Battery Production

Roadmap
Battery Production Equipment 2030

Update 2023

Imprint

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Editorial
Dr. Sarah Michaelis, Jörg Schütrumpf, Jennifer Zienow, Alice Persichetti

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In cooperation with

Fraunhofer Institute for Systems and Innovation Research ISI

Chair of Production Engineering of E-Mobility Components PEM

Battery LabFactory Braunschweig BLB and TU Braunschweig

VDMA Battery Production, a specialist department of the VDMA Electronics, Micro and New Energy Production Technologies (EMINT) association, is the point of contact for everything to do with battery machinery and plant engineering. The member companies of the department supply machines, plants, machine components, tools and services for the entire process chain of battery production: From raw material preparation, electrode production and cell assembly to module and pack production. The current focus of VDMA battery production is on Li-ion technology.

We research technology and market information, organize customer events and roadshows, hold our own events, such as the annual conference, which has established itself as an important industry get-together, and engage in dialog with research and science on current topics and on collaborative industrial research.

https://vdma.org/battery-production-equipment

The Fraunhofer Institute for Systems and Innovation Research ISI conducts research for practical applications and sees itself as an independent thought leader for society, politics and business. Our expertise lies in sound scientific competence and an interdisciplinary and systemic approach. Our assessments of the potentials and limits of technical, organizational or institutional innovations help decision-makers from business, science and politics to set a strategic course and thus support them in creating a favorable environment for innovation.

http://www.isi.fraunhofer.de

The Chair of Production Engineering of E-Mobility Components (PEM) at RWTH Aachen University is synonymous with successful and forward-looking research and innovation in the field of electric vehicle production. The groups around the topic of battery production of the chair of Professor Kampker deal with the manufacturing processes of the lithium-ion battery cell as well as with the assembly processes of the battery module and pack. The focus is on approaches of integrated product and process development to optimize cost and quality drivers in the manufacturing and assembly process. Due to a multitude of national and international industrial projects as well as central positions in well-known research projects, the PEM of RWTH Aachen University offers extensive expertise in the fields of battery cells as well as battery modules and battery packs.

https://www.pem.rwth-aachen.de/

The Battery LabFactory Braunschweig (BLB) is an open research infrastructure for the research and development of electrochemical storage devices from laboratory to pilot scale. The research spectrum covers the entire value chain from material, electrode and cell production to recycling. The existing infrastructure makes it possible to investigate fundamental and application-oriented research and development issues. The focus here is on flexible production strategies and process technologies for increasing the energy density, quality and safety of traction batteries, taking into account electrical, electrochemical, design, ecological and economic aspects. For this purpose the engineering and scientific competences of nine institutes of the TU Braunschweig, the TU Clausthal, the Leibniz Universität Hannover, the Fraunhofer Institute for Surface Engineering and Thin Films IST and the Physikalisch-Technische Bundesanstalt Braunschweig (PTB) are bundled in the BLB.

https://www.tu-braunschweig.de/en/blb/

Content

Executive Summary

References and unique selling points of production solutions create the ideal conditions for establishing a sustainable and long-term position in the future-oriented field of battery production and for becoming an attractive global solution partner. Production research in mechanical engineering provides a foundation for competitiveness. It is the key to process innovations and to the strategically important development of unique selling points. The roadmapping process also makes a valuable contribution by specifying production requirements through 2030 and formulating initial proposals for solutions.

The VDMA Roadmap Battery Production Equipment 2030 addresses the continued development of production technology (not product development). Since its initial publication in 2014, the roadmap has attracted worldwide attention, and many suggestions have been taken up and implemented. We have continued the goal-oriented dialog between battery producers, production research, and mechanical and plant engineering, also taking experiences with international experts and specialists into account. Due to the highly dynamic nature of the battery industry, it is important to incorporate the findings and information gathered in this way into a complete revision of the roadmap every two years.

As a fixed component of the market analyses in the roadmap, the careful assessment of factory capacities and their global supply potential first introduced in 2016 is included in each update. In recent years, the focus has shifted to Europe and especially Germany, with proximity to the automotive industry as an end customer playing a key role. In addition to Europe, China continues to be of major importance as the market leader in electromobility. The Chinese machinery and plant engineering sector has emerged from its strong domestic market to become a world leader. In order for European production equipment suppliers to remain competitive, they must prepare for this kind of competition in Europe. The Inflation Reduction Act has set the course for the establishment of electric vehicle and battery cell manufacturing in the USA. The US market is therefore gaining importance and is considered the third hotspot for battery production.

The core contents of the Roadmap are the 15 technology chapters. These chapters discuss future requirements for battery equipment construction from today's perspective and formulate possible solutions offered by the machinery and plant engineering industry. The starting point for the update was the required technology breakthroughs (*Red Brick Walls*) and solution approaches identified in 2020. These have been updated to the current state of technology.

All *Red Brick Walls* can be traced back to key challenges: **cost savings** from increased throughput (scale-up or speed-up), increased productivity (scrap minimization), **improved quality**, and **sustainability**.

The research needs identified in this Roadmap should be addressed in a targeted manner through cooperation between industrial partners and research organizations. The issue of sustainability is becoming increasingly important, especially in European locations. It is important not to lose sight of the overarching goal of a reduced CO_2 footprint. Access to series production is also still essential, as it is the only way to directly evaluate developments in large-scale production and obtain references. Success in battery production requires strength, perseverance, and a willingness to take risks.

Introduction

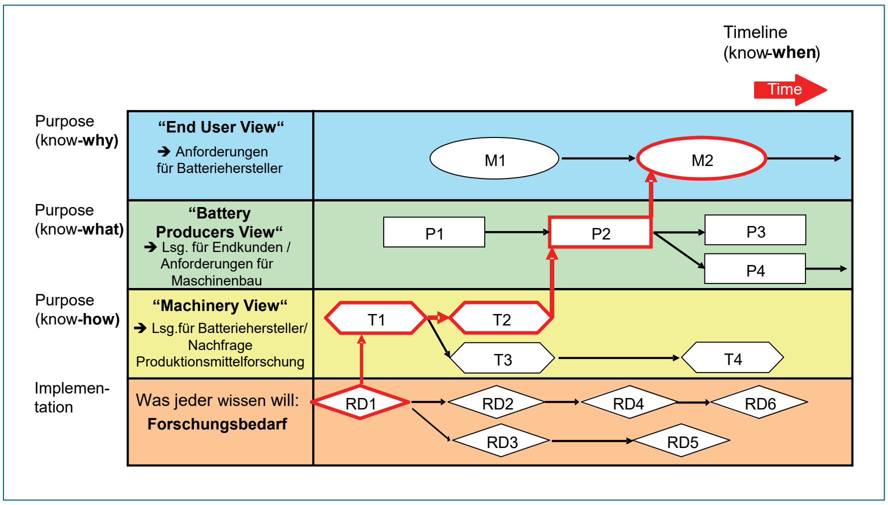
Roadmaps are a proven method for achieving clarity: they provide a coherent picture of a future vision, ideally representing consensus across a broad industrial field, and serve as a guide for investment. They promote pre-competitive collaboration among all stake-holders.

Since the first publication of the Roadmap in 2014, VDMA Battery Production has continued the dialog between the stakeholders and published an update every two years. For this 2023 publication, the contents of the 2020 Roadmap have been reviewed, completely revised, and supplemented with new findings. The basic methodology remains unchanged.

Roadmapping: The complete picture

Technology roadmapping is a strategic innovation management tool. Those who are able to successfully generate concrete product requirements ("know-what"), technologies to be used ("know-how"), and necessary research and development programs over a defined time period ("know-when") can benefit from predicted future mega-trends and markets[1] ("know-why") [Phaal2003a].

This results in separate "lanes," each with their own but interrelated roadmaps.[2] Requirements are formulated from top to bottom, and solutions are proposed from bottom to top. The entire roadmapping process leads from a broad scenario, to products and possibilities, to concrete research needs, which can be visualized in a **milestone diagram** [Phaal 2003b].



Roadmapping: from broad scenario, to products and possibilities, to research requirements. Milestone diagram of development paths. [Phaal2003b]

[1] Popular examples include: digitalization, urbanization, climate change, customization, etc.

[2] Highlighted in different colors in the milestone diagram

In this case, the picture is as follows: the blue “markets” lane represents end-customer markets such as the automotive industry, electricity providers, or mobile machines; the green ”products” lane is the batteries; the yellow lane is the production technology; and the red lane is production research.

Technology roadmapping in mechanical and plant engineering

Worldwide, user markets and battery technologies have already been considered in numerous roadmaps [NPE2016, LiB2015, BEMA 2020]. Although these also emphasize the importance of production for the progress of the industry, they are not technology roadmaps for production technology in the true sense of the word.

VDMA Battery Production first published a technology roadmap which was focused on the further development of production technology and not product development in 2014 [Maiser 2014]. This ongoing goal-oriented dialog between battery producers, production research, and the mechanical and plant engineering sector remains the basis for further discussion.

Starting point, goals, and target groups

Expectations are high for all players along the battery value chain. The race for the best production technology continues in full swing. Cooperation along the process chain is essential for progress. Continuous innovations and consistent internationalization strategies have made a significant contribution to the initial success of European battery production equipment in key sales markets in Asia and North America.

Companies benefit from experience in related industries, which is what makes it possible for them to break new ground and introduce revolutionary ideas.[3]

The objectives of the roadmapping process were described in detail in our roadmap published in 2014 [Maiser2014], and they remain unchanged:

- Determination of the **current status** of the mechanical and plant engineering industry: progress and future challenges
- Specification of comprehensive **production technology research needs**.
- **Benchmarking, expansion of product portfolios, and initiation of consortia** for new and established players.
- **Recommendations** for all stakeholders. Those who actively engage in the dialogue generally benefit the most. [Groenveld1997, Phaal2009].

Methodology

VDMA’s experience has shown that a clearly specified methodology is critical for the roadmapping process [adria2005, VDMA-PV2010]. For battery production equipment, the roadmapping process for the semiconductor industry has been adapted to battery production. The core concept of this approach is formulating independent roadmaps for customers and production equipment manufacturers. This avoids customers making their requirements dependent on the feasibility

[3] For example, semiconductor, photovoltaic and automotive production, but also the food and packaging industries.

of the process technology and technology suppliers only making assertions on process solutions when volume production is imminent.[4]

The meaning of *Red Brick Walls*

The combination of battery manufacturer requirements and the feasibility of process development in the defined timeframe reveals the following for each individual process step:

(1) Process solutions are already available in the field,

(2) Process solutions are only in pilot stages,

(3) Process solutions have been demonstrated or intermediate solutions exist, and

(4) Process solutions are unknown from the current perspective.

If solutions are unknown for multiple steps of a manufacturer requirement, a so-called "*Red Brick Wall*" (RBW) emerges. Technology breakthroughs are required.

Research efforts must now be targeted at overcoming these "*Red Brick Walls*" in order to meet manufacturer requirements. Thus, the identification of *Red Brick Walls* is the core of the roadmapping process, and can be used to derive clearly outlined, concrete research needs.

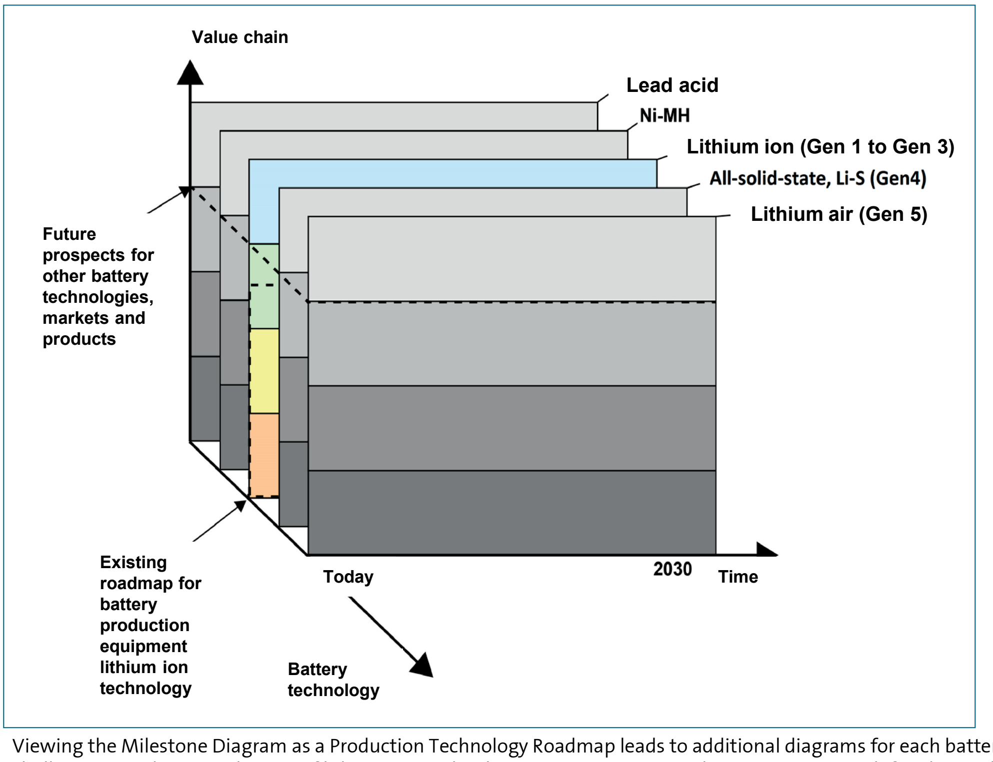
Multidimensional roadmaps - focus on mechanical and plant engineering

The milestone diagram shown above results de facto in a separate diagram for each battery technology. This makes the roadmap "multidimensional" (see figure), and it would be too complex to discuss the production technology in the required depth.

Therefore, we have focused on the battery technology which thus far has been introduced on an industrial scale for an intensive investigation of the process chain: **lithium-ion technology (LIB)** (shown in color in the figure).

Since production research requires technologies that are ready for series production, our roadmap addresses lithium-ion generations 1 to 3 (see table). Within these, the production technology is "upwardly compatible." This means that findings can be directly transferred to the next generation, as changes primarily affect the chemical composition of the active components. Certain process steps could feasibly also be adapted to Generation 4, and plant manufacturers are already receiving corresponding requests. In this case, they are also considered in the Roadmap.

[4] A more detailed description can be found in the roadmap published in 2014 [Maiser2014].



Viewing the Milestone Diagram as a Production Technology Roadmap leads to additional diagrams for each battery technology. This document considers the challenges to volume production of lithium-ion technology generations 1 to 3. The generations are defined according to the Roadmap of the former National Platform for Electromobility.
Source: VDMA

Generation 4 refers to the all-solid-state and lithium-sulfur (Li-S) technologies. The all-solid-state battery is currently much further along in its implementation than Li-S technology and is expected to be ready for series production in the next few years. Generation 5 comprises technologies that may currently be the subject of basic research, but could be used in the future.

Production changes are required from generations 4 onwards. Detailed information can be found in the All-Solid-State process flyer [Heimes2023b].

Due to the competitive environment for European companies, consideration is limited to large-format cells for high-power and high-energy applications.

Lithium-ion technology as a reference scenario

Today, commercially available lithium-ion cells are based on a combination of transition metal-based cathode materials, an organic liquid electrolyte, and a carbon or titanate-based anode. Cells with a cathode made of lithium cobalt oxide (LCO, electronic applications), lithium nickel manganese cobalt oxide (NMC, mobile applications), or aluminum-doped lithium nickel cobalt aluminum oxide (NCA) and a graphite or graphite silicon composite anode are the most widely used. Average cell voltages of 3.6 to 4.2 V can be achieved with these cell types. Lithium-iron-phosphate (LFP) cathodes, which have a lower cell voltage of 3.1 V and with which lower energy densities can be achieved than with NMC, are also used in industrial applications or for stationary storage. LFP is once again being increasingly used in mobile applications where possible, as it is safer and more cost-effective.

The manufacturing processes of the above-mentioned battery technologies are very similar. Large-format cells for mobile and stationary applications will continue to be based on the LIB technologies described. The overall picture of battery research shows that the potential of established large-format lithium-ion batteries is far from exhausted. Even with the potential transition to solid-state batteries with metallic Li anodes, key parameters such as cell voltage and large parts of the manufacturing process are likely to remain similar to today's technology.

The LIB reference technology described above will therefore continue to represent the reference system for many years to come based on its wide range of designs and variety of applications.

VDMA workshops

This Roadmap is regularly revised every two to three years to ensure that it is up to date.

To do so, the authors and chapter sponsors jointly prepare an initial update. The contents of the technology chapters and their required technology breakthroughs (RBW) are evaluated against the current status.

The focus is on the following two questions: Have political conditions changed? Are there new technological trends that may be having an influence? The contents are also evaluated based on their relevance for battery manufacturers as well as the cost-benefit ratio and the estimated timeframe for achieving the breakthrough.

In October of 2022, these updates were presented in an on-location workshop with the support of representatives from the IPCEI battery projects, the ProZell and InZePro cluster projects, as well as the chapter sponsors and technical advisors. The current status of the existing challenges and solution approaches were evaluated, including consideration of content from the cluster projects. Implementation into the chapters was then discussed in individual online workshops together with the technical advisors. Lastly, the final chapters were reviewed by all authors, sponsors, and supporters.

Conclusion: This Roadmap formulates the challenges and solutions of the mechanical and plant engineering sector, as well as research requirements for the large-scale production of lithium-ion high-performance energy storage systems by 2030.

Markets

As a starting point for the present update of the "Roadmap Battery Production Equipment" published in 2014, 2016, 2018 and 2020, the developments of the battery market and the production capacities were again considered. What are the prognoses both overall and in specific applications such as electric vehicles, industrial applications and stationary energy storage from today's perspective? Which battery technology will be the main driver of market growth in the coming years or decades and will therefore generate the highest demand for corresponding production solutions? Who is producing today and in the future and what are the plans for factories worldwide? What drives the demands of battery manufacturers on their suppliers?

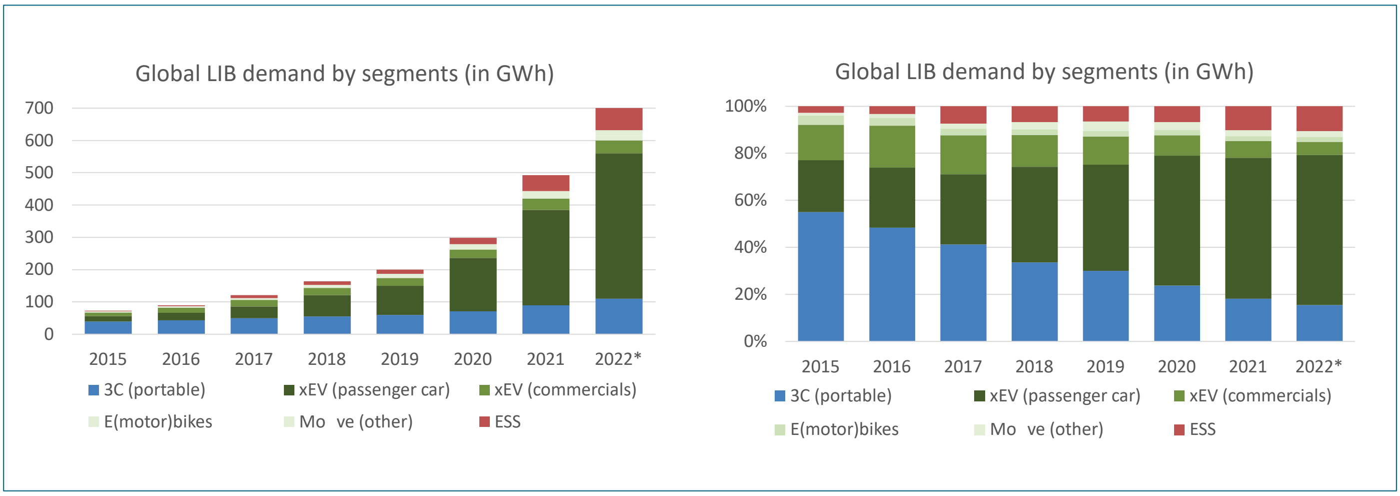
These questions can be answered by looking at markets, demand and supply as well as the product specifications of battery manufacturers. The analysis of markets and demand is based on current research and evaluations of market studies and databases. The data documented below has been updated to 2022 compared with the roadmap published in 2020 [Michaelis2020] and continues to confirm trends and increasing momentum that were already apparent at that time.

Markets, demand, supply

The potential applications for electrical energy storage technologies in general and lithium-ion batteries (LIB) in particular are diverse and range from consumer electronics, electromobility and stationary energy storage to large-scale batteries used directly in industry [Thielmann2015 a, b, c]. Since its introduction in the early 1990s in consumer electronics, the Li-ion battery has undergone a development over more than 3 decades. This development is accompanied by intensive further development of larger cylindrical cells (in the 21700 format, as well as the 4680 format already produced by Tesla.[5]), large-format pouch cells and prismatic cells to various specific applications.

All these cell formats have their advantages and are used in electric vehicles as well as industrial and stationary applications [Hettesheimer2017]. It can still be assumed that lithium-ion battery technology will be developed to full maturity in the next 10 or more years. This means that the next decade will continue to offer great development potential for this technology, which will be optimized step by step over the next few years.

[5] The new cylindrical cell format is expected to reduce battery costs by 50%, increase energy content and performance in the larger cell format, which is expected to be simpler to produce with fewer individual parts. https://www.teslarati.com/tesla-4680-battery-cell/



Global LIB demand by segment (in GWh on the left and by market share on the right): The 3C market includes small-format pouch, prismatic and cylindrical cells up to size 18650. Demand in this segment is not included in the further analyses, but only LIB demand in electromobile and stationary applications. There, large-format pouch and prismatic cells as well as cylindrical cells of sizes 18650, 21700 to 4680 are used. Source: Fraunhofer ISI [based on own data and various market studies including Avicenne, Takeshita, SNE].

LIB cells: global demand

The global demand for LIB cells was around 460-500 GWh in 2021. More than 350 GWh of this can be attributed to the electromobility sector[6] and about 50 GWh to stationary applications. In the area of portable/mobile applications[7] the LIB market in 2021 was around 90 GWh.
Uncertainties arise depending on the source and market study as well as different product-specific unit sales and average battery sizes. The LIB market has developed in recent years (until before 2020) with an average annual growth rate of 25 percent. This growth has been over 40 percent since 2020 (as the size and dynamics of the xEV segment now increasingly come into play). The greatest demand and dynamics come from electromobile applications. Growth rates here have been around 40 percent in recent years and are likely to remain at an average of 30-40 percent over the next few years. As a result, the xEV demand is now significantly higher than for 3C applications (see figure above).

For 2022, the global LIB market is estimated to be up to 700 GWh or even more (3C over 100 GWh, ESS up to 75 GWh, xEV over 500 GWh, thereof BEV up to 450 GWh). In 2023, global demand could already approach the TWh limit and certainly exceed it in 2024.

LIB markets - electromobility

In the field of electric mobility for **passenger cars**, particular attention is being paid to the development of plug-in hybrids (PHEV) and battery-powered electric vehicles (BEV). In the field of hybrid cars (HEV), the demand for cell capacity is low compared to PHEV and BEV.

By 2022, sales of electric cars (PHEVs and BEVs) have risen to 10.5 million (approx. 450 GWh). At the beginning of 2023, there were already 25-28 million electric cars on the roads worldwide and 40 million are expected by the end of 2023.[8] The market share of electric vehicles has been increasing extremely since 2020 (4.2 percent in 2020 to 8.3 percent in 2021 and 13 percent in 2022). The share of BEVs compared to PHEVs has been around 70-75 percent for several years.

[6] Passenger cars, commercial vehicles, etc.

[7] portable or 3C consumption, communication, computer

[8] EV Volumes 2023: https://www.ev-volumes.com/

The market for LIB at BEVs is by far the most important from the point of view of cell demand development. The terawatt hour (TWh) limit of LIB cell demand for electric vehicles as a whole could be reached as early as 2024 and by 2025 in relation to electric passenger cars, assuming an optimistic development of electromobility.

In the case of **commercial vehicles** (e.g. vans, buses) and **mobile machines** (e.g. forklifts), a similar dynamic and thus the development of an equally attractive growth market for LIBs as in the electric car sector can be expected, which will follow the development of the market for electric cars. The range of batteries installed in commercial vehicles can be between 50 kWh to well over 500 kWh. Although the number of units only accounts for one third of the passenger car market, the market volume could grow similarly due to the double to triple capacity of the batteries.

Most battery cells for **buses** and commercial vehicles are still used in the **Chinese** market. Market forecasts see a sustained annual demand in the order of 100,000-300,000 electric buses in China (10-30 GWh). However, the Chinese government's past cuts in subsidies for electric vehicle manufacturers indicate that neither the dynamics nor stability of this market demand in the coming years is considered certain.

Outside of China, sales of e-utility vehicles such as delivery trucks, postal trucks, garbage trucks, trucks, etc. lead to demand in the range of a few GWh. However, the momentum is expected to increase significantly in the coming years.

The demand for electrically powered **two-wheelers (e-bikes)** with LIB cells already amounted to more than 10 million (approx. 5 GWh) before 2020. [Thielmann 2020b[9]]. In the meantime, 10 GWh can be assumed. For **e-scooters and e-motorbikes**, on the other hand, the sales figures are in the low GWh range and thus significantly lower. However, battery capacities of 2 to over 15 kWh are likely to create an interesting market in the future.

LIB markets - stationary applications

Stationary storage systems are playing an increasingly important role in energy supply and due to the expansion of renewable energies. In regions with poor grid connections, autonomous systems are often the only way to provide energy.

The demand and dynamics for LIB cells for stationary applications are estimated differently depending on the market study [Thielmann 2017, Thielmann 2020a]. Until 2020, global demand was still at the level of 10-20 GWh with growth rates between 15 and 30 percent. In 2021 and 2022, the ESS market is partly estimated to reach 50-75 GWh, with growth rates beyond 50-100 percent. While some market studies do not see a global demand of 100 GWh until 2030, optimistic forecasts estimate a market of 200-300 GWh by 2030.

The market is diverse in terms of applications, ranging from off-grid to on-grid applications.[10] [Thielmann2015a, c]. The demand for individual applications such as grid stabilization could be saturated in just a few years. Other applications ensure long-term demand.

Overall, there is a broad portfolio of energy storage solutions for stationary applications. The

[9] AABC 2020: Axel Thielmann, The Emerging Battery Markets Beyond xEV, Fraunhofer ISI.

[10] UPS, stand-alone solutions, grid stabilization, PV home storage, PV & wind farms for direct marketing of renewable energy, self-consumption optimization, etc.

LIB demand results from the substitution of existing technologies (especially Pb batteries) as well as from the increasing demand for decentralized storage solutions. In the medium to long term, existing storage solutions are likely to be put under pressure or even displaced by the cost development of LIB [Thielmann2015a].

However, the development of second-life business models may also lead to a flattening of demand in the future. With the grid connection (V2G, G2V) of electric vehicles, a new and precise definition of stationary storage systems (ESS) is required.

However, the development of second-life business models may also lead to a flattening of demand in the future. With the grid connection (V2G, G2V) of electric vehicles, a new and precise definition of stationary storage systems (ESS) is required.

In the stationary storage market, LIBs represent an enabler for the use of renewable energies. From an economic point of view, significantly better margins can be achieved in this market than in the e-car market with high volume production. The costs for home storage systems, for example, are still around approx. 1000 €/kWh.[11]

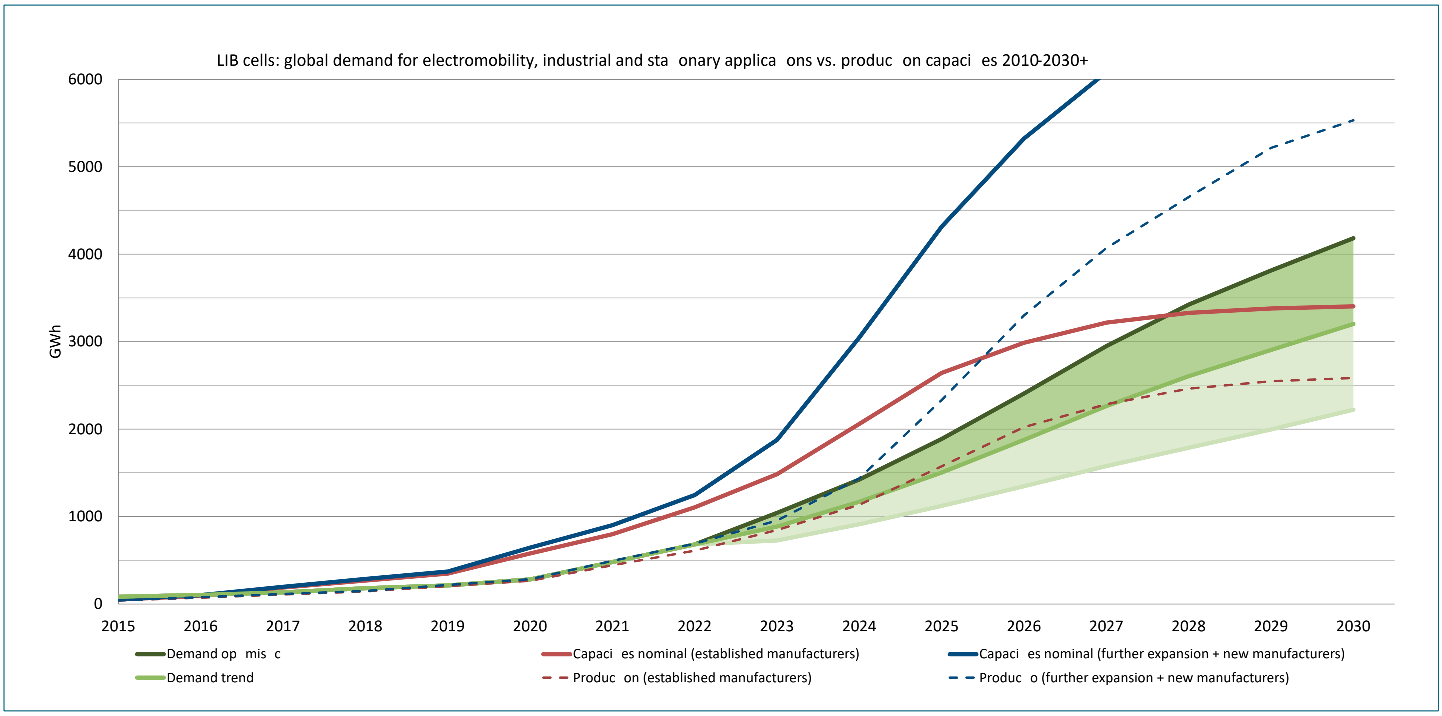
LIB offer: production capacities

In order to be able to reliably state how well producers are meeting demand, a realistic estimate of global production capacities is indispensable. From this, it is possible to determine whether and when new factories need to be built, or more precisely, whether an investment in a factory is worthwhile.

The installed global LIB production capacities for electromobility, industrial and stationary applications were determined on the basis of various studies, press releases and information from the cell manufacturers themselves (see Fig. p. 14): Accordingly, around 650 GWh had been built up by the end of 2020, 900 GWh by the end of 2021 and over 1.2 TWh by the end of 2022.[12] This results in a calculated capacity utilization of around 40-50 percent if we compare with global demand. In fact, we assume that the ramp-up to real cell production will be delayed by 1-2 years and thus production and demand will coincide in reality. Utilization rates of cell production can therefore only be made concretely meaningful at the level of individual cell manufacturers. In the next few years, an annual expansion of several hundred GWh is expected (see table on page 17).

[11] cf. CARMEN e.V. 2022: https://www.carmen-ev.de/service/marktueberblick/marktuebersicht-batteriespeicher/marktuebersicht-batteriespeicher-online-version/

[12] Production capacities for large-format pouch and prismatic cells as well as cylindrical cells (18650 to 21700 and 4680) are considered. The 18650 cells installed by Panasonic through Tesla in recent years are therefore included. Small format pouch and prismatic as well as cylindrical cells for 3C applications are not included.



LIB cells: Comparison of global demand for electromobile, industrial and stationary applications (forecast from 2022, LIB demand does not include small-format pouch, prismatic and cylindrical cells smaller than 18650) with existing and known planned production capacities (base scenario, see also table) as well as published optional expansion plans of different manufacturers and new market players. A realistic assessment of the extent to which production capacities can meet demand is obtained by including empirical values regarding the degree of utilization and yield of factories (dashed curves). Source: Fraunhofer ISI calculations based on [Michaelis 2018].

Comparison of LIB demand and supply: the comprehensive view

In continuation of the comparison of LIB production capacities and LIB demand [Michaelis2016, Thielmann2017, Michaelis2018 and 2020], we compare the cell production capacities announced up to the end of 2022 with the global LIB demand in the figure on page 14.

Ideally, demand must take into account not only the units actually installed, but also the **stock** on hand in factories or at the customer. If there is an oversupply, the customer's warehouses remain empty and orders are placed late. If there is an undersupply, more is often ordered than is actually needed. Demand is unrealistically "inflated" and may be cancelled later.

Price development is an essential factor for the dynamics of demand. In the semiconductor industry, **average sales prices** (ASP) have always been observed. They are closely linked to the cost of production. In the battery industry, prediction models have also been developed [Maiser2015, Michaelis2016, Thielmann 2017].

Prices and the propensity to invest are also significantly influenced by the development of the global economy as a whole.

Production capacities are not fully available in a short time. Factories are "ramped up" gradually. In the year for which the start of production is announced, it is not yet possible to manufacture the full capacity, especially as the start date is not necessarily at the beginning of the year. To take account of this start-up phase in our chart, we have added a one-year offset to the announced production start.

It takes between one and a half years to build a factory, qualify the production and the products, and then put it into full operation, for a so-called "copy & paste factory" and up to four years for a factory with new production technology. Cell manufacturers can therefore only react to rapidly changing demand with a delay. They are dependent on reliable forecasts. Many producers plan several expansion stages of a factory from the outset.

With the interplay of supply, demand and delayed reaction, typical patterns of a so-called "**pig cycle**" are present, as is also known from other industries.

The **capacity utilization** of a factory is never 100 percent. When capacity utilization is permanently above 85 percent, manufacturers usually think about expanding capacity. The remainder serves as a buffer. For the real production capacity used, it is therefore advisable to calculate only with values around 85 percent. In the case of the extremely dynamically growing market for LIB cells, it is indeed evident that (especially Chinese) cell manufacturers are announcing further expansion stages even at significantly lower utilization rates.

A factory never produces only good parts. Well-established factories in the semiconductor industry have a **yield** of over 90 percent. Yields in battery production today are in some cases significantly lower. So here, too, it makes sense to subtract at least 10 percent from the full capacity.

The **quality** of the cells is an additional uncertainty: customers may have different requirements and acceptances depending on the application. Depending on the quality, costs, choice of cell chemistry and format, not all cells produced are suitable for customers. Additionally, not every product can be substituted.

In addition, there are **regional dependencies**, especially when high demand leads to increasing logistical challenges. Cell factories will be built closer to the sales market in the future. All of this is overlaid by sentiments in the industry, as well as government measures for settlement and subsidy policy.

In the above chart, we have depicted both the nominal factory capacities (blue, red solid lines) and the values that are more real due to the dampening effects described[13] more realistic values (broken lines). The development of demand is shown in green, in each case in a conservative, a trend and an optimistic scenario. If the lines run above the green areas, there is calculated overcapacity; if they run below, there is a shortage of production capacity.

The red lines show the expansion of production capacities in the baseline scenario.[14] The blue lines show the expansion when taking into account optional expansions of production by established and new cell manufacturers (new market participants).

The further massive increase in demand between 2022 and 2030 is expected to rise to less than 2.5 TWh (pessimistic scenario, lower green line) up to 3-4 TWh (trend scenario, middle green line) in the coming years up to 2030, or even reach over 6 TWh in the optimistic scenario (over 10 TWh can be expected in the long term)[15]. We currently set the optimistic

[13] Considered were: Utilization rate of 85 percent. The average yield of today's factories is assumed to be 90 percent. Announcements by the manufacturers on the ramp-up of the factories are included. The remaining effects are difficult or almost impossible to quantify and have not been included.

[14] Base scenario: Production capacities of established cell manufacturers in the planning stage

[15] Tesla or Elon Musk even assumes 20-25 TWh by 2040: https://www.onvista.de/news/elon-musks-gigantischer-akku-plan-and-2-further-tesla-shares-news-397436777

scenario for 2030 at about 4TWh for further calculations.

The production capacities of established cell manufacturers (red lines) cover demand in the current trend until 2026. However, since the optimistic demand scenario has always emerged in recent years, further production capacities of established and possibly new cell manufacturers will be required on the market between 2023 and 2026. However, announcements of new market players compete with the expansion plans of the established cell manufacturers (difference between blue and red lines).

The table (p. 17) lists the cell production capacity expansions planned or announced for 2022, 2025 and 2030+ by cell manufacturer, their headquarters and planned location. Minimum and maximum values are given for the three periods due to the high degree of uncertainty as to the extent to which planned capacities will actually be built and commissioned in the corresponding year, as well as the uncertainty as to which new cell manufacturers will be able to establish themselves on the market.

The future expansion plans of the leading cell manufacturers CATL, BYD, Panasonic, Samsung SDI, LG Chem, SK Innovation are increasingly matched by further announcements from cell manufacturers as well as OEMs, which now also want to enter volume production. Such established players as well as new market players have been targeting the growing market in Europe in particular in recent years. Currently, the Inflation Reduction Act (IRA[16]) in the USA is threatening to announced by the USA, production capacities in Europe are threatened to be stopped and even relocated to the USA for the time being.

Thus, solely due to geopolitical reasons and industrial policies of other countries, but also aggravated by increased energy costs (also in connection with the Ukraine-Russia war), location decisions as well as production announcements could be shifted, delayed or stopped.

The overcapacities identified on paper to date may therefore become real production and supply bottlenecks on a larger scale in the near future.

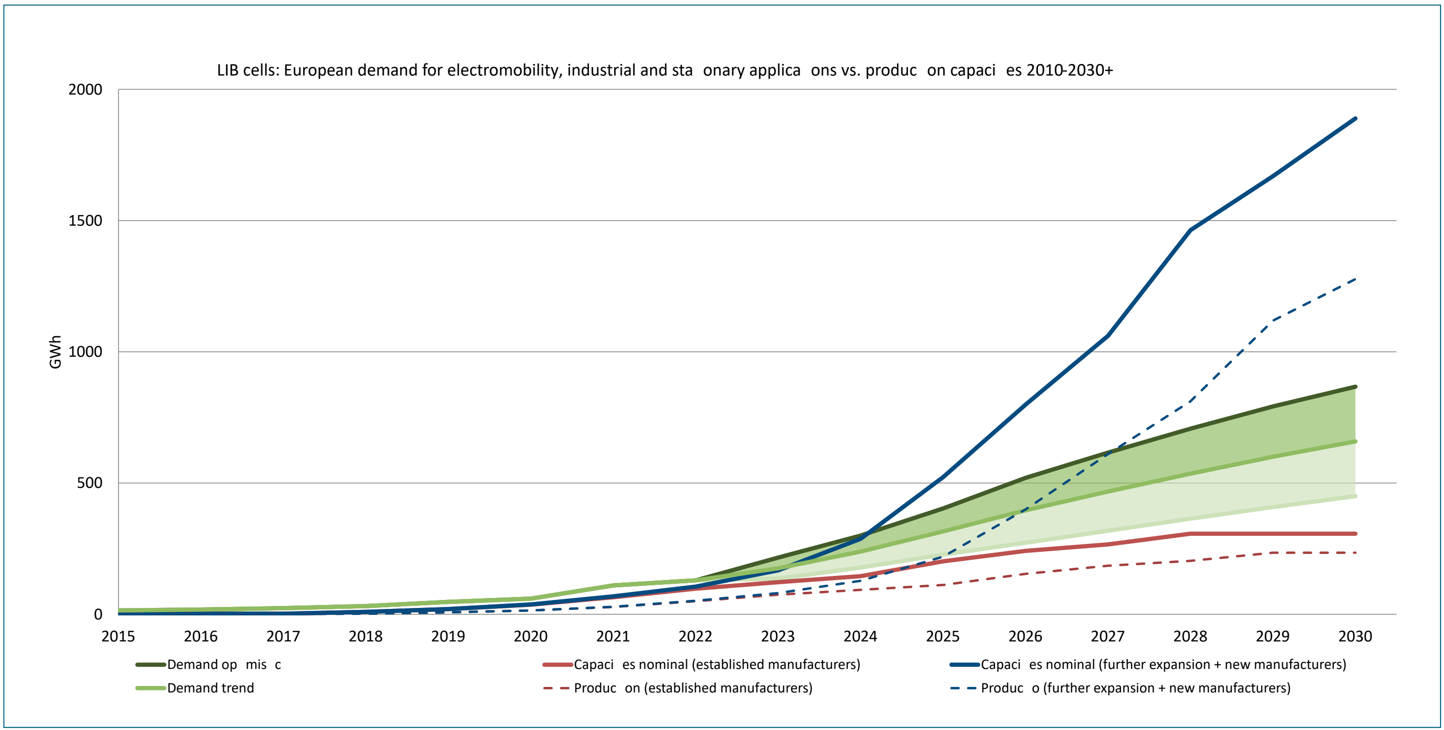
[16] With the Inflation Reduction Act 2022, the U.S. aims to boost its economy and increase its resilience. This program is intended to be a strong response to China's economic and technological leadership or dominance and provides enormous incentives and, in some cases, obligations to shift production to the USA.

Cell manufact	Partner	Region of con	Land of compan	Region of producti	Land of producti	2022-Min	2022-Max	2025-Min	2025-Max	2030-Min	2030-Max
BAK		China	China	Asia	China	14	14	24	24	44	44
BYD		China	China	Asia	China	108	108	247	277	287	332
BYD	FAW	China	China	Asia	China	0	0	15	15	45	45
BYD		China	China	Europe	n.a.	0	0	0	15	0	15
CALB		China	China	Asia	China	150	150	400	400	400	400
CALB		China	China	Europe	Portugal	0	0	0	0	0	60
CATL		China	China	Europe	Hungary	0	0	25	25	100	100
CATL		China	China	Europe	Germany	0	0	14	24	14	100
CATL		China	China	Asia	China	146	146	398	568	538	708
CATL		China	China	Asia	Indonesia	0	0	0	60	0	60
CATL	SAIC	China	China	Asia	China	27	27	36	36	36	36
CNM		China	China	Asia	China	3	15	3	15	3	15
Coslight		China	China	Asia	China	5	13	5	13	5	13
Dynavolt		China	China	Asia	China	12	12	12	12	12	12
EVE		China	China	Asia	China	10	34	86	148	116	282
EVE	Linyang	China	China	Asia	China	0	0	10	10	10	10
EVE	BMW	China	China	Europe	Hungary	0	0	0	20	0	20
Evergrande		China	China	Asia	China	5	15	5	30	5	60
Farasis	Geely	China	China	Asia	China	0	0	32	38	32	72
Farasis		China	China	Asia	China	23	23	41	59	41	71
Farasis	Togg	China	China	Asia	Turkey	0	0	0	15	0	15
Farasis		China	China	USA	USA	0	0	0	12	0	12
GAC		China	China	Asia	China	0	0	0	21	0	36
Ganfeng		China	China	Asia	China	9	9	47	47	83	100
Gotion		China	China	Asia	China	33	33	103	128	103	158
Gotion		China	China	Europe	Germany	0	0	6	10	6	18
Gotion		China	China	USA	USA	0	0	0	10	0	30
Great Power		China	China	Asia	China	8	8	8	28	8	28
Henan Pingm	National Bat	China	China	Asia	China	10	20	10	20	10	20
Linkdata		China	China	Asia	China	0	8	0	24	0	30
Lishen		China	China	Asia	China	20	20	27	40	27	40
Lvqingg		China	China	Asia	China	0	0	0	13	0	27
MGL RiseSun		China	China	Asia	China	21	21	21	45	21	45
National Battery Tech		China	China	Asia	China	19	19	19	19	19	19
Optimum Nano		China	China	Asia	China	12	36	12	36	12	36
Phylion		China	China	Asia	China	28	28	28	28	28	28
Qing Tao		China	China	Asia	China	1	1	1	11	1	11
Ruipu Energy		China	China	Asia	China	10	10	14	20	14	20
SGMW		China	China	Asia	China	0	0	0	10	0	20
Sunwoda		China	China	Asia	China	1	1	79	101	109	131
Sunwoda	Dongfeng	China	China	Asia	China	0	0	20	20	30	30
SVOLT		China	China	Europe	Germany	0	0	0	8	0	40
SVOLT		China	China	Asia	China	21	30	38	225	38	291
Teamgiant		China	China	Asia	China	10	10	10	10	10	10
Wanxiang (A123)		China	China	Asia	China	8	8	8	80	8	80
WeLion		China	China	Asia	China	0	0	0	20	0	100
Rest of China (<10 GWh)		*China*	*China*	*div.*	*div.*	42	46	55	63	55	63
ACC		Europe	France	Europe	Italy	0	0	0	0	0	40
ACC		Europe	France	Europe	France	0	0	0	12	0	40
ACC		Europe	France	Europe	Germany	0	0	0	0	0	40
Basquevolt		Europe	Spain	Europe	Spain	0	0	0	0	0	10
Beyonder		Europe	Norway	Europe	Norway	0	0	0	10	0	10
CustomCells		Europe	Germany	Europe	Germany	0	0	0	1	0	29
ElevenEs		Europe	Serbia	Europe	Serbia	0	0	0	0	0	16
Elinor		Europe	Norway	Europe	Norway	0	0	0	0	0	40
Freyr		Europe	Norway	Europe	Finland	0	0	0	0	0	40
Freyr		Europe	Norway	Europe	Norway	0	2	0	39	0	39
Freyr		Europe	Norway	USA	USA	0	0	0	0	0	50
inoBat	Gotion	Europe	Slovakia	Europe	n.a.	0	0	0	0	0	40
inoBat		Europe	Slovakia	Europe	Spain	0	0	0	4	0	32
inoBat		Europe	Slovakia	Europe	Serbia	0	0	0	4	0	32
inoBat		Europe	Slovakia	Europe	Slovakia	0	0	0	11	0	11
Italvolt		Europe	Italy	Europe	Italy	0	0	0	3	0	70
MES / HE3DA		Europe	Czech Republic	Europe	Czech Republic	0	1	0	10	0	30
Mindcaps		Europe	Spain	Europe	Spain	0	0	0	4	0	12
Morrow		Europe	Norway	Europe	Norway	0	0	0	8	0	43
Northvolt		Europe	Sweden	Europe	Germany	0	0	0	0	0	60
Northvolt		Europe	Sweden	Europe	Sweden	14	14	14	55	14	70
Northvolt	Volvo	Europe	Sweden	Europe	Sweden	0	0	0	5	0	50
Verkor		Europe	France	Europe	France	0	0	0	16	0	50
Volvo		Europe	Sweden	Europe	Sweden	0	0	0	0	0	10
VW		Europe	Germany	RoW	Canada	0	0	0	0	0	40
VW		Europe	Germany	Europe	CZ/PL/SK	0	0	0	0	0	40
VW		Europe	Germany	Europe	n.a.	0	0	0	0	0	80
VW		Europe	Germany	Europe	Spain	0	0	0	0	0	40
VW		Europe	Germany	Europe	Germany	0	0	0	20	0	40
VW		Europe	Germany	USA	USA	0	0	0	0	0	40
West Midlands Gigafactory		Europe	UK	Europe	UK	0	0	0	10	0	60
Rest of Europe (<10 GWh)		*Europe*	*div.*	*div.*	*div.*	10	14	12	32	12	37

LIB cell production capacities in GWh for electromobile, industrial and stationary applications (large-format pouch, prismatic and cylindrical cells of sizes 1865/2170/4680) in 2022 and expansion announcements of established and new manufacturers until 2025 and 2030 according to cell manufacturers, their headquarters and locations of cell production; base scenario (min) of today's existing and planned known production capacities of established manufacturers; manufacturers <10 GWh cell production until 2030 are summed up under "Rest" and listed according to countries. Overall, only concrete announcements of established and new cell manufacturers are listed. If announcements without concrete locations were also taken into account, the global announcements until 2030+ would be over 13 TWh and not 7.6 TWh as currently. Source: Fraunhofer ISI database.

