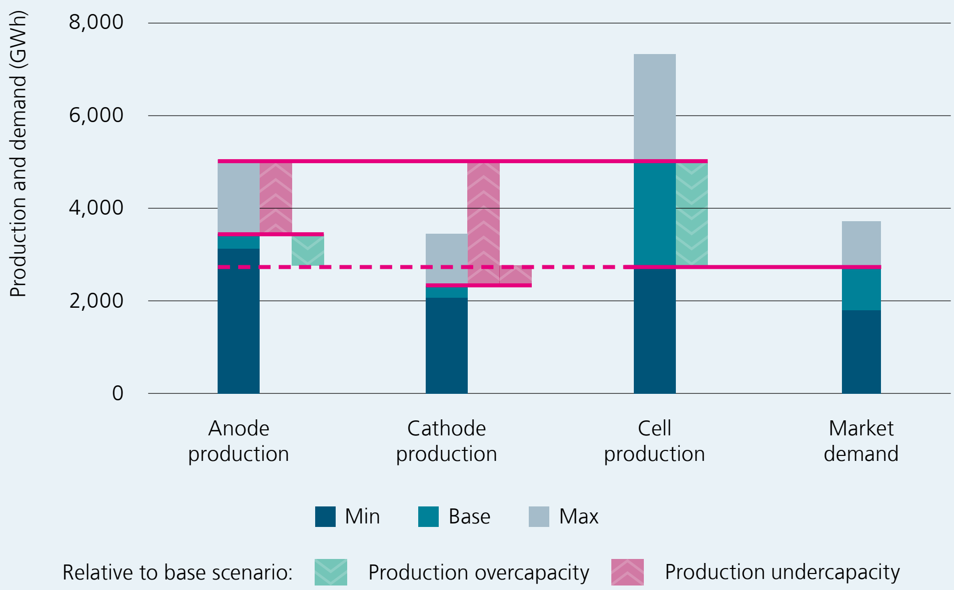
The maximum scenario assumes full realization of all production capacities that were an-nounced with a specified production site or where the required investments seem secure. The base scenario included a delay of one year (real SoP versus announced SoP) as well as a 75 % utilization of the capacities due to scrap or maintenance. The minimum scenario only included the announcements of manufacturers who already produce battery cells on a large scale today and the time delay and utilization rate were the same as in the base scenario.

The maximum scenario could reach a production capacity of more than 8 TWh by 2030 (around 7.4 TWh in 2028). This represents a fourfold increase from the maximum capacities announced by the end of 2023. The minimum scenario only achieves roughly one third of this value in 2028 (2.8 TWh). The base scenario achieves nearly 6 TWh by 2030, and is therefore closer to the maximum scenario. However, in 2028, it is centered between the minimum and maximum scenario with roughly 5 TWh. Since, compared to the maximum sce-nario, the base scenario assumes a significantly lower realistic production capacity by the end of 2023 (around 1 TWh), the increase here until the end of the decade is even greater than in the maximum scenario (increases sixfold until 2030).

Comparison of production capacities with cell demand

To assess the future supply situation, the battery demand forecast for 2028 was compared with the announced production capacity scenarios of the active material and cell producers. Figure 36 shows that the announced production capacities exceed the demand for LIB. If this excess capacity continues in the future, some of the announced production sites may be postponed or even cancelled. However, it cannot be ruled out that additional announcements may be made or that battery demand develops even more dynamically than assumed in the coming years.

Figure 37: Comparison of global active material and cell production capacities as well as battery cell demand for 2028.



In terms of active materials, it can be seen that the announced anode capacities are slightly higher than the announced cathode capacities, but that both fall short of the announced cell production capacities. The supply gap in active material production would be more than 2.5 TWh on the cathode side and around 1.5 TWh on the anode side in the base scenario. Compared to the battery demand forecast, the supply gap of active material production is much smaller for cathode material or even exceeds the demand (anode production) in the base scenario.

It must be monitored how the announced oversupply of cell production facilities develops (section 3.2.5). Looking at the supply chain from raw materials to cells, many OEMs have been focusing on cell production. Other projects seem to be investor-driven and indicate that the high market dynamics in the battery sector are closely linked to cell production. This is why there are currently many announcements concerning cell gigafactories. The up-stream production steps, on the other hand, have not yet received as much attention from the automotive industry. These are often in the hands of large conglomerates. These groups are keeping a close eye on market demand and are able to plan and communicate any corresponding increases in capacity at short notice and much more conservatively. This focus on cell production could change in the future and we expect to see additional announcements regarding material production capacities in the next five years. It is thus very likely that the supply capacity for active materials will increase further toward 2030.