Cell manufact	Partner	Region of con	Land of compan	Region of producti	Land of producti	2022-Min	2022-Max	2025-Min	2025-Max	2030-Min	2030-Max
AESC		Japan	Japan	Europe	Spain	0	0	0	13	0	50
AESC		Japan	Japan	USA	USA	3	3	33	33	33	43
AESC		Japan	Japan	Asia	China	4	4	16	16	20	20
AESC	Nissan	Japan	Japan	Asia	Japan	0	0	9	9	18	18
AESC	BMW	Japan	Japan	USA	USA	0	0	10	10	30	30
AESC	Nissan	Japan	Japan	Europe	UK	0	0	12	12	12	35
AESC	Renault	Japan	Japan	Europe	France	0	0	0	0	0	30
Panasonic	Tesla	Japan	Japan	USA	USA	39	39	43	43	43	43
Panasonic		Japan	Japan	USA	USA	0	0	20	20	30	90
Panasonic		Japan	Japan	Asia	Japan	22	22	26	53	26	66
Rest of Japan (<10 GWh)		*Japan*	*Japan*	*div.*	*div.*	24	24	37	38	37	38
Hyundai	SK On	Korea	Korea	USA	USA	0	0	0	10	0	20
Hyundai	LG ES	Korea	Korea	USA	USA	0	0	0	0	0	70
Hyundai		Korea	Korea	Asia	India	0	0	0	20	0	20
LGES	Stellantis	Korea	France/ Korea	RoW	Canada	0	0	23	30	23	45
LGES		Korea	Korea	Europe	Poland	35	35	65	65	65	65
LGES	Honda	Korea	Korea	USA	USA	0	0	0	0	40	40
LGES	GM	Korea	Korea	USA	USA	5	5	70	80	90	115
LGES		Korea	Korea	Asia	China	44	44	52	52	52	52
LGES		Korea	Korea	Asia	Korea	22	22	35	55	35	65
LGES		Korea	Korea	USA	USA	10	10	36	36	36	36
LGES	Hyundai	Korea	Korea	Asia	Indonesia	0	0	10	15	10	30
LGES	IBC	Korea	Korea	Asia	Indonesia	0	0	0	10	0	10
Samsung SDI		Korea	Korea	Europe	Hungary	30	30	40	40	40	40
Samsung SDI		Korea	Korea	Asia	China	6	6	6	24	6	29
Samsung SDI	Stellantis	Korea	Korea	USA	USA	0	0	23	23	23	33
Samsung SDI		Korea	Korea	Asia	Korea	5	21	6	29	6	33
Samsung SDI		Korea	Korea	Asia	Malaysia	0	0	0	0	0	10
SK On	EVE	Korea	China/ Korea	Asia	China	0	0	0	15	0	25
SK On		Korea	Korea	Europe	Hungary	12	12	17	17	47	47
SK On		Korea	Korea	div. Standorte	div. Standorte	0	0	0	10	0	10
SK On		Korea	Korea	Asia	China	27	27	47	47	57	57
SK On		Korea	Korea	USA	USA	5	5	22	32	22	50
SK On	Ford	Korea	USA/Korea	USA	USA	0	0	43	43	129	129
Rest of Korea (<10 GWh)		*Korea*	*Korea*	*div.*	*div.*	8	8	8	13	8	16
Energy Absolute		RoW	Thailand	Asia	Thailand	1	1	1	4	1	50
Exide		RoW	India	Asia	India	0	0	0	10	0	10
Ford	Sk On	RoW	Turkey	Asia	Turkey	0	0	0	11	0	45
LIBCOIN	BHEL	RoW	India	Asia	India	0	1	0	15	0	30
Megamillion		RoW	South Africa	RoW	South Africa	0	1	0	1	0	32
Ola		RoW	India	Asia	India	0	0	0	1	0	35
Recharge		RoW	Australia	Europe	UK	0	0	0	4	0	30
Recharge		RoW	Australia	RoW	Australia	0	0	0	2	0	30
Reliance		RoW	India	Asia	India	0	0	0	20	0	20
StromVolt		RoW	Canada	RoW	Canada	0	0	0	0	0	10
Vingroup		RoW	Vietnam	USA	USA	0	0	0	0	0	25
Rest of RoW (<10 GWh)		*RoW*	*div.*	*div.*	*div.*	0	2	1	26	1	33
Ford	CATL	USA	USA	USA	USA	0	0	0	0	0	40
ABF		USA	USA	USA	USA	0	0	0	5	0	13
Imperium3		USA	USA	RoW	Australia	0	0	0	12	0	18
Imperium3		USA	USA	USA	USA	2	2	8	16	15	30
Kore Power		USA	USA	USA	USA	0	0	0	8	0	12
Microvast		USA	USA	Asia	China	15	15	15	15	15	15
Nanotech		USA	USA	Europe	UK	0	0	0	0	0	10
ONE		USA	USA	USA	USA	0	0	0	1	0	36
QuantumScape		USA	USA	Europe	Germany	0	0	0	5	0	21
Rivian		USA	USA	USA	USA	0	0	0	30	0	50
Statevolt		USA	USA	USA	USA	0	0	0	12	0	54
Tesla		USA	USA	USA	USA	0	4	0	72	100	210
Tesla		USA	USA	Europe	Germany	0	0	0	20	0	100
Rest of USA (<10 GWh)		*USA*	*USA*	*div.*	*div.*	5	6	10	16	10	16
Total global						**1105**	**1246**	**2630**	**4313**	**3377**	**7617**
		China				756	865	1859	2851	2270	3891
		Europe				25	32	27	244	27	1241
		Japan				92	92	206	246	249	463
		Korea				209	225	503	666	689	1047
		RoW				1	5	2	94	2	350
		USA				22	27	33	212	140	625

LIB cell production capacities in GWh for electromobile, industrial and stationary applications (large-format pouch, prismatic and cylindrical cells of sizes 1865/2170/4680) in 2022 and expansion announcements of established and new manufacturers until 2025 and 2030 according to cell manufacturers, their headquarters and locations of cell production; base scenario (min) of today's existing and planned known production capacities of established manufacturers; manufacturers <10 GWh cell production until 2030 are summed up under "Rest" and listed according to countries. Overall, only concrete announcements of established and new cell manufacturers are listed. If announcements without concrete locations were also taken into account, the global announcements until 2030+ would be over 13 TWh and not 7.6 TWh as currently. Source: Fraunhofer ISI database.



LIB cells: Comparison of **European** demand for electromobile, industrial and stationary applications (forecast from 2022, LIB demand does not include small-format pouch, prismatic and cylindrical cells smaller than 18650) with existing and known planned production capacities (base scenario, see also table) as well as published optional expansion plans of different manufacturers and new market players. A realistic assessment of the extent to which production capacities can meet demand is obtained by including empirical values regarding the degree of utilization and yield of factories (dashed curves). Source: Fraunhofer ISI calculations

Hotspot Europa

Demand for LIB cells in Europe could be 200 to 400 GWh by 2025 (conservative to optimistic scenario) and close to 500 to below 1000 GWh by 2030 (just over 20 percent of global demand). We assume a demand of 600 GWh by 2030 in the current trend. Expansion plans by Asian and European cell manufacturers approach 500 GWh by after 2025 and 1800 GWh (1.8 TWh) by 2030. With the production of cylindrical cells (in addition to the mainly large-format prismatic and pouch cells), growth markets beyond the automotive market are also being addressed (e.g. power tools, e-bikes).

Europe is following the previous hotspot China due to the rapidly growing demand for electromobility and thus LIB cells. In the coming years, a cell production capacity comparable to that in China is to be established and then expanded in Europe. The share of up to 80 percent of global production capacity currently held by China is therefore likely to fall below 50 percent again in the coming years.

The U.S., Europe and other countries will build up corresponding production capacities from 2025 to 2030 - although these will also be heavily in the hands of Chinese companies such as CATL and BYD as well as established Korean and Japanese manufacturers.

The capacities shown in the figure for the European announcements (blue and red lines) again include corrected assumptions regarding the time lag in the build-up, the yield in production and the utilization in operations and sales (dashed lines).

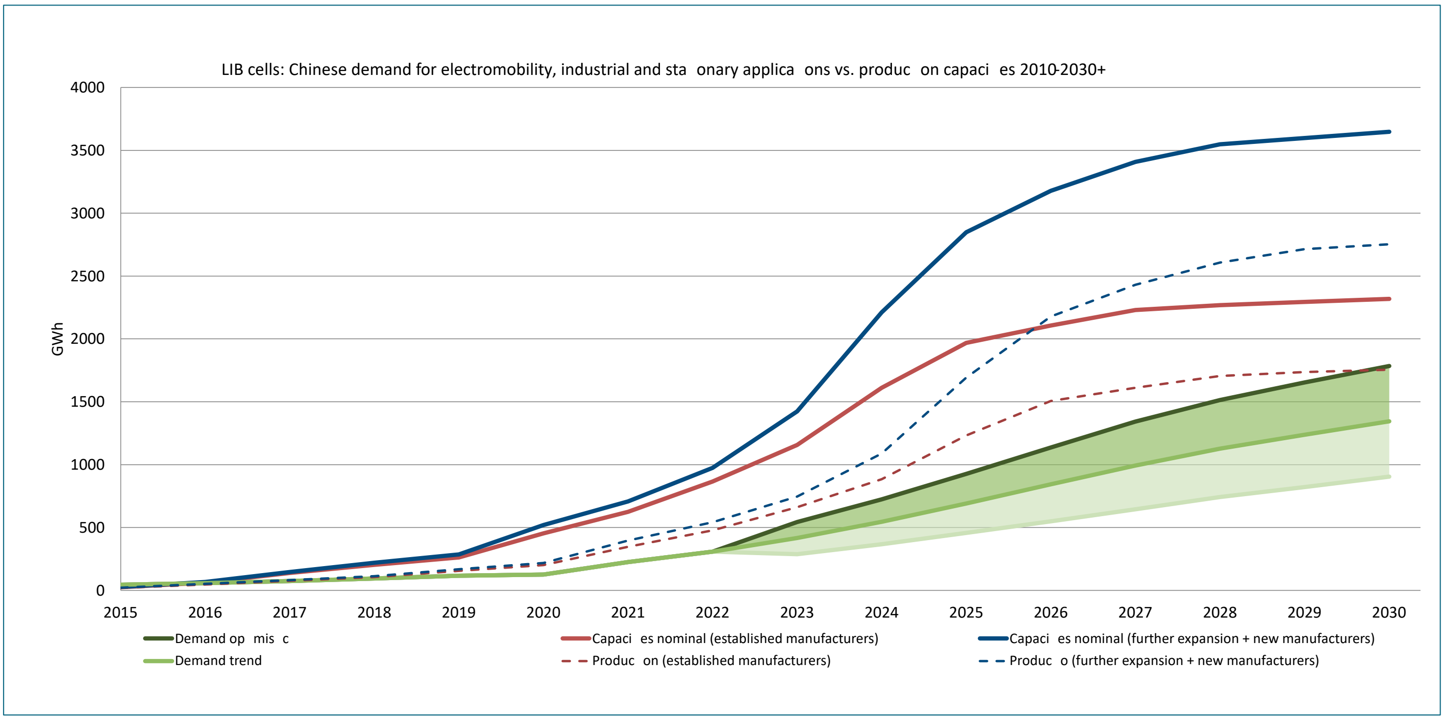
Accordingly, cells are still being imported into Europe today. From 2025 onwards, the European market should be covered by local production as a result of the further expansion of capacities by established manufacturers and the build-up of capacities by new manufacturers.

However, it remains to be seen to what extent European manufacturers will be able to establish themselves here. The announcements of non-European manufacturers by 2030 amount to about 1 TWh, while European manufacturers have announced just under 0.8 TWh of production capacity.

Today's existing production capacities of around 100 GWh in Europe are exclusively from Asian cell manufacturers (Samsung SDI, LGES, SK On) with the exception of Northvolt. Should the already globally established cell manufacturers (red lines) increase their capacities towards their maximum announcements, these would cover European demand in the range of up to 600-800 GWh by 2030. For European cell manufacturers (unless clear supply relationships already exist), this would leave little room for market development.

With the *Inflation Reduction Act* of the USA as an enormous investment program for the reorientation of the US economy to renewable energies, an effect on the location decisions of cell manufacturers is already apparent, which, in addition, due to the increased energy prices in Europe, are stopping the announced production capacities, relocating them to other regions or at least delaying them.

The massive act of state subsidies in the USA, the high energy prices in Europe, high bureaucratic hurdles and long processes are currently seen as key competitive factors that could threaten the development of a European battery ecosystem and prolong dependencies on imported battery cells from Asia.



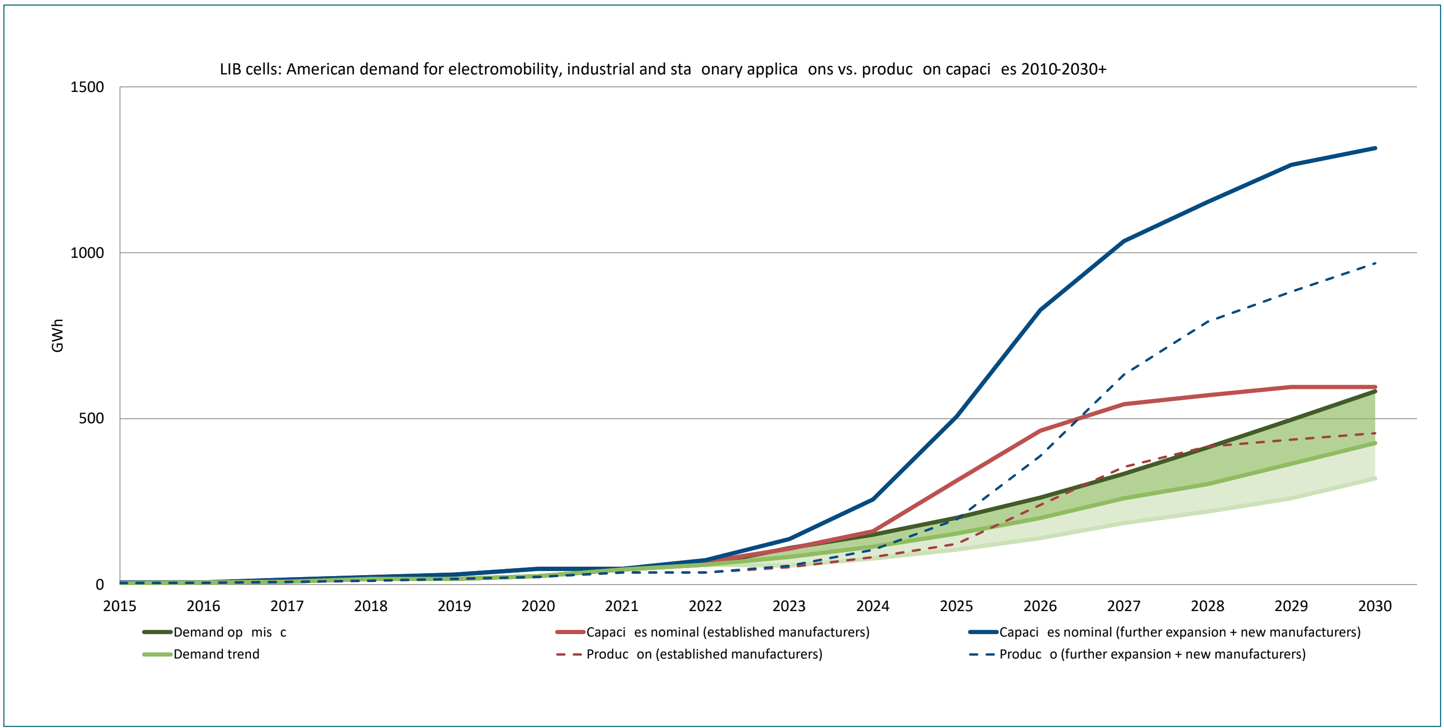
LIB cells: Comparison of **Chinese** demand for electromobile, industrial and stationary applications (forecast from 2022, LIB demand does not include small-format pouch, prismatic and cylindrical cells smaller than 18650) with existing and known planned production capacities (base scenario, see also table) as well as published optional expansion plans of different manufacturers and new market players. A realistic assessment of the extent to which production capacities can meet demand is obtained by including empirical values regarding the degree of utilization and yield of factories (dashed curves). Source: Fraunhofer ISI calculations.

Hotspot China

Demand for LIB cells in China is over 40 percent of global demand and is expected to be as high as 500 GWh in 2023/2024, rising to as much as 1.8 TWh by 2030.

In contrast, the announcements of the established cell manufacturers already cover domestic demand even in the event of delays and reduced capacity utilization and yield (dashed lines). Thus, as in the past, China can export cells to other regions. In addition to Chinese manufacturers, non-Chinese manufacturers (such as Samsung SDI, LGES, SK ON) contribute only about 10 percent of capacity to production in the country.

In addition, Chinese companies, such as CATL in particular, are among the Asian companies that are now expanding worldwide and therefore have the best chances of transferring the production know-how acquired in domestic markets to export markets. The quality of Chinese cells is now seen to be on a par with that of Japanese and Korean cells, and they also set the benchmark in terms of price.



LIB cells: Comparison of U.S. demand for electromobile, industrial and stationary applications (from 2022 forecast, LIB demand does not include small-format pouch, prismatic and cylindrical cells smaller than 18650) with existing and known planned production capacities (base scenario, see also table) as well as published optional expansion plans of different manufacturers and new market players. A realistic assessment of the extent to which production capacities can meet demand is obtained by including empirical values regarding the degree of utilization and yield of factories (dashed curves). Source: Fraunhofer ISI calculations.

Hotspot USA

Demand for LIB cells in the U.S. is about 10 percent of global demand.

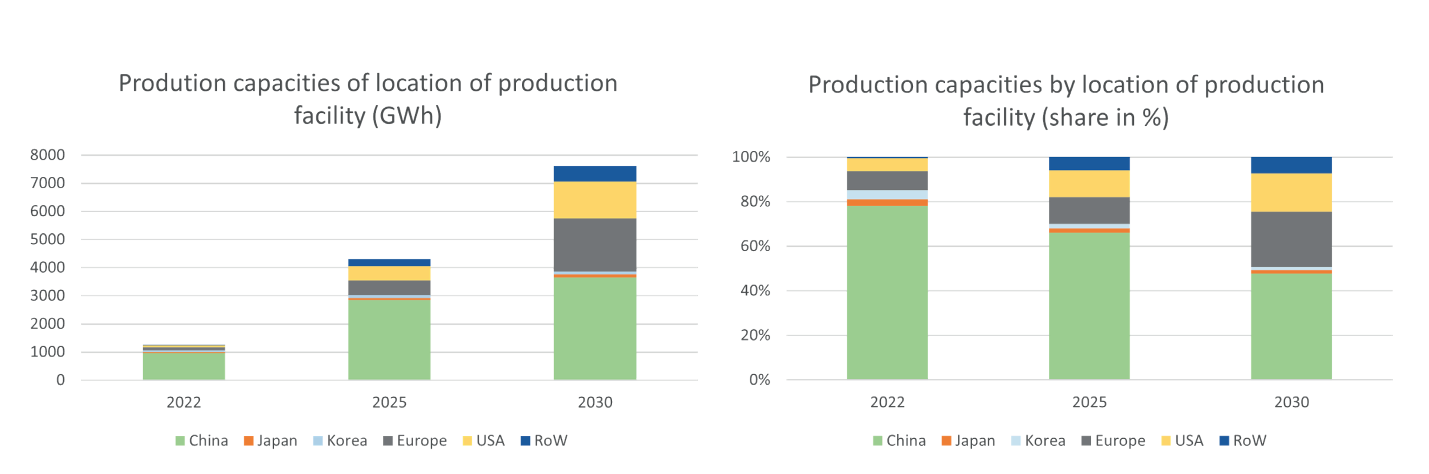
Together with China and Europe, these three hotspots alone already generate 70-80 percent of global demand. Demand by the U.S. is therefore already over 100 GWh in 2023/2024 and is expected to be 300-500 GWh or higher by 2030.

Local joint ventures between US OEMs and Asian cell manufacturers (not least Tesla/Panasonic) have enabled domestic demand to be met locally to a large extent to date.

In the coming years, established cell manufacturers will be able to meet the growing demand, so that there is only limited room for the large number of announcements for capacity expansions or production by new players.

The approximately 1.3 TWh of production capacity announced by 2030 is split between U.S. manufacturers at 400 GWh, local joint ventures at about 300 GWh, and foreign companies at nearly 600 GWh.

Between 2025 and 2030, it is likely to become clear to what extent the Inflation Reduction Act will lead to a relocation of production to the USA and, if necessary, to the emergence of export markets from there.



Global production capacities in GWh by location (left) and percent shares of production capacities (right).
Source: Fraunhofer ISI

What must a production site deliver to be suitable?

According to global announcements for LIB cell production capacities, 4 TWh would already be in place by 2025, quadrupling today's capacities. By 2030, 7.6 TWh have been announced. Over 6.8 TWh in Europa, China and the USA alone. Thus, there will be a shift of shares from China to Europe and the USA. More than 90 percent of global production capacity is then expected to be concentrated in these three hotspots, while they are responsible for 70-80 percent of battery demand.

As things stand at present, 10-20 percent of the cells then produced could be exported from these hotspots to other regions of the world. This is already the case for China, and the USA could follow in the coming years. For Europe, it will probably be decided between 2025 and 2030.

By 2030, a global shift in cell production to locations where cells can be transported as easily as possible to their user markets is emerging: primarily to OEMs.

The particular relevance of the proximity of cell production to the sales market becomes clear when one considers the need and the possible potential for cost reduction for battery cells and packs:

- Transportation costs (especially at future GWh scales) and thus logistics costs can be reduced by locating close to sales.

- Although energy and personnel costs account for only a few percent of battery costs, they are likely to have played a role in the choice of location by LG Chem, SDI, SKI in Poland and Hungary. With the current significant increase in energy costs (especially in Germany), cell manufacturers are already reacting by relocating previously announced production away from Germany or even Europe. Thus, energy costs currently represent a real and central competitive factor.

- Costs for **infrastructure** (land, buildings, etc.) represent a significant part of the initial investment and must be allocated via depreciation. Settlement policies of states, regions, municipalities and cities play an important negotiating role here in order to make their location attractive for cell manufacturers.

- In addition to the pure "economy of scale", **automation** represents an important lever to further optimize process steps, quality, yield and throughput. The proximity of cell manufacturers to equipment suppliers and the supply chain, which provide the opportunity for a unique position in **material and process quality**, can contribute to location decisions. Here in particular, European mechanical engineering could offer added value for Asian and European cell manufacturers and build up references in the future.

- Last but not least, "green battery production" and the reduction of CO_2 emissions also play an important role. emissions have long played a central role for cell manufacturers. In addition to energy-efficient production, the energy mix itself is also decisive for the choice of location. With the European Battery Regulation, sustainability criteria such as the CO_2-footprint, a battery passport, recycling quotas, etc., also provide indirect incentives for local battery production created.

The location Germany might have been decisive for some of the cell manufacturers in the past due to the combination of several factors: energy mix, proximity to OEM as well as access to skilled labor. As this has currently changed with the geopolitical tensions, the subsidy policy of the USA, the energy costs, etc., quick political action, as demanded by the European battery industry in particular, is important. The goal must be to ensure a level playing field and competitiveness, especially vis-à-vis China and the USA.

Markets for machinery and plant manufacturers

The core of every existing gigafactory, whether under construction or announced, is the actual production line for cell manufacturing. Depending on the production step in the manufacturing process, a different number of production lines must be provided or commissioned for the production capacities targeted in the respective factories. The throughput and also the costs of the equipment can sometimes differ significantly between different production lines. Reasons for this are, for example, the cell formats or cell chemistries produced, but also the intended use of the battery has an impact (for example, high-energy cell vs. high-performance cell). In addition, the lines on the market today differ in their technical specifications.

Knowledge of the production capacity of future gigafactories [FraunhoferISI2023a] allows an estimate of the number of machines required and thus also the investment sum in production plants.

Mixing

In current batch mixing, the achievable throughputs (in relation to the battery capacities that can be produced from them) depend, among other things, on the mixer size, the mixing time and the solids content of the slurry. Assuming materials commonly used today and average plant sizes, the throughput per mixer unit (incl. binder digestion, etc.) is slightly over 1.5 GWh per year. Particularly at this process step (at the beginning of the process chain), material must be produced in surplus, since product scrap occurs subsequently to the mixing. Due to higher machine throughputs in the downstream processes, plants often consist of several individual mixers.

In the coming years, it will be possible to achieve further improvements in plant design for pure wet processing. In the case of semi-wet or dry electrode production, other mixing technologies or plant concepts are necessary due to completely different solids contents (80 - 100 percent) (see also Technology Chapter 1, p. 61). Based on expected technological advances, an increase in plant throughput of about 60 percent for discontinuous wet mixing is theoretically possible by 2030 (also due to optimization of cell chemistry). Differences between anode and cathode production exist but depend strongly on the active materials used (e.g. Si anode material). Overall, it can be assumed that the greatest innovation in the next few years will not come from optimization of wet mixing, but from a switch to dry processing. Individual manufacturers are in the process of integrating such processes into their production on a large scale.

A major increase in throughput can be achieved by converting the batch process to continuous mixing processes, e.g. extrusion mixing using twin-screw extruders. Continuously operating extruders have significantly higher material processing capacities of more than 1,000 l/h. Theoretically, throughputs of more than 5 GWh/a can thus be achieved in such a mixing plant today. Processing with anode material can probably be used on the mass market more quickly than cathode production. In the construction of today's industrial plants, batch processes are still being deliberately used.

In relation to current production announcements, approximately 700-750 mixers will be required globally for the increase in cell production in 2023. Due to high investments in the periphery (e.g. dosing units, etc.), a gigafactory requires an investment of about 3-11 million euros per GWh of production capacity.

Coating and Drying

Compared to the mixer, there are several design measures for coating systems to increase production capacities. A higher coating speed and coating width is a common topic of discussion (see also Technology section 2, p. 68). Thus, the current production capacity of about 5 GWh/a can be more than doubled in 2030.

The drying process downstream of the coater is strongly linked. Usually, it is a combined production plant. In the case of a development towards dry coating, the drying step is omitted completely. Increasingly, research is being conducted into alternative drying processes which, in addition to improvements in energy efficiency, can also have an increasingly important influence on throughput rates.

If the machine throughput of a large SoA tandem coater is put in relation to the expansion of production capacities, approximately 200 plants will be needed globally in the entire year 2023. Based on the plant costs of 3-6 million euros per GWh of annual production capacity, this results in investment sums of between 1.8 and 3.6 billion euros. In practice, it can be assumed that demand will be even higher, since on the one hand the run-in processes generate a lot of production waste, and on the other hand smaller plants are used in some cases. In coating and drying, there is still clear potential for development and innovation. Due to the complexity of the various plant components, competitiveness can be achieved on the basis of technical know-how.

Calendering and Slitting

In today's gigafactories, a calender is often mounted downstream of every tandem coater-dryer unit. Due to the high roll speeds that can be achieved and other major development advances, the production capacity of the calender does not represent a bottleneck of throughput in the linking of the individual production steps. The slitter or the separating system is often located directly behind the calender. For this reason, identical quantities can also be assumed here.

The required number of units for 2023 thus corresponds to the number of coater-dryer units worldwide and, calculated with theoretical plant throughputs, amounts to 200 units each. Per GWh of production capacity per year, approximately 1 million euros must be invested in the calender and 1-3 million euros in the slitter (depending, for example, on whether lasers or knives are used for cutting). According to the coater-dryer unit, more equipment will probably be installed in practice.

It can be assumed that through optimizations, the throughputs can be adjusted according to the upstream steps. Although there are also film handling challenges in calendering (see Technology Chapter 3, from p. 76), these can in all expectation be solved for the required throughputs. For calender manufacturers, there are competitive advantages if there are quality benefits over competitors (e.g. through precise pressure adjustment or sensor/camera monitoring).

Vacuum-drying

In order to completely dry the electrode foil (daughter) coils after slitting, they are placed in a drying oven for approx. 24 hours. Possible increases in the throughput of the process step could be achieved by larger geometric dimensions or also by reducing the length of stay of individual coils. Currently, electrode foils with a capacity of approximately 1 GWh/a can be dried in a vacuum oven unit. This throughput could double by 2030. In most cases, several drying ovens are required after each electrode foil production unit. In the field of drying oven development, competitive advantages cannot be clearly predicted due to technical know-how. For example, there are also alternative approaches such as continuous vacuum drying.

In terms of worldwide production capacity, the achievable plant throughputs indicate a global demand of 900-1000 vacuum drying units in 2023. The costs are around 0.5 million euros for a plant throughput of 1 GWh/a.

Separator production

Modern production lines for separator film have a throughput of approx. 110 million m² per year. This is enabled by a produced film width of 5 to 6 meters and line speeds between 60 to 80 m/min. Based on a typical electrode load and thus the required amount of separator film per battery capacity, the machine throughput means an annual producible battery capacity of 11 to 12 GWh/a.

Film production and film handling of polymeric materials from a direct extrusion process has been tested and optimized for many years using extrusion. However, continuous development is still conceivable (see Technology Chapter 4, p. 83).

Separators for cell production of the newly built gigafactories in 2023 can be served with the help of 50 additional production lines. Due to machine costs of over 2 million €/(GWh/a) and peripherals that are even more expensive, the market size amounts to up to 2.5 billion euros.

Cell assembly

Further processing of the electrodes takes place in drying rooms. The machines required there differ depending on the cell format produced. A precise prediction of the cell formats that will be used in the future is difficult. For simplification, this chapter considers cylindrical/ pouch/ prismatic cells in equal proportions.

Investment costs for the entire cell assembly steps amount to approx. 8 to 12 million euros per GWh of annual production capacity. In total, investment sums of approx. 5 to 7.5 billion euros will be required worldwide in 2023 for the various machines and the structural measures to provide the necessary process atmosphere (drying room).

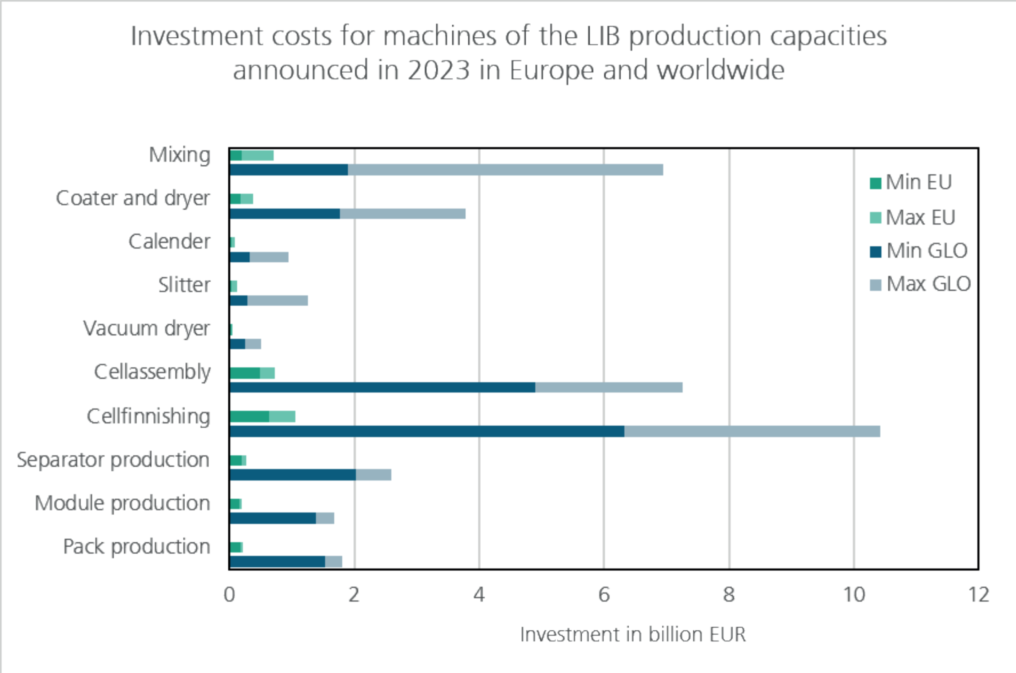
Winding as well as slitting and stacking

The pouch cell stacking process has somewhat lower machine throughputs compare to other cell formats due to the more complex and so far not completely continuous material handling. In the future, the highest machine throughputs will be achieved with cylindrical cell formats (due to increasing cell sizes and higher production rates). However, the acceleration of the future production rate can also stagnate with increasing cell sizes, since more windings or larger cell stacks are required. In the stacking process, it is assumed that two separation systems (for anode and cathode respectively) are designed to produce the sheets and are installed upstream of the process step, depending on the throughput of the stacking system. Averaged over different cell formats, the plants can achieve production capacities of 0.6 GWh/a today. By increasing the winding and stacking speed in combination with an increase in cell size, a plant could produce about 1.8 GWh/a by the end of the decade (2.2 GWh/a for winding plants and 1.3 GWh for stacking plants).

The machine throughputs make it obvious that there is a need for parallelization of the plants. The design development work required for further speeding up the plants (above all automation topics, including in combination with sensor-based process monitoring) represents possible potential for mechanical and plant engineering (see Technology Chapter 6, p. 95).

Insertion into housing/packaging and contacting

Compared to the winding or stacking machines, the subsequent assembly steps (insertion into cell housings and contacting there) have faster throughput rates. There are different coupling methods of e.g. contacting and packaging machines, but most of them have coordinated throughputs. Averaged over the different cell formats, a plant today has a production throughput of approximately 2 GWh/a. The machines can be optimized. This can be achieved through technical improvements (e.g. in welding technology, or in cell handling and the resulting increase in assembly speed), but also with the size of the cells. Thus, the capacity can be more than doubled. Even more clearly than in the upstream process step, the cylindrical cell format has the highest throughput. Corresponding to the upstream process step, several lines have to be started up in parallel.



Overview of European as well as global plant investments for announced production facilities in 2023, broken down into individual manufacturing steps.
Source: Fraunhofer ISI

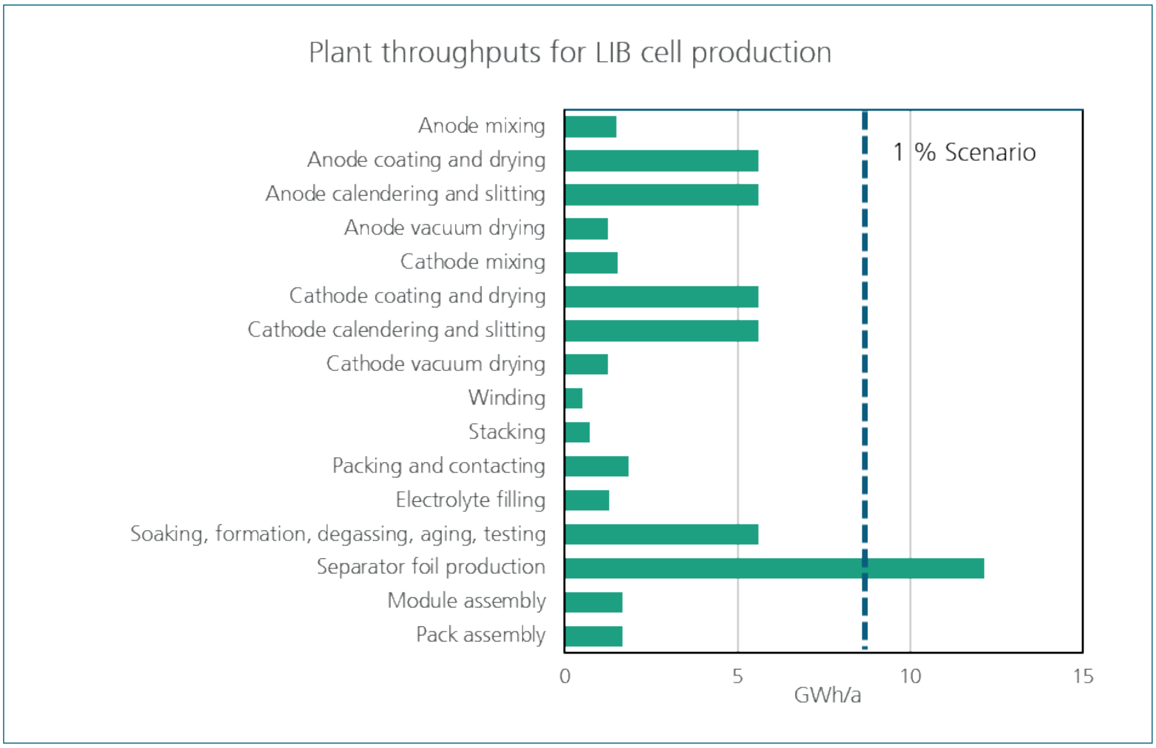
Electrolyte filling and degassing

Electrolyte filling systems, like the other process steps of cell assembly, are normally parallelized. Cylindrical cells are filled faster due to their volume, but the other cell formats have more energy content. Currently, throughputs of 0.5 to 0.6 GWh/a per system are possible. Improvements in production rate and cell size (in parallel with upstream manufacturing steps), as well as different innovative approaches, will bring significant throughput increases in the future (see technology chapter 7, p. 100).

Cell finalization

Due to the sometimes long dwell times in this step of cell production, the battery cells are not treated continuously during finalization, but are predominantly at rest. The wetting, forming, degassing and aging steps, as well as the final testing take place in warehouses in which approx. 30 pouch or prismatic cells or over 250 cylindrical cells are arranged next to each other.

These are fed into a fully automated system. Due to the plant interlinking, all steps are combined and considered as one plant. In this plant, the cells are first stored for electrolyte wetting (assumption: 6 hours), then there is a formation (assumption: 24 hours), degassing, and aging (assumption: 2.5 weeks) step. At the end of cell production, the cells are tested. The plant is usually designed according to the accumulated throughputs of the parallelized cell assembly. The lever for the greatest throughput increase in the next few years in cell finishing is the reduction of all individual dwell times (see technology chapter 9 p. 113). New gigafactories in 2023 will require approximately 100 cell finishing plants. These in turn will incur costs of up to 9 billion euros.



Currently possible plant throughputs of different manufacturing processes (separate anode and cathode produc-tion) as well as an illustration of the required throughputs for the one percent scenario.
Source: Fraunhofer ISI

Module- and pack production

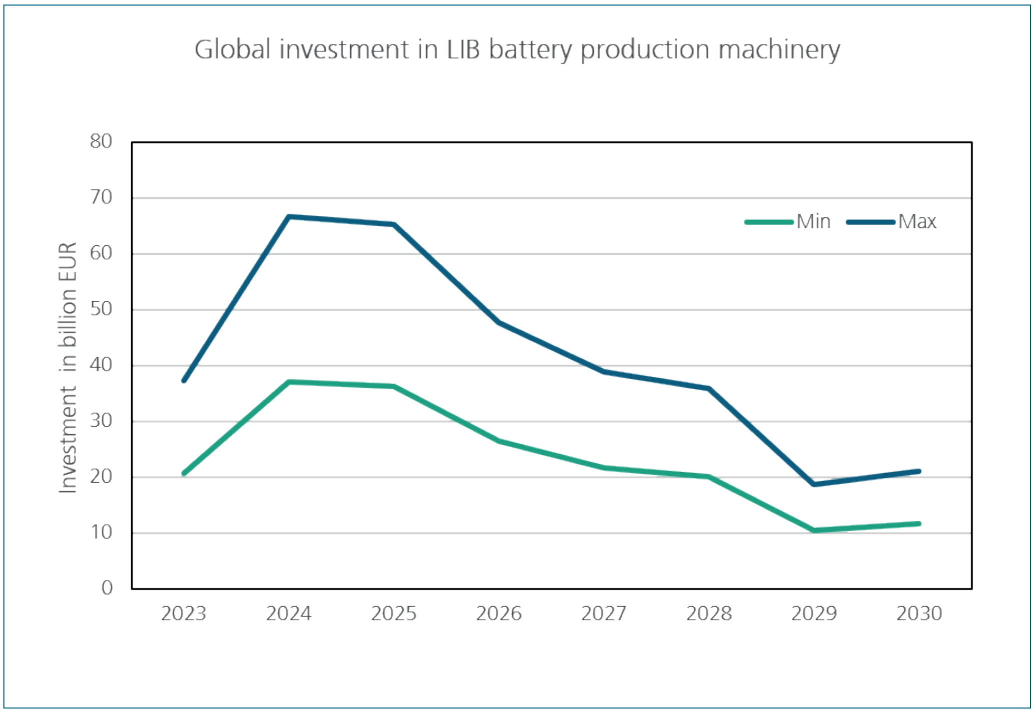
Module and pack production itself usually takes place at different locations apart from cell production. In the automotive sector, modules (or packs) are often manufactured directly in the vehicle production plant. Due to the coupling to the vehicle production line, the production speed of the modules is adapted to the speed of the vehicle production. The average production capacity of a plant is about 1.6 GWh/a.

The production capacity required for a fast-working production line or even an entire factory can be realized by parallelized systems. It can be assumed that the plant capacity will be further improved (potentially to double the throughput) due to innovative contacting technologies, cell format optimizations and fundamentally new module and pack designs. Depending on the battery applications (e.g. in the consumer sector), no modules or packs are required in some cases. In total, this results in a machine requirement of about 300 to 350 module production lines and about a similar number of pack production lines in 2023. For module production, investments of 2.5-3 million €/(GWh/a) are required, for pack production slightly over 3 million €/(GWh/a).

Machine sizing coupled to global production capacity

An interesting aspect of the total number of production plants required in the future is the extent to which production throughput will grow in parallel with the greater market demand. From other industries, there are rough guidelines that production plants with manufacturing capacities of about one percent of global demand hit a sweet spot in economic terms (e.g. raw material supply, scaling effects, location dependency, transport routes).

In 2023, the expected cell demand amounts to approx. 880 GWh [FraunhoferISI 2023b]. A one percent global production would thus mean a plant throughput of just under 9 GWh per year.



Minimum as well as maximum investment sum in process plants of the announced cell production capacities until 2030 at constant plant costs.
Source: Fraunhofer ISI

The figure on the page before shows that for some production steps this limit seems to be achievable. Separator production even exceeds this value. For other process steps, in particular cell assembly, it is evident, as described above, that plants must be operated in parallel. For the year 2030, it can be assumed that the demand will increase to over 3 TWh [FraunhoferISI 2023b]. The previously mentioned increases in throughput (in some cases by 100 percent) will not be sufficient to maintain the throughput required for a constant market share of a single production line.

There is no question that a one percent market share at one location is feasible (e.g. giga-factories with more than 100 GWh production capacity announced by CATL in Debrecen, Hungary or CALB in Hefei, China). However, in this gigafactories several production lines are operating (or set up) in parallel. This can offer advantages in individual cell production (i.e. simultaneous production of different formats or cell chemistries). At the same time, a scaling of the individual production lines (at least for some production steps) would offer the possibility of increased cost efficiency of production and, above all, of the production equipment.

Market development until 2030

The further development of the various plants and plant throughputs that will take place in the future also has very large development potentials in some cases, as shown. Plants can therefore increase their throughput. However, the number of machines required is growing due to the relatively stronger increase in demand for batteries. A particularly strong increase in demand is expected in the coming years. During this period, there will be a large number of announcements of new gigafactories. The figure on p. 30 gives an overview of how large investment sums would be for the announced production facilities if investment costs in plants remained constant over the next few years.

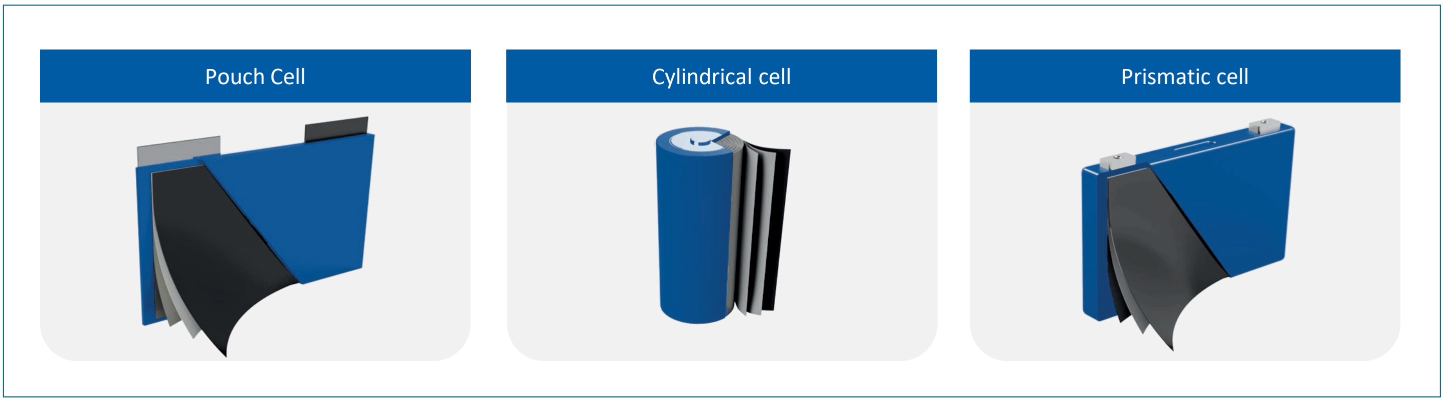
Expert assessment of the economic situation in the machinery and plant engineering sector

A survey of experts from the European mechanical and plant engineering industry conducted during the VDMA expert workshop "Battery Production of Tomorrow" in Frankfurt in October 2022 suggests that the increasing demand for production equipment worldwide will also have a positive impact on industry growth for the German and European mechanical and plant engineering industries. There are various reasons for this. According to the participants, the mechanical and plant engineering industry based here is, for example, a leader in the field of process automatization. In addition, plants can often keep up with or even surpass non-European competitors in terms of sustainability and quality. Another advantage is the exchange between European companies in the industry, which can be a catalyst for innovation.

An important point is that, with the help of various innovations, advantages in terms of OPEX and TCO can be achieved, e.g. through new types of process control. However, Asian competitors in particular have a head start in terms of time and industry-specific know-how.

According to the majority of those surveyed, the cell production currently establishing itself in Europe is leading to additional positive trends in the general business climate. Overall, it can be assumed that the sum of all global equipment manufacturers will be able to serve the planned cell production capacities with the correspondingly required equipment. For the European market, the question arises as to how many of the emerging projects are relevant for European machinery and plant manufacturers. Asian investors will usually bring their own suppliers. The question of whether European production capacities can be built up to meet demand depends on many aspects and cannot be answered clearly today.

New players in the cell production market are often interested in turn-key solutions, as there is still too little process understanding to implement individual plant selection and coupling. Experienced cell manufacturers, on the other hand, can engage in a kind of "cherry picking" and integrate the best plant concepts for their companies into a production line. Whereas in Asia companies are already established that can manufacture complete production lines, in Europe the aim can be to form joint ventures. This may be a strategically useful way of offering turnkey production lines manufactured within Europe for the European market.



Relevant cell formats in the automobile industry
Source: RWTH Aachen PEM

Cell formats: advantages and disadvantages of each format

Comparison of cell formats

Lithium-ion battery cells are used in a wide variety of products. From consumer electronics to the automotive industry, these cells are used as energy storage devices. Due to the wide range of applications, a large variety of battery formats and sizes is available. Generally speaking, a distinction is made between three different cell formats. The majority of battery cells can be classified as either pouch cells, cylindrical cells, or prismatic cells.

Cell housings are used to determine the format. Pouch cell housings are typically made of a plastic-aluminum composite foil, with thin metal strips used for electrical contact in the cell. In contrast, cylindrical and prismatic cells are housed in rigid sheet metal components (often stainless steel or aluminum). Electrical contact is made via contact surfaces on the housing assemblies.

Production of the different cell formats is generally similar. Due to the different housing types, the greatest differences in the production of the various cell formats lie in the cell assembly.

One major difference in the cell assemblies is the integration of electrodes and separator. Stacking processes are used for the production of pouch cells. Cylindrical cells are manufactured using winding processes. Prismatic cells can be manufactured using both stacking processes and winding processes. A large proportion of prismatic cells have thus far been assembled with so-called flat windings, but increasing numbers of cells are being manufactured with stacked electrode-separator assemblies for the automotive industry.

There are good arguments for both stacking processes and winding processes. A significant advantage of winding is the higher process speed. However, stacking allows better utilization of the installation space within the housing. This means that the energy density of the battery cells can be increased. Various development approaches are currently being used to increase the stacking process speed. One approach is to laminate the separator and electrode so that they can subsequently be stacked together [Kwade2018b], refer to technology chapter 6, p.99).

A great deal of effort is required to convert a production line from one cell format to another. Similarities in electrode production and cell finalization (to a certain extent) generally make it possible to convert existing lines can be generally be converted. In cell assembly, however, plants are precisely matched to the cell format so it makes sense to commit to a specific format.

Each cell format is available in a large number of variants with different dimensions. The goal is always to optimally adapt the battery cell to the

	Pouch cell	Cylindrical cell	Prismatic cell
Energy density on cell level	High (low housing weight, good utilization of installation space)	High (low housing weight, good utilization of installation space)	Medium (increased housing weight, insufficient utilization of installation space)
Packing density on system level	High	Medium (Cylindrical geometry)	High
Number of parts	Low		High
Mechanical properties	Low stiffness (force transmission limited by housing)	Very high stiffness	High stiffness
Thermal properties	Good surface-to-volume ratio, efficient temperature control	Poor heat dissipation	Good surface-to-volume ratio, efficient temperature control

Comparison of the different cell formats
Source: RWTH Aachen PEM

available installation space and the characteristics of the battery system. System concepts must address the high diversity of cell variants.

Energy density is one of the most important technical parameters of the battery for mobility applications. Available space is limited and the weight of the vehicle greatly influences the subsequent energy consumption. In general, a distinction is made between volumetric and gravimetric energy density. The volumetric energy density relates the stored energy to the required installation space. Gravimetric energy density, on the other hand, relates the stored energy to the required weight.

The selected active material, the inactive material, and the utilization of the installation space are key for the potential energy density at the cell level. Due to their low housing weight, round cells (cylindrical cells) and pouch cells theoretically have higher energy density than prismatic cells at the cell level. However, with the trend toward large-sized prismatic cells and pouch cells, they will be able to exceed the gravimetric energy density of cylindrical cells in the near future.

Pouch cells benefit from the low weight of the plastic-aluminum composite film. The housings of prismatic cells, on the other hand, have a higher weight for the same size. As the battery cells are integrated into battery systems for mobility applications, the energy density at the cell level is of limited significance [Löbberding2020].

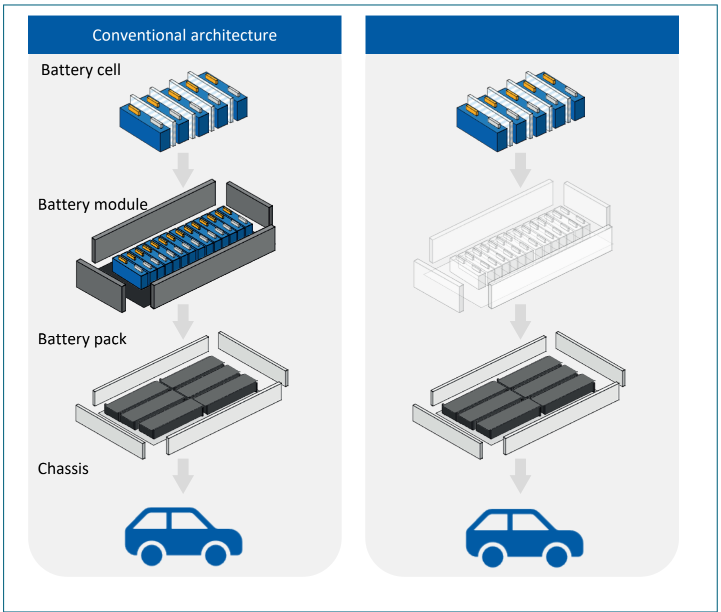
At the system level, the energy density is particularly influenced by the packing density of the battery cells and the quantity of other components. Here, cylindrical cells lose part of their advantage over prismatic cells and pouch cells due to the lower packing density of cylindrical bodies [Löbberding2020].

In addition to energy density, the mechanical properties of the cell formats also play a role. The rigid sheet metal housings of cylindrical and prismatic cells are advantageous from a mechanical perspective. The individual battery cells can also perform mechanical functions at the system level, and these cell housings are also easier to handle. Cylindrical cells are the most rigid due to their geometry.

A trend towards ever larger cell dimensions can also be seen in cylindrical cells. However, cylindrical cells are smaller and have a lower energy content relative to the other cell formats. Therefore, a greater number of cylindrical cells is required for a comparable battery system. The advantage of this is that additional bracing of the cells in the radial direction is not required.

The volume change of cylindrical cells during operation is negligible [Warner2014]. However, significantly more joints are required at the system level, which makes assembly more difficult.

For cylindrical cells, the 46xx format (46 mm diameter, xx mm height) is increasingly gaining acceptance in the automotive industry. For example, Tesla is increasingly relying on cylindrical cells in the 4680 format. It can be expected that the smaller 18650 (18 mm diameter, 65 mm height) and 21700 (21 mm diameter, 70 mm height) formats will mostly be displaced by these larger cells. Advantages include higher energy density, easier assembly, and lower costs. An additional increase in diameter is not expected for the time being, as the packing density and cooling do not permit it.



Comparison of conventional system architecture to the cell-to-pack approach
Source: RWTH Aachen PEM

Due to their format and size, prismatic cells are particularly suitable for the production of modules with less of a supporting structure. Pouch cells are less rigid due to their foil envelope, and therefore must be positioned using a plastic frame.

In principle, all cell formats can be tempered by suitable cooling systems. The differences lie primarily in the **required cooling effort** and the options for **dissipating and supplying heat**. In electromobility, fast charging typically induces the greatest thermal load in the cell. The goal of cooling is to produce a uniformly low temperature in the cell. The uniformity of the temperature distribution has a major impact on the aging of the cell. The heat is typically dissipated by a cooling liquid.

In cylindrical cells, the heat generated during charging processes, particularly in the core, can best be dissipated via the outer surface of the cylinder, although the geometry makes producing a homogeneous temperature distribution a challenge. Due to the cylindrical shape and the distance between the cells at the system level, air cooling is used in isolated cases. This is inexpensive, but not as efficient.

The direct thermal connection of the electrode material to the cell walls in pouch cells allows for good heat dissipation via the current conductors as well as the sides of the cell, thus offering the best cooling performance. The disadvantage of the prismatic cell format is a long cooling path, as they are usually cooled via the bottom. This can lead to undesirable temperature gradients in the system, since the top of the cell is quite far from the cooling surface. However, the cell housings have good thermal conductivity, which can partially compensate for this disadvantage. Cooling between the individual prismatic cells is another possible cooling concept. The ever-increasing charge currents, which lead to higher heat generation, require higher-performance cooling systems.

The **service life** is difficult to compare across cell formats. It depends heavily on the cell chemistry, influences from the manufacturing process, and the stress during operation. Due to the so-called aging of the battery cells, the capacity for storing energy decreases. In general, a distinction is made between calendar aging and cyclical aging of the cells. A cell has reached the end of its service life when the remaining capacity falls below a certain percentage of the initial capacity.

New system architectures in the automotive industry

In the automotive industry, multiple battery cells are conventionally combined to form a battery module. In addition to the cells, electronic and mechanical components which are necessary for proper functioning are also integrated into the battery module. Multiple battery modules are then installed (with additional peripherals) in a battery pack, which is finally integrated into the chassis. (see the figure on left side of page 34).

This modular system architecture offers several advantages. For example, the use of standardized modules in different pack and vehicle variants can reduce complexity, development time, and costs. Furthermore, a uniform interface in the battery pack allows modules with different battery cells (e.g., manufacturer or cell format) to be installed. This can reduce dependencies on individual suppliers.

Disadvantages of the modular design are the large quantity of components, the associated manufacturing costs, and poor utilization of installation space. For this reason, an integral system architecture is increasingly being pursued. The cell-to-pack approach, in particular, should be mentioned here (see the figure on the right side of p. 34). By integrating the battery cells directly into the battery pack, gravimetric and volumetric energy density can be increased at the system level. Cost savings can also be achieved through component reduction.

In current battery systems, the cells take up about one third of the total volume at the system level. In electric vehicles, the cells account for over 70 percent of the total system weight. The rest of the volume and mass is distributed among dead volume, other components such as the battery management system, and also the housing components and cooling system.

Overall, there is a trend in the automotive industry toward the increasing use of large-format cells, partly because they can be assembled into a module or system with less manufacturing effort. In order to be able to bypass the module level, the cells must be large enough to be directly interconnected to form a battery system and have sufficient capacity for the respective application. A very thick cell would be disadvantageous due to poor heat dissipation, and a tall cell cannot meet the tight installation space requirements in the vehicle, which is why it makes sense to design cells with elongated dimensions.

The size means that a lot of energy is stored in a single cell, which increases the overall risk in the event of a thermal runaway of the cell (thermal runaway into an exothermic reaction). One way around this is to use a comparatively safer cell chemistry, such as lithium iron phosphate, while accepting a lower energy density.

From a product perspective, the concept of larger cell formats seems logical, but it increases the demands on cell production. The stacking or winding of extremely long electrode assemblies and thus elongated cells makes the handling of the electrode sheets very complex, as positioning inaccuracies can lead more quickly to critical safety or quality defects. The uniform distribution of the electrolyte in a very large cell also increases the filling time and requires new filling concepts. Ultimately, from a quality assurance perspective, it is much more expensive to reject individual large-format cells during end-of-line testing, as required by the *cell-to-pack* approach, because much more value is lost than with a small cell. Despite progressive digitalization, the fact remains that the quality of a cell can only really be determined at the very end of the production process.

It remains to be seen whether these increased demands on cell production process can be implemented economically in the long term. Here, cell producers are dependent on innovative solutions from mechanical and plant engineering.

Product requirements and specifications

The central technical performance parameters for electrical energy storage systems are:

- Gravimetric energy density [Wh/kg] also called specific energy and volumetric energy density [Wh/l].
- Gravimetric power density [W/kg], also called specific power, and volumetric power density [W/l], as well as the fast-charging capability derived from these.
- Cyclic and calendar lifetime
- Environmental conditions such as tolerated temperatures in [°C] or vibrations
- Safety according to EUCAR level
- Cost [€/kWh]
- Ecological footprint in manufacturing, use and recycling [kg_CO2_eq/kWh].

Other relevant criteria are voltage stability during the discharge process or the integration effort in the application. In addition, specifications such as the environmental compatibility of the production and the cost-effective, environmentally friendly disposal need to be taken into account, as well as the growing interest in re-manufacturing and recycling of the components.

The central topic is the reduction of storage costs at system level. This can be achieved, among other things, by further developing the energy density at the cell level, which can also increase the range of electric vehicles and improve their competitiveness compared with internal combustion engines. In addition, a change in cell chemistry can have a major impact on material costs and, at the same time, cell costs.

For plug-in hybrid electric vehicles (PHEV) and hybrid electric vehicles (HEV), power density in particular plays a role. In the case of purely electric vehicles (EVs), the requirements of automobile manufacturers (OEMs) for volumetric energy density in particular have increased considerably in recent years, since the dimensions for installing the battery in the vehicle are generally specified and the achievable energy density at the pack level is decisive for the range. Electric vehicles available today have ranges of up to 700 km.

Developments in recent years clearly show that the lithium-ion cell is a suitable technology for the realization of electromobility that still has further potential.

Performance parameters for electromobility applications

The development of the prices of small-format lithium-ion cells, e.g. for consumer electronics applications, shows the optimization potential of the large-format lithium-ion cells currently used for mobile applications. This is made possible both by material innovations and by economies of scale in mass production.

For a long time, the highest energy densities were achieved in cylindrical cells. Today, the gravimetric energy densities achievable in the three cell formats pouch, prismatic and cylindrical are similar, with maximum values for automotive cells ranging from 240 (prismatic) to 300 Wh/kg (pouch). In the future, maximum values of well over 300 Wh/kg could be achieved.

In terms of **volumetric energy density**, the cylindrical cell still dominates. The value of over 750 Wh/l achieved more than 5 years ago still represents the industry benchmark. In the future, with LIB technology, even more than

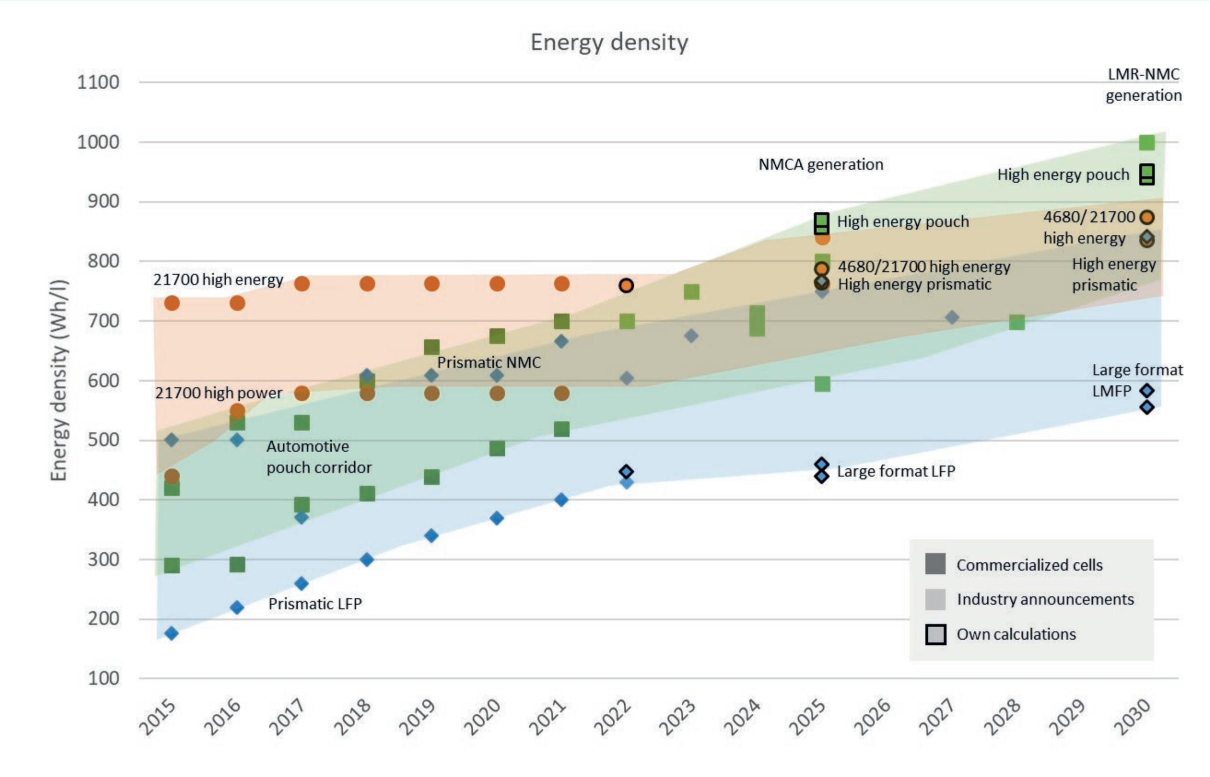
900 Wh/l could be achieved. Peak values for the prismatic and pouch cell are currently over 650 Wh/l. In the long term, up to 800 Wh/l (prismatic) and over 900 Wh/l (pouch) are conceivable.

Compared to the cell level, the volumetric energy density at the module level in module-based designs drops by 20-22 percent for the prismatic cell, 30-50 percent for the pouch cell and about 50 percent for the cylindrical cell. Many of the current developments in the automotive sector are therefore aimed at more efficient integration of the battery cells in the battery pack. This can be achieved by eliminating the module level or by more efficient arrangement of cooling and safety systems. In current cell to pack designs, the gravimetric energy density at the pack level drops only about 12 percent compared to the cell [FraunhoferISI2023c], while the volumetric energy density drops about 28 percent [FraunhoferISI2023d].

The **power density** of batteries is differently relevant for individual powertrains. In contrast to purely electric vehicles, where volumetric energy density and high power during charging are the decisive criteria, a high power output of the lithium-ion cell is of particular relevance for hybrid drive concepts in order to enable acceleration peaks. Currently, the gravimetric power density at the pack level is over 500 W/kg for EVs and a few 1000 W/kg for HEVs. The gravimetric power density of the lithium-ion cell should stay at least at the same level with an increase of the remaining power parameters. **Environmental requirements** are taken into account by specifying the power density at a low temperature of -20°C. At this temperature the gravimetric power density is about a factor of five below the power density at room temperature.

The **calendar lifetime** varies across all electric vehicle types, as it depends on the stress on the battery. Manufacturer warranties for EVs today typically exceed 10 years with mileages in excess of 150,000 km. To match the useful life of today's internal combustion engine vehicles, which often spans several phases from initial registration to used markets, lifetimes of 15 to 20 years must be realized. During this period, mileage of several 100,000 km can be achieved, but it is still unclear to what extent this can be achieved with a battery. The charging power has a major influence on the service life. Fast charging can accelerate degradation. Another major influencing factor is the driving and charging profile of the vehicle batteries. According to typical use, it can be assumed that EV batteries in particular are only fully discharged during infrequent long journeys. Battery use in partial cycle operation leads to low degradation, so that even high km performance with over 1000 full cycle equivalents can be covered by the battery over its service life.

The situation can be different for hybrid vehicles with significantly higher cycles and possibly higher depth of discharge. Corresponding batteries have lifetimes of several 1000 cycles. Commercial BEV applications such as trucks may also require several 1000 cycles.



Evolution of volumetric energy density of LIB cells on cell formats [Link2022].

With increasing fast-charging capability, the stress on the cell increases. This results in up to 800 W/kg for BEVs, and in some cases even more for PHEVs and HEVs during charging.

The EUCAR level is used to assess **safety** at battery system level and at cell level. For a safety level of "EUCAR≤4", the cell must be shatterproof, fireproof and explosionproof.

Acceptable at this level is a weight loss or leakage of the electrolyte (or solvent and salt) of more than 50 percent, as well as the so-called venting. This essential safety standard can be achieved by cell chemistry, for example by using safe electrolytes or so-called "shutdown" separators. The latter prevent further ion transport when the cell overheats.

In addition to cell chemistry, the design of the Li-ion cell and the battery modules as well as packs plays an important role. At the cell level, safety valves prevent excessive internal cell pressure and thus an explosion of the cell. At the battery module level, the circuit can be interrupted by thermal fuses to prevent overheating of the cell. The mechanical stability of the cell is structurally established by the individual housings [Balakrishnan2006]. Relevant safety standards at cell or package level are covered, for example, by UL1642, UN38.3 or the new Chinese standard GB38031.

Performance parameters for stationary applications

Compared to mobile energy storage, stationary energy storage can be covered by a wider range of storage technologies. Stationary storage is used both decentrally, e.g. as solar home storage with < 10 kWh, and centrally with storage sizes in the gigawatt hour range [Thielmann2015c]. Therefore, even within a specific segment, it is important to know which specific application it is. A rough classification can be made based on the application area as energy or as power storage [Kaschub2017].

Power storage systems, which have to deliver and absorb high currents in the short term, have particularly high criteria for cyclic lifetime, while energy storage systems, which have large storage volumes, require a long calendar lifetime.

Usually, for both types of storage, it is assumed that the cost requirements are high, which have to be considered in overall economic calculations over the entire life cycle. The level of investment and operating costs is significantly influenced by the fulfillment of lifetime requirements. The efficiency of an energy storage system also plays a major role, since the temporarily stored energy should be fed back into the power grid with as little loss as possible in order to realize a sustainable energy supply.

Key applications of stationary energy storage are decentralized PV battery systems, peak shaving, direct marketing of renewable energies, provision of balancing, and the so-called "multi-purpose" design. The state of the art for the reference technology and its range of application has been comprehensively documented in the roadmap by Thielmann et al. with regard to the storage solution used [Thielmann2015c].

Due to further cost reductions, lithium-ion cells optimized for mobile applications are also becoming more attractive for stationary applications. If the performance parameters meet the requirements of stationary applications in principle, they are also used there. Often, however, these can only be met by a certain overdimensioning. "Second-use" concepts represent a second application for BEV cells and modules [Fischhaber2016].

Battery manufacturer requirements

Product requirements (and the performance parameters derived from them) for high-energy and high-performance applications are documented in existing sources and have been included in the road-mapping process. Detailed specifications of the battery manufacturers for the production technology are often subject to NDAs and are only accessible to a limited extent. The customer perspective and their requirements for machine and system construction were ensured by involving battery manufacturers and the automotive industry. The dialog at international events also provides important input for the roadmap.

Cell production

Cost efficiency in cell production is one of the main requirements of battery manufacturers and their customers. Possibilities for machine and plant manufacturers to achieve cost degression are described in the following chapter. At the same time, the high quality standards for stationary and mobile applications must be maintained. The prerequisites are the stabilization of production processes and the avoidance of overengineering by optimally adapting the machines to the corresponding use case.

Especially for the European location, the development of sustainable, energy-efficient and high-quality processes is coming into focus, which can be improved, for example, by reducing of solvent content and the further development of the drying process or the formation as well as the digitalization of the process control. The development of so-called "micro-environments" is intended to reduce energy consumption and operating costs of the clean and drying rooms. Another customer requirement is high production precision. In this way, a higher degree of monitoring and automation can reduce scrap and costs. Finally, higher energy densities or larger cell formats help to further reduce manufacturing costs per kilowatt hour.

The safety of the batteries is an equally important aspect. In cell production, this is guaranteed by high quality standards. In addition to end-of-line testing and certified, standardized test criteria, the optimization of product and plant hygiene can contribute to increasing the safety of production.

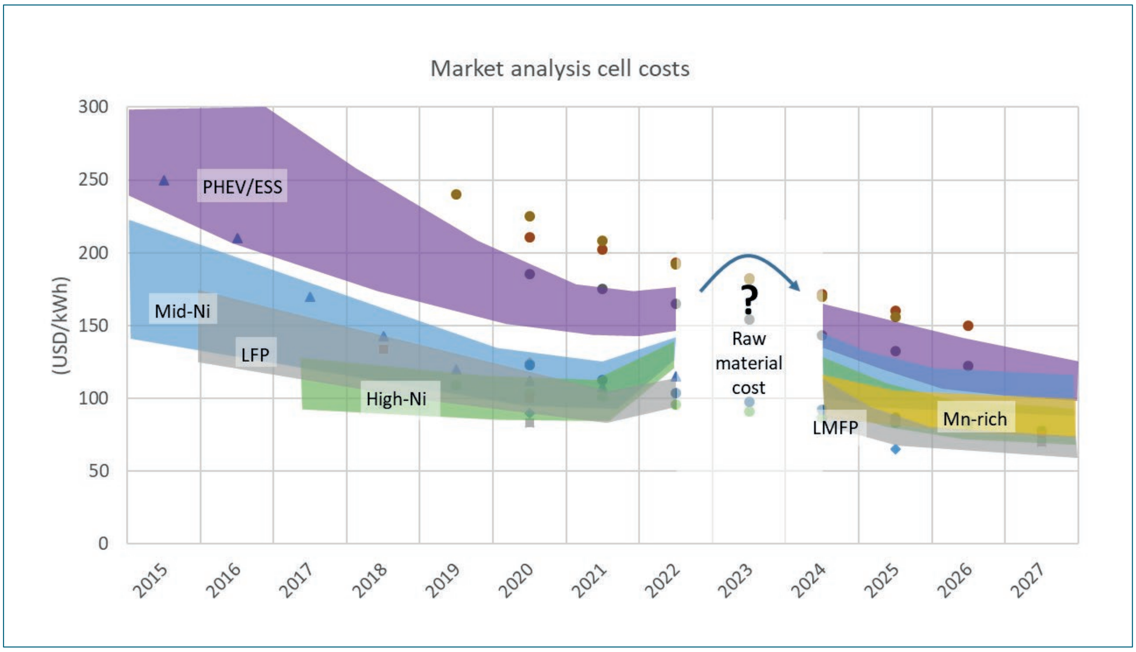
The great potential for optimization through the automation and digitalization of factories is known to manufacturers and is increasingly in request (Industry 4.0).

Module and pack production

In the field of module and pack production, increasing production capacity is a central issue. At the same time, the demands on the flexibility of the production line are increasing, e.g. through compatibility with several cell formats. Fast-charging capability in particular places high demands on cell contacting, since high currents must be controllable.

The recyclability of the battery is another requirement. Legal requirements and the lack of primary sources of the critical raw materials in Germany and Europe intensify the need to recover the materials as completely as possible. Dismantling technologies are required and possibilities for repair or the initiation of battery service facilities are sought [CEID2020].

Finally, the battery is to become a "smart product" through the introduction of "battery passports". These are products that collect data about their own manufacturing process and can then pass this on in further processing steps. In this way, it should ultimately also be possible to develop business models based on data analysis. To this end, machine and plant manufacturers must provide options for how data about the production process can be communicated with the product.



Historical development and forecast of battery cell cost development in US dollars per kWh
Source: Fraunhofer ISI

Cost structure and cost development of LIB cells

The largest cost factors for the production of LIB are on the one hand the material costs, e.g. for active materials but also current conductors, electrolytes and others, and on the other hand costs associated with manufacturing such as energy, personnel costs and depreciation of manufacturing infrastructure. Many of these cost components are influenced by location factors as well as by the manufacturing scale, i.e. the volume of production per location.

Historical cost development

A meta-literature analysis of market studies from different suppliers[17] helps to better understand the current as well as the future changing costs of LIB cells and their reduction potentials (see figure on this page). Various analysts publish price quotations for this purpose, which refer to typical or leading automotive cells and packs, for example.

A continuous reduction in costs was observed up to around 2021. The main drivers here were the generation of economies of scale and a significant increase in cost efficiency in production. This was achieved because, due to growing demand, entire lines or cell factories could now be utilized for the production of a single cell technology, thus leveraging volume effects in material purchasing, process technology and process quality. In addition, a cost reduction in cathode material could be achieved, especially through the transition to low Cobalt materials. Other components, such as the separator foil or cell housing, have also become cheaper due to mass use.

Since 2021, the costs for LIB cells have been rising again, although global production is still growing and further economies of scale could have been expected. In addition to rising energy costs overall, which also affect LIB production, the strong growth in demand has led to a shortage and thus an increase in the price of battery raw materials. On the spot markets, the price of Li-carbonate, for example, has increased almost eightfold since the beginning of 2021 (as

[17] esp. BNEF, B3 Corporation, Yole 2020-2022

of the beginning of 2023). In part, these price increases could be offset by the transition to less critical materials such as LFP. Overall, however, the high spot market prices are also having an increasingly strong impact on real supply conditions for material and cell manufacturers.

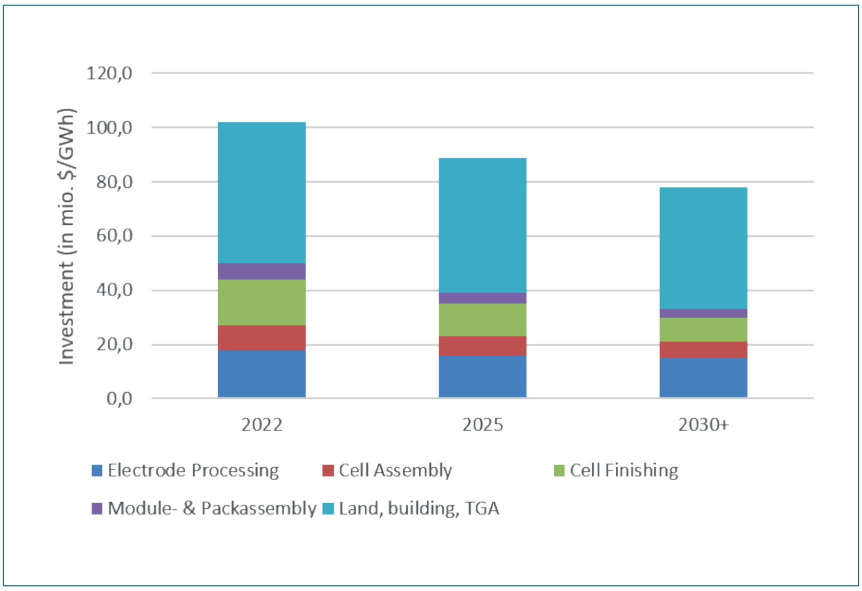
Last year, it became particularly clear how strongly the long-term development of LIB costs is linked to raw materials and energy. The reason for this is the high price share of raw materials (especially on the cathode side) in the total cost of a cell. It must therefore be assumed that the cost structure of LIB will continue to fluctuate. Technological starting points for a further reduction in costs exist in particular in the development of even more raw material-efficient materials (e.g. g_{Li} per kWh) and more energy-efficient production processes, as discussed in this study.

The costs incurred in the context of cell production, such as R&D, sales overheads (SG&A), warranty, etc., can be reduced through corresponding economies of scale in volume production.

Certain factors, each contributing about 3-5 percent to cell costs, show even higher cost reduction potentials. These can be associated with process optimization and automation, such as quality inspection and control to reduce scrap and the number of skilled workers required (for a given factory size). In addition, process innovations with relevance for the plant investment can contribute to cost reduction.

At present, the investment required to set up battery production is around USD 100 million/GWh (Fig. p. 44). About half of this is accounted for by the necessary production equipment and the other half by the acquisition of the land, the construction of the building and the establishment of the complete production infrastructure. In the case of the production facilities, high investments are required in particular for electrode production and cell finishing. Investments per GWh are expected to continue to decline in the future, reaching about USD 90 million/GWh around 2025 and less than USD 80 million/GWh in 2030. However, these are only approximate values, as the actual costs depend heavily on the respective cell technology and production volume. Nevertheless, the decline in production equipment is likely to be more pronounced than for the item "land, buildings and building services equipment", primarily due to the greater dependence of production equipment on economies of scale or changes in the cell technology produced compared to buildings. It can also be seen that within the production facilities, the decline in cell finishing (from 17 to 9 million USD/GWh) and cell assembly (from 9 to 6 million USD/GWh) has a greater impact than, for example, in electrode production (from 18 to 15 million USD/GWh). The reason for this is that cell assembly and cell finishing are predominantly individual processes and not flow processes which benefit more than proportionally from an improvement in cell chemistry or technology. In total, the required investments for production plants of currently about 50 million USD/GWh should be reduced by about another third.[18]

[18] Assumptions for the calculation based on the average sizes of battery factories: 8 GWh (2022), 15 GWh (2025) and 25 GWh (2030). In addition, a steady improvement in cell chemistry was assumed



Forecast of cost shares for initial investments in cell production infrastructure, investments in production facilities in million €/GWh, Source: Fraunhofer ISI

In the following, the most important cost components are discussed in more detail: the material and production costs. In addition to the "top-down" analysis from meta-market data, the identified cost factors are evaluated and plausibilized "bottom-up".

Cost of materials

In LIB cells, the cathode active materials are the largest cost factor among the material costs [B3 2019; Schmuch 2018]. Starting with the mining of the metal ores, their purification and deposition as metal salts, e.g. as sulfates or carbonates, various material- and energy-intensive process steps are necessary. The production of the actual active materials in "battery quality" is carried out on an industrial scale using high-temperature processes.

As a result of this process chain, the costs for the finished active materials are significantly higher than the pure metal prices. Raw material prices are sometimes very volatile. Since around 2021, the prices for lithium hydroxide, lithium carbonate, nickel sulfate and cobalt sulfate have increased significantly. The price increases of up to 800 percent for lithium salts are unprecedented and resulted in an overall increase in the cost of battery materials.

The trend toward nickel-rich materials has already significantly reduced the impact of the cobalt price trend on material costs. However, these now depend all the more on the nickel price. In the long term, no further cost savings can be expected from the transition to even more nickel-rich materials beyond NMC 811, since the reduction in expensive cobalt also means that less manganese is used, which is one of the less expensive components.

A significant reduction in cathode costs is being sought by many OEMs through the use of other materials such as LFP (lithium iron phosphate) or manganese-based compounds. Even in these material classes the impact of lithium costs is significant, but by eliminating cobalt and reducing nickel, significantly lower cell-level costs can be achieved compared to NMC.

The most common material for use as anode is still graphite. Synthetic graphite is often used for BEV cells. Natural graphite is inexpensive to obtain, but additional costs are incurred due to the downstream steps. Synthetic production offers a good control of the material parameters from the outset. Today, suitable graphites from both processes are available for about $10/kWh.

From today's point of view, it is still unclear what impact the transition to silicon-based anodes will have on material costs. However, comparable costs to graphite of several $/kWh are conceivable.

The current conductor foils in Li-ion cells have typical thicknesses of a few µm and are usually produced using electroplating processes. The metal price for 8 µm thick copper foil (anode) is about $0.5/m², the foil price can be more than double. For the aluminum foil used on the cathode side, the ratio of foil to metal price is even higher. Although the trend towards thinner current-conducting films is reducing the metal costs per m², the manufacturing and handling costs are increasing, so that no major cost reduction potentials can be expected overall. Only the elimination of additional conductive tabs, which ensure the contacting of the electrodes to the outside, could reduce costs in future cell designs.

The production of organic electrolytes places very high demands on material and environmental purity. Overall, the cost of electrolytes significantly exceeds the price of the Li metal they contain and is around $20/kg, depending on the composition.

Separators can be manufactured very cheaply today. The main component is a polypropylene or polyethylene film, which is basically inexpensive to manufacture. The additional coating with ceramic nanoparticles improves the safety properties.

The cost of other components, such as the housing and lid, depends essentially on the manufacturing process selected. Thanks to the use of industrial processes, they already account for less than 5 percent of the material costs at cell level.

The material costs and, ultimately, the raw material and energy costs represent a lower limit for the future cost development of LIBs. Against this background, price forecasts based solely on the extrapolation of cost reductions achieved in the past should be treated with caution. The most cost-efficient high-energy battery cells (e.g. LFP base) can be produced today with material costs of about $80/kWh. The further development of these costs depends mainly on the future development of raw material and energy costs. If these remain at a high level, other battery technologies (e.g. sodium-ion) may become more important in the future (comparable to the photovoltaic sector) [VDMA-PV2018].

Production costs

Production costs currently represent the second largest cost block in LIB cell production after material costs. In the form of depreciation, the investments to be made for machinery and equipment are allocated to their useful life (usually between 4-8 years). Up to now, the share of depreciation for machinery and equipment has been between 10 and 20 percent of the cell costs. However, the exact share is strongly dependent on the cell format, cell chemistry and factory size, i.e. economies of scale. Cost degression is therefore one of the main drivers of the current trend towards the construction of the largest possible cell production facilities in the sense of gigafactories.

Economies of scale are also one of the most important levers for reducing production costs across formats. Economies of scale are not limited to investments in production facilities alone (also affect labor costs, R&D activities or general administrative activities), but are sometimes most noticeable there.

Other drivers for the significant reduction in production costs across formats and the associated necessary investments in production facilities are, in addition to economies of scale, process innovations and material substitutions. In the case of process innovations, faster throughput, lower energy costs or a reduction in waste lead to an increase in production capacity.

Material substitutions leading to cells with higher energy densities allow higher battery capacity outputs to be achieved with the same plant technology and number of plants. In addition, the average battery capacities (in kWh) of vehicle batteries are constantly increasing, as is the specific energy density of the batteries (in kWh/kg or Wh/l).

How the economies of scale affect the specific investments for production facilities under these general conditions is shown in Fig. p.44 (taking into account increasing battery capacities and changing cell chemistries). The figure illustrates that the specific investments of approx. 50 million €/GWh are expected to decrease by approx. 30-35 percent over time. Looking at the spec. investments in equipment for cell manufacturing and module & pack manufacturing shows that investments in machinery and equipment for cell manufacturing account for the largest share with more than 85 percent.

Cell production can be divided into the areas of electrode production, cell assembling and cell finishing. While electrode production is still strongly characterized by continuous production processes, such as coating or calendering, cell assembly and cell finishing are predominantly single processes. An analysis of the investments at this process level shows for 2022 that the highest investments per GWh will be made in the area of cell finishing (approx. 35-40 percent) and electrode production (approx. 35-40 percent). However, this share will not remain constant over the coming years.

The trend toward larger battery capacities can in principle be realized in two ways: By increasing the number of cells in the battery system or by using battery cells with higher energy densities while maintaining the same number of cells. Since the space available in vehicles is limited, the second option will probably be the most widely used (at least in the automotive sector).

Assuming a higher energy density[19] with the same number of cells, the specific share of electrode production could increase from 35 to 45 percent in the future, while that for cell assembly and cell finishing would decrease. However, this effect could be offset by the trend toward large-format cells.

In summary, it can be said that production costs are strongly dependent on both depreciation for machinery and equipment and energy costs. The main drivers for falling investment costs are innovations at product and process level and, in particular, the realization of economies of scale. Investments for cell production are significantly higher than those for module and pack production. At the process level, the highest specific investments are currently being made in electrode production and cell finishing. The high demand for manufacturing equipment and the general increase in energy and material costs, especially in 2022, have led to increasing investments in equipment even though there are continuous process innovations. A future reduction that follows the historical trend again is only likely if supply and demand are aligned and inflation weakens.

[19] Due to the use of better materials at a constant coating thickness, the number of cells per kWh can be reduced at the same coating capacity

Both the amount and the relative share of specific investments for a complete PHEV battery system are strongly dependent on the product to be manufactured. In the production of a PHEV battery system, for example, the specific investment per GWh in the area of cell assembly and cell finishing is likely to be higher than for a BEV battery system with a high energy density due to the larger number of individual process steps. Likewise, the percentage distribution is likely to differ again for future cell technologies with a different production structure, e.g. solid-state batteries. Thus, the results of such considerations must always be interpreted against the background of the product to be manufactured.

Solutions offered by the mechanical and plant engineering sector

Cost degression

It is known from numerous other industries, such as semiconductors or photovoltaics, that increasing quantities lead to a process-side cost degression through corresponding learning effects. Improvement levers can be technological innovations, better yields, the economy of scale, a higher degree of automation and knowledge of the process-quality correlations. This applies to electrode production as well as to module and pack production. These points are discussed in more detail below. Energy and resource efficiency, which also has a significant influence on cost reduction, is considered under the heading of sustainability.

Better yields

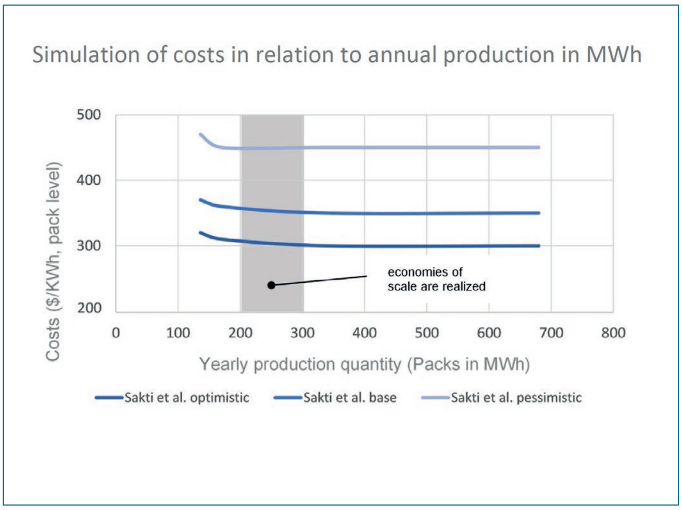
Due to the high material cost share in the cell of up to 70 percent today, increasing the yield is crucial to strengthen competitiveness [Heimes2019, Kwade 2018b]. Increasing speed must not reduce yield. The advantage of increasing throughput would otherwise be obsolete.

The yield in the production of lithium-ion cells can be around 90 percent in well running factories. However, it must be assumed that the yield is often lower and can even be 50 to 70 percent during the ramp-up of a factory. Since the scrap of each individual process step is multiplied, their number is directly related to the overall yield. Cost reduction can be achieved by reducing or integrating them into upstream or downstream production steps.

Causes for reduced yield can be unstable, nonrobust production processes and the resulting product deviations or defects (e.g. edge protrusions, positioning errors, foreign particles). Further development and optimization of the production processes - as described in the Red Brick Walls - can make a significant contribution to increasing the yield.

In addition, the early detection of quality degradation in the intermediate products of electrode production is crucial. This is the case when a defective electrode or module is detected inline in the process - e.g. by a suitable camera technology - and ejected from the production process. The monitoring of the intermediate product properties and thus an evaluation of the process variants and safety with the aid of inline measurement technology can be carried out at selected points by so-called "quality gates".

The achievable advantage through the use of inline measurement technology must be evaluated individually for each system with regard to the background of the resolution of the quality signal, the associated differentiation of rejects and the costs incurred [Schmitt 2008]. In addition, the evaluation of measurement data can identify process-internal and process-external interdependencies. Thus, an accelerating effect on the learning curve can be expected. Influences of process parameters on the quality of the intermediate product can be understood on a knowledge-based basis and the potential for optimizing processes and products can be tapped. In order to realize an accelerated process optimization, control loops must be connected to the quality system for process control and monitoring. A prerequisite for process optimization is the traceability of the results of production parameters used, for example by means of a QR code on the cell or module. This makes it possible, for example, to adjust the positioning, number and content of quality gates accordingly, which makes a interactive and self-optimizing control system for quality management in cell, module and pack production.[Schnell2016].



Source: BLB based on [Sakti2015]

Economy of Scale

The growing demand for lithium-ion batteries will lead to an expansion of production capacities in the coming years. This expansion can be realized by increasing the number of machines ("numbering-up") or the throughput of the machines ("scaling-up"). Due to the high plant costs, only upscaling contributes to a significant cost reduction.

"Economies of scale are the cost savings that occur for a given production function as a result of constant fixed costs when the output quantity grows, because as the size of the operation grows, the average total costs decrease up to the so-called minimum optimal technical operation or company size" [Voigt2018]. This means that when the output quantity is multiplied, there is no simple multiplication of the operating equipment. A scale-up can be implemented in different production steps and is therefore addressed in many RBWs.

By adapting the production steps to the production capacity, economies of scale in battery production already occur from an annual production volume of 200-300 MWh/ a (see figure above). Further increases have only an indirect influence on cost degression through material cost savings, learning effects and innovations [Sakti2015].

Economies of scale in lithium-ion battery production can therefore be achieved not only at large production sites with an output of 35 GWh/a, but also at smaller production sites with an annual output of 1 - 1.5 GWh/a can be achieved [Panasonic2015]. Due to the high demand of the automotive industry, the trend is moving towards double-digit GWh/a production capacities.

Higher level of automation

For the continuous further development of Li-ion batteries, highly automated production concepts are being developed in the battery production area in order to reduce costs and increase quality. Such concepts are characterized by process intensification (time reduction), integration, optimization and process substitution.

In the field of industrial cell, module and pack production, fully automated individual processes already predominate today. These are usually rigidly interlinked in order to achieve the shortest possible cycle times and high throughputs.

Digitization is closely related to the degree of automation. The aim is to increase product quality and minimize scrap in production through intelligent manufacturing. For this purpose, the principles of Industry 4.0 are applied, such as the use of cyber-physical systems, networked processes, data feedback or active, measurement-based machine control. The basis for networking the production line is the integration of a data exchange and communication platform for all plants and machines, such as a standard Open Platform Communications Unified Architecture (OPC UA) and cloud solutions [Panda2018, Schneider2019].

The goal is also to collect, process, and use every battery cell produced to record and verify all physical relationships, including parameters as well as compliance with specific fault tolerances and cell quality [Schnell2019]. This topic is considered in more detail in technology chapter 13.