Estimated recycling volume

The data available do not make it possible to forecast recycling capacities with the same degree of reliability as for production volumes. The demand for recycling is still low at present due to the small number of EoL batteries, and the material to be recycled mainly consists of production scrap. However, from 2030 onwards, traction batteries are expected to play an increasingly important role and will become dominant in recyclate return quantities in the 2030s. The global recycling volume from EoL LIB and production scrap could rise to approx. 1.6 megatons in 2030 [282]. Other aspects make projections even more difficult such as uncertainties about battery service life and whether battery usage in second-life applications will postpone recycling. It is likely that further industrial activities will be announced in the next few years so that sufficient recycling capacities are realistic. In terms of second-life applications, for example, volumes between 110 and >200 GWh are estimated per year [393] – assuming that the current challenges are overcome.

4.3. A European Battery

A number of challenges need to be addressed to build up a competitive, independent, and sustainable European battery ecosystem:

- CAPEX, investment conditions: Subsidies and funding mechanisms (such as IPCEI) can help create a more level playing field and attract investments. However, streamlining bureaucratic processes and reducing time-intensive procedures would also help to accelerate the development of the battery ecosystem in this critical phase.
- Energy costs: Ensuring internationally competitive energy costs is essential to narrow the gap to other regions like China and the USA. This can be achieved through policies that promote cost-effective and sustainable energy sources.
- Skilled workforce: Developing a skilled workforce with expertise in scaled production is essential for a successful European battery ecosystem. Investments in education, training, and re/upskilling programs can help bridge the skills gap.
- Local value chain creation: Establishing a sustainable and self-sufficient value chain is crucial. This includes addressing issues related to the European Battery Directive, ensuring access to raw materials, promoting recycling, and exploring potential alternative technologies like Na-ion batteries.

The still fragmented nature of the EU-wide battery landscape requires joint efforts and collaboration among countries. Combining complementary strengths and resources can help build a stronger and more competitive ecosystem that can serve as a counterweight to Asia.

There are strong OEM in the downstream value chain, who are driving the demand for bat-teries in Europe and consequently the need to develop local upstream supply chains as well as recycling capacities in order to achieve high-volume production and a circular bat-tery economy in the coming years. The specific European industrialization activities from materials, components, cells to recycling can be summed up as shown below.

Active materials

In the field of high Ni CAM, some European manufacturers have products on the market and supply to cell production, e.g., Umicore and its customers Samsung SDI and SK On. The development of production facilities for cathode materials mainly relates to NMCs and thus to high-energy materials. Important players here are Umicore, BASF and Northvolt, but also the Chinese and South Korean manufacturers Beijing Easpring, XTC and Ecopro.

In the LFP sector, however, the industry in Europe appears to be weaker. LMFP, one of the more recent and very important innovations, originated in China and was commercialized there. So far, there is no major or established player that wants to produce LFP in Europe. Companies such as IBU-Tec and Nano One Materials are active on a smaller scale, but they do not plan to operate large-scale plants. European cell manufacturers will therefore continue to be dependent on imports of this important material for low-cost batteries in the long term.

Both start-ups and established players are also working on anode materials, especially next-generation materials (e.g., silicon, graphene), so that Europe certainly has technological expertise in these materials. However, this expertise is rather sporadic and does not fully encompass all cell components (e.g., also electrolytes, separators, etc.).