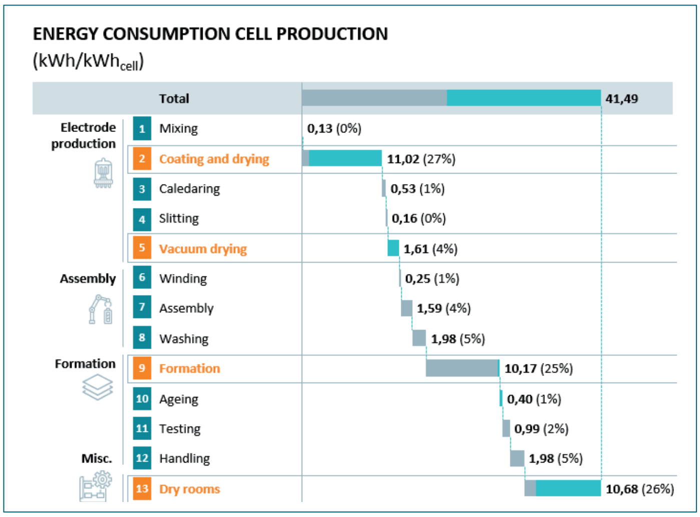
Sustainablity

A central motivation for the use of batteries in electric vehicles is the reduction of CO_2-emissions and the conservation of energy and resources over the entire vehicle life cycle. Equally crucial is the use of batteries in electrical energy storage systems. For a sustainable energy supply, the use of renewable energies and their storage is indispensable. At the political level, the European Battery Regulation 2020 will provide new sustainability incentives

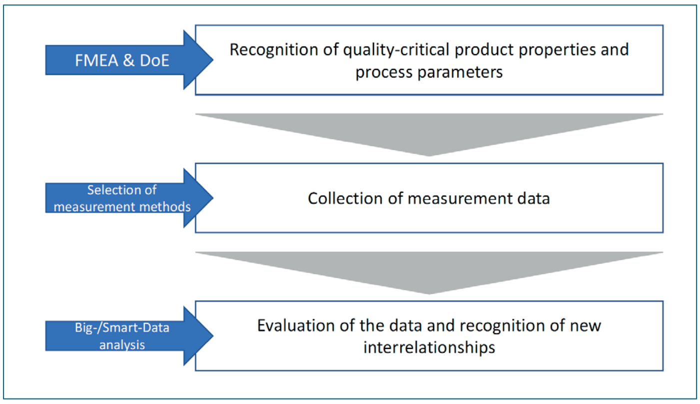
Energy efficiency

Energy-intensive processes are necessary in the production of batteries - especially in cell production. Coating and drying, forming, and the preparation of conditioned drying room atmospheres are the most energy-intensive process steps [Degen2022]. Together, they represent the significant share of energy consumption in cell production [Pettinger2017]. These topics are discussed in more detail in technology chapters 2, 8 and 9.

From a business perspective, the energy costs of production are a significant factor, accounting for up to 5 percent of the production costs of a Li-ion cell [Schüne- mann2015]. Energy consumption in battery production is also particularly relevant from an ecological perspective. In the future, the CO_2-footprint reated during battery production will be made transparent, by including it in the battery passport.



Energy consumption in cell production
Source: Fraunhofer Research Manufacturing Facility Battery Cell FFB



Procedure for quality assurance of complex process chains Source: BLB, TU Braunschweig

In its production, the Li-ion battery causes about 80 kg of greenhouse gas emissions per kWh of battery capacity, according to a study by Eindhoven University of Technology

[Hoekstra 2020]. This corresponds to about 40 percent of the greenhouse gas emissions of the entire vehicle production of a BEV. It is further described that 75 percent of the greenhouse gas footprint of battery production alone is due to cell production. The largest contribution of over 50 percent comes from electricity consumption. Relevant contributions are also made by the cathode and anode materials as well as the housing and the battery management system [Meyer2018].

Overall, the CO_2-balance of battery supply is strongly dependent on the electricity mix of the respective country of production. The use of green electricity from renewable energy sources leads to an improvement in the CO_2-balance.

Resource efficiency

The material accounts for up to 70 percent of the costs of a lithium-ion cell and thus motivates the realization of high resource efficiency in production from a purely economic point of view [Schünemann2015]. The aim is to minimize the production waste that arises along the process chain, e.g. through start-up losses during coating and calendering or offcuts during confectioning. In addition, increasing the yield leads to better resource efficiency.

The materials copper, cobalt and nickel in particular, as well as the solvents, also contribute to different environmental impact categories, including eutrophication, human toxicity and biotoxicity [Ellingsen2014]. Approaches to increasing material efficiency are economically and ecologically interesting and necessary. For mechanical and plant engineering, this means that resourceefficient plants will become more attractive in the future as production capacities increase.

Recycling

Battery recycling and remanufacturing represent another significant factor that can contribute to increasing both resource efficiency and energy efficiency [Becker2019]. These have the potential to positively influence the CO2 balance of the battery, its costs and the supply of raw materials . Recycling refers to the process of recovering material components of the battery. In particular, recycling can become the most important source of raw materials for Europe and thus reduce dependencies, especially from China, since natural resources are very low or non-existent here [Miedema2013]. Accordingly, high collection rates and recyclate use rates are an important component of future battery cell production. The recycled material share is the proportion of secondary raw materials that go into new products. Battery reuse includes all methods of reusing aged traction batteries in secondlife applications. With the ramp-up of electromobility and stationary storage, there will be a significant increase in used lithium-ion batteries. For the recycler, relevant information will be provided in the future by the battery passport [Neef- 2021]. In recent years, a lot has been invested in the research and development of efficient recycling processes. More detailed information can be found in technology chapter 14.

Quality improvement

Quality has a direct impact on costs. An increase in quality can contribute to an improved yield in the production process and thus to a reduction in costs. However, quality improvement can also lead to higher-quality products. These can achieve higher prices on the market. Reducing costs at the expense of quality, on the other hand, is not expedient.

In volume production, measuring and testing technology ensures quality assurance and -control in all production steps. In addition, an increase in the degree of automation with the possibility of direct production parameter adjustment and process reliability with predictive engineering or maintenance, for example, can contribute to quality improvement.

Measuring and testing technology

The battery production chain is a complex interplay of many disciplines. Due to the three cell formats and many cell chemistries, some of which are still under development, there is a large overall variation in the manufacturing processes. This results in many unknown interactions between process and product parameters. Together with the high number of process steps, these can lead to high shot rates. A consistent and intelligent measurement technology enables an early reaction and thus the chance to stand out from the competition [Trechow2018, Schnell2016]. The integration of quality measurements into the production process (inline measurement) and the associated online evaluation is a key objective. Quality-critical process steps and sensitive product properties with low tolerance ranges must be identified. The process can be optimized adjustments. In general, analytical methods by means of quality testing equipment and suitable product and process parameter must be robust to environmental conditions. Stable control loops can be used to realize:

- Fast response due to small control process loops
- Stabilization of the manufacturing process
- Quality increase
- Cost reduction

In addition, the measurement technology used should be non-destructive and contribute to early defect detection.

The quality assurance of complex process chains is described in the figure above. First of all, quality-critical product and process characteristics must be identified and evaluated according to their relevance. The FMEA (Failure Mode and Effects Analysis) or a DoE (Design of Experiments) are common methods for this [Westermeier2013]. The table on p. 56-57 shows quality parameters of battery production and possible measurement methods. The selection of measurement methods and the collection of test data is the second step. Finally, the measurement data are evaluated. In the best case, new interrelationships between individual production steps can be identified (machine/process-structure-property relationships). Digitally networked production lines and Big Data applications are used to collect data and identify these quality-structure relationships. Based on the evaluations of the collected data, a targeted adjustment of the process parameters follows, the quality of the

LIB is increased, the reject rates are reduced and the profitability of the production is increased. Processes that follow the described procedure have been developed by Schnell et al. for the entire battery production and by Kölmel et al. for battery module and battery pack assembly [Kölmel2014, Schnell2016].

Degree of automation

In general, automated processes are less prone to errors than manual production steps. This makes automation an important instrument for increasing quality and minimizing rejects. In principle, the aim is to increase the degree of automation to a reasonable level and thus avoid overengineering:

- Avoid disproportionate automation
- Establish sensitive, flexible automation that can be easily customized
- Link information processes
- Intelligent production through the use of learning

Automation allows the machine to be adapted to possible quality fluctuations and measured process data to be evaluated via the software. It is also possible to compare the process result with the target quality. This results in which manipulated variables in the process have to be changed [Linke 2017]. Further developed, this evaluation process can potentially network all plants of a production line with each other, since upstream or downstream processes directly influence the intermediate process.

assurance or for process control. Data mining and big data analyses can be used to identify new relationships between process and quality parameters (see RBW 14). Based on measured Interfaces, especially with measurement and testing technologies, are used to provide information along the process chain that is important for further processing and quality material and component characteristics, production parameters can be automatically adjusted during the production process. This leads to significantly lower scrap rates.

Process reliability

In the production process, a large number of factors influence the performance of the battery cell. In order to improve the energy and power density, the cost as well as the cycle stability and the lifetime of battery cells, a detailed knowledge of product- and production-relevant parameters and their interactions is required. Process reliability and robustness are to guarantee constant product quality over months and years. As already described, quality-relevant plant and product parameters must be recorded for this purpose.

To increase process reliability, the failures of machines and systems should be kept as low as possible with the help of predictive engineering or maintenance. A high number of failures usually occurs during the ramp-up of the production process, which can be reduced to a minimum by means of a learning curve of the machine builder in connection with the determination of machine/process structure/property relationships.

The random failures occurring in constant continuous operation due to wear effects should determine the type and scope of the quality controls. In the case of random failures, there is the difficulty of identifying process safety-relevant para- meters and recording them with sufficient accuracy. In order to maintain process robustness in the event of wear, control loops are necessary to compensate for the wear. In the context of data mining in the production of LIB cells, suitable quality parameters are identified as well as tolerable ranges of variation - without influence on the cell performance - by targeted parameter variation along the process chain [Heins2017].

This creates the prerequisites for new product and production strategies and more efficient battery cells, which can be used as the basis for active control of production processes. In the future, intelligent database systems can make a significant contribution to process reliability. They make it possible to optimize batteries with regard to various criteria, to recognize causal relationships and to define tolerances in a meaningful way.

		Important quality parameters	Important measurement methods in production
Electrode production	Mixing	• Purity • Suspension density • Solids content • Homogeneity • Viscosity • Agglomerate size • Particle size distribution • Temperature • pH value • Surface tension • Electrical conductivity	• Elemental analysis ICP • Pycnometer • Solid balance, moisture determination • Grindometer, sieve filtration • Rheometer, viscometer • Laser diffraction particle size analysis • SEM microscopy • PT100 thermometer • pH measurement • Tensiometry • Impedance measurement
	Coating	• Surface finish • Coating positions (both sides to each other) • Wet film thickness and accuracy • Edge geometry • Adhesion	• Chrome. White light sensor, camera • Camera • Laser triangulation • Camera, laser triangulation • Mechanical (including forehead trigger test, etc.)
	Drying	• Material temperature • Surface finish • Layer thickness homogeneity • Fractures in the material • Weight distribution • Residual moisture • Adhesion • Binder and conductivity additive migration	• Pyrometer • Camera • Laser triangulation • Camera • Infrared camera • Area mass scanner • Mechanical (including forehead trigger test, etc.) • EDX
	Calendering	• Layer thickness, density and porosity • Surface roughness • Surface finish • Weight distribution • Pore size distribution • Adhesion	• Laser triangulation • Reflectometer, measurement of the refractive index • Camera • Area mass scanner • HG Porosimeter (off-line) • Tensile testing machine
	Slitting/Separating	• Burr quality, surface finish • Geometry of the cut edges • Metallic foreign particles • Microstructure deformation	• Chrome. White light sensor, camera • Laser triangulation • Ultrasonic sensor • Camera
	Vacuum drying	• Residual moisture content • Solvent residues • Surface finish	• Moisture meter • Laser triangulation
Cell Assembly	Winding/Stacking	• Positioning • Foreign particle concentration • Electrical charge	• Laser triangulation • Camera, X-Ray
	Contacting	• Contact resistance • Mechanical stability • Weld quality • Foreign particle concentration	• Resistance measurement • Short circuit test • Weld seam monitoring, current measurement • X-Ray
	Insertion & Closure	• Electrical insulation • Tightness • Sealing seam quality • Positioning	• Measured after electrolyte filling • X-Ray
	Electrolyte filling	• Tightness • Electrical insulation • Electrolyte temperature • Dosing accuracy • Deformation test	• Pressure sensor, optical coherence tomography • Insulation measurement • Temperature sensor • Gravimetric measurement • X-Ray
	Sealing	• Tightness	• Pressure test, optical coherence tomography • Test gas procedure
Formation and maturation	Press Rolling	• Homogeneous distribution of the electrolyte • Temperature	• X-Ray • Pyrometer
	Formation	• Cell internal resistance • Capacity • Cell temperature • Optimal formation of the SEI	• Electrochemical impedance spectroscopy • Measurement of the stress profiles • Calculation • Temperature sensor
	Degassing	• Tightness • Residual gas	• Pressure test, optical coherence tomography • Mass spectrometer
	Aging & EOL test	• Self-discharge • Capacity • Cell internal resistance • Positioning	• Measuring the open circuit voltage • Calculation • Electrochemical impedance spectroscopy • X-Ray

Source: PEM der RWTH Aachen, BLB und TU Braunschweig

		Important quality parameters	Important measurement methods in production
Module production	Pre-assembly	• Capacity • Cell internal resistance • Positioning	• Calculation • Electrochemical impedance spectroscopy • Laser triangulation
	Insulation and bracing	• Positioning • Contact pressure	• Laser triangulation • Camera • Pressure sensor
	Electrical contacting	• Weld quality • Joining quality	• Weld seam monitoring • Resistance measurements
	Slave board mounting	• Positioning • Weld quality	• Laser triangulation • Camera • X-ray measurement
	Mounting the end plate	• Sensor functionality • HV strength • Cooling circuit tightness	• Software testing • Resistance measurement • Leakage test
Pack production	Use of the cell modules	• Positioning	• Camera
	Fastening the cell modules	• Damage-free mounting	• Camera • Torque monitoring
	Electrical & thermal integration	• Positioning • Correct wiring	• Camera • Laser triangulation
	Sealing & Leak Test	• Positioning • Adhesive bead quality • Tightness battery pack	• Camera • Kleberauben monitoring • Leakage test
	Load & Flash	• Heat generation during charging	• Thermographic camera
	EOL test	• Electronics connections • Optical texture	• Software testing • Camera

Source: PEM of RWTH Aachen University, BLB and TU Braunschweig

Frugal innovation vs. full digitization

The frugal innovation approach targets the essential core functionality of a product. The term frugal stands for less is more. In contrast to current practice in many areas, a frugal product is not characterized by new additional functionalities, but rather by a simplified and thus less complex subsequent version. The product should offer the best possible benefit relative to the price [Radjou2014]. The focus is on target group-specific or application-oriented functions [Zeschky 2010]. At the same time, a frugal innovation is based on a new idea or discovery that is implemented in the product, service or process, successfully applied and penetrates the market (diffusion) [Dörr2011].

Frugal innovation is essentially applied in product design and addresses the battery as such. From the perspective of mechanical engineering, frugal innovations concern the "production system" with the machines and systems it contains.

Battery production is characterized by a complex process chain in which a large number of process-structure-property relationships must be understood and mastered in terms of process technology. This challenge can be met with two solution approaches, which stand in the area of tension between frugal innovation and full digitization.

In the sense of Industry 4.0, the aim is to achieve optimization through networked production lines with continuous data acquisition and artificial intelligence. Full digitalization is made possible by the latest hardware and software. Software solutions that introduce more functionality and intelligence into the production system or the machines and plants. As a rule, this results in an increase in complexity and thus also in the susceptibility to errors in the system. The frugal innovation approach aims to reduce this complexity, which can be achieved in a variety of ways. This in no way excludes the targeted, effective use of advanced technologies in frugal products and solutions [Hitech 2018]. Industry 4.0 solutions can therefore also be used specifically for frugal innovation.

In the past, the topic of overengineering has come into sharp focus. Often, excessive process requirements result from process ignorance. Although these have a negative impact on costs, they are more likely to be accepted than a supposedly unsafe product. The approach of frugal innovation is opposed to this. However, it presupposes an adequate understanding of the process. Continuous data acquisition and evaluation in the sense of Industry 4.0 can make a significant contribution here. Depending on the issue, additional but useful functions can be incorporated into the manufacturing process or processes can be simplified on the basis of the additional understanding of the process.

A fully digitized and automated production line aims to reduce costs by increasing efficiency. In contrast, frugal innovation offers the opportunity for process simplification and throughput increase and for comparatively lower costs. To make the best possible use of the potential in the battery production chain, both approaches should be pursued and combined.

Challenges and required technology breakthroughs (*Red Brick Walls*)

Red Brick Walls at a glance

Since a large part of the added value of battery cells, modules, and packs is created in production, the largest investments must also be made in this area [Kampker 2015a]. The multitude of existing technology alternatives in cell production leads to diversity in battery production lines [Heimes2014]. At the same time, different interlinked technologies are needed in the individual production processes [Kwade2018b]. In the roadmapping process, this manifests itself in the significantly higher number of challenges in cell manufacturing compared to module and pack assembly. At the same time, cell manufacturing also has higher revenue potential.

In the roadmapping processes, challenges are identified based on existing and future requirements for the entire process chain. The required technology breakthroughs (*Red Brick Walls*) are derived from these challenges.

The foundations for the quality of the cells are laid during **electrode production**. This is also reflected in the technology chapters on mixing, coating, calendering, separating, and separator production and the *Red Brick Walls* identified in those chapters.

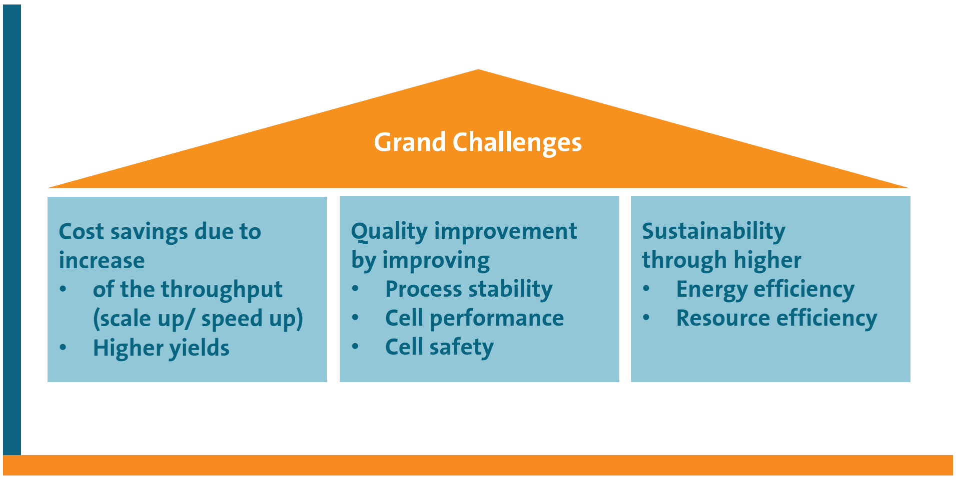
Cell production is further subdivided into cell assembly and cell finishing. The stacking, electrolyte filling, and forming and ripening processes in particular are bottlenecks in the production process. These also have a considerable influence on the quality of the final product. The environmental conditions which must be maintained for cell production require working in dry and clean room atmospheres. Aside from forming, the operation of the dry and clean rooms is the most energy-intensive part of the cell production process.

Housings are subject to strong cost pressure in both the cell and module sectors. The challenges lie in saving material and avoiding redundancies, as well as efficient production. It may also be necessary to “think outside the box" and develop new battery module and pack concepts that are more cost-effective in terms of production technology. For the entire cell manufacturing process, including electrode production, it is also becoming increasingly important to recognize the interdependencies between process and quality parameters. This is the only way to effectively prevent overengineering.

Lower investments are required in the field of **battery module and battery pack assembly** than in cell production, but process alternatives are highly concept-dependent [Kampker 2015b]. Flexible production in terms if variants and number of units is a key challenge for applications outside the electromobility market (e.g.; commercial vehicles, stational applications, power tools). The contact technology *Red Brick Wall*, which was already addressed in 2018 and 2020, also continues to be an issue. Fast-charging capabilities and the associated higher currents still require high-voltage connectors suitable for mass production, which should also be detachable for the recycling process.

Overall, the **circular economy** poses challenges for mechanical and plant engineering at various levels, which are addressed in the corresponding technology chapters.

As with the two previous roadmaps, the *Red Brick Walls* (RBW) were identified and revised according to the current state of the art.



The 15 *Red Brick Walls* for future battery production are discussed in detail in the following chapters. Each chapter presents the basic principles and challenges and outlines possible solutions for breaking through the *Red Brick Wall*.

Although the success of a process technology depends primarily on the point in time when all *Red Brick Walls* are overcome, individual suppliers of production equipment must also concern themselves with the issue of effort and benefit. Therefore, each of the *Red Brick Walls* is also evaluated according to an effort-benefit portfolio matrix.

Great Challenges

The term "Great Challenges" was first introduced in 2014. All *Red Brick Walls* can be traced back to these core challenges

The first Great Challenge is **cost savings** through increasing throughput (scale-up or speed-up) and productivity (scrap minimization). Upscaling, speed-up, and scrap minimization are aimed directly at reducing costs. However, cost savings are also indirectly the driving force behind quality enhancement and sustainability.

The second Great Challenge is **quality improvement**. On one hand, this refers to process quality in the form of stability and high yields. On the other hand, it also addresses the quality of the product itself. This refers to the influence of production on subsequent cell performance (e.g.; energy density, fast-charging capability) and safety.

Battery production has high reject rates compared to other industrial sectors. This is a primary cost driver due to the high material costs of a battery cell and the consequential costs of defects. An increase in process speed can have a negative impact on process stability. Demand-optimized plant engineering, quality-optimized handling, mass-production, and standardized interfaces in the production cycle allow for higher speeds with simultaneous process stability and low reject rates.

The third Great Challenge is **sustainability** in battery production. "Green production" refers to the environmentally friendly and secure processing of raw materials throughout the entire manufacturing process, as well as the processing and use of environmentally friendly and secure materials. This also includes energy- and resource-efficient production. This is supplemented by the so-called circular economy, which ensures that as many raw battery materials as possible are reused and not converted into other degradation products. In Europe in particular, climate-neutral or CO_2-neutral production is becoming more relevant due to increasing environmental regulations. The combination of efficient manufacturing processes, resource-conserving production, and sustainable value chains creates an opportunity for a pioneering role in battery production as well as significant cost advantages.

2023 *Red Brick Walls* in detail

The following technology chapters were updated based on the assessments of the RBW from 2020. The key RBWs for the process step are prioritized at the beginning of each chapter. For the highest priority RBWs, the **milestone diagram** with parallel "lanes" is included for visualization and analysis of projected technology development paths.

Only those battery manufacturer requirements for which no production solutions exist today are included in the following diagrams - by definition, these are the *Red Brick Walls*. The current state of production technology for volume production is the "2023" starting point in the milestone diagram.

Four symbols are used to represent milestones in the development path: the circle represents the process technology currently in use, the hexagon represents research needs or research projects, rectangles with rounded corners are used for pilot plants or demonstrated solutions, and rectangles with sharp corners are used for technologies which are suitable for mass production.

The milestone diagram is supplemented by a graphical representation of the **effort-benefit assessment** and a qualitative **assessment** of the contribution that overcoming the *Red Brick Wall* makes to the Great Challenges. The **target system** is considered for cost savings, quality, and sustainability. "Cost savings" refers to increased throughput and productivity. "Quality" refers to reduction of the reject rate through more stable processes or improvements in product properties, such as performance parameters or service life. “Sustainability” refers to resource and energy efficiency as well as recyclability. Since all three goals cannot be clearly separated from each other, this **representation of the target system** is only intended to provide an **indication** of where the focus of the respective benefit lies. (What is the driver for solving this challenge?).

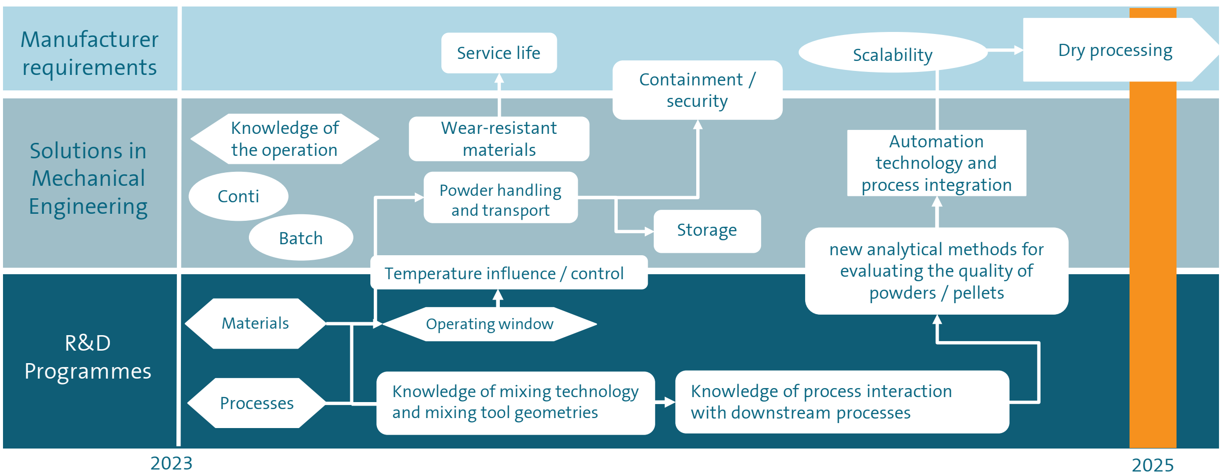
The term battery manufacturer includes electrode and cell manufacturers as well as producers of battery modules and packs.

In the context of production research and the *Red Brick Walls* presented in this roadmap, there are already a large number of research projects that have addressed or are addressing open issues in battery production. An overview of these can be found at the end of this chapter.

1: Raw Material Handling and Mixing

No.*	Red Brick Wall	Current status in comparison to 2020	Relevance**	Timeline***
1.1	Dry processing	Progress made	Very High	2025
1.2	Material handling	No progress	High	2025
1.3	Reduction of rejects/product monitoring	Progress made	High	2026
1.4	Throughput vs. flexibility	Progress made	High	2024
1.5	Raw material logistics	No progress	High	2025

RBW 1.1: Dry processing
Resource-efficient and thus cost-optimized production of electrodes can be made possible by reducing the solvent used (e.g., granules) or completely dry processing. New materials (especially binders) are needed to ensure high-quality electrodes, even with reduced-solvent content or completely dry processing. Defining and monitoring of quality parameters in the mixing and dispersing process is necessary to establish the relationship between operating parameters and modes and the raw material and cell properties to ensure quality at an early stage.



Legend: ○ State of the Art ⬡ Research approaches/projects ▭ Pilot plants/approaches to solutions ▭ Technology suitable for mass production

*RBW priority decreases from top to bottom.

**Relevance from the point of view of a battery manufacturer

***Timeline indicates when breakthrough should occur (The timeline considered is until 2035).

Source: VDMA, PEM of RWTH Aachen, BLB of TU Braunschweig according to Phaal2003b

Raw Material Handling and Mixing

Basics

Material handling and the mixing process is the beginning of the battery cell production process chain, which consists of a large number of consecutive process steps. The aim of the mixing process is to homogenize and structure the powdery initial materials. This can be done either fully dry or in combination with a solvent (wet). The current *state of the art* is a two-stage mixing process. First, the different raw materials are mixed in a dry mixing process. The components are mixed at a low intensity so that all of the initial components are evenly distributed in the mixture. Alternatively, this process step can be performed with a high mixing intensity for dispersive mixing. With dispersive mixing, the structure of the initial materials is changed, for example by deagglomeration. The powder mixture thus produced is then dispersed in a wet mixing process. The powders are wetted with solvent and agglomerates are broken up. With increasing demand and the large number of *gigafactories* under construction, both the operation and the supply of raw materials to the plant are crucial for smooth production. This includes viable powder logistics and quality assurance, along with defined procedures for handling materials from the container in the production line and, in the case of a product changeover, back into intermediate bins. The evaluation and definition of the OEB levels for the various raw materials and the associated protective measures for different areas along the production line is very relevant for both the plant manufacturer and the operator.

The mixing process forms the basis for the production of reproducible electrode layers with good electrical conductivity and suitable porosity, or homogeneous electron and ion current density distribution and good power and energy properties, especially for large-format cells with a width of up to 500 mm [Kwade2018b].

Fully automated 2 GWh mixing plant for coating compounds with Eirich MixSolver® (bottom left) and AZODOS® metering system (top left) at the UK Battery Industrialisation Centre (UKBIC)
Source: AZO GmbH + Co. KG, Maschinenfabrik Gustav Eirich GmbH & Co KG

The aim is to homogeneously mix the powdered initial materials (active material, conductive additive, and binder) and to selectively adjust the particulate structure. The requirements for the structure are largely determined by the subsequent coating step. Conventional production of electrodes is based on wet processing. Pasty coating compounds are typically produced. However, the solvent used must then be removed again in a drying step after coating. Due to the energy required to evaporate the solvent, drying (see RBW 2) is the most cost-intensive process step in electrode production.

Challenges

With rising energy prices, resource-efficient processing is more important than ever. In order to reduce energy costs as much as possible, there are currently major efforts being made in both research and industry to move toward solvent-free or reduced-solvent processing (RBW 1.1).

This can reduce the costs for subsequent drying of the electrode or remove the drying process from the process chain. Dispensing with solvents poses new challenges, primarily for the design and operation of the equipment, but also for the transport and dosing capabilities of the materials. If wet dispersion is completely eliminated, the conductivity additives and the binder must reach their final structure in the dry mixing process. Without the solvent, the densely packed particles in the mixing chamber leads to increased friction, and thus to heat input with a simultaneous reduction of heat transfer to the container walls. This increases the effort required for temperature regulation of the mixing process. In contrast to wet processing, in completely dry processing the materials not only need to be cooled, but in some cases also heated and kept in a defined temperature range to promote binder disintegration, depending on the process. Thus, good system temperature management is a high priority for dry processing, especially with regard to scalability. The lack of solvents also leads to increased wear in the process. This results in new challenges with regard to the wear resistance of the system, especially in combination with the materials used, some of which are highly abrasive (e.g., nickel-containing cathode and silicon-containing anode raw materials). A high level of wear resistance must be ensured in order to guarantee a long system service life with low wear costs, and to minimize contamination of the mixture produced. The structuring of the powder mixtures for reduced-solvent/solvent-free processing changes the flow properties of the mixtures, which are also temperature dependent. The structured mixes are generally extremely cohesive and not free-flowing. This results in new challenges with regard to storage and dosing of the materials for further processing. In addition to consistent low-pulsation longitudinal transport to the coating application, a high level of uniform transverse distribution to the coating application must also be ensured.

Due to the construction of *gigafactories,* a competitive, stable, robust (preferably over years), and process-integrated production of the suspensions/pellets/powder mixtures is essential, with the goal of a continuous supply to the downstream processes. The battery cell requirements change depending on the vehicle type. In order to meet these requirements, the trend is toward prismatic unit cells with a defined, consistent housing design which is equipped with different cell chemistries. In order to ensure a continuous supply to the downstream processes even in the event of material changes, the mixing process must provide a high throughput and above all must also be able to react flexibly to material changes (RBW 1.2). This combination requires extensive process knowledge, a high degree of automation of the process sequences, and targeted plant design. Optimized process control during mixing and/or dispersion can maximize the flexibility of the plants in both continuous and batch operation and minimize the time and energy required.

Due to the high material costs (approx. 70 - 75 % of the total cell cost), production rejects must be minimized and ideally completely avoided, especially in large-scale production. Only ideally continuous monitoring (RBW 1.3) of defined quality parameters makes it possible to identify reject-relevant deviations from the mixing process (such as metering errors, raw material changes, or insufficient preparation) and increase resource efficiency. New approaches are needed, especially for reduced-solvent /solvent-free processing. The current analysis methods and quality parameters from the wet mixing process are not suitable for the pellets/powder mixtures used in reduced-solvent /solvent-free, or only suitable to a limited extent. Therefore, it is important to develop and establish new methods to ensure the production of high-quality electrodes.

Prior to the mixing process, dedicated powder handling (RBW 1.4) of the raw materials with regard to storage and feeding is of great importance in order to ensure that work is as contamination free and low-moisture as possible. The handling of the prepared mixtures is also of great importance. This is the only way to ensure that the properties of the mixture remain unchanged when it is fed to the downstream processes and to create a reproducible process. For this reason, it is necessary to establish suitable intralogistics that ensure careful dosing without possible separation effects and minimize contamination of the raw materials. Containment requirements must also be met, and handling must take place in a defined atmosphere to prevent product aging. The plant technology must be designed for changing powder/active material characteristics (e.g., bulk density and tapped density) and end-product properties. Efficient cleaning systems concepts are relevant in order to be able to use the plant flexibly without high product loss and with the shortest possible cleaning times. In addition to handling, the raw material logistics (RBW 1.5) should be considered more closely, particularly in large-scale series production. Conventional delivery in big bags and sacks is not suitable for *gigafactories,* or only suitable to a limited extent, and involves a high level of personnel work. The required manual refilling processes result in additional costs for containment at the filling stations, costs for additionally required PPE, material loss associated with refilling due to residual quantities in the containers, and considerable quantities of waste packaging and outer packaging, some of which must be disposed of as hazardous waste.

Possible solutions

Significant energy and investment cost savings can be achieved by dry or greatly reduced solvent processing of the initial materials. These include costs for drying, the solvent itself, exhaust air treatment and solvent recovery. On the path to resource-efficient production, the goal must be to minimize these resource costs. To this end, the mixing and coating processes must be considered in an integrated manner and enhanced, either using reduced-solvent or completely dry processing. For example, highly viscous coating compounds can be applied directly to the flow collector in pre-dosed form via nozzles or can be drawn in from a reservoir in self-dosing mode. Established mixing processes are sometimes completely unsuitable for the production of extrusion-ready mixtures or for dry processing. Downstream process steps that do not require a coater, as well as other electrode thicknesses, require modified mix properties as input material. The mixing process can either take place in batch operation on specially-designed mixing units, or continuously, for example using extrusion. A reduction of the solvent content is only possible in close cooperation with the development and identification of new binders and processing machines. The selection of suitable process parameters and mixing sequences is crucial to ensure ideal properties for further processing of the compounds as well as for cell performance. On the machine and plant side, it is particularly important for dry processing to use wear-resistant materials in the processing machines and to improve the temperature management of the plant. This is the only way to ensure reproducibility.

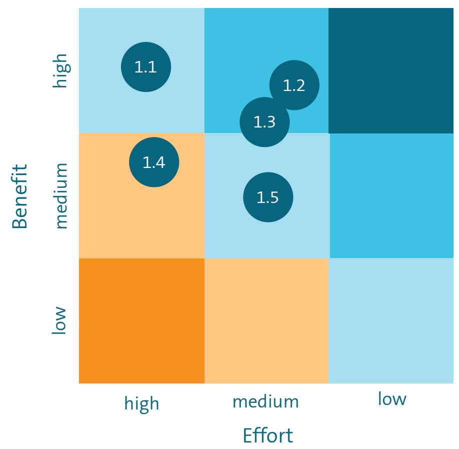
Another important aspect is the development of a quality management strategy for electrode materials. Automated control systems can be developed and specific quality parameters can be monitored by combining process expertise and inline sensor technology. This ensures the quality of the electrode while reducing operating costs by minimizing rejects. For dry processing, it is essential to first define suitable parameters and establish new offline and inline analysis methods with which can guarantee evaluation of the properties.

Machine, process, and process parameters for control/regulation as well as inline detection of production anomalies and defects must also be recorded in addition to the product parameters. Seamless inline process and product monitoring makes it possible to determine machine and process capability metrics. The goal is to ensure a low variance of the subsequent cells in terms of electrochemical parameters and to operate the mixing process in a manner that is compliant with 6 Sigma.

Detailed process knowledge combined with a high degree of automation and low-maintenance plant design is crucial to ensure flexible plant operation despite high throughput. Automated cleaning processes can be used to reduce plant downtime and thus increase flexibility. For example, pigging systems could be used to clean the piping system, make slurry adhesion usable, and also reduce solvent use. Furthermore, an optimized system and material flow concept can minimize the area in contact with the product and the associated cleaning effort. Discharge concepts for powder residues in feeding stations and dosing units enable rapid discharge and reuse of the raw materials in the next batch. Directly linking the mixing process with information from the subsequent process steps can also help to increase flexibility and ensure just-in-time supply.

Different types of containers (e.g., sacks or big bags) with different dimensions are currently used for transporting raw materials, depending on the raw material supplier. This leads to increased engineering effort for the plant manufacturers, as the filling processes have to be adapted to the individual customers' requirements, and containment must also be reconsidered or developed. The introduction of standardized or at least uniform containers and/or container sizes for certain raw material classes offers plant manufacturers the opportunity to offer cost-effective standardized interfaces for filling processes, which also ideally meet uniform containment requirements. Another potential alternative for general raw material logistics would be the operation of raw material silos or exchange containers in which large quantities of materials can be made available on demand. Silo systems offer the additional advantage of automatic filling via a pneumatic filling system, which allows the material to be transported without exposure in operation. However, raw material suppliers would also need to meet the necessary prerequisites.

Effort-benefit diagram and impact on sustainability, quality, and costs



	1.1	1.2	1.3	1.4	1.5
Sustainability	↑	↑	→	→	↗
Quality	→	↗	↑	↗	→
Cost savings	↗	→	↗	↑	↑

Contribution: ↑ = Significant ↗ = Moderate → = None

1.1 Dry processing 1.2 Material handling 1.3 Reduction of waste/ product monitoring 1.4 Throughput vs. flexibility 1.5 Raw-material logistics

Effort and benefit assessment
The establishment of reduced-solvent or solvent-free process technologies (RBW 1.1) involves a great deal of effort, but also provides benefits. The use of reduced-solvent processes is both ecologically and economically efficient. In addition to high cost, energy, and space savings from the reduction or complete elimination of the drying step, highly reduced-solvent pellets or structured blends also have a good shelf life. This significantly increases the flexibility of the mixing and production processes, allows the mixing process to be separated from the other process steps in terms of location and time. The long shelf life also makes it possible to carry out production campaigns independent of the subsequent process steps, thus ensuring a continuous supply along the process chain independent of the operation of the mixer (e.g., in the event of a product change or maintenance/malfunction). In addition to these advantages, the drying process can also be reduced or even completely removed from the process chain. This brings additional cost savings, in terms of both capital expenditure and operating costs.

The material-related temperature regulation (heating and counter-cooling) of completely dry processing requires increased effort as well as sound material and process engineering knowledge. However, this can be acquired through cooperation and close collaboration between research and manufacturers of materials, machines, and plants, and brings significant benefits.

To ensure stable operation of the production line, the mixing and dispersing process should be designed for both high throughput and to be as flexible as possible (RBW 1.2). This is necessary to ensure a continuous or quasi-continuous supply to the downstream coating process. This requires in-depth process and machine knowledge. Extensive automation and plant interlinking requires significant effort, but it does bring advantages such as increased flexibility and reduced setup times.

One promising approach for the reduction of waste (RBW 1.3) is the implementation of inline sensor technology for automated and continuous product monitoring. This involves a great deal of effort to develop and establish suitable systems. However, product monitoring is the basis of control concepts for minimization and detection of rejects at an early stage. This results in significant benefits, especially in terms of reducing costs and increasing resource efficiency.

In the short term, material handling and raw material logistics (RBW 1.4; RBW 1.5) pose challenges which are primarily associated with financial expenditures for raw material suppliers and existing plants, but in the long term it will help to significantly reduce costs. The introduction of standardized unit containers is initially associated with increased costs, but offers significant benefits for plant manufacturers and operators. Adequate measures for storing and conveying bulk materials under defined conditions can ensure high material quality. At the same time, the containment requirements must be defined on a product- and application-specific basis in order to achieve optimum employee protection at a reasonable cost. Alternative concepts for powder logistics (such as transportation via tankers and raw material silos in plants, or RFID-tagged interchangeable containers in combination with automatic filling systems) are associated with higher costs. However, they could significantly reduce the considerable personnel effort for powder logistics at and in the mixing plant, enable an error-reducing and more consistent quality assurance chain, and also increase sustainability by reducing material losses and waste quantities via/for containers and outer packaging.

Technical support

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Battery Production
VDMA
Online Industry Guide
Raw material handling and mixing:
Machines and plants

Battery Production
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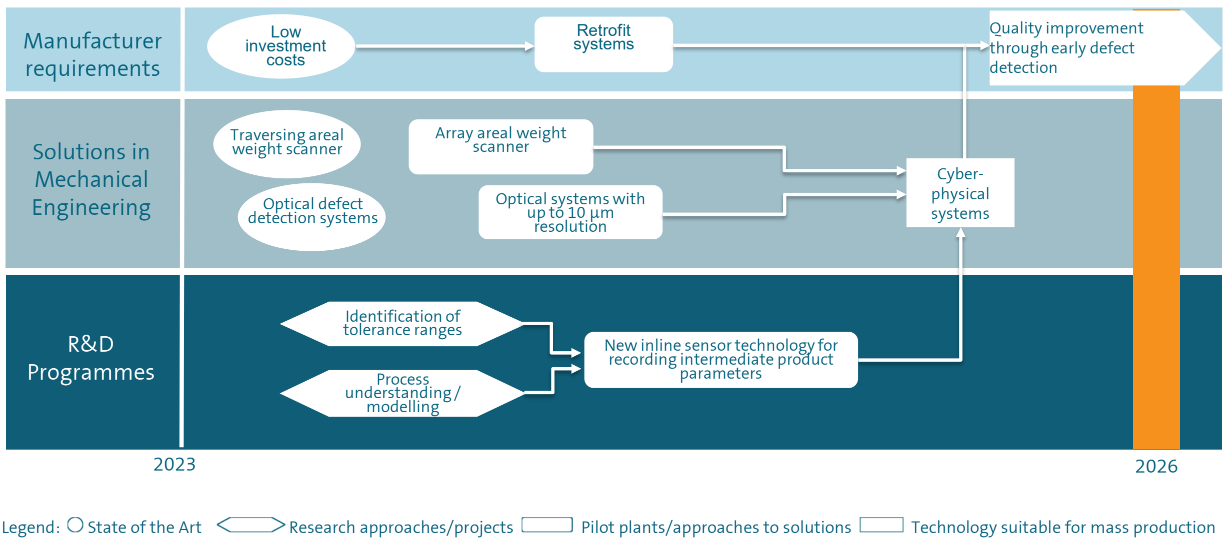
2: Coating and drying

No.*	Red Brick Wall	Current status in comparison to 2020	Relevance**	Timeline***
2.1	Increase/improve quality	Progress made	High	2024-2026
2.2	Energy efficiency and avoidance of critical raw materials	Little progress	High	2027-2028
2.3	Increase throughput	Progress made	Medium	2024-2027

RBW 2.1: Quality increase/improvement
Due to the direct influence of the coating and drying process steps on the electrode structure, technologies are required which, for example, quantify and inline monitor the homogeneity of the coatings and actively intervene in the process if set limit values are exceeded or not reached. On the one hand, the identification of tolerance ranges can be decisive for the economic efficiency of the coating process in order to reduce scrap. On the other hand, active intervention in the process can prevent quality fluctuations and achieve desired cell properties at a later stage. For this purpose, pre- and intermediate product characterization is necessary so that possible product fluctuations can be detected as early as possible and rejects can be avoided.



*RBW priority decreases from top to bottom.

**Relevance from the point of view of a battery manufacturer

***Timeline indicates when breakthrough should occur (The timeline considered is until 2035).

Source: VDMA, PEM of RWTH Aachen, BLB of TU Braunschweig according to Phaal2003b

Coating and drying

Basics
In the coating process, the suspension is applied continuously or intermittently to a carrier film (substrate) via an applicator. Intermittent coating poses a particular challenge with regard to the quality of the coating edges and is usually performed at lower web speeds compared to continuous coating. However, due to advantages in electrode assembly and with regard to the reduction of material losses, it can still make sense to accept the aforementioned challenges in intermittent coating. Round cells offer particular advantages in terms of electrode fabrication. Intermittent coating is also a prerequisite for certain stacking technologies, such as helix stacking or when lamination processes are used. With wound prismatic cells, it may be useful to adapt the coating to match the cell design. In this case, the open spaces between the coated areas are planned so that the areas in the flat winding where the radii are smallest remain uncoated. This avoids flaking of the coating in these areas.

Slot die coating is currently the most common industrial practice in industry. Typical values for the thickness of the wet film are between 200- 250 µm for energy electrodes. The respective electrode suspensions are applied to copper (anode) or aluminum (cathode) foils. If multiple or so-called multi-chamber nozzles are used, the coating width can be up to 1400 mm. Application and drying have a significant influence on the quality of the coating.

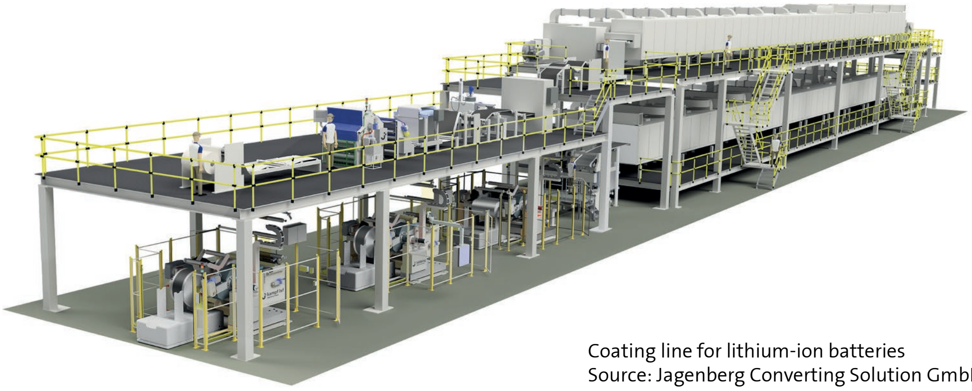
Drying determines the speed compared to the application of the coating. A guide value for the drying dwell time is approx. 40-60s, depending on the wet film thickness, the solid content of the suspension, and the solvent used. Thus, the throughput speed is essentially limited by the dryer length. Acceleration of drying is the main lever for increasing throughput.

Recirculating air dryers are generally used today, sometimes in combination with IR dryers [Kwade2018b]. At the same time, science and industry are currently focused on alternative drying processes [von Horstig2022]. For example, drying by microwaves, near-infrared, laser, or induction shows promising potential for increasing throughput. These processes are already used in other industries, but still need to be adapted and validated for the comparatively thin substrates and coatings of battery electrodes.

Depending on the system, the top and bottom sides of the film are either coated on both sides simultaneously or sequentially (tandem coating), as is especially common today in mass production systems with large working widths. Carrier rollers can be used instead of air bearing floatation nozzles for single-sided coatings. Additional demands on the process include avoiding cracking in the coating material and minimizing binder migration to the coating surface [Schoo2023]. These occur when the coatings are dried too quickly. Thus, there is an optimization issue between cost/throughput and achievable quality (e.g., energy and power density) for the drying processes, which can be significantly influenced by the machine technology, especially the drying technology.

As the susceptibility to the development of electrode defects varies over the drying process, a corresponding adjusted variation of the drying intensity over the drying process can improve the quality of the electrode. This can be influenced by temperature profiles, varying air velocities, nozzle profiles, or complementary drying technologies.

Contact of the wet/damp coating with the carrier rolls must be avoided with simultaneous double-sided coating, making a levitation track necessary. Simultaneous coating halves the



Coating line for lithium-ion batteries
Source: Jagenberg Converting Solution GmbH

necessary length of the dryer section. Special attention must be paid to a stable trajectory to ensure a high-quality coating application at the nozzle, especially with large working widths.

Challenges

Increasing quality is one of the most significant challenges for competitive electrode manufacturing on a mass production scale. Solutions must be actively pursued, especially with regard to high material and energy costs and consistent electrode quality.

On one hand, the identification of quality gates to reduce rejects can be decisive for the economic efficiency of the coating process. Due to the direct influence of the coating and drying process steps on the electrode structure, technologies are required which, for example, inline monitor and quantify the homogeneity of the layers and actively intervene in the process if set limits are exceeded or not reached and define/mark the electrode as a second choice or reject, if necessary. On the other hand, in addition to the reduction of rejects, active intervention in the process can avoid quality fluctuations and achieve the desired cell properties for a later stage. This requires in- and online pre- and intermediate product characterization to detect product fluctuations as early as possible and avoid rejects. The drying process is a particular challenge, as it has a significant influence on the electrode structure and thus its characteristics. It is necessary to develop a mechanistic understanding of the process-structure-property relationships in order to identify the causes of quality defects and implement effective countermeasures (RBW 2.1).

In addition to increasing quality, the responsible use of materials is a critical issue in terms of sustainability. Alternatives to the expensive and toxic solvent NMP must be found for cathode coating, equipment must be optimized, and rejects must be avoided. Parallel to the reduced-solvent or solvent-free production of electrodes, it is imperative to focus on the optimization of recovery and exhaust air purification systems as well as aqueous-processed cathodes. Furthermore, the reduced-solvent or solvent-free production of thin power electrodes will be very difficult to achieve even in the long term. Out of responsibility to the environment and future generations, this plays a critical role to avoid worsening the overall ecological balance of e-mobility (RBW 2.2).

Rising prices for gas and electricity add an economic dimension to efficiency improvements, especially in the European Union. The importance of this is further reinforced by the fact that Europe already had high energy prices before these increases. The high cost of energy reinforces the importance of plant energy requirements when making economic trade-offs in plant procurement. Since a large part of the energy expended during electrode and cell production is incurred in the coating and drying process, energy efficiency in these process steps is crucial and the potential for reducing the total energy demand of battery production is particularly high [Drachenfels2022] (RBW 2.2).

In addition to improving quality and increasing energy and material efficiency, plant manufacturers must also address the issue of increasing throughput. Planned large-scale *gigafactories* must achieve high throughput to meet market demand and be economically competitive. Normal scale-up processes of conventional dryers face high initial costs and manufacturing issues. For example, increasing the length of the drying section creates challenges for the web run, which can lead to wrinkling or even breaks in the substrates (diverter films). This means that current dryer lengths are mainly limited by substrate properties. In particular, the trend towards thinner and thinner conductive films poses additional challenges for web runs. The use of new materials such as metallized polymer films as substrates aims to increase cell safety compared to metal films, as well as to save material and increase energy density. However, this makes the demands on the processes much more challenging, especially on web tension control. In addition to plant engineering developments for processing these films, it is also important to integrate plant engineering early in the development of substrate films (RBW 2.3).

Possible solutions

To achieve the desired increase in quality (increased monitoring and early detection of rejects), optical defect detection systems can be used which detect surface defects at an early stage and identify their sources. For example, streaks on the coating can be attributed to an agglomerate in the die gap. Defect assessment is also required to determine the extent to which the detected defects affect the quality. Classifying defects into categories can be used to draw conclusions on whether defects lead to cell failure or to a reduction in quality (second choice).

Furthermore, quality gates must be determined that detect potential fluctuations that may reduce the quality as early as possible and intervene in the process accordingly. Cyber-physical systems (i.e., the direct evaluation and use of data measured inline) can be established to issue recommendations for action, or the data can be used as a predictor for the creation of a digital twin. The conductive film can also be pretreated to increase the adhesion of the coating to the film and reduce waste. This includes laser microstructuring as well as plasma-based and electrochemical processes.

The responsible use of materials is critical for sustainability. Due to the high cost of materials and the high ecological footprint, avoiding rejects is essential. For example, when setting up the coating lines, camera-based control systems can ensure that the coating positions are automatically positioned relative to the substrate as well as to each other (top to bottom) and adjusted throughout the production process.

The surface inspection described above and the corresponding assignment of defects can also be used to quickly intervene in the process and avoid rejects. With additional automatic closed-loop layer thickness measurements, coating lines could be almost completely automated.

The achievable increase in throughput in all approaches is always offset by quality issues. Stable processes must be established and continually optimized in order to avoid rejects and maintain the necessary cost structures. This requires detailed knowledge of the interaction between process control and the achievable product quality (e.g., to avoid separation/cracks or the formation of rough edges).

This knowledge can contribute to the general acceleration of the drying by optimizing the process and equipment parameter setup. A significant increase in the speed of the drying and coating process can be achieved by reducing the dwell time in the drying process. This is the aim of efforts to produce suspensions with higher solid contents as well as to extend the drying process by combined drying (e.g., convective with IR). For this process, the application tools of the coating equipment must be adapted to the processing of extremely high-viscosity suspensions.

Dry coating processes which dispense with solvents completely have already been successfully implemented, at least on a pilot plant scale. Powder is used in place of a suspension, which can be compressed via hot calendering to form a film which is applied to the base film directly or via lamination processes. Other alternatives include PVD processes or electrostatic coating approaches.

The advancement of binder materials is essential for both high viscosity and dry coating and must be adapted to the machine concept. Overall, intensive materials research is required for both solvent reduction and dry coating. Furthermore, the reject rate must be reduced. Among other things, this can be achieved by developing reliable and uniform metering of the powder, especially for high process speeds. Surveyed partners expect dry coating to be suitable for the mass market by 2030. Reducing the solvent content to the point of dry coating is also the most important approach to increasing energy efficiency.

Achieving high process speeds greater than 80 m/min with consistent quality makes a significant contribution to increasing throughput with wet coatings. The coating application can limit the speed, especially with intermittent and/or double-sided simultaneous coating. This will become even more important the more as the drying time is reduced by solvent reduction and innovative drying technologies.

In addition to the established processes, new approaches could include screen printing or gravure printing. The inclusion and development of new drying processes such as infrared, laser, or conductive drying is fundamental.

Research results show that infrared and laser drying can achieve a more efficient energy input and thus lower energy consumption compared to conventional drying ovens. Laser drying connected upstream of the convection dryer is also conceivable, for example by VCSE lasers. The electrode coatings could also be dried conductively, which could be implemented with system technology by heating the substrate using induction. Inductive substrate heating offers particular potential for simultaneous double-sided coatings, since the heat input into the electrode does not have to occur exclusively via the outer electrode surfaces.

Previous drying processes have mainly used conventional convective drying. What is challenging is an efficient combination of different drying processes (e.g., convection and infrared) to increase the drying speed. Extending the length of the dryer is not economically viable, nor is it readily possible since the carrier film limits the length of the dryer. By combining drying processes, drying speeds can be increased and dwell times or possibly even the dryer length can be shortened.

For sequential coating, "pre-drying" the first side so that carrier rolls can be used for transport offers potential for optimized use of the drying section. After the subsequent coating of the second side, the overall drying of both sides can be carried out simultaneously. An alternative to this is the direct simultaneous double-sided coating of two wet layers. One advantage is that it is easier to ensure that both sides of the coating are congruent. In addition, the above-mentioned effects of "cupping" can be avoided, since the tensions arising during drying act against each other in the electrode. However, the floating guidance of the film from the second coating nozzle and the adhesion of the suspension on the underside is challenging.

Further demands on the coating process arise when the coating width is increased to increase throughput. A prerequisite is the further development of the substrates, so that multi-strip coatings on substrates wider than 1.4 m will be possible in the near future (e.g., 4 strips of approx. 500 mm each). In the future, multi-strip coating in these widths can be implemented on both sides as simultaneously as possible, as well as intermittently for certain electrode formats.

Technologies for exact dosing of the suspension volume flow and for nozzle deaeration are crucial for setting precise edges in intermittent coating for both simultaneous and sequential coating. For example, uniform coverage of the edges can be implemented by optical methods for automatic web control.

Multilayer coatings are being applied more and more widely to optimize electrodes to combine very good charging performance and outstanding energy properties (range). Electrode properties can be adjusted depending on the distance to the substrate, especially the ionic diffusivity and electrical conductivity. Multi-slot nozzles can be used for this purpose. Another approach for improving the ionic diffusivity in the anode coating is to vertically align the elongated graphite particles immediately after coating using the diamagnetic properties of iron oxide nanoparticles which have previously been applied to the graphite [Billaud et al. 2016].

The use of NMP as a solvent for cathode coating, which is both expensive and highly toxic, must be reduced or even avoided. This would also contribute to reducing energy costs and minimizing the CO_2 footprint. However, since a replacement for NMP in solvent-containing cathode suspensions will continue to be necessary in the medium term, the focus of ongoing developments of recovery systems is the energy-efficient almost complete recovery of the solvent.

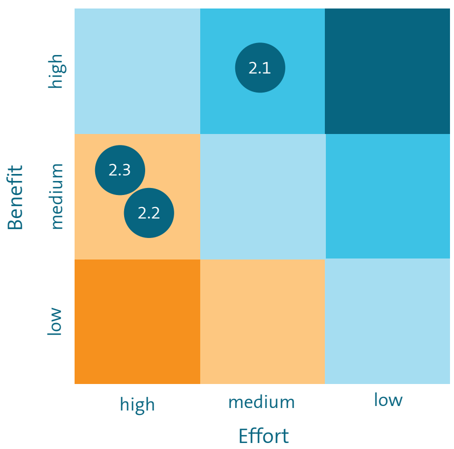
Research on water-based cathode suspensions shows progress. However, the susceptibility to the development of surface reactions and the associated loss of capacity of nickel-rich active materials upon contact with moisture has not yet been satisfactorily reduced. Surface coatings can remedy this situation.

Effort and benefit assessment

Quality assurance measures are generally considered very relevant and serve to reduce costs as well as predict tolerance ranges for the manufactured product. The benefit is rated high and the effort is rated moderate due to the availability of many technologies from other industries. Reducing scrap has a direct impact on cost and sustainability. The benefit is thus assessed as high.

Alternative drying technologies are currently the focus of many research projects, as they can achieve not only an increase in throughput, but also a considerable increase in energy efficiency. Avoiding the use of critical materials is also an important consideration for European locations. Dry coating for solvent reduction or avoidance and the replacement of NMP with water on the cathode side were discussed here. The effort is estimated as high since extensive material and equipment development is necessary. Increasing energy efficiency is assumed to result in significant cost savings by reducing high energy costs. Investment costs and the CO_2 footprint

Effort-benefit diagram and impact on sustainability, quality, and costs



	2.1	2.2	2.3
Sustainability	↑	↑	↗
Quality	↑	→	→
Cost savings	↗	↑	↑

Contribution: ↑ = Significant ↗ = Moderate → = None

2.1 Increased/improved quality 2.2 Energy efficiency and avoidance of critical raw materials 2.3 Increased throughput

are also significantly reduced. With regard to quality, separation of the binder and conductive additive can be avoided, even with thicker coatings. The benefit is therefore rated as moderate.

The increase in throughput plays an important role in battery production, as it can substantially reduce costs. The benefit was rated as moderate. The use of innovative drying technologies (IR, NIR, laser, or conductive drying) and the continued development of simultaneous coating processes offer an opportunity to increase throughput and thus reduce costs, but also requires an increase in development effort. Therefore, the effort was rated as high. Quality assurance measures are generally considered very relevant and serve to reduce costs as well as predict tolerance ranges for the manufactured product. The benefit is rated high and the effort is rated moderate due to the availability of many technologies from other industries. Reducing scrap has a direct impact on cost and sustainability. The benefit is thus assessed as high.

Technical support

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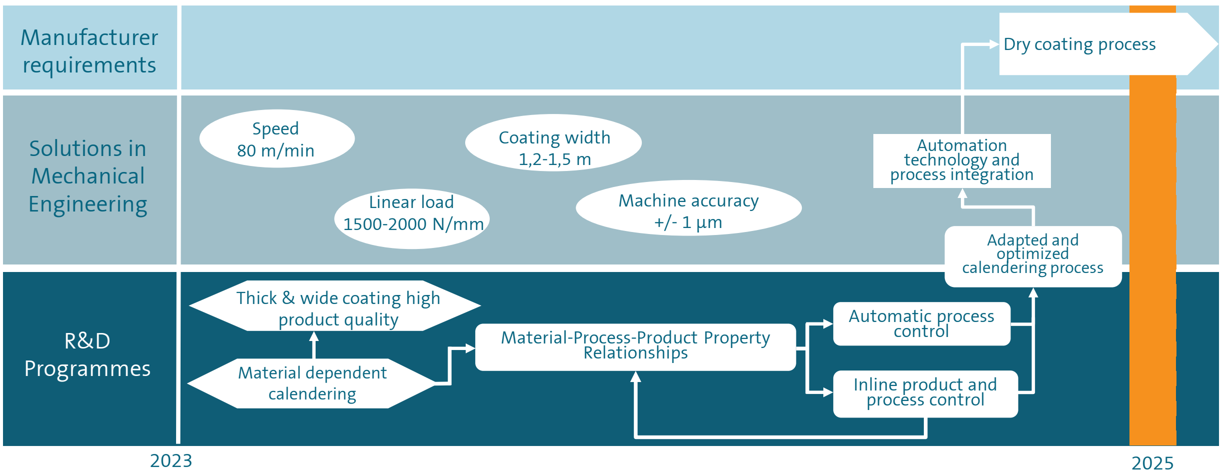
3: Calendering

No.*	Red Brick Wall	Current status in comparison to 2020	Relevance**	Timeline***
3.1	Convert calendering to a dry coating process	Progress made	High	2024/25
3.2	Increase throughput: higher speed speed with consistent quality	Progress made	High	2025
3.3	Ensure homogeneous electrochemical properties and uniform layer structures with larger web widths	Progress made	Medium	2025

RBW 3.1: Transfer from calendering to a dry coating process
Conventional electrode production is characterized by high energy and resource consumption. The primary focus is on the drying step, as it the most cost-intensive. Transferring to a dry coating process can completely eliminate the drying step and thus the need for solvents. This leads to a significant improvement in the energy and ecological balance as well as a reduction in costs.



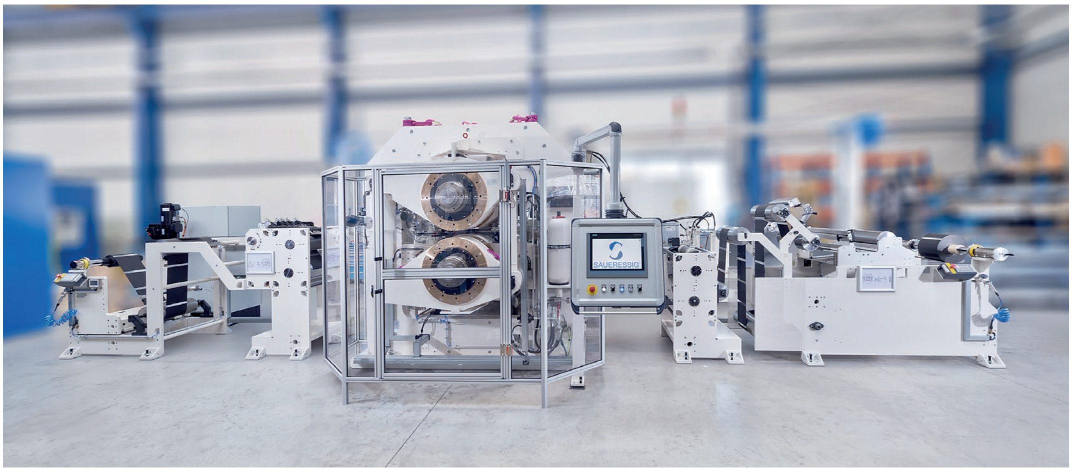
Legend: State of the art, Research approaches/projects, Pilot plants/approaches to solutions, Technology suitable for mass production

*RBW priority decreases from top to bottom.

**Relevance from the point of view of a battery manufacturer

***Timeline indicates when breakthrough should occur (The timeline considered is until 2035).

Source: VDMA, PEM of RWTH Aachen, BLB of TU Braunschweig according to Phaal2003b



SAUERESSIG GKL 500 MS - Calendering system for intermittently coated electrodes
Source: Matthews International GmbH

Calendering

Basics
Calendering (continuous roll compaction) is currently the final process step in electrode production. It is therefore of particular importance as a "quality gate" before the transfer to the cell manufacturing processes. Force is used during the calendering process to reduce the porosity of the coating, with the particles being rearranged by pressure and shear forces. In some cases, deformation or fracture of the particles may occur during this process. The initial electrical percolation pathways and mechanical polymer-binder linkages (solid phases of the electrode) that are established after the drying of the coating are broken up, and the particle-particle and particle-binder contacts are re-established, which defines the final structure of the electrode. For this reason, there are interactions with the upstream processes of suspension and layer production.

The compaction process ultimately defines all key electrode properties for the electron and ion transport processes, such as the energy and power density as well as the cycle stability, along with the correlating physical coating properties such as structural and mechanical properties. Achieving the highest possible energy densities (range) while at the same time offering fast charging capability (densities: NMC cathode > 3.5 g/cm^3; graphite anode ≥ 1.5 g/cm^3) is the key challenge for conventional liquid electrolyte batteries for electric cars. For graphite and especially graphite-silicon anodes, high energy densities are not as important as in the cathode, since significantly higher specific capacities are introduced on the material side. Moderate density is often used to avoid ion diffusion limitations. A key goal of densification is establishing mechanically advantageous coating properties to compensate for stresses that occur during subsequent manufacturing processes or layer breathing (expansion) of the electrodes as a result of electrochemical cyclization. Especially with silicon-containing anodes, the remaining portion of the theoretically possible elastic deformation is critical to counteract the large volume fluctuations of silicon of approx. 280-300 vol. % between charge and discharge (by comparison, the volume expansion of conventional graphite is only around 10 %).

Challenges
The development of reduced-solvent/solvent-free electrode production processes is currently one of the most important issues for cell and equipment manufacturers. The potential for cost reduction is very high, as almost 40 % of the required energy is used in the drying of solvent-

containing pastes. Compared to conventional electrode production, reduced-solvent electrode production combines coating and compaction into a single step in the calender system. In reduced-solvent electrode production, a residual amount of solvent remains in the high-viscosity pastes, which acts as a kind of lubricant and enables the self-dosing feed of the paste into the roll gap. This residual moisture is eliminated in solvent-free electrode production, which makes the dosing of the dry powder mixture a particular challenge. Therefore, suitable flowability of the powder must be achieved to prevent separation.

SAUERESSIG GKL 500 MS – Calendering system for intermittently coated electrodes (close-up)
Source: Matthews International GmbH

Heavy wear is also a problem with the use of highly abrasive materials (e.g., metal oxides or silicon), due abrasion of the equipment. This not only affects the mixing equipment, as described in Chapter 1, but is also challenging for the calender rolls. High wear resistance of the equipment must be ensured to avoid long downtimes, such as during a roller change. Although equipment manufacturers already offer systems that allow reduced-solvent or dry coating, large-scale dry coating processes are not yet established in cell production. This can be achieved by close cooperation between research, material and equipment suppliers, and cell manufacturers (RBW 3.1).

Increasing the speed without affecting quality is another challenge (RBW 3.2). Central parameters of the calendering process are the gap width or the line load to be applied, which are used as control variables. There is also the influence of the web speed (up to 100 m/min) which, together with the roller diameter and the electrode geometry (width, thickness), defines the catchment area of the compaction rollers and thus the intensity of the compaction process per unit of time. Large roller diameters are associated with gentler compaction processes. High surface loads also increase the catchment area, and thus the stress area at constant roller diameter, and increase the compaction intensity. High throughput rates increase the necessary compaction performance per unit of time in the catchment area. However, this cannot have any effect on the quality. In terms of maintaining quality, increasing the rolling temperature can favor binder polymer deformation and reduce the required cathode line load. This can minimize electrode deformations ("cupping," "wrinkling," electrode corrugation, and the formation of creases) as a consequence of mechanically induced residual stresses at the interface with the substrate. Another approach to limit residual stresses and ensure high quality is to pre-stretch the substrates to avoid pronounced stretching during calendering.

A decisive quality feature of a calender system is the uniformity of the nominal gap size at high throughput speeds. Thick electrodes and high line loads can cause the actual gap to widen due to high mechanical compaction stresses and the associated deformation of the roller mill, thus limiting the compacting ability of a calender. In addition to the suitable conductive carbon black structure discussed above, the smallest possible deviation between the actual and nominal gap is critical for ensuring homogeneous electrochemical properties, since the homogeneity of the layer structures is influenced at the micro level on both sides. The objective is homogeneous distribution of electron and ion current densities, even with large electrode widths (RBW 3.3). The specific goal is low variance of the ion transport hosts (the electrolyte-filled cavity structure) and thus an effective diffusion coefficient of the electrode material. This is challenging for machine technology with high coating widths of up to 1.5 m (anode) and 2.0 m (cathode), since large roller diameters are required the deflection of the rollers must be kept as low as possible. There are also deviations due to deformation in the bearings or the roller mill. The global target is a machine accuracy of at least +/- 1 µm. The achievable accuracy in the product should simultaneously be monitored inline and used as continuous quality control. In the near future, it should also be used for intelligent process control, preferably by establishing methods for using artificial intelligence (AI). Other quality parameters at the micro level (e.g., pore distribution) should be included in combination with the coating thickness in the overall concept in order to enable the most accurate and precise quality measurement and process control possible at the quality gate to the cell manufacturing processes.

Possible solutions

High product quality and product-oriented process and machine development can only be achieved with systematic knowledge generation in the field of material/process structure property relationships. Understanding of the interaction of the mixing and drying processes with calendering is crucial, as is the interaction of calendering with downstream processes such as electrolyte filling and forming. As the final step in electrode manufacturing, compaction allows for targeted adjustment of the microstructure and thus the final pore structure within the coating. The pore structure has a direct influence on the electrolyte distribution and the wettability of the electrode. With adequate knowledge of the compaction process, fast and knowledge-based adaptation of process and machine technology to new material and cell generation types is economically feasible in the industry. Calendaring systems must be outfitted with advanced in-line measuring technology to utilize the full potential of the material and maintain product quality. Above all, this includes in-line measurement of the coating thickness/density as well as in-line detection of coating defects and defect patterns for early detection of rejects and associated resource savings in the subsequent cell assembly process steps. In-line systems for the application of codes for tracking and tracing materials and cells are also gaining importance. Beyond detection of layer defects, clustering of different defect patterns and the establishment and recognition of correlations between detected defects and process control is crucial. Reliable and precise in-line measurement data (e.g., on the achieved layer thickness) is required to setup or integrate autonomous and adaptive control systems (closed-loop control) in the calendering system. Such control systems enable the calender to react independently, quickly, and precisely to any problems or deviations between actual and target values, which is of great importance for increasing the productivity of the calender system.

Other approaches for increasing throughput without affecting quality, while also ensuring homogeneous electrochemical properties, are mechanical preloading of the substrates, temperature-controlled calendering with a preheating section, and/or heatable rollers to avoid effects such as "dishing" (warping and corrugation of the electrode due to internal stresses) at high cathode line loads. Due to temperature-related deformation properties of the binder, temperature can be used to reduce the line loads required for uniform electrode densities. However, the increased deformation of the machine and changes to the actual gap must be taken into consideration.

An alternative approach to avoid dishing, especially with very thick electrodes, is two-step compaction processes, which can be conveniently implemented in a machine unit. The coating film is coated and compacted on a polymer film and then transferred to a metal film via a lamination process. The same machine can be used to laminate a separator to the electrode coating, further increasing production efficiency by reducing the number of individual parts involved in the cell structure.

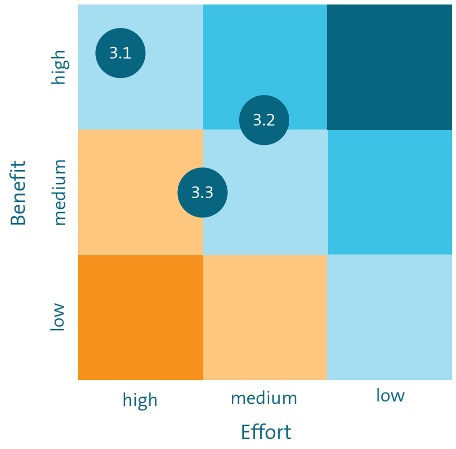
Low deformation of the calender (mill and rollers) is absolutely essential on the machine side to ensure the smallest possible difference between the nominal and actual gap dimensions. Continuous recording of the real actual gap dimension directly between the calender rolls is an essential measure that should be implemented first and used as a process quality and process control variable. The accuracy of the coating thickness and line load should be monitored in-line and used as continuous quality control. In the near future, it should also be used for intelligent process control - preferably using established methods, real-time capable models, and artificial intelligence (AI). Once this is done, "in-production research" concepts open up in order to be able to continuously develop the production process and the specific product. Additional quality measurement variables combined with the layer thickness and line load should be included in the overall measurement concept in order to enable the most accurate and precise quality measurement and process control possible at the quality gate to the cell production processes. Defect detection should be performed after coating and after the calender gap and linked via a tracking system. This way, coating defects can be rejected directly or after detection by calendering. Rollers that can be locally and precisely depressurized based on information from the upstream analysis processes could provide a competitive advantage by avoiding damage to the roller from possible coating defects. The immediate benefits would be long roller service life (tool protection) and the avoidance of downtime.

Achieving homogeneous electrochemical properties and uniform layer structures with ever larger web widths within a robust and stable compaction process requires precise conductive carbon black structuring with active material and binder. Intelligent design is also required on the machine and plant side to minimize deformation during compaction with high line loads. Suitable approaches could include bombage[21] of the calender rollers as well as roll-bending systems to effectively dissipate forces.

Another key issue is the ability of the calender to handle emerging electrode widths of 1.5 m and prospectively > 2 m. The rollers must be increased in diameter and width while maintaining accuracy. Design measures must be used to minimize roller deflection and machine deformation, especially to be able to compact thick layers of high-capacity electrodes smoothly.

[21] Bombage is a deviation from the cylindrical roller profile in which the rollers are slightly thickened in the center. This counteracts the deflection of the roller.

Effort-benefit diagram and impact on sustainability, quality, and costs



	3.1	3.2	3.3
Sustainability	↑	↗	↗
Quality	→	→	→
Cost savings	↑	↑	↗

Contribution: ↑ = Significant ↗ = Moderate → = None

3.1 Dry coating process

3.2 Increase throughput with consistent quality

3.3 Ensure homogeneous electrochemical properties

Effort and benefit assessment

The effort required to introduce a dry coating process as well as the associated benefits are estimated to be high. Dry coating processes have the potential to significantly improve the economic and ecological aspects of cell production. However, the conversion of cell production to solvent-free electrode manufacturing requires a high level of development effort. This applies to both calendering and upstream process steps such as the mixing process. Significant expertise is required, from powder handling to application of the powder bed onto the metal foil.

Increasing throughput without compromising quality is generally regarded as one of the core objectives in manufacturing. Therefore, the benefit is still classified as high with medium effort. Progress has already been made in increasing throughput; in the future, the focus should primarily be on automating the calendering process.

This requires stable and highly precise in-line measurement technology that meets the demands of a fast and highly dynamic calendering process.

Ensuring homogeneous product properties is essential for quality assurance in production, which is why the benefit is rated as high, while the effort is rated as moderate. Ensuring homogeneous distribution of the coating density over the entire electrode width is challenging in terms of machine technology. The deflection of the rollers must be kept low, while increasingly thicker and wider rollers are required for higher throughput. On the equipment side, this challenge can be met by approaches such as bombage the calender rolls and roll-bending systems.

Technical support

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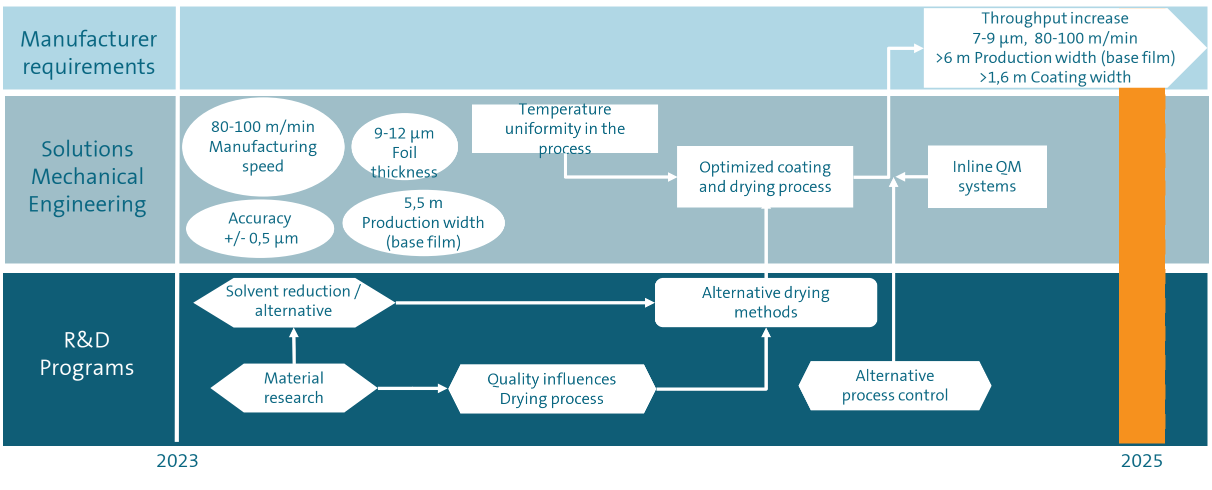
ISRA VISION GmbH
Lenze SE
Pepperl+Fuchs SE
SCHUNK GmbH & Co. KG

4: Separator production

No.*	Red Brick Wall	Current status in comparison to 2020	Relevance**	Timeline***
4.1	Increase throughput	Progress made	High	2024 - 2025
4.2	Reduction of separator (film) thickness/film handling in conjunction with high yield rate	Progress made	High	2024 - 2025
4.3	Sustainability and environmental protection (solvent substitution)	Progress made	Medium	2023 - 2026
4.4	Coating and film quality for large widths	Progress made	Medium	2023 - 2025

RBW 4.1: Increase throughput
The growing European value chain for battery components also requires European separator production, which involves higher environmental protection requirements compared to Asian production sites. This leads to various challenges (e.g., alternative solvents) that must be met.



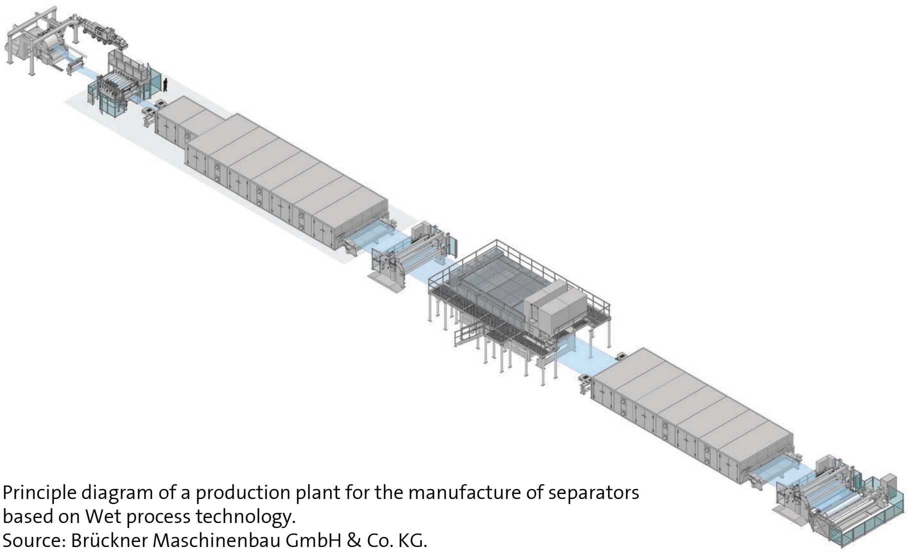
Legend: ◯ State of the art ⬡ Research approaches/projects ▭ Pilot plants/approaches to solutions ▭ Technology suitable for mass production

*RBW priority decreases from top to bottom.

**Relevance from the point of view of a battery manufacturer

***Timeline indicates when breakthrough should occur (The timeline considered is until 2035).

Source: VDMA, PEM of RWTH Aachen, BLB of TU Braunschweig

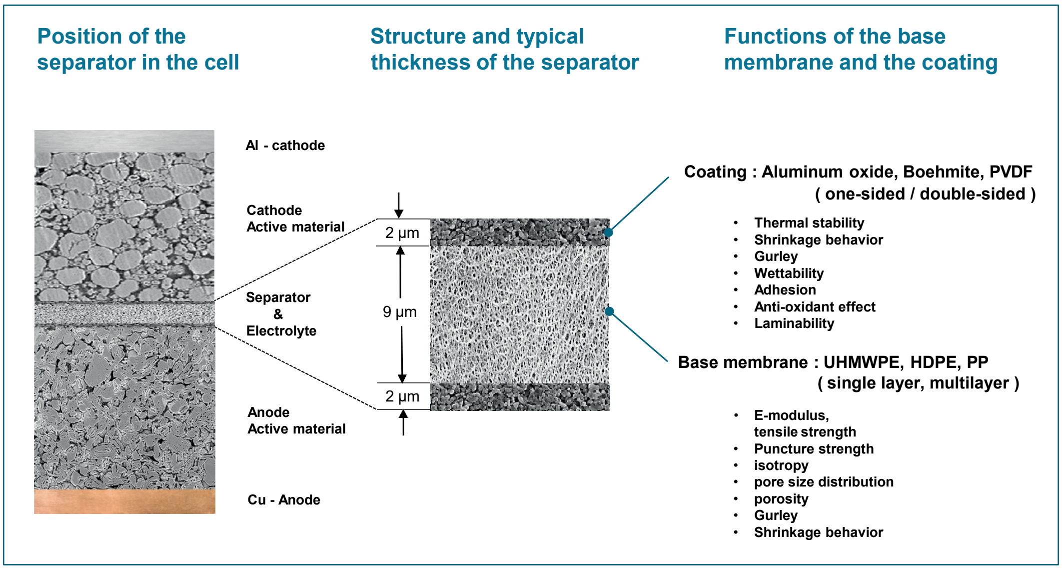


Principle diagram of a production plant for the manufacture of separators based on Wet process technology.
Source: Brückner Maschinenbau GmbH & Co. KG.

Separator production

Basics

The separator is a crucial component for the production and operation of lithium-ion battery cells which significantly influences the safety, performance, and manufacturing process of a cell. The selection of suitable separators also depends on the cell type (cylindrical, prismatic, pouch) and the application. Since the demand for Li-ion batteries for electromobility will be dominant in the next decade, with a share of approx. 90 % of the total Li-ion battery market, the special requirements for this market segment are discussed here. For EV applications, large-scale polyolefin-based membranes have become common, consisting of polyethylene (PE) or polypropylene (PP) and often additional ceramic coatings. Other separator types, such as ceramic-impregnated polyester (PET) or aramid-based non-woven materials, play a minor role for this application. With polyolefin-based separators, the task of the base film is to ensure high mechanical strength (Young's modulus, puncture resistance) with a low thickness and a porosity of approx. 35-50%. For PP, the desired porosity and pore structure is achieved in the "dry" process via the semi-crystalline structure typical of polypropylene in conjunction with a monoaxial stretching process in the longitudinal direction. The "wet" process is used for PE, in which preferably ultra-high molecular weight polyethylene (UHMWPE) is melted by a twin-screw extruder using large proportions of mineral oil (60-75%), extruded by a slot die, and subsequently cooled. The film is then biaxially stretched to achieve the pore structure and strength. In the next step, the mineral oil used must be completely removed by an extraction and drying process using dichloromethane (DCM). DCM is used for its good solubility for mineral oils and its lower boiling point, but it is also toxic and harmful to the climate. The thermal stability can be significantly increased via the ceramic coating applied in a separate process, which is beneficial to the safety of the cells. Ceramic materials (e.g., aluminum oxide, boehmite) are mainly used for this purpose, as they significantly reduce the thermal shrinkage of the separator and can ensure electrical separation of the anode and cathode even above critical temperatures of 150 °C, thus preventing internal short circuits. The ceramic coating can be applied to one or both sides, each with a typical thickness of 2 µm. In addition to the advantage of thermal resistance, the coatings improve the wettability for the electrolyte liquids, which is beneficial for the cell production process. The long-term stability of the cells is also increased by the antioxidant effect of the coating. For two-dimensional cell types, the electrodes can be laminated together with the separator. To do so, PVDF must first be applied as a further coating, usually in spot form [Wu 2019].



Schematic diagram of a separator typical for EV applications
Source: Brückner Maschinenbau GmbH & Co. KG.

Challenges
Fully automated production processes, high efficiency (low defect rates), pronounced process integration, and knowledge of interdependencies are all essential for competitive mass production of separators. A further increase in the achievable output rates (e.g., larger widths and production speeds) is inevitable for the targeted cost reduction (RBW 4.1). This applies to both the base membrane and the coating process. Consistently high quality of both the base membrane and the coating must also be ensured, as this has a direct impact on the production processes, the separator specification, and ultimately on the safety of the battery cells (RBW 4.4). In particular, local defects in the base membrane and the coating are regarded as critical. This requires 100% optical control for the produced area; however, the detection of defects in the µm range is a major metrological challenge. Most separator parameters can only be determined by random sampling in the laboratory. Therefore, the goal should be improved process control involving as many inline measured values as possible (including thickness, coating thickness, porosity). To increase the gravimetric and volumetric energy density of the cells, the film thicknesses of the separators must be further reduced to < 13 µm (9 µm base film + 4 µm coating), and prospectively to 9 µm (7 µm base film + 2 µm coating). The greatest challenge with these thinner films is to maintain the high quality of all film properties in order to meet high cell safety requirements. The films also become more challenging to deal with as the separator thickness decreases (RBW 4.2), and the production yield decreases as a result. Currently, separator films are primarily produced in Asia (Japan, Korea, and China). There is great interest in local separator production in Europe, not least for the purpose of overcoming current dependencies. Thus, the European Union's high requirements for sustainability and environmentally friendly processes represent both a hurdle and an opportunity (RBW 4.3). One of the greatest challenges for the base film is to find an environmentally-friendly substitute for the solvents used, as only water-based coating processes should be used for the coating process in the future.

Possible solutions
Both the production capacity and the share of production for the base membrane and the coating should be considered to achieve the desired increase in throughput.

Base membrane
To increase throughput, the rate of production of the base film must be increased to speeds of >

80 m/min and widths of > 6 m. Additional productivity increases can be realized both for the base film and for the downstream processes by increasing the roll length to > 1000 m. This enables the production of "parent rolls," which increases product capacity and reduces the frequency of roll changes in the subsequent cutting and coating processes. To achieve these increased speeds and roll lengths, film properties (particularly the film thickness and porosity) must be kept within a narrow window and tensile stresses in the winding process must be tightly controlled to prevent film breakage and winding defects. High quality of the base film must be maintained over the entire working width in order to increase the yield of the film.

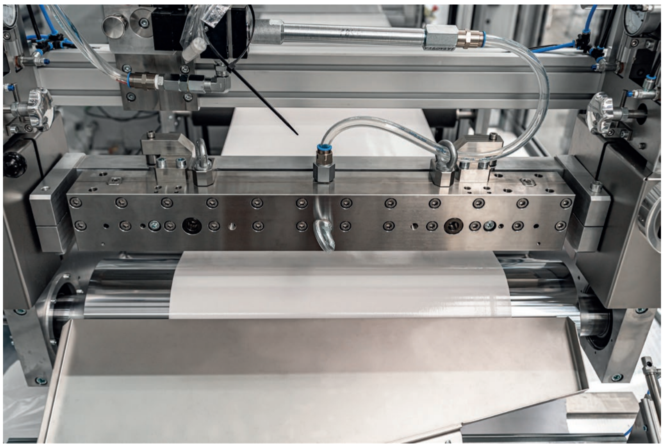
Coating
After an initial cutting process, the base membrane is currently coated to a width of 1.0 - 1.6 m. Optimum flatness and consistent coating thickness over the entire width must be ensured to achieve economically viable widths of 2 m. A speed increase from the current 300 m/min to 500 m/min is possible. Limitations are encountered which can only be overcome by fine-tuning of the coating dispersion (viscosity, foaming) and the application process (e.g., with engraving rollers). The web guidance and the drying technique using a long oven at low tensile stresses of approx. 10 - 20 N are also of particular importance. Quality and yield increases can be achieved in the preparation of the coating dispersions through continuous mixing and dispersing processes which can feed the coating systems with a high degree of dosing accuracy.

The thickness of both the base membrane and the coating must be reduced, but different measures are required.

Base membrane
Reduced film thicknesses down to < 5 µm for the base film can already be achieved today and are mainly called for the consumer market. The challenge is to produce the film at consistently high speeds, since the tensile stresses and thickness tolerances must be controlled within a narrow window. Particular attention must be paid to the dielectric strength, which decreases with film thickness, as this value plays an important role in cell safety. To compensate for the decreasing strength, films must be produced with ultra-high molecular weight polyethylene (UHMWPE) and with higher aspect ratios.

Coating
Raw material and formulation improvements are essential to achieve the required thermal stability with a reduced coating thickness. There are approaches which combine nanoscale ceramic particles with suitable binder systems to significantly reduce the thermal shrinkage of the entire system which could potentially be used to reduce the thickness of the coating. Ensuring the narrowest possible particle size distribution while avoiding larger individual particles and impurities is a significant challenge for machine manufacturers and producers of ceramic coating materials.

The manufacturing processes used for the base membrane and the coating must meet the applicable environmental standards in Europe, and will be evaluated according to these criteria in the future. In particular, the carbon footprint is increasingly being used to compare and select different products and processes. This leads to critical evaluation of the raw materials used as well as the specific energy consumption. is increasingly being used to compare and select different products and processes. This leads to critical evaluation of the raw materials used as well as the specific energy consumption.



Breitschlitz-Beschichtungsanlage für Batterietechnologien,
Source: Coatema Coating Machinery GmbH

Base membrane
In addition to lowering the specific carbon footprint by increasing throughput, attention must be paid to the use and recovery of the solvents and mineral oils used in the wet process. The extraction agent DCM, which has been widely used up to now, must be replaced by suitable, environmentally friendly alternatives, which will have an impact on process control and solvent recovery. By using high quality mineral oils, the recyclability can be improved in order to minimize the need for raw resources.

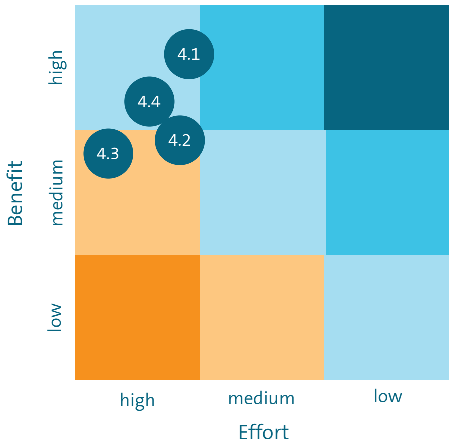
Coating
Both solvent-based and aqueous dispersions are used for the coating process. Aqueous systems are preferable from an environmental point of view, partly to eliminate energy-intensive solvent recovery and toxic solvents. The energy required for evaporation of the water content decreases with lower coating thicknesses and increased solid content, which is more environmentally friendly.

Comprehensive process and product monitoring is essential to achieve sustainable competitiveness in separator production. This includes the real-time recording of machine, process, and product parameters for quality control and direct control/regulation of process management. AI methods are already being used for this purpose. It is useful to record the data at an early stage during preliminary tests in order to teach the inspection systems accordingly. It is equally important to integrate with the other cell production steps to create an association to the quality of the final product. The separator has an influence on the subsequent processes and on the final product, and it would be negligent to regard it as just another purchased part. Critical end-product control should also be performed to ensure the highest possible safety and compliance with final product requirements.

Base membrane
The homogeneity of the film properties across the working width is critical for the quality and yield of the final film. Standard film thickness measurements can be extended to include inline measurement of the porosity and Gurley value as well as optical inspection systems to detect deviations at an early stage and adjust the processes accordingly. Additional productivity increases can be achieved by interlinking the measurement data from base film production with downstream processes.

Coating
Inline measurement technology for the coating process should at least include recording of the wet and dry film thicknesses. The measuring systems used must be improved to achieve sufficient resolution at low thicknesses of 1 - 2 µm. Optical inspection systems for input and end controls are required as a 100% check of the surface produced to detect defects. With the

Effort-benefit diagram and impact on sustainability, quality, and costs



	4.1	4.2	4.3	4.4
Sustainability	↗	↗	↑	↗
Quality	→	↗	→	↑
Cost savings	↑	↑	↗	↗

Contribution: ↑ = Significant ↗ = Moderate → = None

4.1 Increase throughput

4.2 Reduction in separator (film) thickness/ film handling in conjunction with high yield rate

4.3 Sustainability and environmental protection

4.4 Coating and film quality for large widths

widths and speeds that will be required in the future, there are limits to the measuring accuracy and resolution that can be overcome through advancement of measuring techniques.

Effort and benefit assessment

Increasing the throughput (RBW 4.1) has the highest benefit due to the significant potential cost savings. However, this also requires a high level of effort to develop fast coating and web guiding technologies. In particular, "breaking through" RBW 4.3 would make the largest contribution to sustainability, for example by substituting toxic solvents. However, the effort required for this is considered to be particularly high.