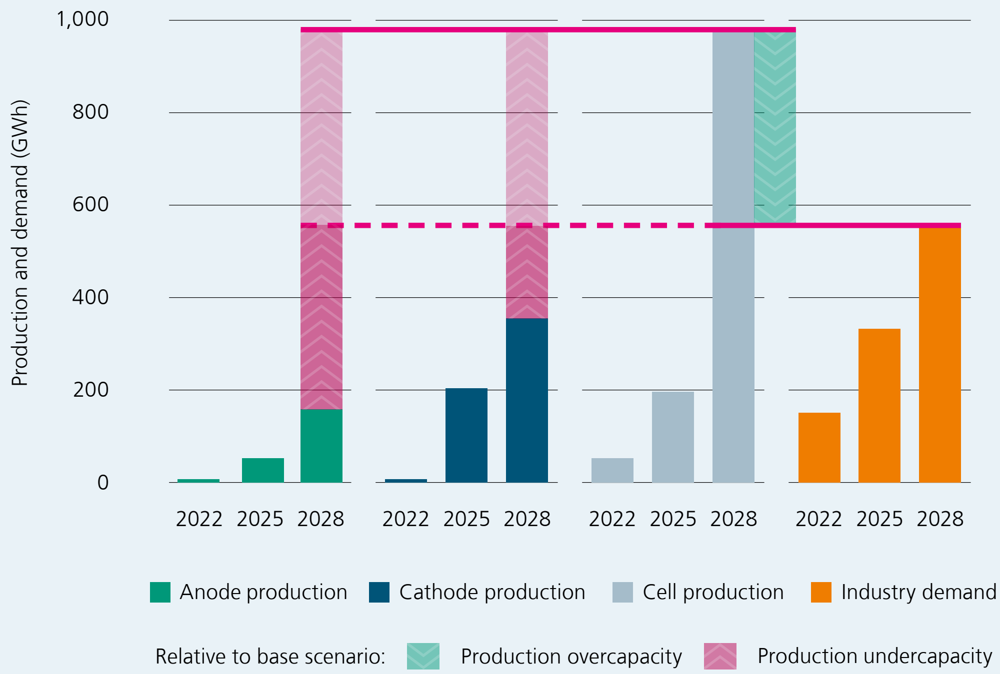
While cathode materials are already being produced in Europe, so far, there is no major manufacturer of anode materials. The plants planned in the next few years by European and Asian companies, e.g., Vianode, Talga, Shanghai Putailai and Epsilon, relate to graphite production. Large plants for the production of Si materials have not yet been announced, although Elkem, Wakker and others certainly have the relevant technological expertise in Europe.

Cell production

There are dynamic activities within Europe with more than 2 TWh of cell production capacities announced, which would come close to the goal of having 30 % of global battery cell production located in Europe. Many companies are jostling for a position on the EU market, which makes the upcoming ramp-up more resilient, e.g., to start-up failure. Both European and non-European companies have announced plans to develop production capacities of a similar magnitude by 2030. Currently, there are more non-European companies, but a shift toward European companies is possible after 2025.

An increasing share of LFP batteries could make the European battery cell economy more cost competitive. Energy costs have a significant impact, but raw material costs are more important, and these fluctuate strongly. Securing contracts and stockpiling, as planned by the EU, could mitigate these effects.

Figure 38: Base scenario of the planned production capacities for active materials and cells as well as demand forecast in Europe. Additionally a comparison of demand and supply in 2028.



There are only a few direct joint ventures (JV) to set up cell factories, but further strategic JVs (e.g., PowerCo + Gotion) can lead to a transfer of knowledge.

Attracting cell manufacturers to Europe was therefore successful, but now it is important to realize the plans within the announced time frames.

Recycling

Recycling in Europe is driven mainly by the European Batteries Regulation, which entered into force in August 2023. The regulation features targets for waste battery collection, material recovery from waste batteries, mandatory minimum levels of recycled content and recycling efficiency. The respective targets will be introduced gradually from 2025 onwards.

Market activities have already started to emerge, as high return volumes of used batteries from electric vehicles are expected from the 2030s onwards. Projects in Europe include big and well-established companies such as Umicore, BASF and automotive OEMS such as Mercedes-Benz or Volkswagen, newcomers installing pilots, such as Northvolt's Revolt, Düsenfeld as well as non-European companies like Li-Cycle and Redwood Materials. Particularly in America and Europe, recycling activities are divided into spokes (pre-treatment and production of black mass) and hubs (material recovery). According to recent announcements, spokes tend to be more decentralized and hubs large plants for actual metallurgical recycling.

Most industry capacity for material recovery is expected to be located in China (amounting to approx. 3,300 kilotons per year until 2030) but substantial capacities have also been announced for Europe. An additional capacity of ~40 kilotons per year (hubs) and 130 kilotons per year (spokes) is planned in Germany alone until 2030. Sites are often planned in close proximity to battery material producers, battery cell manufacturers or automotive manufacturers. Thus, market dynamics in the European region are driven, among other things, by the establishment of battery cell production sites.

Is the announced supply of materials and cells sufficient to meet the demand for batteries?