Technical support

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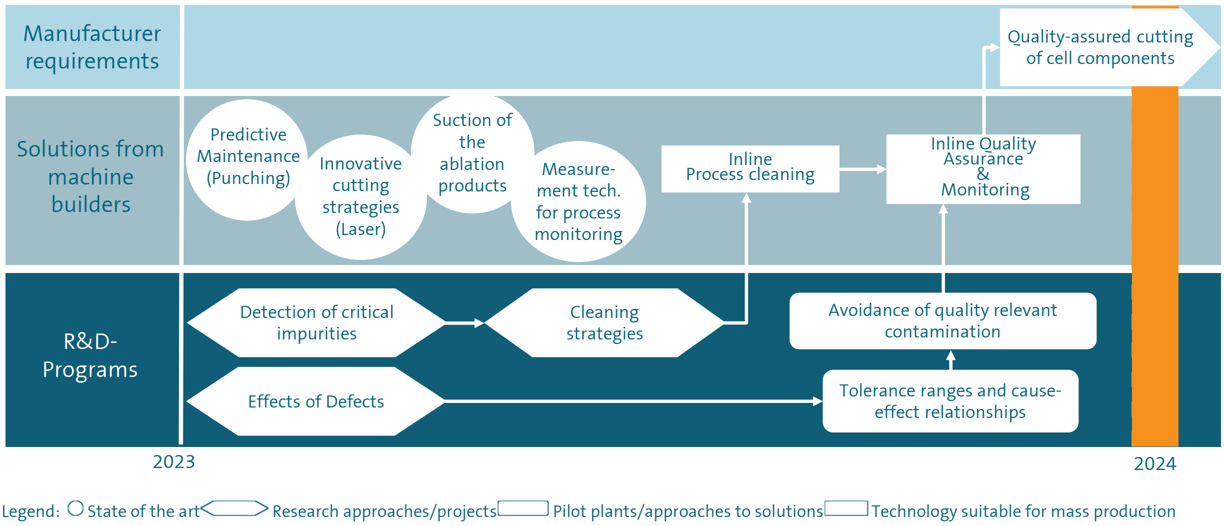
5: Separation

No.*	Red Brick Wall	Current status in comparison to 2020	Relevance**	Timeline***
5.1	Inline quality assurance and process monitoring	Progress made	High	2024
5.2	Reduction/prevention of contamination	New	High	2024
5.3	Improved cycle time through more productive handling systems	Progress made	High	2025
5.4	Quality-assured separation of new/innovative electrode materials	New	High	2026

RBW 5.1: Quality and reliable monitoring
The cutting processes for electrodes as well as separators are essential in battery production. However, the currently used cutting techniques cause residues, that vary in size and result in short circuits in the cell if their size exceeds a defined level. This should be prevented by adequate process parameters, exhaust and filtering techniques, and fine-tuned quality control methods. Currently, quality optimization can already be achieved by filtering techniques and predictive maintenance of the tools. These techniques must be further developed and supplemented by additional processes and appropriate quality measurements.

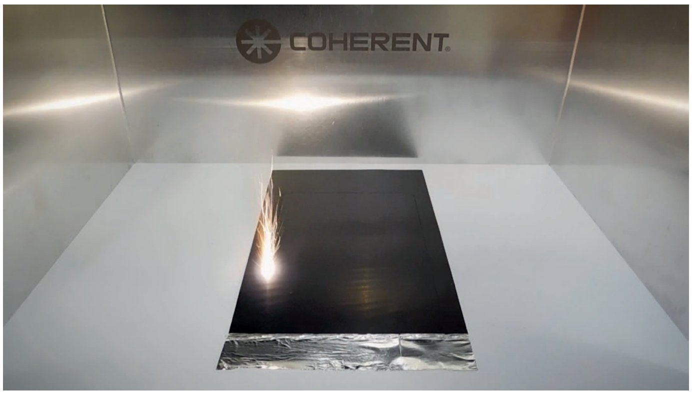


*RBW priority decreases from top to bottom.

**Relevance from the point of view of a battery manufacturer

***Timeline indicates when breakthrough should occur (The timeline considered is until 2035).

Sources: VDMA, PEM of RWTH Aachen, BLB of TU Braunschweig according to Phaal2003b



Laser cutting of coated and uncoated electrode material
Source: Coherent

Separation

Basics
In the cutting process, individual anode, cathode and separator sheets are separated from the electrode/separator coils. Two processes have been established for this purpose: punching using a shear blade and thermal cutting using laser radiation.

The advantage of punching processes is that very clean cut edges can be achieved. This makes it possible to meet the highest quality requirements. However, a disadvantage of this process is that the cutting tool comes into direct contact with the electrodes. This causes wear on the dies, which requires maintenance and reconditioning. The wear of the dies also negatively influences the cutting result, since the quality of the cutting edges decreases continuously. Mechanical deformation of the cutting edges and, in the worst case, detachment of the coating from the current collector can occur due to wear of the punching tool.

Laser cutting is a contactless and thus wear-free process, which results in constant and reproducible cutting edge quality. The high flexibility of laser guidance also essentially allows the cutting process to be adapted to changing production conditions, where plant-specific boundary conditions must be considered. However, one disadvantage of separation by laser cutting is that it is a thermal separation process, which results in a heat-affected zone (HAZ) along the cutting edge. In addition, the local heating and the different rates of evaporation of the coating and the carrier film can cause burr formation at the cutting edge, especially with high coating thicknesses. Higher coating thicknesses also require a higher energy input during cutting. This results in increased evaporation at the cutting edge, which then leads to a higher degree of contamination [Schmitz 2014].

Cutting speeds with punching are up to 0.1 s/sheet. With laser cutting, speeds between 1 and 4 m/s can be achieved, depending on the electrode thickness. This translates to cutting speeds of up to 0.06 s/sheet. Regardless of the cutting process, the gripping and handling process of the electrodes and separator sheets is always the time-limiting factor during separation, which prevents higher cycle times [Luetke2011], [Korthauer2013].

Challenges
Generally speaking, both cutting processes can produce high-quality cut edges. However, there are challenges with both cutting processes that need to be addressed.

The cutting processes place high demands on quality assurance and process monitoring (RBW 5.1). This is due to the fact that the cutting processes are highly dynamic, regardless of the cutting method used. Therefore, suitable monitoring systems are required that are capable of assessing the quality of the cutting result based on the recorded data. This leads to high demands on both data acquisition and on data processing and evaluation. Evaluation of the cutting edges is of critical importance. Incorrect cutting parameters during laser cutting or wear of the die during punching can lead to imperfect cutting edges. Examples of defects which may occur include detachment of the coating from the current collector during punching or the formation of a pronounced heat-affected zone (HAZ) with undefined properties of the active material as well as melt residues on the current collector during laser cutting.

Established methods for offline evaluation of cutting edge quality, such as evaluating micrographs or performing measurements using a laser scanning microscope, cannot be integrated into cutting systems. Therefore, suitable methods must be developed and implemented for ensuring quality in the cutting process.

Quality-critical impurities can occur with both cutting processes. For example, contamination can result from the sublimation of removed material during laser cutting and from burr formation and flaking of the coating during punching. This results in loose particles on the coating of the electrode. In lithium-ion cells, these impurities can lead to local compaction of the separator, which can result in increased mechanical and thermal stress. This increases the risk for lithium plating in the cell, which in critical cases can lead to damage of the separator and short-circuits in the cell. Therefore, avoiding contaminations in the cutting process for conventional electrodes is a fundamental challenge (RBW 5.2).

Fast handling of the material with increasingly large battery/electrode formats (e.g., blade format with electrodes up to 1.2 m long, or round cell 4680) is another challenge (RBW 5.3). Due to the high cutting speeds that can be achieved, the cutting process is not the limiting step, but rather the handling or the feeding and removal of the electrode material. Achieving high-speed handling is particularly challenging due to the changed intermediate product state from continuous to discontinuous as well as the sensitivity of the products.

Cutting processes must be adapted to new and innovative types of electrodes and separators (RBW 5.4). This applies to the processing of thick high-performance electrodes as well as cutting processes for new materials. An example of this is the current research work on lithium-containing anodes[21], which are not suitable for mechanical separation and must therefore be processed using contactless technologies. Furthermore, a metal-coated foil with a plastic core is being tested[22] for lighter and thinner current collectors, which requires an adaptation of the cutting process due to the different properties between the coating, the copper/aluminum layer, and the plastic core [Gruhn2023]. These adaptations do only apply to the cutting process itself, but also to the system periphery. For example, the separation of thin films requires adapted exhaust strategies.

Possible solutions

A wide variety of measures are being pursued to meet the challenges resulting from the cutting processes. For example, monitoring systems to determine the cutting edge quality as well as the surfaces of the sheets (e.g., thermographic methods) are being investigated in order to enable reliable detection of inhomogeneities. This requires contactless or optical systems with high resolutions that can, for example, identify critical contaminations on the surface or detect the shape of the cutting edges. The challenge here is the high process speeds which prevents an industrial implementation. New inline surface inspection methods from related industries offer the potential for process optimization. These techniques are being adapted to battery production and further

[21] PräLi: „Prälithiierung von Elektroden“ (Prelithiation of electrodes) (Förderkennzeichen 03XP0238B, 2022); ProLiMA – „Prozessierung von Lithium-Metall-Anoden – Konfektionierung, Handhabung und Kontaktierung“ (Processing of lithium metal anodes - fabrication, handling, and contacting)(Förderkennzeichen 03XP0182F, 2023)

[22] PolySafe: „Forschungsprojekt zu Metall-Polymer-Stromkollektoren zur Steigerung der Sicherheit von Lithium-Ionen-Batterien“ (Research project on metal-polymer current collectors to increase the safety of lithium-ion batteries) (Förderkennzeichen 03XP0408)

developed in research projects using technology transfers.

With the punching process, predictive maintenance[23] is also used to detect wear on the cutting tool at an early stage and prevent contamination by foreign particles. Thus, countermeasures can be initiated at an early stage to prevent poor-quality cutting edges. A positive side effect is the resulting longer service life of the tools.

In the cutting process, the exhaustion of contaminants (gases, micro- and nanoparticles) is a measure to minimize quality-critical contaminations. In particular, optimized exhaust techniques are necessary with laser cutting to avoid the sublimation of particles on the cutting edge and cutting residues on the electrode. It is also necessary to filter the exhausted air, as the extracted particles can be hazardous to health. This requires exhaustion and filtering technology that meets the requirements of the cutting process, since the particle sizes depend to a large extent on the laser source and the cutting conditions [extraction and filtering case study].

Another approach is to find alternative laser sources with higher brilliance and greater average laser power that have a high Rayleigh length to reduce particle generation (single mode fiber lasers).

If contamination cannot be avoided and adequate exhaustion cannot be guaranteed, cleaning the electrode sheets after separation is an alternative solution. The challenge here is to ensure that the properties of the cell components do not change. The increased expense must also be acceptable for the cell manufacturers. One solution is CO_2 snow jet cleaning, in which carbon dioxide is used to remove impurities in a dry process without leaving any residues. Advantages are good automation capabilities and the option of continuous process control. However, its use depends on the temperature and material compatibility of the carbon dioxide with the coated carrier film [CO2 snow jet cleaning case study].

In general, it is important to research and validate tolerance ranges and cause-effect relationships to avoid quality-relevant contaminations. For example, it has been shown that it is possible to reduce the size of the contaminations to such an extent that no damage to the separator occurs simply by adjusting the cutting parameters [Jansen2022].

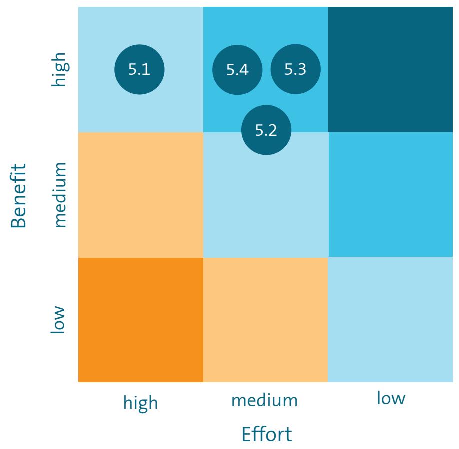
New cutting strategies are also required for laser cutting in order to improve cycle times. Laser cutting on the fly in a continuous manufacturing process offers the highest potential for improving cycle times. Continuous processing is particularly advantageous because it avoids transient stresses on the electrode material, thus eliminating film cracks or damage due to high start up and shut-down speeds. An alternative approach is to use a high-powered laser and beam-shaping elements to implement a laser punch, which is currently being researched in the HoLiB research project.

Effort and benefit assessment

Since the cutting process has a significant impact on the subsequent cell performance, the overall benefit of optimized cutting processes is considered to be high. Lower contamination levels from improved cutting processes and improved cutting edge quality from process-integrated quality assurance measures result in a longer service life of the lithium-ion cells, which contributes to sustainability.

[23] Predictive maintenance based on historical data or quality parameters available in real time

Effort-benefit diagram and impact on sustainability, quality, and costs



	5.1	5.2	5.3	5.4
Sustainability	↗	↗	→	↑
Quality	→	→	↗	↑
Cost savings	↑	↗	↑	→

Contribution: ↑ = Significant ↗ = Moderate → = None

5.1 Inline quality assurance and process monitoring

5.2 Reduction/avoidance of contamination

5.3 Improved cycle time through more productive handling systems

5.4 Quality-assured separation of new/innovative electrode materials

The introduction of reliable methods for inline quality assurance and process monitoring offers the potential to significantly increase the quality of the cutting result and the quality of the cutting edge in particular. This reduces scrap and increases sustainability. However, it should be noted that the effort required to implement process monitoring and assurance is significant. This partially negates the cost benefits from increased production quality (RBW 5.1).

The avoidance or reduction of contamination also offers the potential to increase the quality of the separated sheets (RBW 5.2). The use of suitable exhaust and filter technologies can extend the service life of battery cells and increase sustainability. However, this is accompanied by high costs for the exhaust and filter technologies. Thus, the contribution to cost savings is limited.

Considering the steadily increasing cell output and the high number of planned production lines, improved cycle times from more productive handling and cutting systems offer a high cost benefit in *gigafactories*. The effort required to implement these processes and the necessary development work is in the medium range, while the benefits can be rated as high (RBW 5.3).

A quality-assured separation of innovative electrodes with new, sometimes thick coatings or innovative polymer-based current collectors is challenging. Considered as a whole, these materials have a medium to high benefit. Innovative materials and cell structures can extend service life and increase sustainability. Polymer-based current collectors also provide a valuable additional function, in that they can prevent thermal runaway. Cost savings from the reduction of possible cell failures or novel current collectors are classified as low. Since existing cutting processes can be adapted, the effort required for implementation is considered moderate (RBW 5.4).

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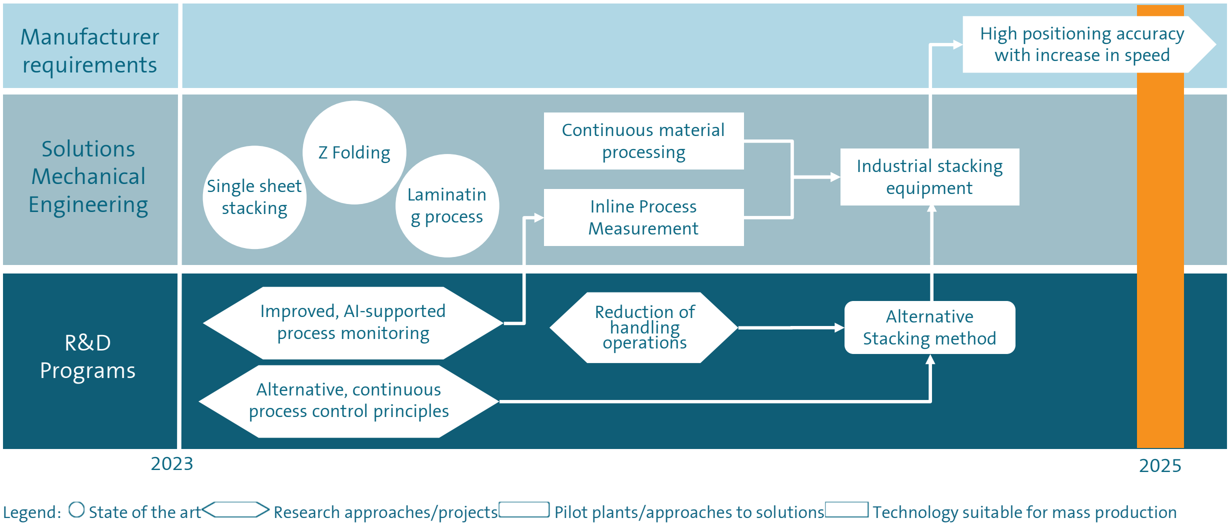
6: Stacking and winding

No.*	Red Brick Wall	Current status in comparison to 2020	Relevance**	Timeline***
6.1	High positioning accuracy with simultaneous increase in speed	Progress made	High	2024 - 2025
6.2	Handling of thin and delicate materials	Progress made	High	2024 - 2026
6.3	Avoidance of particle contamination and implementation of high cleanliness requirements	New	Medium	2024 - 2026
6.4	Processing capability of new materials for solid-state batteries	New	Low	2026 - 2028
6.5	Reduce plant space requirements	New	Low	2025 - 2026

RBW 6.1: High positioning accuracy with simultaneous increase in speed to less than 0.2 s/electrode composite.
The stacking process is significantly slower than the winding process and is one of the bottlenecks in cell assembly. Advantages compared to winding are the material-specific fabrication of electrode-separator composites and better space utilization of the electrode stack. Speed can be increased by combining several technologies or reducing pick-and-place operations. However, this must not be at the expense of positioning accuracy, cleanliness, or careful material handling.



*RBW priority decreases from top to bottom.

**Relevance from the point of view of a battery manufacturer

***Timeline indicates when breakthrough should occur (The timeline considered is until 2035).

Source: VDMA, PEM of RWTH Aachen, BLB of TU Braunschweig

Stacking and winding

Basics

Different assembly processes are used to manufacture lithium-ion battery cells, depending on the cell format. Pouch cells are generally produced with a stacking process, while cylindrical and prismatic cells are produced with a winding process. Increasingly, prismatic cells are also stacked to increase space utilization in the cell housing and improve electrolyte wetting. The material of the electrodes is also less stressed during stacking, as the tight bending radii that occur in the core of a flat wind are eliminated.

Industrial stacking typically uses Z-folding or, less frequently, as cut sheet folding. With Z-folding, the separator is unwound from a coil and the separated electrodes are inserted alternately between the separator (e.g., using vacuum grippers). In cut sheet stacking, the separator, anode, and cathode are placed on top of each other in alternating order. Z-folding is much faster than the cut sheet process. The process can be accelerated even further by laminating or gluing the cut sheet electrodes onto the separator before stacking, [Kwade2018b, Müller 2021].

In the winding process, the separator and electrode strips (anode and cathode) are wound onto a core, producing a so-called “jelly roll.” For round cells, this results in a round winding; for prismatic cells, it results in a flat winding. It is expected that stacking will be more suitable than winding for future cell generations, such as lithium metal or *all solid state* batteries. Another advantage over winding is better heat control or dissipation when the cell is in operation, which goes hand-in-hand with increased safety and longevity.

With stacking, the achievable cycle times are greatly dependent on the electrode size and the production technology used. In Z-folding, cycle times of 0.4 to 0.8 s/electrode composite (anode + separator + cathode) can now be achieved. In winding, speeds of 0.1 s/revolution are possible thanks to continuous process control. A cell can thus be wound in a few seconds, whereas the stacking process with several dozen layers is at least an order of magnitude slower [Heimes2023a]. The stacking process must measure up to this significantly higher winding process speed and compensate for this disadvantage by better utilization of the available volume and higher cell quality.

With Z-folding, the above-mentioned speeds can be achieved with a stacking accuracy of less than +/- 0.2 mm. This is made possible by the use of image recognition systems for the positioning of the electrode and separator sheets and an evolutionary improvement of the handling technologies.

Challenges

Stacking continues to be one of the most time-critical production processes on the cell production line, and therefore represents a bottleneck. High demands on positioning accuracy and cleanliness must be met despite the required increase in throughput. The quality of the stacking and winding process significantly influences the subsequent cell performance [Thielmann2017]. For example, offsetting of the electrode sheets can lead to a loss of capacity, as not all of the active material area can be used. Maintaining high positioning accuracy and cleanliness while increasing speed is therefore considered the most important challenge for this manufacturing step (RBW 6.1 and 6.3).

There is a trend towards larger cell formats, both in order to obtain cells with higher energy density and to increase throughput. This trend poses challenges for film handling. In addition, both the size and the use of very thin and thus sensitive conductive films complicate the process due to the careful handling required (RBW 6.2) [Kampker2014].

Innovative assembly technologies are currently being researched for new materials to be used in solid-state batteries (e.g., the OptiKeraLyt research project). It appears that stacking processes will be preferable to winding processes due to the solid materials. However, challenges do exist, such as gripping of new materials (RBW 6.4).

Finally, the high space requirements of current stacking or winding lines also pose a challenge (RBW 6.5). Beyond the stacking process, inline measurement technology (e.g., X-ray analysis) may require additional space. A high plant footprint leads to a larger dry room, which results in high costs due to energy consumption.

Possible solutions

Stacking optimization is focused on increasing the process speed by implementing a continuous process sequence, developing new gripper technologies, and implementing faster image scanning technology for position control [Schröder 2016]. Therefore, nearly contact-free grippers with ultrasonic guidance or air-guided systems are gaining relevance, but are not yet ready for series production.

Another approach to increasing process continuity is the use of robust electrode-separator composite intermediates. For example, the electrode sheets can be laminated or glued to the separator. This intermediate step reduces the required number of stacking operations per lithium-ion battery cell and counteracts the wrinkling and buckling of the electrodes and separators. This process promises improved handling in the stacking process and even more precise positioning, especially with increasingly large cell formats. More sensitive materials may also require stable semi-finished products in manufacturing. This approach could contribute to overcoming RBW 6.2.

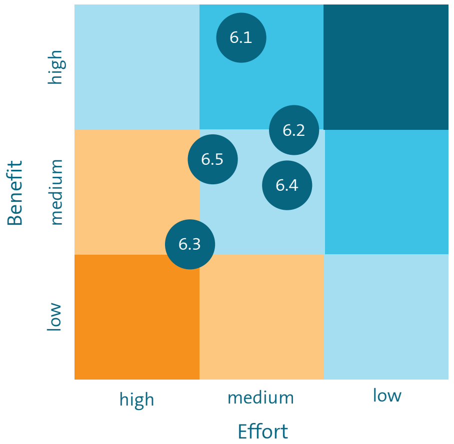
Several new stacking technologies are being tested in various research facilities throughout Germany and prepared for subsequent industrial application [Weinmann2020, Baumeister2014, Pelisson-Schecker2017, Fleischer2017], some of which have already been patented. For example, the differences compared to Z-folding include material guidance in different planes, offset material guidance systems ("Helix process, KIT - [IPR2015]), combination with conveyor belts, or more efficient folding mechanisms (KontiBAT research project). One example of this is a stacking process using a rotating stacking wheel, which is intended to replace the classic pick-and-place process (e.g., HoLiB research project) [Müller 2021]. Together with existing inline process measurement technology and knowledge of continuous material processing, these methods can help to reduce unproductive downtime and further accelerate the stacking process.

Defining reasonable tolerances for the stacking and winding process based on knowledge of process interdependencies and using AI-supported monitoring can also help to make a sensible trade-off between accuracy and process speed. This should help to reduce the process time for stacking to 0.2 s/electrode composite in the future.

Effort and benefit assessment

Since stacking or winding of the electrode-separator composites is one of the bottlenecks in cell production, the benefit of reducing the process time and handling larger and more sensitive materials is considered high. In recent years, work has been performed in various

Effort-benefit diagram and impact on sustainability, quality, and costs



	6.1	6.2	6.3	6.4	6.5
Sustainability	↗	→	→	↗	↑
Quality	↗	↗	↑	↗	→
Cost savings	↑	↗	→	↗	↑

Contribution: ↑ = Significant ↗ = Moderate → = None

6.1 Increase speed
6.2 Handling of sensitive materials
6.3 High cleanliness requirements
6.4 Processing of new materials for solid-state batteries
6.5 Reduce plant space requirements

research projects to improve existing processes and develop new ones, so that the breakthrough of RBW 6.1 and 6.2 is realistic in the next two to three years. Experts estimate the effort required as medium to high.

Current handling methods are reaching their limits, so alternatives must be developed and made suitable for mass production [Thielmann2017, Michaelis2018]. The use of stable intermediates must stand up to conventional production processes, especially in terms of economic efficiency. This could be an alternative in the future, especially for sensitive materials. The use of more sensitive materials requires more sophisticated film handling. The effort to achieve the targeted speeds and position accuracies is rated as medium to high.

In summary, the benefits of addressing the aforementioned challenges can be considered very high, as increasing the speed can reduce the plant investment and footprint, and consequently reduce the manufacturing cost of the batteries.

Technical support

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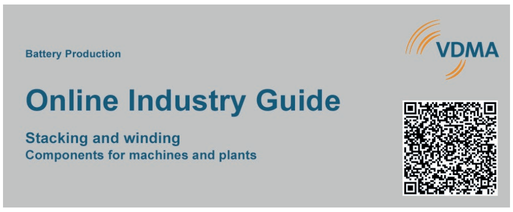
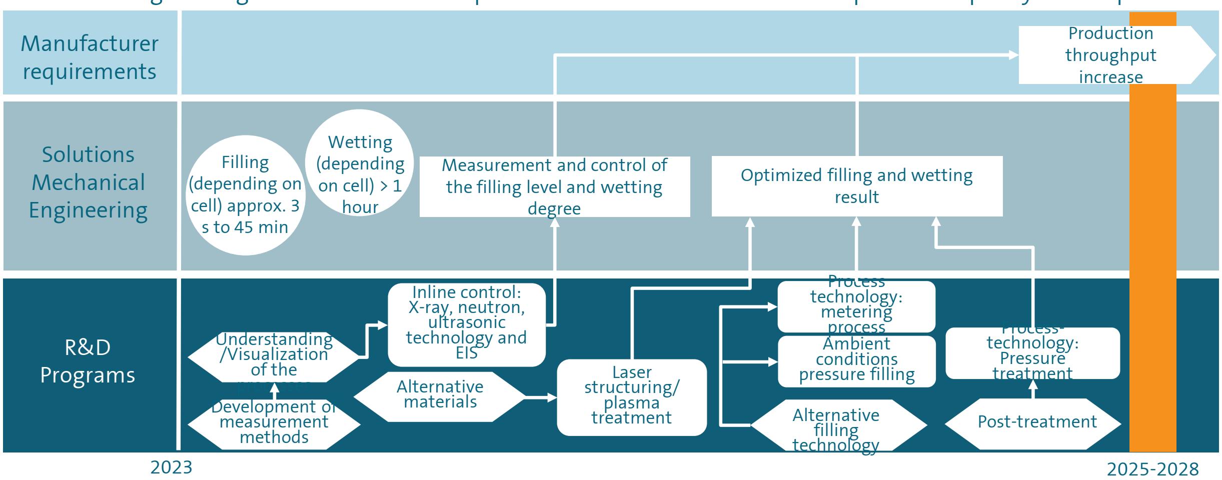


7: Electrolyte filling and wetting

No.*	Red Brick Wall	Current status in comparison to 2020	Relevance**	Timeline***
7.1	Reduced process time and homogeneous wetting of the cell stack	Progress made	High	2025 - 2028
7.2	High-precision filling (volume, pressure or vacuum)	Progress made	High	2024 - 2025
7.3	Reliable monitoring of filling and wetting process in volume production (e.g., temperature, pressure, etc.)	Progress made	High	2025
7.4	Format-dependent filling strategies or system concepts (electrolyte, process parameters & prediction, dead volumes and porosities, etc.)	New	Medium	2025
7.5	Electrolyte handling & processing in dry and clean rooms	New	Medium	2024 - 2025

RBW 7: Reduced process time and homogeneous wetting of the cell stack
The overarching goal in the "electrolyte filling and wetting" process is to use reliable process monitoring to shorten the process time while also ensuring sufficient wetting, irrespective of the cell design. Close cooperation between mechanical engineering and materials-development and -research is needed to improve this quality-critical process.



Legend: ○ State of the art ⬡ Research approaches/projects ▭ Pilot plants/approaches to solutions ▭ Technology suitable for mass production

*RBW priority decreases from top to bottom.

**Relevance from the point of view of a battery manufacturer

***Timeline indicates when breakthrough should occur (The timeline considered is until 2035).

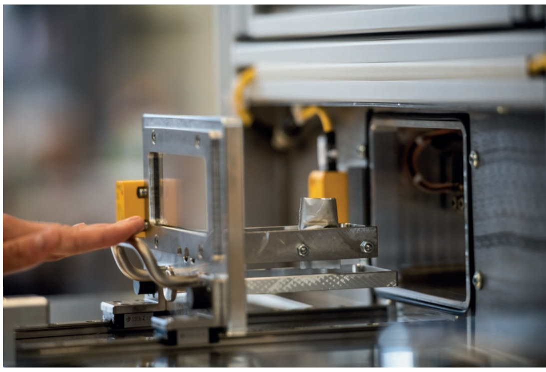
Source: VDMA, PEM of RWTH Aachen, BLB of TU Braunschweig

Electrolyte filling and wetting

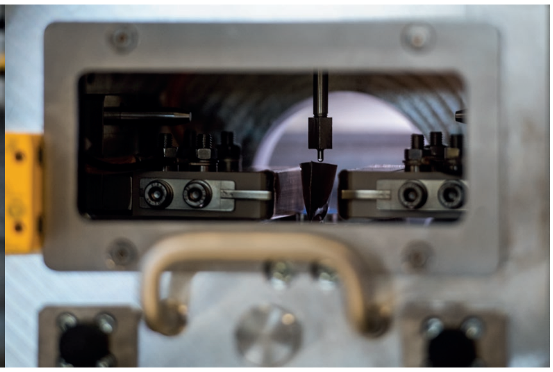
Basics
This process step is divided into two subprocesses: filling and wetting of the cell. Filling describes the process of filling the electrolyte into the cell. Wetting describes the process of penetrating the electrolyte into the pores of the electrode and separator to establish ionic contact. Just the filling process can take from a few seconds (pouch) to several minutes (large cylindrical and prismatic cells), depending on the format. Regardless of format, wetting is an extremely time- and quality-critical production process in cell assembly, which can take up to 24 hours. Due to their porosity, the electrodes have a large area that must be completely wetted by the electrolyte fluid. Areas that are not wetted cannot exchange charges and are therefore inactive. These areas not only affect the performance of the cell, but also pose a safety risk. Non-wetted areas cause local current differences in the cell, which can lead to dendrite growth. If large enough, these dendrites can penetrate the separator and cause a short circuit and subsequent thermal runaway.

Negative pressure filling is currently the most common method. This involves creating a vacuum in the lithium-ion cell so that the electrolyte can be filled into the cell quickly and efficiently. By evacuating the cell, almost no air molecules are left. The standard electrolyte with $LiPF_6$ is highly flammable and forms hydrofluoric acid on contact with water. This attacks the cell components and also greatly reduces their service life [Korthauer 2013]. For this reason, it is necessary to ensure that almost no residual moisture is contained in the cell by vacuum drying and the drying chamber.

Research has shown that the wetting time can be halved in a vacuum-pressurized cell, and that the amount of electrolyte has a decisive influence on performance [Günter2019]. A vacuum less than the electrolyte vapor pressure is usually selected during initial filling. A higher vacuum pressure level is then selected for subsequent filling steps so that the filled electrolyte does not evaporate. Temperature also influences the wetting time. If the temperature is doubled from 20 to 40 °C, the wetting time can be reduced by a third [Günter2021].



Electrolyte Jet: Semiautomatic electrolyte filling machine for pouch cells with vacuum chamber
Source: Industrie-Partner IP PowerSystems GmbH



Electrolyte Jet: Precise and fast electrolyte filling system for Li-ion pouch cells
Source: Industrie-Partner IP PowerSystems GmbH

As the fill level increases, the pressure is equalized to prevent foam formation. The process is also repeatedly interrupted to allow the foam to break down. The wetting process begins at the same time. The capillary forces cause microscopic wetting of the pores in the active materials and separators. Filling and pressure equalization can be repeated until the lithium-ion cell is sufficiently wetted. It has been shown that the wetting time can be significantly reduced by post-treatment of the filled and sealed pouch cell with mechanical pressure (press rolling) or pressure cycling (other cell formats). This has allowed the wetting time of a battery cell to be reduced by 50% in recent years.

Challenges

Electrolyte filling is still a bottleneck within cell assembly. Despite significant improvements in recent years, the filling process can take over an hour, depending on the cell type. The formation of foam and the long wetting time are largely responsible for the long process times. Therefore, increasing the speed through process and material adaptations remains a core challenge, especially for large-format battery cells (RBW 7.1).

Electrolyte filling and wetting are also influenced by the electrolytes, separators, and active materials used, as well as the contact angle. Insufficient knowledge of the relationships between process parameters and the quality of filling leads to less than optimal filling. The factors influencing the wetting process have also been poorly researched to date. Insufficient quantities lead to non-wetted areas, excessive quantities to a longer process time and higher internal resistances, as well as lower gravimetric energy densities due to increased cell weight (RBW 7.2). Therefore, another challenge is to increase process accuracy via configurable parameters (volume, positive/negative pressure) in order to be able to adapt the process specifically to the various cell formats and sizes (RBW 7.4)..

There is also a lack of reliable inline monitoring technologies for controlling and optimizing electrolyte filling and wetting in the production process (RBW 7.3). The handling and processing of the electrolyte in clean and dry rooms also poses a challenge (RBW 7.5). The clean and dry room conditions affect the system as well as the handling. Components must be used whose density and material are resistant to the ambient conditions.

Possible solutions

There are several approaches for optimization of this process. The most important factors for increasing the speed are avoiding foam formation, faster wetting, and the selection of optimum filling parameters. Understanding the influence of electrolyte properties as well as the interaction between active material, separator, and electrolyte on the filling and wetting process is essential for a faster process. The coefficient of penetration (COP), the solid state permeability (SPC), as well as the electrolyte salt concentration are all important influencing factors. The filling and ambient pressures are also critical parameters for the quality of the filling process. For wetting, the volume and the post-treatment with pressure in particular influence the quality of the cell [Davoodabadi2019].

It is also conceivable to reduce the process time by using alternative process controls. Possibilities include setting different pressure gradients and filling pressures as well as implementing filling in multiple steps, including interruption, to stimulate wetting. Filling at multiple points of the lithium-ion cell oriented to the fill level is also possible, especially for pouch cells. Implementation in hardcase cells is considerably more difficult. Another way to accelerate wetting is to use higher temperatures of up to 50°C.

The development of alternative separator materials and surface structures is equally promising. The use of laser structuring in electrode production and its influence on the filling and wetting results in particular has been investigated in recent years. In laser structuring, the trade-off between higher pore volume for faster wetting of the cell and performance degradation due to excessive removal of active material must be considered. These changes have a significant influence on foam formation and wetting time.

Above all, new separators, electrodes, and electrolytes must meet the increasing demands on the safety of the cell or the technical requirements for the realization of high-voltage 5v cells. A promising approach to improving separator materials is to pre-treat the separator with a plasma. By modifying the separator surface (increasing the hydrophilicity), the degree of wetting and adhesion (i.e., the adhesion between the electrode and the separator) is improved, which increases the ionic conductivity of the separator. Pre-treating the electrodes with plasma is also conceivable. Here, too, a more hydrophilic surface could contribute to a better and faster degree of wetting. The use of additives in the electrolyte can reduce foam formation and/or improve wetting.

In addition to process and material adaptation, the development and integration of new measurement methods is necessary to enable industrialized, detailed process monitoring. This analysis contributes to a better understanding of the processes and interactions, and is necessary to optimize the throughput of cell production and the quality of the lithium-ion cell. A distinction is made between macroscopic and microscopic wetting control. In macroscopic wetting control, it is important to develop methods that measure the fill level and the macroscopic degree of wetting during the process. Ultrasound imaging methods for visualizing the wetting process are used in research for this purpose [Deng 2021]. This method offers the advantage of being able to analyze the cell non-destructively. In microscopic inline controls, checking the penetration of the electrolyte into the pores of the active material is crucial.

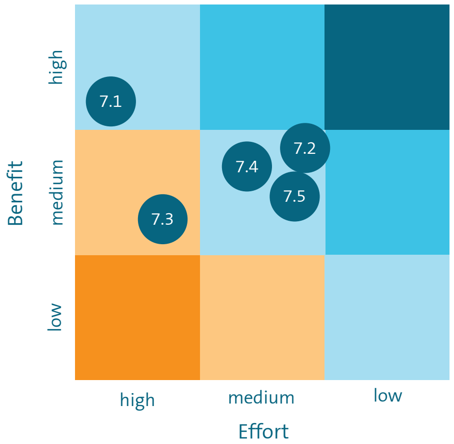
Changes in electrochemical impedance spectroscopy (EIS) show great potential for inspecting the microscopic wetting degree, especially for large format cells [Günther2019]. Other important process parameters for monitoring include the cell temperature, internal cell pressure, pressure gradients, filling pressure, mass flow rate, and lithium-ion cell weight and density. This potential solution will contribute to the breakthrough of RBW 7.3, and will also lead to the breakthrough of RBW 7.2 via knowledge gained regarding parameter-quality relationships [Knoche2016, Weydanz2018]. The increased use of intelligently networked production can contribute to evaluating the collected data and adjusting the production parameters accordingly.

Effort and benefit assessment

The benefits of all RBWs in the area of electrolyte filling and wetting are rated as medium to high. In particular, costs can be greatly reduced by reducing process times, especially for wetting. At the same time, more homogeneous wetting also leads to an increase in quality. Experts rate the effort required to achieve this as medium to high, as improvements have already been made in this area through material adaptations. Sustainability is only moderately improved by achieving this RBW.

The improvement in filling accuracy in RBW 7.2 has a significant effect on performance, and thus on the quality of the battery cell. Defined filling quantities also allow the process time to be reduced and electrolyte to be used in a more targeted manner. This is beneficial for costs. This RBW only has a minor effect on sustainability. The effort required to achieve RBW 7.2 is estimated to be medium to low, since the

Effort-benefit diagram and impact on sustainability, quality, and costs



	7.1	7.2	7.3	7.4	7.5
Sustainability	→	↗	↗	↗	↗
Quality	↗	↑	↑	↗	↗
Cost savings	↑	↗	↗	↗	↗

Contribution: ↑ = Significant ↗ = Moderate → = None

7.1 Reduced process time & homogeneous wetting 7.2 High-precision filling 7.3 Reliable monitoring 7.4 Format-dependent filling strategies 7.5 Electrolyte handling & processing in dry and clean rooms

findings from research projects can be transferred relatively easily into industrial practice (e.g., with regard to adjusting the filling quantity, filling angle, and wetting time).

The development of an inline quality control system for achieving RBW 7.3 also shows a high benefit, although integration and the high investment costs pose challenges. By better understanding the filling process, it can be better controlled and adapted to different formats and sizes. This has a significant effect on the quality of the cell.

Electrolyte scrap can be reduced through better understanding of the filling and wetting process. This has a positive impact on costs and sustainability. However, this is offset by increased effort, as it is difficult to integrate inline measurement methods, such as ultrasonic imaging or EIS, to detect the level and degree of wetting in a closed cell. Previous approaches cannot be easily integrated into a production line.

Technical support

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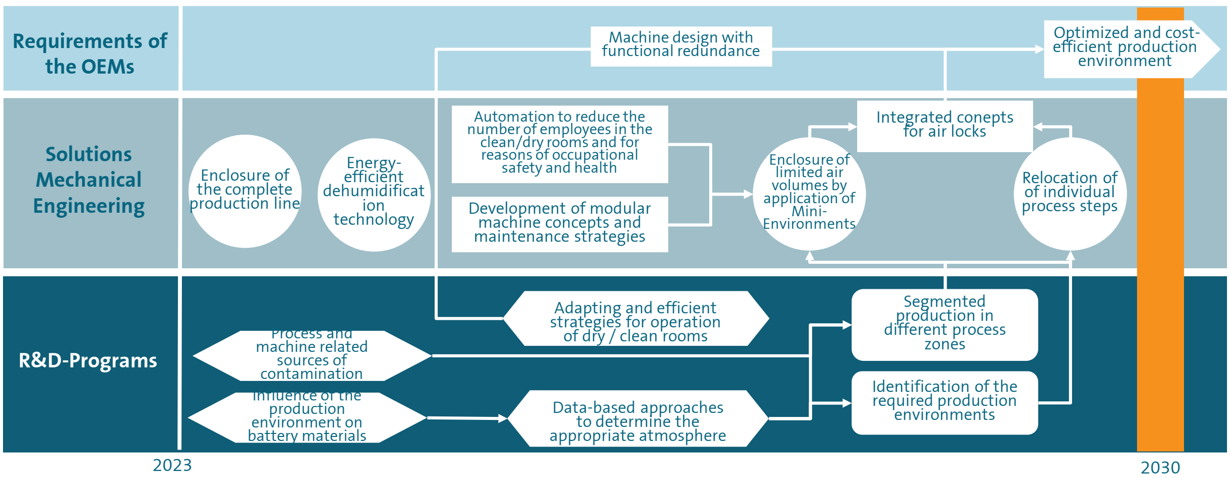
8: Clean and dry rooms

No.*	Red Brick Wall	Current status in comparison to 2020	Relevance**	Timeline***
8.1	Demand-oriented and economical clean and dry room design	Progress made	High	2028
8.2	Improved clean and dry room energy efficiency	Progress made	High	2025

RBW 8.1: Demand-oriented and economical design of the clean and dry room
Against the background of the continuous development of battery technology and the materials used, the provision of a suitable clean and dry environment continues to be a technical and economic challenge in battery production. The design of clean and dry rooms for current and future battery materials is becoming a critical factor for long-term competitiveness.



Legend: ◯ State of the art ⟨ ⟩ Research approaches/projects ▭ Pilot plants/approaches to solutions ▭ Technology suitable for mass production

*RBW priority decreases from top to bottom.

**Relevance from the point of view of a battery manufacturer

***Timeline indicates when breakthrough should occur (The timeline considered is until 2035).

Source: VDMA, PEM of RWTH Aachen, BLB of TU Braunschweig according to Phaal2003b

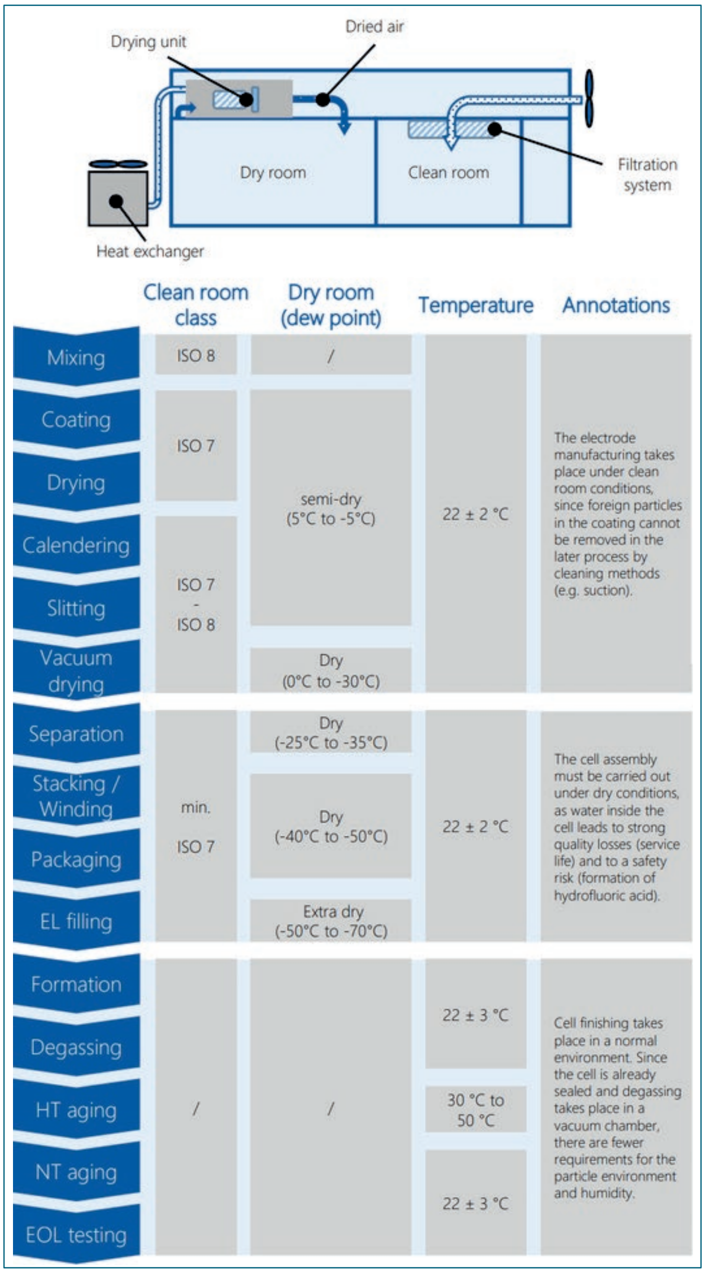
Clean and dry rooms

Basics

The production environment along the entire process chain plays a crucial role in the production of lithium-ion batteries. Contamination by foreign particles or excessive humidity during the production process can significantly impair the quality and safety of the battery cell, and must therefore be strictly controlled and avoided to the greatest possible extent. Less stringent requirements for the production environment can only be permitted after the battery cell has been sealed at the end of the assembly process.

The production environment requirements differ for each process step (see Fig. 1) and must be considered in the early planning phase of production. A large part of the process currently takes place in monitored clean and dry rooms in order to comply with the required environmental conditions.

Planning, construction, and operation of clean and dry rooms are increasingly becoming the focus of battery cell production for several reasons. These include the high investment costs for the premises (room enclosure, floors, airlocks, etc.) and the ventilation or dehumidification technology, as well as the high running costs and CO_2 emissions during the operation of the infrastructure. The operation of clean and dry rooms is one of the largest items in the analysis of production-related energy consumption, along with the drying processes in electrode production. Scientific studies show consumption in the range of 20 - 80 Wh/Wh [Jinasena2021, Degen2022, Nelson2019, Yuan2021, Pettinger2017].



Dryness and purity requirements along the production chain, according to [Heimes2023]

Challenges

Within the dry air atmosphere, moisture is removed from the ambient air in order to prevent possible reactions of the moisture-sensitive cell materials (cathode, electrolyte) with water. The ambient conditions in the clean and dry rooms are often determined by the prevailing dew point[24]. While electrode production is generally less strict with regard to the dew point, significantly lower dew points are required in the subsequent assembly process. The dew points set here depend on the cell chemistry, especially the active materials used. The most stringent requirements are found in electrolyte filling, with dew points in the range -60°C to -70°C. The reason for this is the highly reactive liquid electrolyte, which reacts to toxic hydrofluoric acid (HF) even in contact with small amounts of humidity. With the separation of atmospheres, a less dry production environment with controlled temperature and cleanliness is only permissible and adequate after the cell is sealed following electrolyte filling.

In addition to the dry room environment, the production of lithium-ion batteries is subject to cleanliness requirements in order to minimize the risk of contamination with foreign particles and to avoid cross-contamination between individual process steps. Clean rooms of ISO classes 7-8 are usually required.[25] Meeting the strict requirements for dryness and cleanliness at the same time is a particular challenge in battery cell production. For this reason, the design of a reliably functioning infrastructure requires consideration of a large number of potential sources of contamination (personnel, machines, material, etc.) and process-specific features (process emissions, different dew point and positive or negative pressure atmosphere requirements). There are currently no uniform guidelines on requirements for the design of machines in clean and dry rooms for Li-ion battery cell production. Therefore, strict criteria are often applied for the selection of materials for the machine components used.

For both dry and clean room environments, even small deviations from the required values can have a negative impact on the service life, and thus the quality of the cell [Heimes2018]. For this reason, the relationship between material properties and the resulting requirements for the clean and dry rooms is an integral part of current research. Laboratory studies suggest that even stricter requirements for the production environment are to be expected, particularly with the move towards cathode materials containing nickel (e.g., NMC 9-.5-.5) or new battery technologies (e.g., solid-state battery) [Busà2021, Yersak-2022]. Material properties that are only partially known and not completely researched represent a key challenge for the design and retrofitting of existing clean and dry rooms for future cell generations. These uncertainties are reflected in particularly conservative design and over-dimensioning of the supply technology, which in turn is associated with high investment and operating costs. The complexity of the plant technology and the operating costs are not linear, but rather increase sharply with stricter requirements. For this reason, reducing the requirements to a minimum level is also of great economic interest (RBW 8.1).

Due to the continuous maintenance and conditioning of the dry and clean room atmosphere during production, a large amount of the energy required for cell production is used to operate this infrastructure. Innovations aimed at saving energy and increasing energy

[24] The dew point refers to the temperature at which condensation of the air humidity begins and the humidity is 100% (fully saturated air). A dew point of -50°C at a temperature of 20°C corresponds to a relative humidity of < 1%.

[25] For clean room class 7, a maximum of 83,200 particles ≥ 1 µm and 2,930 particles > 5 µm per m³ of air are permissible. 10 times as much of each is permitted for clean room class 8.

efficiency can make a significant contribution to reducing operating costs and emissions. Ensuring at least consistent product quality is crucial (RBW 8.2).

In order not to endanger the health of the production employees and to minimize disturbance variables for the operation of the clean and dry rooms, the topics of personnel and material logistics must also be specifically addressed. The focus is on reducing avoidable moisture ingress and limiting the maximum exposure time of personnel to the clean and dry room atmosphere. The latter requires particular attention, as drying out of the mucous membranes and respiratory tract would otherwise be detrimental to the health of the employees. Long-term exposure to particularly dry atmospheres can also lead to chronic diseases such as "dry eye syndrome" [Cho-2014]. Similarly, process emissions, such as those from laser-based machining and airborne particles or dust, can also pose a safety and health risk.

Possible solutions

The aforementioned challenges can be addressed by development and strengthening of the understanding of the relationships between material requirements and the operating and design parameters of the clean/dry rooms. The evaluation of the material-related cleanliness and dryness requirements is a challenge that will continue to accompany the dynamic development of new battery materials on an ongoing basis. Benchmarking of existing pilot and research plants as well as an intensified exchange between cell manufacturers and machine/plant builders can have a supporting effect. Finally, data-based approaches from increasing experience with ongoing production also offer significant optimization potential. In addition to determining the minimum necessary requirements, material and process engineering changes also represent an important opportunity to reduce the dew point requirements in the process and enable further savings. Examples include approaches for coating or structuring the active material particles, especially for nickel-rich material systems. The implementation of an additional post-drying step prior to filling ("stack drying") can also reduce the dew point requirement during the upstream cell assembly steps.

Furthermore, uncertainties still exist for the use of materials and components in clean and dry rooms. The stringent requirements for the atmosphere are often equated with stringent requirements for the materials used (e.g., with regard to contamination and electrostatic charging). At the same time, these atmosphere requirements also stress the materials used, especially seals and plastic parts, and can lead to increased wear and maintenance due to embrittlement. Additional empirical data must be obtained and compiled from users and the mechanical and plant engineering sector. Corresponding standards on machine design, maintenance, and wear in clean and dry rooms should then be developed based on these findings.

Conclusions about possible contamination risks within and between individual process steps are essential for the planning and operation of demand-oriented and economical infrastructure. The risk of danger to people and products can be significantly reduced with additional process- specific measures, such as local filtering and extraction systems.

Various approaches are emerging for reducing energy requirements. In general, the energy requirements of dry and clean rooms depend on the volume of air treated and the dew point to be maintained. Adaptive operating strategies with which the energy-intensive air treatment can be adapted to the actual prevailing conditions on a demand-specific basis offer significant added value. The degree of drying or the mixing ration of recirculated and reconditioned air can be flexibly adjusted based on the number of people in the room and the resulting moisture emissions. Further energy savings can be achieved by using more energy-efficient components such as pumps and adsorption units, by using multi-stage systems for conditioning, and by utilizing waste heat generated within the overall process. Finally, using electricity instead of natural gas for the regeneration of the adsorption units also offers an opportunity to dispense with fossil energy sources and save additional combustion emissions.

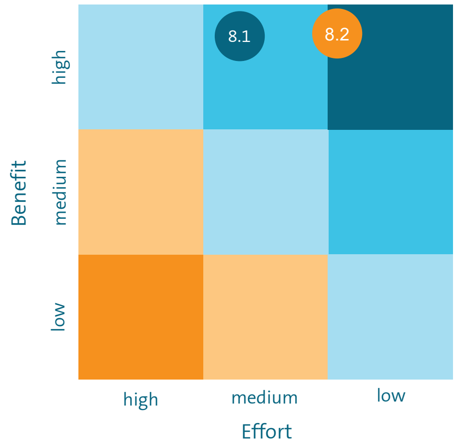
Lower plant footprints can be achieved by the operation of smaller clean and dry rooms, which offers the combined advantages of lower energy consumption and more precise control. Furthermore, new concepts are increasingly being tested which partially reduce the conditioned room volume down to the production plant itself, thereby significantly reducing the conditioned air volume flow. These encapsulated environments are referred to as micro- or mini-environments, depending on the size of the volume to be conditioned. These micro- or mini-environments provide a process environment with pre-filtered or dried air or a high-purity inert gas atmosphere, depending on the technical design of the system. Designated interfaces then control access to the process area by personnel, in particular for maintenance purposes. For example, access can be provided via glovebox gloves so that personnel are not exposed to the clean/dry room environment and human contamination paths can also be almost completely eliminated. Another option is a modular machine design in which individual areas can be hermetically separated from the rest of the machine prior to opening. This limits the loss of the conditioned atmosphere to a required level (e.g., the area to be maintained). Encapsulation or segmentation of closed air volumes with different conditioning is also possible. In this case, a dry space with lower dew point requirements is built around the encapsulated machine, in which process space with strict dew point requirements are implemented. This is a so-called meso-environments. As a result, the machine can be opened for maintenance and merely returns to the lower dew point of the drying space surrounding it (instead of unconditioned atmosphere). Thus, the dimensioning of the conditioned air volume is not only dependent on the process and material requirements, but also on the operation and maintenance of the plant.

In order to keep the risk of contamination inside and outside the mini-environment low, there are high requirements for the impermeability of the system and the permissible leakage rates. The specification of interfaces is the greatest challenge to the scaled implementation of mini-environments. Interfaces must be defined between the individual process steps along the process chain (e.g., by integrated airlock systems that enable a continuous flow of materials).

The use of mini-environments also requires a very high degree of automation and corresponding process stability due to the limited possibilities for intervention by personnel. For this reason, scaling up and transferring the concept to large-scale production is challenging. However, according to expert estimates, the successful use of mini-environments can result in significant energy savings (by a factor of 5-8) compared to the conditioning of large rooms.

Further considerations are aimed at outsourcing entire process steps from the dry and clean room. To do so, the entire process chain must be considered, including any possible expenses or quality losses due to additional cell infeed and outfeed, as well as the higher time expenditure.

Effort-benefit diagram and impact on sustainability, quality, and costs



	8.1	8.2
Sustainability	↑	↗
Quality	↗	→
Cost savings	↑	↗

Contribution: ↑ = Significant ↗ = Moderate → = None

8.1 Demand-oriented and economical clean and dry room design

8.2 Improved clean and dry room energy efficiency

Effort and benefit assessment
The benefits of optimally designed dry rooms and clean rooms (RBW 8.1) are rated as high. The dimensioning of the supply technology has a leveraging effect on other measures to increase energy efficiency, so that significant contributions can be made to cost and energy savings. Considering the progress already achieved for smaller lines, the effort associated with the use of mini-environments is estimated to be medium due to the isolation requirements and linking of individual process stations. Completely new concepts are required for upscaling. The new interfaces and additional lock systems result in several changes along of the process chain and in some cases create additional work in production. The benefits of RBW 8.2 are estimated to be medium. The changes can achieve additional savings in energy requirements and reduce CO_2 emissions, which has a positive effect on the overall cost and sustainability goals of battery cell production. However, the overall savings are not as great as those from breaking through RBW 8.1.

Technical support

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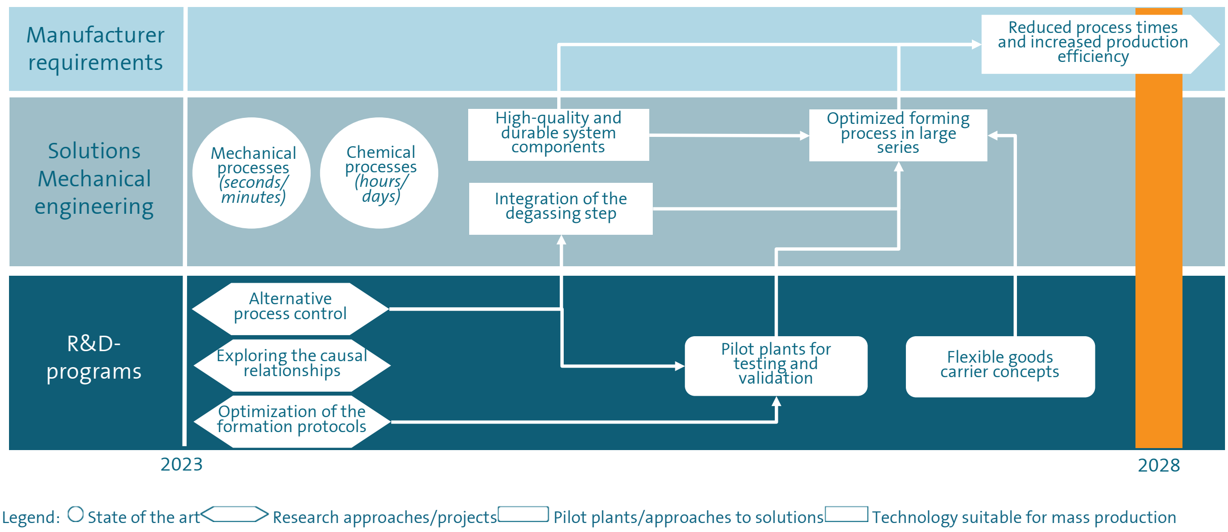
9: Formation and aging

No.*	Red Brick Wall	Current status in comparison to 2020	Relevance**	Timeline***
9.1	Reduced process times (cell finalizing parameter optimization)	Progress made	High	2028
9.2	Reduced energy consumption (increased energy efficiency)	Progress made	High	2025

RBW 9.1: Reduced process times (cell finalizing parameter optimization**)**
Several approaches exist to further reduce the long process time and lower energy costs using optimized process control and research into new cause-effect relationships. Therefore, a key challenge is a deeper understanding of the battery cell as a product and the formation as a process to derive optimal (time and energy optimized) formation protocols, taking interactions into account.



*RBW priority decreases from top to bottom.

**Relevance from the point of view of a battery manufacturer

***Timeline indicates when breakthrough should occur (The timeline considered is until 2035).

Source: VDMA, PEM of RWTH Aachen, BLB of TU Braunschweig according to Phaal2003b

Formation and aging

Basics
During formation, the battery cells are charged and discharged for the first time in cycles with a defined current profile. This forms the so-called Solid Electrolyte Interface (SEI), which is an important quality parameter that is decisive for the cell function and has a great influence on the safety and service life of the battery cell [Li2017].

During the formation process, several lithium-ion cells are always cycled simultaneously within a rack. There are two basic concepts that are used by machine and plant manufacturers. With the rack concept, the battery cells are contacted and stored in racks. With the chamber concept, the battery cells are contacted on a dedicated carrier and placed together in a chamber for formation. The rack concept can also include the use of cell-specific carriers. The main difference between the two concepts is that the battery cells are placed in a closed and encapsulated environment. Other differences primarily relate to the integration of safety and emergency concepts.

Contact pins are used for the required charging and discharging of the battery cell, which ensures a secure connection and low contact resistance. The individual contact connections are generally referred to as channels. The subsequent formation of the connected battery cells can take up to 24 hours, depending on the cell chemistry. The exact interdependencies of the formation process have not yet been fully investigated and explored. However, it has been shown that initial capacitance losses and contact resistance are higher at elevated C-rates, so longer formation protocols at low current levels are preferred.

The subsequent self-discharge test, known as "aging," is used exclusively for quality assurance, and is therefore often assigned to the "end-of-line test" process step. The lithium-ion cells are stored for several weeks and the cell voltage (open circuit voltage) is measured at regular intervals. The measured self-discharge rates are used to determine the cell quality and predict the service life. Due to the long resting periods of up to several weeks, a significant amount of capital and factory space is tied up in this process for storage and equipment racks. The energy released during the discharge of individual lithium-ion cells is used to charge other battery cells in the loading process. This has a positive effect on the overall energy consumption balance during formation.

In total, the processes of formation, aging, and EOL testing of a lithium-ion cell account for around one third of the total cell costs and usually take one and a half to three weeks. Thus, the relevance for battery manufacturers remains high [An2016].

Challenges
The high process times for formation and aging are a key challenge. The goal is a deeper understanding of the battery cell as a product and cell finalization as a process to leverage potential time and cost savings, taking interdependencies into account. Reducing energy consumption is another key challenge. Formation is one of the most energy-intensive process steps in battery cell production. Operation of the equipment is one of the largest cost factors due to the high connected loads in continuous operation and long formation cycles at low C-rates. The goal is to either reduce energy losses or to use new approaches to optimize the formation time together with lower energy consumption. The costs saved by modifying and adapting the formation process must offset the initially higher investment costs.

The final challenge is the potential hazards associated with formation. These can result from a possible channel failure or incorrect current flow in the contacted lithium-ion cells and lead to thermal runaway. This can be caused by contacting problems, cell defects, or faulty formation protocols. There is a risk of heat buildup that can lead to overheating and thermal runaway of the cell, especially at the contacting points. The damage to the system and technology from this type of failure is usually irreparable. Reliable safety concepts (e.g., early warning systems with gas sensors, inert gas extinguishing systems, fireproof fire containers) are required to account for the increased fire risk from the large number of simultaneously cycled cells in a confined space during formation.

Possible solutions

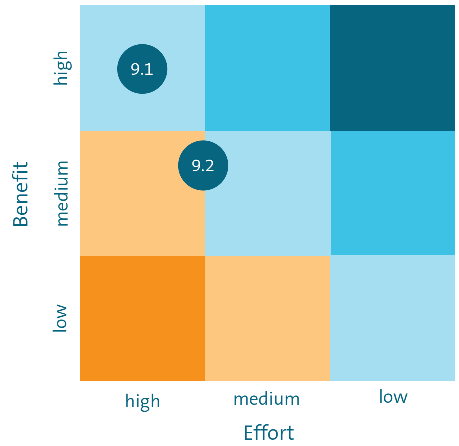
Current research is primarily focused on identifying quality-relevant interactions to increase product quality and energy efficiency during the formation process. The goal is to form a stable, homogeneous SEI layer that is as thin as possible while minimizing energy consumption (RBW 9.2) and shortening formation time (RBW 9.1). The collection, measurement, analysis, and utilization of process and product parameters is becoming increasingly relevant in the investigation of these relationships. Knowledge gained here should help to develop optimized formation strategies (e.g., reduction of the charging voltage, pulse shaping). Digitalization of the production line is essential for the investigation of these relationships in order to collect data and establish meaningful analysis models and intelligent AI-models. Digitalization of the aging step will also make it possible to deepen the understanding of the final cell quality and the cell aging process and use it for further process optimization. For example, a battery management system (BMS) integrated into the product carrier could be used to implement this digital connection. Projects such as the "OptiPro" project funded by the German Federal Ministry of Education and Research (BMBF) seek to use innovative measurement techniques to evaluate all process and quality parameters of cell finalization [PEM2022]. The collected data and the analyzed information are then stored in a virtual production system and used for analysis and evaluation with the assistance of artificial intelligence.

Another approach to reducing the formation times directly addresses the product level and examines the use of electrolyte additives, modified electrode materials, the lamination of individual electrodes to form so-called electrode-separator composites, as well as adapted binders and separators, with the aim of accelerating the chemical reactions taking place inside the cell during formation. This not only reduces the initial capacity losses due to the formation of the SEI-layer, but also improves the fast-charging capability and increases the energy efficiency due to fewer losses during the formation [Frankenberger2019].

For example, the electrolyte composition must be adapted as precisely as possible to the (graphite) anode to ensure high-quality formation of the SEI structure due to potential decomposition [Buga2006]. The wettability and electrolyte absorption of the separator are also key criteria, as the low internal resistance and improved ionic conductivity contribute to optimal formation results [Davoodabadi2020]. The effectiveness of additional process steps, such as pre-charging, is also evaluated in this context. In this case, the cells are pre-charged to low voltage levels using very low currents and degassed [Xiaoyan2021].

Setting defined temperature profiles and mechanical pressures during the formation cycles is another promising approach. For example, increasing the temperature to ca. 50°C has shown a positive effect on the conductivity of the electrolyte through the separator, the solid diffusivity in the active material particles, and the charge transfer resistance at the electrode-electrolyte interface [Leng2017]. These factors improve the reaction rate and

Effort-benefit diagram and impact on sustainability, quality, and costs



	9.1	9.2
Sustainability	↗	↗
Quality	→	→
Cost savings	↑	↗

Contribution: ↑ = Significant ↗ = Moderate → = None

9.1 Reduced process times 9.2 Reduced energy consumption

reduce the overall internal resistance of the battery cell. Temperature-controlled formation thus promises a faster, more uniform formation of the SEI, which in turn increases capacity during subsequent cycling [Bhattacharya 2014]. The temperature also has a significant effect on cell aging, as resting storage at elevated temperatures accelerates the reaction processes within the battery cell. In addition to quicker stabilization of the SEI layer, potential quality defects can also be dete cted faster. However, the battery cells are also highly temperature-sensitive, so temperature windows must be precisely maintained. Even small temperature deviations above 50°C can lead to undesirable side reactions which degrade the cell performance.

Due to the elasticity of the separator, the physical distance between the individual electrodes can be reduced by applying additional pressure during the formation process. This reduces the internal resistance in the cell and increases the diffusion of the electrolyte [Weber2014]. The lamination of individual electrode-separator composites in the lithium-ion cell follows a similar approach.

Effort and benefit assessment

The benefit of reduced process times in the formation and aging of lithium-ion cells is assessed as very high due to the costs and factory space currently tied up in these processes. However, improvements in this field are also associated with a high degree of effort, as the cause-effect relationships in cell finalization need to be researched and understood in greater detail.

The benefit of reduced energy consumption in the formation is rated as moderate, since manufacturers face higher initial investment costs, which must be amortized over the service life. Breaking through RBW 9.2 contributes to higher sustainability and cost savings. However, the associated effort is estimated to be high due to the need for re-engineered equipment.

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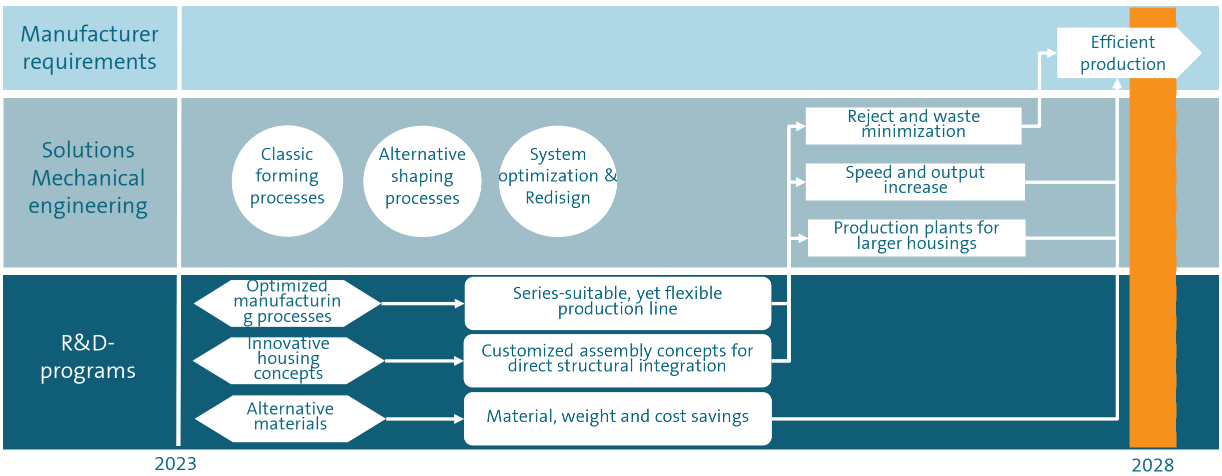
Battery Production
VDMA
Online Industry Guide
Formation and aging
Machines and plants

Battery Production
VDMA
Online Industry Guide
Formation and aging
Components for machines and plants

10: Housing production (cell)

No.*	Red Brick Wall	Current status in comparison to 2020	Relevance**	Timeline***
10.1	Minimize scrap and stamping waste	Progress made	High	2028
10.2	High-speed equipment for increased productivity	New	High	2028
10.3	Processing of alternative housing materials	Progress made	Medium	2026

RBW 10.1: Minimize scrap and stamping waste
The variety of different battery cell variants continues to increase due to the growing range of applications for lithium-ion batteries. There is a general trend towards larger dimensions for the individual cell formats. This poses new challenges for cell housing production, which must be met on the process side with adapted manufacturing processes and equipment, and on the product side with innovative housing concepts. To ensure sustainable profitability, the focus remains on efficient production paired with minimized scrap and waste rates.



Legend: ◯ State of the art ⬭ Research approaches/projects ▭ Pilot plants/approaches to solutions ▭ Technology suitable for mass production

*RBW priority decreases from top to bottom.

**Relevance from the point of view of a battery manufacturer

***Timeline indicates when breakthrough should occur (The timeline considered is until 2035).

Source: VDMA, PEM of RWTH Aachen, BLB of TU Braunschweig according to Phaal2003b

Housing production (cell)

Basics
With the rapid growth of electromobility and the associated growing demand for battery cells, the production of cell housings is also becoming increasingly important. Different process technologies are used in production, depending on the cell format or housing type. The forming of metallic housings from aluminum or aluminum alloys for prismatic cells and from nickel-plated steel for cylindrical cells is based on the deep drawing and impact extrusion processes [Pettinger2013]. Impact extrusion offers a clear advantage, with a significantly shorter process chain for forming the housing and almost complete utilization of the input material. For example, the production of a prismatic aluminum housing can be performed in a single step, which is followed only by stretch forming and trim cutting to obtain the final dimensions. The output rate can be increased about fivefold with this process compared to deep-drawn housings. However, extrusion has clear limitations in terms of the types of material that can be processed, which restricts its use to selected housing materials. For example, nickel-coated steel, which is used as a standard material for cylindrical cell housings, is not compatible with this process technology.

In impact extrusion, the yield point of the material is exceeded and the material starts to flow. With deep drawing, a flat metal sheet is drawn into a forming die and a punch is used to push the metal into a die cavity, forming it into the desired shape. In contrast to impact extrusion, the outer periphery of the sheet metal is rigidly fixed by a blank holder. With the increasingly tighter tolerance limits of battery manufacturers, the multi-step deep-drawing process offers the advantage of targeted and precise design options.

Deep drawing is also used to produce the housings of pouch cells. In this case, an aluminum-plastic composite foil is used as an input material instead of a purely metallic material. The composite foil is then transformed into a half-shell structure with a defined cavity [Singer2020]. The foil is either directly fed from a roll with subsequent automatic cutting or provided in the form of prefabricated cut-to-size single layers.

Both process technologies for the production of cell housings have been continuously optimized in recent years, with progress being made in production speeds and process accuracy.

Challenges
The production processes established in the manufacture of cell housings must be further optimized in order to deal with the increasing number of variants, rising cost pressure, and high demand volumes. Specific action is required to enable the production of new housing variants and to further increase the efficiency of the production processes by high material utilization and minimization of scrap (RBW 10.1). The aim is to reliably manufacture the required production volumes using precise high-speed equipment (RBW 10.2). The challenges outlined are exacerbated by the trend towards even stricter tolerance specifications coupled with growing cell formats. This makes it necessary to adapt the processes and materials currently used in housing production, which in turn requires further adjustments along the entire process chain (RBW 10.3).

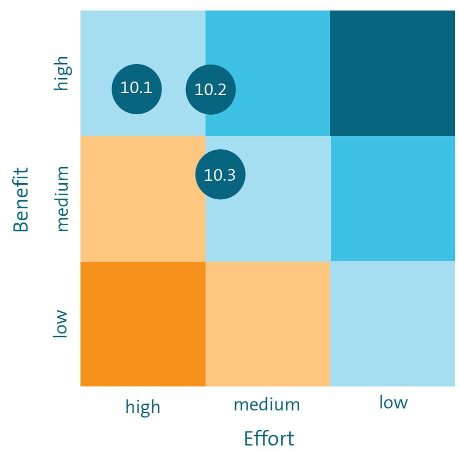
With growing cell formats, it becomes apparent that potentially critical sealing surfaces become larger and joining techniques must be all the more reliable. Leakage of the harmful electrolyte from an improperly sealed housing immediately renders the battery cell unusable and must be avoided, especially due of the safety risks involved. For pouch cell housings in particular, defect-free processing of the aluminum composite foil and subsequent sealing requires precise process control. Deep-drawn half-shells currently have depths of up to 10 mm, but the risk of unwanted thinning and damage to the material increases significantly with higher forming degrees. A low material utilization rate of around 65% with deep drawing renders more than a third of the original material unusable.

Possible solutions

In response to these challenges, the required machines and systems for the production of larger and materially modified cell housings must be further developed, and the processes used must be optimized in order to reduce disadvantages such as high processing times and low material utilization. Technology transfer from neighboring industries also appears promising, provided that the corresponding processes can be used in cost-optimized and scaled series production. For example, approaches are emerging in which the metallic cell housings are produced by a combination of forming processes (extrusion, bending) and joining processes (mainly welding). Depending on the housing specification and defined requirements, these processes offer advantages over the established processes mentioned above. Parameter studies can make a valuable contribution to the production of aluminum half-shells for different pouch cell formats [Fleischer2017]. The knowledge gained from experimental investigations can be transferred to the development of optimized composite films, whose structure enables even higher forming degrees.

Research and development into innovative materials and housing concepts, which should enable lighter housings with thinner wall thicknesses and at least the same strength, is also promising. New approaches can also be identified to improve safety as well as performance by introducing additional sensor technology directly into the cell [Thielmann2017, Foreman2017, Hong2019, Zhang-2019]. Especially for hard case cells, these optimized cell housings open up the potential for structural integration that can significantly increase energy density on the battery system level. However, the production equipment used must first be adapted or equipped for the processing of corresponding materials. In the meantime, an increase in the use of aluminum, which is already in use, can be observed on the material side. Housings made of aluminum offer several advantages, such as higher formability and strength, higher thermal conductivity, and high recycling rates. Special aluminum alloys can also be used to achieve smaller wall thicknesses for weight savings [Thielmann 2018].

Effort-benefit diagram and impact on sustainability, quality, and costs



	10.1	10.2	10.3
Sustainability	↑	→	↗
Quality	→	↑	→
Cost savings	↑	↗	↑

Contribution: ↑ = Significant ↗ = Moderate → = None

10.1: Minimize scrap and stamping grid waste

10.2: High-speed equipment for increased productivity

10.3: Processing of alternative housing materials

Effort and benefit assessment
In light of the increasing number of units produced and the growing competitive pressure on the markets, the benefit of reject reduction in cell housing production will only increase in the coming years. The processes and materials used must be further optimized for this purpose. The cost and effort of these measures are both considered to be high. However, significant savings potential can be achieved through increased material efficiency and productivity, so that successfully implemented solutions also bring high benefits.

Novel housing concepts and materials, which enable the production of (weight-)optimized, sustainable cell housings, possibly equipped with integrated sensors, offer moderate potential with currently low to medium levels of maturation.

Technical support

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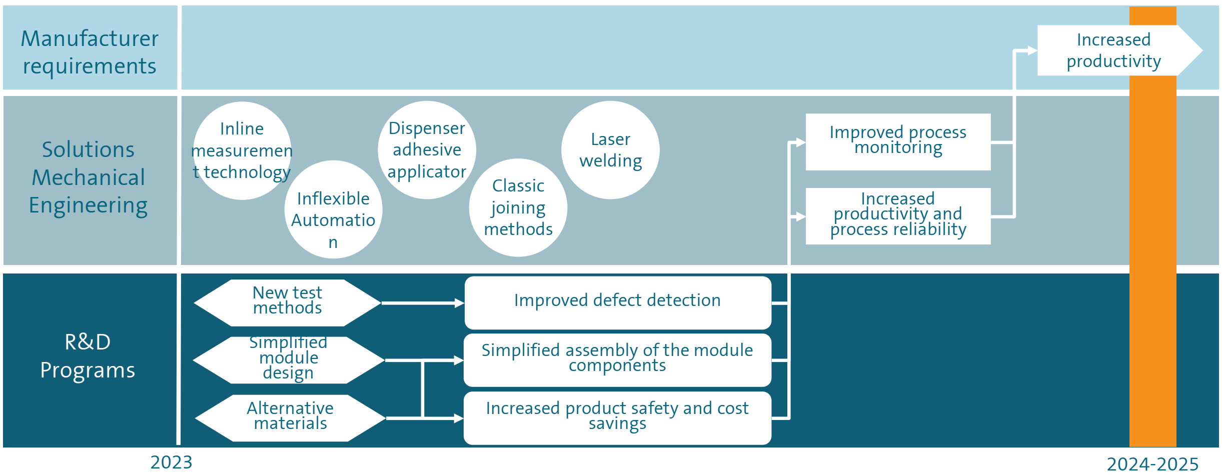
11: Module production

No.*	Red Brick Wall	Current status in comparison to 2020	Relevance**	Timeline***
11.1	Trade-off between product complexity and high automation	Progress made	High	2024 - 2025
11.2	Implementation and integration of Cell-to-X concepts	Progress made	Medium	2023 - 2025
11.3	Optimal cell bracing (incl. next-gen materials)	Progress made	Medium	2023 - 2024
11.4	Reduce BoL test time, optimize cell clustering, and increase throughput	Significant progress made	Medium	2023 - 2024
11.5	Integration of an inline quality measurement system	Progress made	Medium	2023 - 2024

RBW 11.1: Trade-off between product complexity and high automation
In module manufacturing, efficient production is playing an increasingly decisive role due to high cost pressure. To enable mass production, costs must be reduced and processes improved. Module production requires many different joining processes, which increase process complexity and necessitate an increased quality assurance effort.



Legend: State of the art / Research approaches/projects / Pilot plants/approaches to solutions / Technology suitable for mass production

*RBW priority decreases from top to bottom.

**Relevance from the point of view of a battery manufacturer

***Timeline indicates when breakthrough should occur (The timeline considered is until 2035).

Source: VDMA, PEM of RWTH Aachen, BLB of TU Braunschweig

Module production

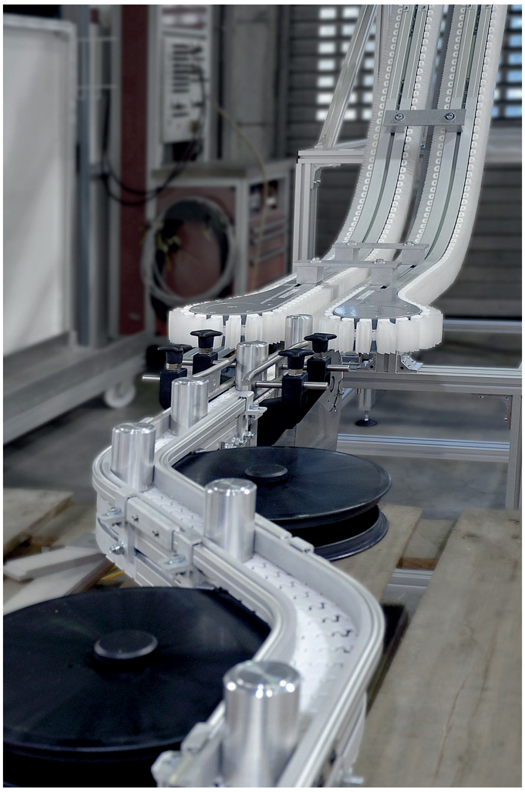
Basics
In module production, battery cells are sorted by quality and cleaned for further processing. An insulating layer must be applied for round and prismatic cells. Round cells are generally covered with a protective film. Coating is a good alternative, especially for prismatic cells. Subsequent bonding ensures strength and crash safety.

After being pressed into a stack, the individual cells are contacted and linked at the module level and inserted into a housing. This requires many precise handling and joining processes with a low level of automation, especially in smaller series. This includes safe handling of the cells as well as joining technologies in the housing (such as bonding, screwing, and welding), all in the immediate vicinity or on the cell itself, with corresponding safety concepts [Larsson2019, Kampker2014, Das2018, Schmidt2015]. Functional adhesives can also be used for thermal management.

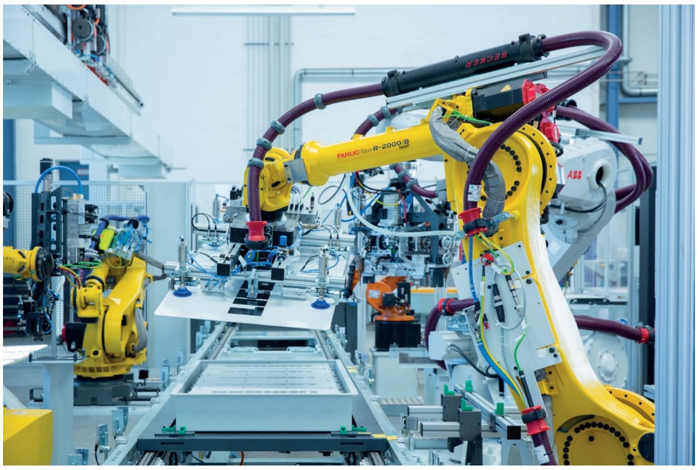
Challenges
To continue to meet the cost pressure of mass production in the automotive industry, the production processes currently used in module manufacturing and quality assurance must be made more efficient. The focus is on increasing productivity and raising the level of automation (RBW 11.1) with high product complexity. Trends such as increasing safety requirements and standards, as well as design and weight reductions for non-performance components, will further increase product complexity. The large number of variants with special applications is another challenge which must be addressed (see RBW 13). The implementation of new concepts such as "cell-to-pack" or "cell/module-to-chassis" (RBW 11.2.) poses new challenges for automation due to the larger cells and, in some cases, different product structuring and component placement.

Another major challenge in module production is researching optimal process parameters, such as cell biasing parameters to improve battery performance and lifetime (RBW 11.3), as well as cell contacting (see RBW 12) [Cannarella2014].

High demands are also placed on the Beginning-of-Line (BoL) test in module production. In order to increase product quality, the cells must be clustered according to certain properties (e.g.,



Versaflex conveyor system for the ultra-fast transport of battery round cells in the incoming goods department of an automotive manufacturer - without workpiece carriers, with maximum throughput and high process reliability
Source: Maschinenbau Kitz GmbH



5 modules are assembled to the pack. Picture shows mounting of the upper part of the housing/lid and screwing to the battery pack housing.
Source: Liebherr-Verzahntechnik GmbH

capacity, resistance) before they are installed in the module (RBW 11.4). Different cell qualities cause the module to age more quickly, leading to a reduction in battery life. These tests, which can be time-consuming, lead to an increase in cycle time and to insufficient cell clustering due to the greatly reduced number of tests. The variety of different process and quality parameters could also make the identification of defects more difficult. The lack of an inline quality measurement system thus increases the susceptibility to defects (RBW 11.5).

The fundamental challenge is that knowledge of process technology capabilities often does not align with the designs of system developers.

Possible solutions

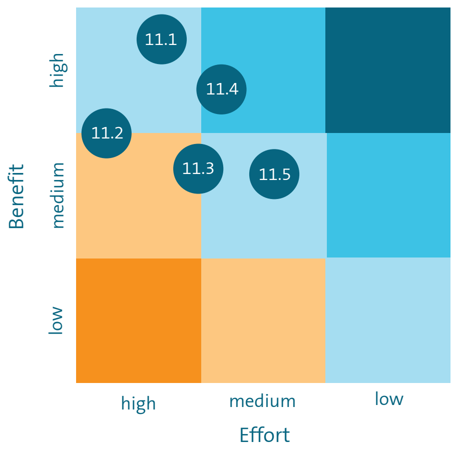
Standardizing of components and process sequences can make a significant improvement to achieving a high level of automation with simultaneously high product complexity. Design flexibility can be realized by modular product design, such as adaptable clamping elements. Fully automated system solutions are possible for applying a coating to insulate the cells. Various formats of prismatic cell modules can be coated without contact in a continuous process. Furthermore, product complexity can also be reduced by combining components in upstream processes outside the module production line or by integrating functions.

For the development of innovative "Cell-to-X" concepts, the exchange between experts from plant engineering, manufacturing technology, and battery module development should be intensified to improve synergies. The design and quality of the finished product must be integrated into the vehicle development process, especially with the battery component being used as a structural part of the vehicle. Poorly accessible and heavy components must be avoided at the battery manufacturing level so as not to jeopardize production capabilities. On the other hand, product complexity and thus the required production effort can be significantly reduced by omitting various levels (such as the module or system level) and integrating them directly into the vehicle.

The cells are either clamped by the housing itself or a separate clamping device. In addition to the pressure settings, homogeneous pressure distribution is also important for optimum tensioning. The relationship between cell size, material, and optimum pressure control has not yet been sufficiently investigated, so additional correlations could be identified in cooperation with development and research.

Increased use of innovative measuring technologies and novel testing methods, such as *optical coherence* technology for checking the successful application of adhesive beads, can optimize quality assurance and increase module production quality. Automated guided handling systems with in-situ measurement technology are a possible solution for increasing module production efficiency. The use of gripper and robot arms with integrated measurement technology can also shorten the BoL test by synchronizing the transport process and measurement period. In addition to these concepts, the measuring technology must also

Effort-benefit diagram and impact on sustainability, quality, and costs



	11.1	11.2	11.3	11.4	11.5
Sustainability	↑	↗	↗	↗	↗
Quality	↗	→	↗	↗	↑
Cost savings	↗	↗	↗	↗	↑

Contribution: ↑ = Significant ↗ = Moderate → = None

11.1 Trade-off between product complexity and high automation

11.2 Implementation and Integration of Cell-to-X concepts

11.3 Optimal cell bracing (incl. next-gen. materials)

11.4 Shortening the BoL test time and optimized rationing of the cell clustering

11.5 Integration of an inline quality measurement system

be improved. Promising approaches include the use of EIS measurement and a combination of real data and simulations, which can quickly assess the quality using just a few individual measurement points.

Effort and benefit assessment
Because module production uses common manufacturing processes, it is already highly industrialized compared to other Red Brick Walls in battery production. All advances in this area are equally aimed at optimizing costs, quality, and sustainability. The effort required to increase the efficiency of module production and the associated benefits are considered high (RBW 11.1). Overall, these measures contribute to reduced costs as well as increased sustainability and quality. The implementation of new concepts for the production of Cell-to-X is assessed as only being feasible at a high cost. The benefits are rated as moderate to high (RBW 11.2). The effort required to design optimal cell bracing in module production is also rated as moderate to high in terms of both effort and benefit (RBW 11.3). The implementation of abbreviated and optimized BoL testing is rated by experts as moderate to high, but can generate a significant reduction of both scrap and process times (RBW 11.4). Both the effort and benefits associated with the implementation of a quality assurance system are rated as medium, since some technologies are already in use and many approaches have already been integrated into an automated process, such as module production (RBW 11.5).

Technical support

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Omron Electronics GmbH
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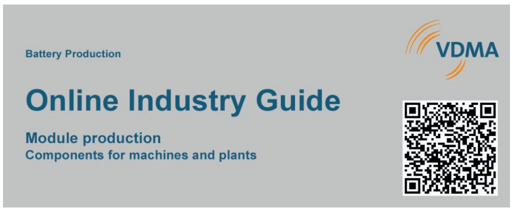
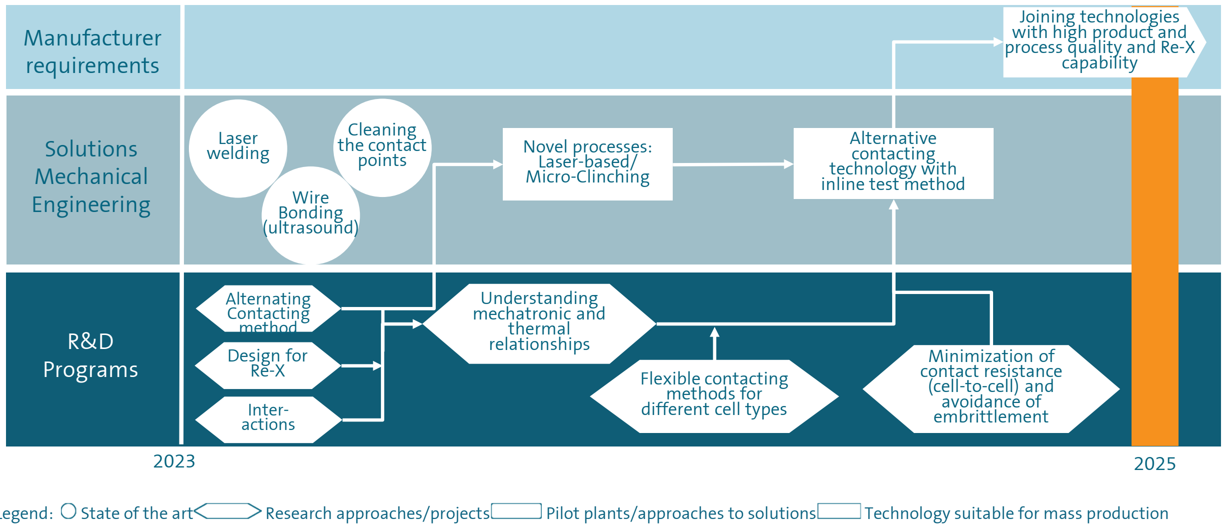
Plasmatreat GmbH
Rockwell Automation GmbH
SCHUNK GmbH & Co.KG
Sick AG
VENJAKOB Maschinenbau GmbH & Co. KG



12: Contacting

No.*	Red Brick Wall	Current status in comparison to 2020	Relevance**	Timeline***
12.1	Improve product quality for stable long-term contacts (minimize wear from mechanical stress)	New	High	2026-2028
12.2	Minimize contacting scrap rates through improved process quality (especially at cell level)	New	Medium/High	2023-2025
12.3	Contacting technology for remanufacturing/recycling and fast contact interruption	Progress made	Medium	2023-2024
12.4	Contact surfaces for larger currents and larger cells	Progress made	Low	2023-2024

RBW 12.1/12.2: Improve product and process quality
The core challenges in the area of contacting at the module and cell level are preventing brittleness or corrosion of the contacts and minimizing wear due to the high mechanical stress in mobile use. In addition to product quality, improving process quality is also very important, especially at the cell level.



*RBW priority decreases from top to bottom.

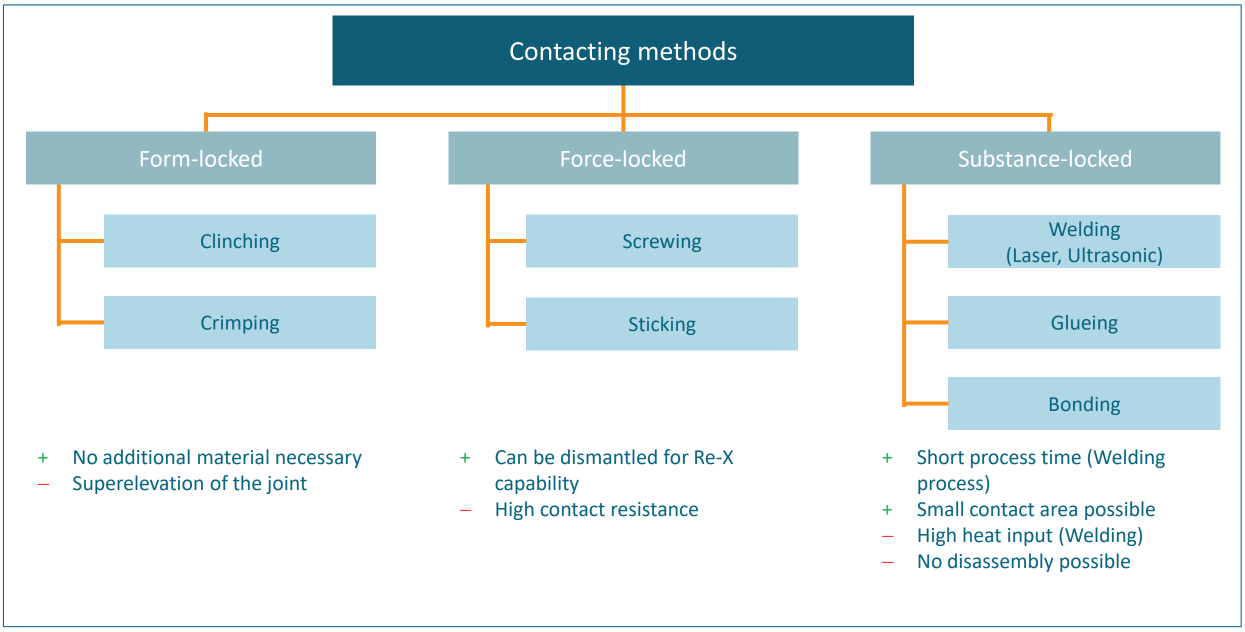
**Relevance from the point of view of a battery manufacturer

***Timeline indicates when breakthrough should occur (The timeline considered is until 2035).

Source: VDMA, PEM of RWTH Aachen, BLB of TU Braunschweig

Contacting

Basics
In contacting, a distinction is made between the cell level and the module level. At the module level, the individual cells are connected either in parallel or in series, depending on the desired module voltage. The individual cells are contacted via central contacting systems, so-called busbars. The objectives of increasing energy and power density with faster charging cycles is responsible for the demand for increased system voltages in the battery system. In connection and contacting technology, a distinction is made between three types of contacting: form-locking, force-locking, and substance-locking connections. As a rule, the modules are contacted by laser welding, laser bonding, or ultrasonic bonding/wire bonding, depending on the cell format and busbar materials used. Alternatively, the connections can be made using a force-locking connection (e.g., by interlocking). An overview of the various contacting methods and their advantages and disadvantages is provided in the following figures. The choice of contacting method depends on many factors, such as the material used for the busbars, the cell format, and the required production speeds. For example, wire bonding is often used for round cells, whereas prismatic cells are often contacted by laser welding [Das2018, Heimes2018].