In order to analyze the supply and demand for cells in an individual region, cell production must be compared with demand in industry, which then installs the cells in BEVs or smartphones, for example. Market demand can be equated with industrial battery demand so that it becomes clear whether a region imports or exports more products containing batteries. Compared to the international average, the demand for batteries in Europe is dominated by the automotive industry. Large OEMs such as Volkswagen and Stellantis have several vehicle plants as well as sales markets in Europe and, as discussed in chapter 2.2, their demand for cells is very high. In 2022, the demand for batteries in European industry amounted to around 150 GWh and this could rise to almost 200 GWh in 2023. The demand for batteries currently exceeds cell production by around 200 %. However, many new production sites have been announced for the coming years. In a base scenario, up to 4,000 GWh of production capacity could be developed in Europe by 2030. Some of these announcements are from new players on the market. Their lack of experience might mean delays in commissioning production facilities (section 3.2.5). As with the analysis of global production sites, some production sites might not go into operation at all, e.g., due to less favorable economic conditions. Some of the announced production capacities are already on hold. Possible reasons include electricity prices or tax advantages, such as the IRA, in other regions.

To date, there is no relevant material production capacity (7 MWh anode and 11 MWh cathode) located in Europe. Materials for the sites already producing cells have to be imported. Over the next few years, the aim is to develop a supply structure in Europe to lower the need for imports. In particular, cathode production capacities (375 GWh) but also anode production capacities (160 GWh) will be installed by 2028. As cathodes are more expensive due to their raw materials, the corresponding revenues are higher here and production in Europe itself is more interesting. However, neither cathode nor anode production can meet industry's demand for batteries of around 550 GWh in 2028 and thus there is scope for additional capacity announcements. The deficits increase correspondingly if cell production expands in line with the announcements made. There would be a production capacity shortfall of 600 or 800 GWh.

Market demand is about 10 % lower than industrial battery demand. German car manufacturers in particular are expected to be able to export high volumes of electric vehicles in the future. This overdemand will be reduced by imports, particularly from China.

List of Abbreviations

Abbreviation	Description
2W, 3W	Two wheel, three wheel (electric vehicle)
3C	Consumer, computing, communication
AAM	Anode active material
BEV	Battery electric vehicle
BMS	Battery management system
BTMS	Battery thermal management system
C	Charge or discharge C-rate
C2C	Cell-to-chassis concept
C2P	Cell-to-pack concept
CAM	Cathode active material
CNT	Carbon nanotube
EoL	End-of-life
EPO	European Patent Office
ESS	Energy storage system (stationary)
EV	Electric vehicle
GHG	Greenhouse gas
HE	High-energy
HP	High-power
HV	High-voltage
ICE	(Vehicle with) internal combustion engine
IoT	Internet of things
IRA	US inflation reduction act
KPI	Key performance indicator
LCA	Life cycle assessment
LFP	Lithium-iron-phosphate (olivine-like)

Abbreviation	Description
LIB	Lithium-ion battery
LMFP	Lithium-manganese-iron-phosphate (olivine-like)
LMNO	Lithium-manganese-nickel-oxide (spinel)
LMO	Lithium-manganese-oxide (spinel)
LMR	Lithium- and manganese-rich oxide
LMT	Light means of transport
LTO	Lithium-titanate
NCA	Lithium-nickel-cobalt-aluminum-oxide (layered)
NG	Natural graphite
NMC	Lithium-nickel-manganese-cobalt-oxide (layered)
NMCA	Lithium-nickel-manganese-cobalt-aluminum-oxide (layered)
NMCxyz	NMC with x:y:z giving the ratio of Ni:Mn:Co
NMP	N-methyl-2-pyrrolidone
NMX	Lithium-nickel-manganese-oxide (layered) containing other metals
OEM	Original equipment manufacturer
PCM	Phase change material
PFAS	Per- and polyfluorinated substances
PHEV	Plug-in hybrid electric vehicle
PVDF	Polyvinylidene fluoride
SG, AG	Synthetic graphite, artificial graphite
SHE	Standard hydrogen electrode
SIB	Sodium-ion battery
SoC	State-of-charge
SoH	State-of-health
SSB	Solid-state battery
TRL	Technology readiness level
V2G	Vehicle-to-grid concept
WIPO	World Intellectual Property Organization
WLTP	Worldwide Harmonized Light Vehicles Test Procedure

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