Source: Fraunhofer-Einrichtung Forschungsfertigung Batteriezelle FFB, PEM der RWTH Aachen

	Laser welding	Laser bonding	Ultrasonic welding	Ultrasonic bonding
Connecting quality	++ High precision and control + High strength + Welding of coated materials + Continuous quality (no wear parts) + No vibration	+ High flexibility, even with height variations + Easy securing of the zero gap	+ High strength + Quality inspection possible through process parameters	+ High flexibility, even with height variations
Heat input	+ Low heat input + Small heat influence zone	+ Low heat input		+ Low heat input into the cell
Costs (economic efficiency)	+ No wearing parts + Flexibility	+ Cost effective alternative	+++ Lower investment costs	+ Low investment and operating costs
Particle contamination	+ Possibility to control and reduce contamination in the process	+ Low particle contamination	+ No splashes	+ Very low particle contamination
Speed	++ High speed + High automation possible	+ High speed + Possibility of automation		+ High speed + Possibility of automation

Source: Fraunhofer-Einrichtung Forschungsfertigung Batteriezelle FFB, PEM der RWTH Aachen

At the cell level, contacting processes are used for welding the cell arresters, known as tab welding, or welding the tab-terminal connection. For tab welding, ultrasonic welding or, more rarely, laser welding processes are normally used to contact the individual electrode sheets with each other. Ultrasonic welding offers advantages in contacting multiple layers, and is associated with lower costs due to lower energy consumption. Tab-terminal welding, on the other hand, is mostly used with laser welding due to the high speed and contactless process.

Challenges

The core challenge in contacting is to improve product and process quality (RBW 12.1 and RBW 12.2). Battery performance and lifetime can be affected by faulty or damaged contacts. For example, brittleness or corrosion on the contacts of the module and cell level can lead to increased electrical contact resistances, and consequently to increased heat generation. Dynamic stress in mobile applications also poses a challenge (RBW 12.1). Damage can occur as a result of the high wear on the contacts, which in turn can lead to high material defect costs. Therefore, the durability of the contacts must be verified in extensive service life tests.

At the cell level, faulty processes can result in short circuits or inadequate contacting, which can lead to high reject rates (RBW 12.2). Typical error patterns include an insufficient contact area or incomplete contacting of all cell arresters. This can result in increased contact resistance, which can affect the efficiency and safety of the cells due to high heat generation. In addition, there is a risk of safety-critical particle contamination in the contacting process, especially at the cell level. Examples of causes for this can be sonotrode wear during ultrasonic welding or welding spatter during laser welding.

The advantage of substance-locking processes is that they enable a high degree of material bonding, typically with low transition resistances between the different materials. However, non-destructive detaching of the connections is not possible without major effort. As a result, cell replacement is currently not economical at the module level (RBW 12.3). Force-locking connections, such as screws, can usually be easily disassembled. However, these are rarely used in the automotive sector because they have a very high contact resistance. For example, screws as a force-locking method for contacting on the module level have a contact resistance that is two to three times as high as that of contacting methods using lasers [Schmidt2015]. The challenge is thus to develop

A battery block consisting of cylindrical cells and busbar for the investigation of clamping technology and process parameters in laser welding
Source: PIA Automation Holding GmbH

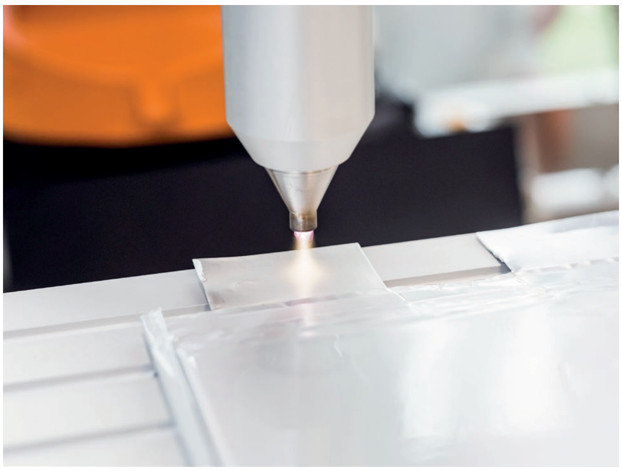
a process which ensures good contacting of the components, but also allows the contact to be detached quickly with as little impact on the material as possible in order to allow the Re-X of batteries (RBW 12.3). The term Re-X covers all processes for optimizing the service life of a battery and the battery components, including reuse, remanufacturing, and recycling [Heimes 2021]. Another challenge is the contacting of the individual components of the module at higher currents and with large-format cells (RBW 12.4). For higher currents in the battery module, the arresters must be enlarged to reduce contact resistance. This challenge has been solved to a large extent in recent years; it still applies for pouch cells, since contacting is a limitation of the thickness.

Possible solutions

Optimized contact designs and material selection are essential to improve product quality over a long service life. To be able to meet requirements for both lightweight construction and a long service life, the understanding of material behavior over the product lifetime must be strengthened in the next few years through the examination of field failures. The application of new contacting technologies can also contribute to an improved product lifetime. For example, electromagnetic pulse technology (EMPT) is a promising approach. EMPT can enable a substance-locking bond between different materials, such as aluminum and copper, and achieve connections with high mechanical strength as well as high electrical conductivity.

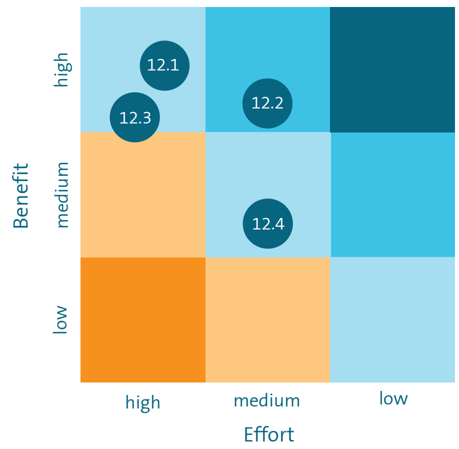
The improvement of process quality at the cell level should first be achieved by identifying all relevant contacting defects. This requires deepening process knowledge by analyzing cause-effect relationships in the ultrasonic and laser welding processes. The optimization of inline quality measurements (e.g., camera-based process control, thermographic analysis) should enable the early identification of faulty contacts in cell production. In addition, approaches such as predictive maintenance can be used to forecast the wear and optimize maintenance intervals of contacting tools like the sonotrode.

The contacting technology at the module level faces major challenges with regard to 2nd-life use of automotive cells as stationary storage or renewed mobile applications. In particular, these arise when the contacts are welded with a non-detachable connection (form- or material-locked connections). Laser bonding and mechanical connections at the module level address this challenge. The thin wire connections in laser bonding, so-called ribbons with a width of 1-3 mm and a thickness of 200-300 µm, can be removed with minimal effort and allow reuse or



Plasma cleaning of the contact point of a pouch cell
Source: Plasmatreat GmbH

Effort-benefit diagram and impact on sustainability, quality, and costs



	12.1	12.2	12.3	12.4
Sustainability	↗	↗	↑	↗
Quality	↑	↑	→	↗
Cost savings	↗	↑	→	↗

Contribution: ↑ = Significant ↗ = Moderate → = None

12.1 Improve product quality

12.2 Minimize reject rates

12.3 Contacting technology for remanufacturing/recycling

12.4 Contact surfaces for higher currents and larger cells

replacement of defective cells. The improvement of existing processes or the development of new processes which contribute to better contacting are necessary to realize series-suitable contacting of high-voltage connectors in the system. Laser bonding and micro-clinching are also promising approaches.

The development of flexible contacting processes for the requirements of the different cell formats is important for variant-flexible production of battery modules and packs. This can avoid changeover times and a production standstill [Ebert2014, Just2018]. Even in a production where only one cell format is used, adaptation of the contacting tool can be useful if it leads to reduced process times or increased quality.

Effort and benefit assessment

Improving product quality (RBW 12.1) is the most urgent Red Brick Wall in contacting to reduce embrittlement and corrosion in operation. Even if the effort required to solve this challenge is high, the contribution to quality and cost savings would be significant. However, there are currently no economic solutions that address this challenge.

The minimization of reject rates is another Red Brick Wall (RBW 12.2) that would make a significant contribution to profitability and quality in contacting technology. Reject rates can be reduced with moderate effort through the implementation of new inline measurement technology along with improved process knowledge.

The sustainability and quality of battery systems can also be significantly increased through remanufacturability. The service life of the battery can be extended through detachable connections, and quality will improve with continued process development. The effort required to improve existing contacting processes and research new alternatives for Re-X capability is particularly high.

RBW 12.4, on the other hand, is only of moderate relevance, since contacting for higher currents and larger cell formats has already been partially solved and is on the verge of a breakthrough for pouch cells.

Technical support

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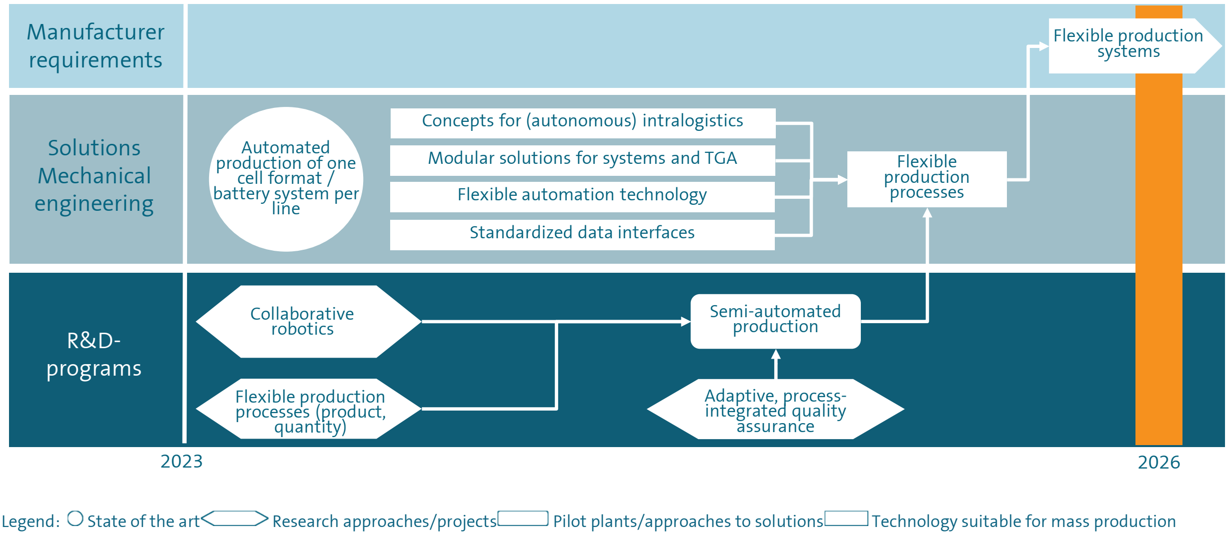
13: Flexible production in module and system assembly

No.*	Red Brick Wall	Current status in comparison to 2020	Relevance**	Timeline***
13.1	Design of flexible production processes (scalability, production flexibility)	Progress made	High	2026
13.2	Adaptive and process-integrated quality assurance concepts	New	High	2026
13.3	Production of different product variants on one production line	Little progress made	Medium	2028

RBW 13.1: Design of flexible production processes (number of units, product flexibility)
The number of different cell formats and battery systems continues to increase. This creates numerous new challenges for production with regard to changing formats and design specifications. This increasingly demands the use of modular and flexible concepts, which can create the necessary framework conditions to implement the required scalability and adaptation of equipment in the production system with minimal effort.

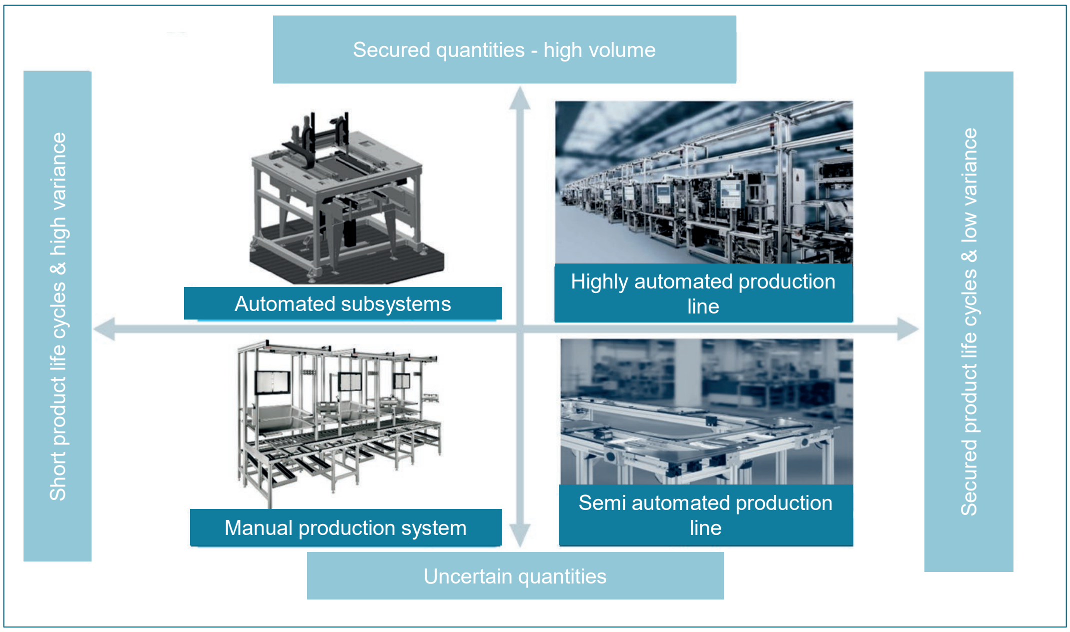


*RBW priority decreases from top to bottom.

**Relevance from the point of view of a battery manufacturer

***Timeline indicates when breakthrough should occur (The timeline considered is until 2035).

Source: VDMA, PEM of RWTH Aachen, BLB of TU Braunschweig according to Phaal2003b



Design options for production systems depending on the number of units and life cycle
Source: Bosch Rexroth

Flexible production

Basics
A look at today's battery market shows a wide variety of different battery systems. The development of new market fields continues to drive this increase in the diversity of variants and quantities. At the module level, the individual battery cells are stacked (pouch cells, prismatic cells) or inserted (cylindrical cells), contacted, and placed in a housing during production (see RBW 11). These modules are then placed in a battery pack with other components (e.g., thermal management system, battery management system) and connected to each other and to other system interfaces using cables or suitable connecting elements. In a final step, the battery pack is sealed to protect the internals from environmental influences. This design results in several degrees of freedom in the product structure and architecture. The structure and functional scope of the final battery system is thereby determined by the requirements of the end application.

In the automotive sector in particular, there is a high degree of diversity in terms of the cell formats used and the battery modules and packs assembled from them. Rapid scalability of the new variants is also needed. Against this background, the cost- and energy-optimized production of battery cells along with their flexible integration into the battery system is becoming more important.

Due to the high production volumes in the automotive sector, there is tension between high levels of automation geared toward maximum efficiency and high flexibility for rapid adaptation of existing production systems. Particularly in the area of module and system assembly, production that is as flexible as possible in terms of variants and unit numbers while at the same time being highly cost-effective is becoming critically important.

The dynamic development of battery technology means that there are significant differences between individual vehicle generations. Changes can extend across all system levels, down to the individual battery cell and the materials used. The development of flexible production systems based on modular and freely-configurable plant concepts offers the possibility to react effectively and purposefully to such short-cycle product changes.

Challenges

The challenges in implementing flexible production are manifold. First of all, a deeper understanding of the product and process is needed to enable future flexibility requirements to be correctly anticipated and scaling requirements to be properly considered. In addition to pure plant and automation planning, aspects of logistics, technical building equipment, and IT-supported monitoring and organization of production must also be considered for the implementation of flexible production concepts. The objective is to create a coordinated overall system of flexible equipment which enables rapid adaptation of existing production systems to changing product designs and upscaled production volumes, with universally applicable operating resources, modular production stations, and trained personnel. With the focus on production processes, the question arises of how capacities and existing flexibility corridors can be exploited in the course of product-side adjustments. Particularly in battery module and system assembly, a detailed understanding of joining, screwing, gripping and dispensing technology is required (RBW 13.1).

In addition to adapting production technologies and processes to product changes or scaled volumes, it is also necessary to ensure quality assurance and traceability of the manufactured (intermediate) products (RBW 13.2). Intelligent systems that can be flexibly adapted to changes or expansions are needed, especially in the areas of cell inspection and grading, component insertion, and contacting.

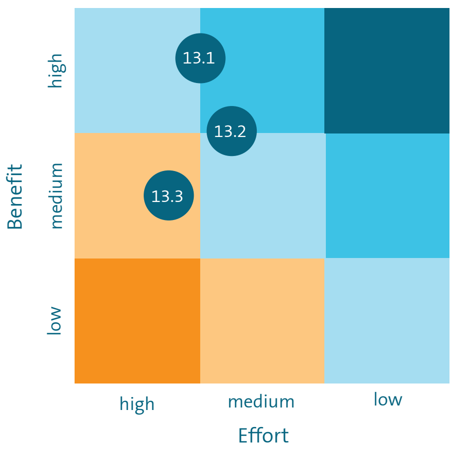
In addition to high sales volumes for the mass market, there is also an increasing demand for niche production for small series and special applications. These are often produced in campaigns of a few months. In order to economically meet such demand, systems must be designed to allow different products in terms of size, format, and other design features (e.g., contacting, cooling system, etc.) to be manufactured in the existing production system (RBW 12.3).

Possible solutions

Promising solutions are aimed at designing flexible processes, plants, and production systems. These would make it possible to respond to changes in product variants or quantities with little effort (RBW 12.1). In smaller production plants, semi-automated processes and human-robot collaboration can be used to flexibly implement complex assembly work in a single process station. Battery system assembly in particular lends itself to the use of such human-robot collaboration. Human coordination and motor skills are particularly suitable for delicate cable assembly, while robotics with precision, repeatability, speed, etc. can be used for repetitive pick-and-place operations and processes with high accuracy and safety requirements. Finally, assembly processes can be further optimized with the aid of *augmented reality*-supported operator guidance and other assistance systems (e.g., pick-to-light, put-to-light, etc.)

For larger production volumes, standardization of interfaces can facilitate expansion and adaptation of the production line. Different sizes and formats can be accounted for by selecting flexible production technologies (e.g., laser

Effort-benefit diagram and impact on sustainability, quality, and costs



	13.1	13.2	13.3
Sustainability	↗	↗	↗
Quality	→	↑	→
Cost savings	↗	↗	↑

Contribution: ↑ = Significant ↗ = Moderate → = None

13.1 Design of flexible production processes

13.2 Adaptive and process-integrated quality assurance concepts

13.3 Production of different product variants on one production line

welding as an option for all three formats) and adjustable gripping and handling systems. Ideally, the production of "similar" product variants can be accommodated by adapting the process parameters; otherwise, quick and easy changeovers can be implemented.

Matrix-based production, with specific manufacturing technologies for each production module, can meet high product flexibility requirements and allows different module types to be manufactured on one production line. In coming years, the focus will be on increased optimization of the costs and efficiency of the individual modules. In addition, the battery itself as a product is also undergoing rapid and dynamic development. Machine and plant manufacturers must be involved in these changes at an early stage, so that changes and adaptations can be implemented quickly (RBW 13.3).

The challenge of traceability of manufactured (intermediate) products can be addressed by track & trace systems along with standardized data structures and interfaces. Unique identification and clear assignment is the basis of every quality system. This can be achieved with RFID tags and scanning of suitable QR codes on every type of subcomponent. These measures are supplemented by continuous monitoring and logging of relevant production data (torques, rotation angles, dosing quantities, etc.). All in all, the development and expansion of digital infrastructure offers a multitude of new possibilities, ranging from a completely digital representation of the production and the product (e.g., digital twins) to real-time production control. In both cases, standardized interfaces simplify the required data exchange for the quality system, so that tailored testing and measurement technology can be integrated along the entire process chain depending on the relevant product requirements and characteristics (RBW 13.2).

Effort and benefit assessment
Flexible production systems offer a high degree of adaptability by being able to rapidly respond to production changes. However, these benefits are also accompanied by substantial efforts, reflected in the complex planning and interlinking of the underlying production systems (RBW 12.1). All (sub-)systems must be coordinated with each other, and it must be ensured that the flexibility requirements do not lead to reduced system reliability and increased probability of failure. It is equally important to consider the economic aspects of overall production.

Modern digitization technologies, which enable adaptive and process-integrated quality assurance concepts, are an essential element of flexible production systems (RBW 12.2). However, direct implementation and application in battery production has its own challenges due to the complex process chain. Nevertheless, the benefits that can be achieved through these measures in the form of higher quality products, increased variant flexibility, and reduced scrap can also be classified as high.

The production of completely different product variants on a single line is assessed as expensive and only moderately useful (RBW 12.3). Although this offers the greatest possible flexibility, it also results in maximum complexity in the production system. A compromise solution is often preferred at this point, which assigns high-volume systems to fully automated lines and other specialized and low-volume variants to separate, semi-automated lines.

Technical support

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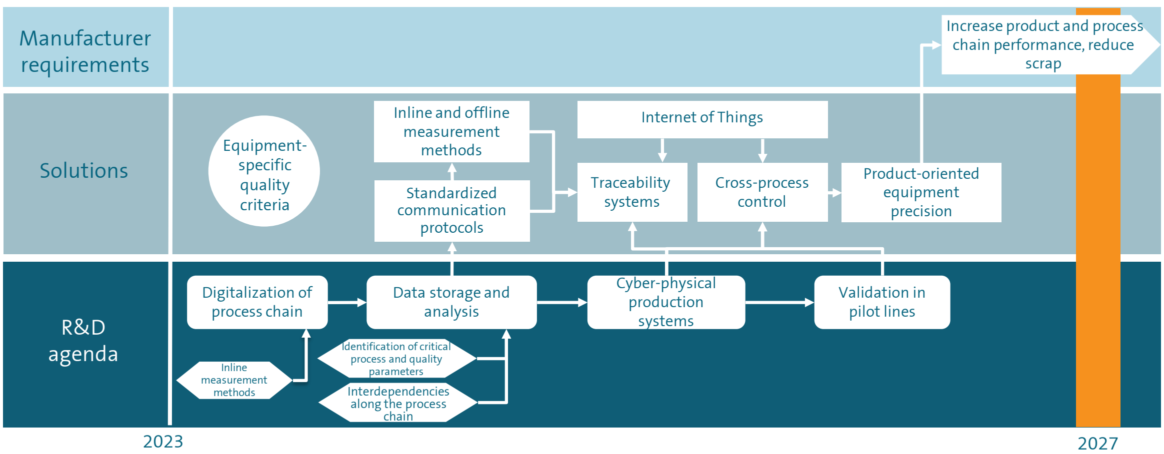
14: Interdependencies - use of digitalization, Industry 4.0, efficient production

No.*	Red Brick Wall	Current status in comparison to 2020	Relevance**	Timeline***
14.1	Identification of key interactions along the process chain and their impact on battery cell performance	Progress made	High	2027
14.2	Communication between heterogeneous production plants + cross-process control/regulation	Progress made	High	2027
14.3	Traceability of the battery cell and its product characteristics over the entire life cycle	Progress made	High	2026

RBW 14.1: Identification of key interdependencies along the process chain
Recording the critical process parameters of the plants, quality parameters of the intermediate products, and the electrochemical properties of the final battery cells forms the basis for identifying the complex interactions within battery cell production. For example, this knowledge can be used with the aid of model-based control systems to reduce the influence of the environment or fluctuating material parameters on production. Communication between heterogeneous production plants via uniform standards enables the exertion of cross-process influence on fully automated, flexible production to increase product quality and production performance and reduce waste.



Legend: State of the art / Research approaches/projects / Pilot plants/approaches to solutions / Technology suitable for mass production

*RBW priority decreases from top to bottom.

**Relevance from the point of view of a battery manufacturer

***Timeline indicates when breakthrough should occur (The timeline considered is until 2035).

Source: VDMA, PEM of RWTH Aachen, BLB of TU Braunschweig according to Phaal2003b

Interdependencies - use of digitalization, Industry 4.0, efficient production

Basics
Battery cells and their production are characterized by complex interdependencies between the processes, equipment, environment, the structure of the individual intermediate products, and the properties of the final cell. Due to the strongly interlinked process chain, these interdependencies also influence economic and environmental aspects of production, such as throughput and energy consumption. Investigation of these interdependencies requires a high level of understanding in the fields of electrochemistry, electronics, mechanics, process engineering, production engineering, and others. The lack of extensive knowledge of the interdependencies along the process chain, especially in battery cell production, is currently reflected in the high scrap rates (low double-digit percentage range) and very long ramp-up phases to series production.

This currently results in unrealized potential in both process and production efficiency. This potential must be tapped using Industry 4.0 approaches (e.g., digitalization, connectivity, and intelligent control of processes and production).

For example, by using a large database and suitable analyses, conclusions can be drawn about the possible causes of production errors so that they can subsequently be automatically corrected. Furthermore, models and simulations of processes, process chains, and battery cells help to reproduce and quantify the complex interdependencies. Cyber-physical systems provide decision-making support and intelligent control of production by coupling production systems, production environment (factory), and (intermediate) products to digital models and information (digital twins). Thus, these and other Industry 4.0 solutions can lead to a significant reduction of the previous scrap rates as well as an increase in flexibility and energy efficiency.

Challenges
A deep understanding of the interdependencies is required to unlock process and process chain potential (RBW 14.1). Each process step has individual parameters which have a direct influence on the quality of the intermediate products and the final battery cells. Even low scrap rates for each process step can quickly lead to significant scrap rates and high costs along the process chain.

For example, process efficiency of 99.5% causes an overall efficiency of about 88% for a process chain with 25 steps (0.995^{25}) (see Table 1). Material and energy efficiency are also strongly affected. Thus, the identification of quality-critical parameters and their effects along the process chain is one of the main challenges to efficient process design and sustainable battery cell production.

In addition, the heterogeneity of production equipment, mostly from different manufacturers, results in a wide range of different parameters and communication interfaces (RBW 14.2). The implementation of suitable algorithms and standards for communication between systems is needed, especially considering the increasing emergence of intelligent control based on artificial intelligence (AI). Similarly, standards must be defined for recording and structuring the acquired data (e.g., equipment parameters, key performance indicators [KPIs]) to enable higher-level components to relate production data to the produced cells. To comply with European Union Battery Passport regulations and to support a circular economy for battery production, data from the production and usage phases must be considered in a lifecycleoriented evaluation and analysis of the battery cells (RBW 13.3). This poses a variety of challenges regarding suitable KPIs for monitoring as well as the storage and security of the generated data.

Efficiency of the individual process steps	Process chain efficiency (with 25 processes)
99.5	88.2
99	77.8
97	46.7
95	27.7

Table 1: Effect of different process efficiencies on the overall process chain efficiency with 25 process steps. process steps.

The heterogeneity of data generated over the life cycle of battery cells also requires cross-competitive standardization for integrating different systems across domains and hierarchies due to the multitude of battery cell types, manufacturers, OEMs, and possible applications.

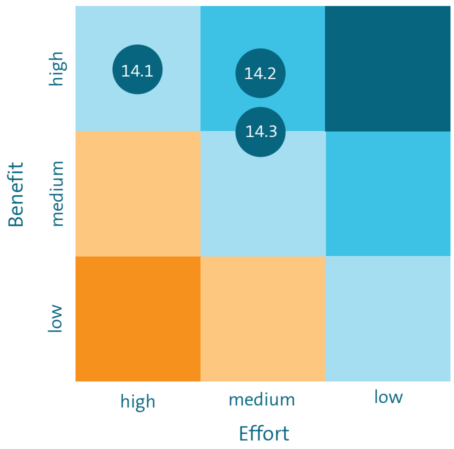
Possible solutions

The digitization of production and the use of Industry 4.0 approaches such as cyber-physical production systems can make a valuable contribution to the systematic control of the diverse interdependencies along the entire process chain and the resulting complexity (RBW 14.1), for example by increasing transparency of the various interdependencies along the process chain or identifying sensitive parameter settings.

Among other things, digitization enables the continuous gathering of relevant process and quality parameters. This also provides the basis for subsequent decision-making support and system control or regulation using Industry 4.0 methods. Key process and quality parameters should be identified in a pilot line prior to implementation in series production. The goal for this pilot line is to monitor all measured variables in order to reduce them to a necessary minimum for subsequent scaling up to series production. Due to the enormous amount of data that is generated during continuous process parameter measurement, it is important to pre-select the relevant data and to buffer it at the automation level, if necessary. Furthermore, inline measurement methods should be increasingly used for the characterization of intermediate products to support the development of efficient production. Inline measurement technology is the basis for adaptive control and can be enhanced by virtual measurement systems (e.g., virtual quality gates). The entirety of the data can either be stored on internal servers, in a cloud platform, or a hybrid solution.

The true value of these considerations is not the collection of the data itself or continuous monitoring during series production, but rather in the evaluation and the associated knowledge gained. This approach of systematically analyzing large amounts of data is also known as data mining. Typical approaches include the individual areas of data classification, segmentation, forecasting, dependency, and variance analysis. The processing and evaluation of extensive data sets makes it possible to use specially developed methods to identify the underlying process interconnections and their interdependencies. The knowledge-based determination of production tolerances based

Effort-benefit diagram and impact on sustainability, quality, and costs



	14.1	14.2	14.3
Sustainability	↑	↗	↗
Quality	↑	↗	↗
Cost savings	↑	↑	→

Contribution: ↑ = Significant ↗ = Moderate → = None

14.1 Identification of the interdependencies

14.2 Communication and control/regulation of heterogeneous production plants

14.3 Traceability over the entire life cycle

on measured data or models also provides an opportunity to further reduce production costs or increase product quality by avoiding unnecessarily precise tolerances. For example, supervised learning models can be used in electrode production to automatically detect coating defects and optimize process parameters.

Manufacturer-independent standards for plant interfaces and data structures are needed for linking sequential production equipment, such as OPC UA CS[27] (RBW 14.2). Automated control of successive process steps without the need for human intervention can also be achieved by linking the various systems. In the future, controls will be based on AI approaches (i.e., machine learning) to reduce the effects of environmental influences and stochastically fluctuating product properties as much as possible. The experience of equipment operators can and should also be incorporated into the development of control algorithms.

In addition, the use of a cyber-physical production system can also create a digital representation of the actual production/product, which continuously gathers essential production parameters and uses suitable models and simulations (e.g., artificial neural networks, process chain simulations) to provide decision-making support for production. These can also provide support for the planning of new factories or the scaling of existing production lines.

The final quality control of the battery cells is monitoring the cell performance in the usage phase. Significant conclusions can be drawn about quality-enhancing parameters within

[27] OPC UA - Open Platform Communications Unified Architecture is a platform-independent, service-oriented architecture (SOA) for standardized data exchange and is described in so-called Companion Specifications.

production by linking data from production and the usage phase (RBW 14.3). As with production, only those parameters that contribute a high level of information on the quality of the battery cell should be measured in the usage phase. However, this requires a binding legal framework on access, ownership, data use, and more. All data gathered over the entire life cycle can be bundled in the battery passport.

Effort and benefit assessment

Evaluation of the interdependencies within production (RBW 14.1) creates a foundation for estimating the potential of activities related to process integration in future production lines as well as process adaptations and monitoring methods. Consideration of the identified critical process parameters and the resulting effects on the quality of intermediate and end products makes it possible to limit process monitoring to essential parameters in order to reduce investments for digitalization (e.g., measurement infrastructure, including maintenance and operation, as well as storage) as much as possible. This kind of demand-oriented equipment design can increase the return-on-investment for plant equipment. Similarly, deep knowledge of the interdependencies along the process chain can make a significant contribution to reducing high scrap rates, energy demand, and CO_2 emissions. Consequently, the high additional effort required for data acquisition, digital mapping, and analysis of large volumes of data to obtain a deep understanding of the process is offset by significant contributions to sustainability, quality, and cost savings.

The establishment of fully automated production based on communicating equipment (RBW 14.2) also offers a high benefit at a medium cost to battery manufacturers. This contributes to a significant reduction of effort and associated costs during ramp-up phases. Furthermore, the support of AI-based control or regulation systems is expected to increase process stability, positively influencing battery cell quality and reducing production scrap. This has a positive impact on the sustainability of battery production.

In addition, intelligent control systems can be used to identify tolerances for intermediate product characteristics in the individual processes for the final battery cell performance. The aim is to specifically avoid unnecessarily high process accuracies, which do not have a decisive positive influence on battery performance but do increase the investment and operating costs (e.g., for more precise systems).

Similarly, the implementation of fully automated process controls and regulations creates moderate effort for the development of standards for machine-to-machine communication, provision of data to AI systems, and especially AI-based control algorithms.

Linking data from production with data from the usage phase offers a high benefit (RBW 14.3). Suitable product characteristics for battery cells or individual battery cell types for different applications can be derived from the collected data. This data can also provide decision-making support following the initial use phase as well as recycling.

Furthermore, findings can be integrated into the product design and the production process to increase the quality of the battery cell in the usage phase. For example, adapting the batteries to the subsequent usage profile enables suitable dimensioning or selection of a sufficiently high-performance battery cell to meet the relevant quality requirements, which also has a positive impact on sustainability.

The moderate effort required for implementation is related to the development of uniform standards for monitoring and the creation of overarching legislation that regulates the ownership and handling of the data generated during the utilization phase.

Technical support

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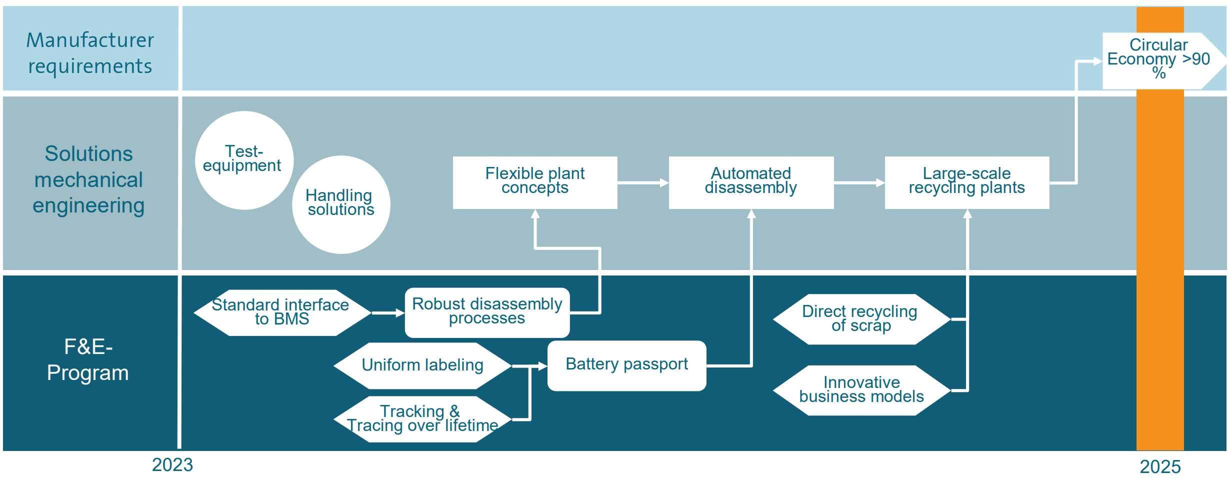
15: Circular economy

No.*	Red Brick Wall	Current status in comparison to 2020	Relevance**	Timeline***
15.1	Automation of disassembly with large packing variety	Progress made	High	2025
15.2	Direct recycling of rejects in production	New	High	2025
15.3	Innovative business models to support 2nd life and reuse	Progress made	Medium	2025
15.4	Consideration of Design for Re-X in product development and design of production processes	New	Medium	2025

RBW 15.1: Automation of disassembly with large packing variety:
Large-scale facilities for material recycling at the cell level are currently under construction. Technical processes for material recovery must enable a yield of up to almost 100 % so that genuine recycling is possible. The flexibility and automation of the plants and especially of battery system disassembly are gaining importance due to the increasing quantities and variety of returned battery systems. The automation of disassembly has a major influence on the economic and ecological sustainability of recycling, especially with regard to the purity of the input materials into the recycling process and thus on the quality of the recyclate. Non-destructive removal and disassembly of individual battery components can also support second-life applications and thus extend the useful life of batteries.



Legend: ○ State of the art ⬡ Research approaches/projects ▭ Pilot plants/approaches to solutions ▭ Technology suitable for mass production

*RBW priority decreases from top to bottom.

**Relevance from the point of view of a battery manufacturer

***Timeline indicates when breakthrough should occur (The timeline considered is until 2035).

Source: VDMA, PEM of RWTH Aachen, BLB of TU Braunschweig according to Phaal2003b

Circular economy

Basics

The recycling of battery materials is of critical importance for the sustainability of the battery system as a whole. The environmental impact, which is mainly caused by the extraction and initial processing of raw materials, can be greatly reduced by reusing cell materials. This approach can also increase Germany's security of supply and reduce the social, ethical, and political conflicts associated with the extraction and processing of battery materials. A key prerequisite for the successful implementation of the circular economy is high quality and reusability of secondary battery materials.

To secure important raw materials for battery cells, the goal is to establish a functioning recycling economy by 2025 in which more than 90 % of the critical raw materials are retained in the cycle, in contrast to current material recovery rates of between 50 and 80 % [Roland-Berger2019]. Special emphasis is placed on the recycling of economically valuable, resource-critical, and environmentally harmful materials. The basic technical prerequisites for material recovery rates above 90% are already largely in place. In the past, pyrometallurgical recycling processes were mainly used because they are very resistant to the mixing of different input materials. However, mechanical-hydrometallurgical processes are becoming increasingly more common due to their higher material recovery rates and lower energy consumption. Furthermore, a variety of special processes are also being developed in combination with established recycling processes [Ciez2019], [CEID2020], [Harper2019], [Sommerville2021], [Neidhardt2022].

European industry and research have given high priority to the development of new recycling concepts for the circular economy. At the political level, the recycling of batteries is being promoted by the European Green Deal, among other things. In this context, EU Battery Directive 2006/66/EC has been reviewed and a proposed update has been prepared, which is expected to go into effect in 2023[28]. According to the current status of discussions, the industry for the European market will be confronted with a number of requirements regarding the recyclability of batteries. For example, this applies to minimum recycled quantities in the production of new battery systems, material recovery rates in recycling, and the provision of battery-specific information and data in the form of a battery passport. The material-specific recyclate rates planned for 2031 for cobalt (16%), nickel (6%), and lithium (6%) are described as ambitious by both industry and non-governmental organizations (NGOs) due to the projected market growth [Recharge2021], [DUH2022]. In addition to an overall recycling efficiency of 70%, material-specific recycling efficiencies for cobalt (90%), nickel (90%), lithium (50%), and copper (90%) are required for 2027.

Challenges

Numerous challenges must be overcome in parallel to enable a successful battery circular economy. This begins with the identification and return of the spent batteries to the dismantling or recycling company. Due to their classification as hazardous goods, transportation requirements for spent batteries are high and cost-intensive[29].

Beyond the requirements of the Battery Directive, the economic efficiency of the recycling process, which depends on the costs of

[28] Legislative text on battery regulation from the Council of the EU, ST-5469-2023-INIT_en.pdf (Jan. 2023)

[29] MB_36_Shipping_Lithium_Ion_Batteries_2022.pdf (zvei.org) (Jan. 2023).

the spent batteries and the recycling process as well as the proceeds from the secondary materials, also plays a central role for a successful recycling economy. Secondary materials are an opportunity for the European market to become less dependent on international primary materials. Primary materials often have volatile prices, which are determined by political and economic decisions. The higher the material prices, the greater the incentives for high material recovery rates. One example of this is cobalt, which already has a recovery rate of about 95% in pyrometallurgical processes [Chen2019]. However, recycling is not currently focused on materials of lower economic value, such as lithium. The updated Battery Directive primarily provides incentives for the development of holistic recycling processes in which a wider range of materials is recovered.

Due to the large variety of battery cells, modules, and systems used, the dismantling process is currently limited and carried out in time-consuming and cost-intensive manual work. In view of the increasing quantities of returned batteries of over 500,000 in 2030 and over 1.2 million predicted for 2040 in Germany alone, intelligent automation solutions for battery disassembly will be increasingly required in the future [CEID2020]. It is essential to address this challenge today in order to establish a reliable and sustainable recycling network within Germany and Europe.

The end-of-life (EoL) route taken by the batteries at the end of their service life depends on a large number of factors. A decision on the EoL strategy to be applied can only be made after an analysis of the returned batteries using specially-defined test criteria, such as the residual capacity and State-of-Health (SoH). In this context, a high degree of disassembly enables the materials to be separated by type, which is particularly helpful in highly specialized processes. The possibility of non-destructive removal of individual components also supports the use of batteries in so-called second-life applications (e.g., as stationary energy storage devices), which contributes to extending the service life. With the optimization of current battery systems for maximum energy density, minimum production costs, and maximum safety, non-destructive dismantling is currently challenging. Due to the high variety of current battery systems, especially with regard to the cell chemistries used, mixed fractions of different active and inactive materials must be processed in recycling processes [Diekmann2017]. Therefore, either flexible process technology or efficient pre-sorting is needed to allow recycling processes to deal with different material fractions [CEID-2020]. Ideally, the respective advantages of thermal, chemical, and mechanical process categories can be combined in the future and converted into economical processes that can be implemented on an industrial scale.

In addition to the design and optimization of material recovery, another challenge is avoiding production rejects that are not reused and must be disposed of. Strategies for direct and in-plant recycling are being explored in production for this purpose.

Possible solutions

During disassembly, the battery modules and systems are first discharged so that the peripheral components can then be dismantled and reprocessed. Mechanical engineering already offers very good solutions for testing and discharging. Flexible and AI-based handling and system technology is also being developed to automate these process steps. A uniform, standardized BMS interface that is accessible to the decision-makers can support robust process management. This interface could be used to determine important information about the usage profile and possible faults of the battery, in particular about the State of Health (SoH). This information could then be used by subsequent processes to precisely control the discharge process and respond to potential safety risks. Safe, non-destructive, and cost-effective analysis procedures as well as disassembly and recycling processes have to be established for this purpose [CEID2020], [Thompson2020]. Future battery generations should also be developed and designed to support the recyclability of the materials or even individual components. This sense of "design for recycling" in product design can significantly facilitate the dismantling and recycling process, and is therefore a key research topic. Design approaches include modularization of the battery, substitution of adhesives or other material bonds, and reduction of battery module voltage. Cooperation between OEMs and machinery and plant manufacturers, which is increasingly evident on the current market, can drive the development of recycling concepts and innovative second-life business models.

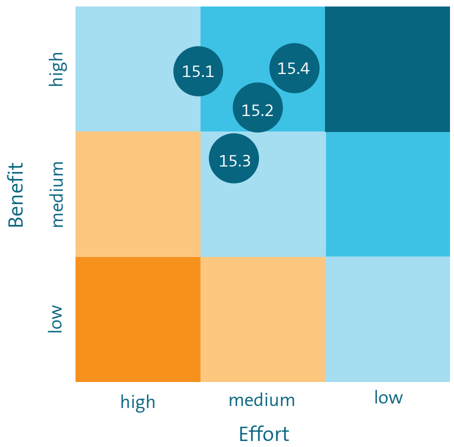
A uniform identification of the battery systems could also support the automation process. This approach would be particularly effective in combination with a transparent database in the form of a battery passport which supplements the labeling and BMS interface, and can track and trace the materials and connections used as well as their status in the life cycle of the battery system. This battery passport is required by the new EU Battery Regulation, and the static (manufacturer, battery type, composition, disassembly instructions) and variable (SoH, expected lifetime) information to be provided is clearly defined. Comprehensive implementation of this concept will enable system concepts that can react flexibly to the specific battery system during the dismantling process. Furthermore, this would also allow the battery to be used for an optimal EoL application for its properties. The implementation of this system requires the development of suitable solutions which can be used to collect and evaluate relevant information, ideally in an automated process.

In addition to recovering the individual substances with the required purity, approaches are being pursued to recondition the active materials and reuse them in cells. The BMBF "Recycling/Green Battery" competence cluster, launched in 2020, is researching innovative recycling processes to increase the achievable recovery level to more than 80 % of the battery [greenBatt-2022].

Finally, approaches for implementing or expanding a circular economy can already be seen in battery cell production. The starting point is minimizing production waste, effectively reducing material waste and material consumption. Inspection systems integrated into the production line which can reliably detect anomalies or defects and remove them before further processing are particularly suitable for this purpose.

In addition to scrap reduction, solutions are being developed which can be used for the direct reprocessing of intermediate products classified as scrap, such as direct recycling. The overarching goal is to preserve the material structure and a high level material quality so that it can be returned to the original production process. Processes for this are available in the European industry portfolio. One example is electrohydraulic shredding, in which sound waves are used to break down selected materials.

Effort-benefit diagram and impact on sustainability, quality, and costs



	15.1	15.2	15.3	15.4
Sustainability	↗	↑	↗	↑
Quality	↗	↗	→	↗
Cost savings	↑	↑	↗	↗

Contribution: ↑ = Significant ↗ = Moderate → = None

15.1 Automation of disassembly 15.2 Direct recycling 15.3 Innovative business models 15.4 Design for Re-X

Effort and benefit assessment
The benefits resulting from the RBWs depend heavily on the business models of the respective economic stakeholders in the market. The benefits for all RBWs, which are in the moderate to high range, are therefore subject to a certain degree of uncertainty.

With rising production numbers and increasing production in *gigafactories*, the variety of battery packs on the market is decreasing and the quantities are becoming sufficiently large for automated dismantling. Therefore, the effort is classified as moderate, while the benefit for the automotive sector is high (RBW 15.1). Absolute scrap volumes also increase with production figures. The recycling of production scrap is rated as a moderate effort with high benefit (RBW 15.2).

The circular economy takes on a central role from an economic, ecological, and social perspective for current battery technologies, as it can reduce material-related emissions and effects. Closed material cycles contribute to increased economic efficiency and improved eco-balance. The design of new concepts and business models by battery manufacturers and recycling companies is crucial and must be competitive, not least from an economic perspective (RBW 15.3). Clear legislation such as the new Battery Directive strives for the development of the circular economy in the European market. The defined specifications for recycling quotas and secondary material quantities make it important to consider Design for Re-X in product development and the design of production processes. Here, a high benefit can be achieved with medium effort (RBW 15.4).

Technical support

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Project	Brief description	Research Institutes	Runtime	RBW
Action (greenBat)	Scrap utilization electrode production	TU Braunschweig iPAT, Fraunhofer-Institut für Schicht- und Oberflächentechnik (IST, Zentrum für Sonnenenergie- und Wasserstoff-Forschung Baden-Württemberg (ZSW)	2021-2024	1, 2, 3, 5, 6, 7, 8, 9, 10, 11, 13
ARTEMYS	Scalable, low-cost manufacturing technologies for composite cathodes and electrolyte separators in solid-state batteries.	TU Braunschweig iPAT	2018-2021	1, 2, 4
AutoSpEM	Automatic handling for the process-reliable and economical production of storage batteries for e-mobility	Karlsruher Institut für Technologie (KIT)	2012-2015	10
BaSyMo	Battery system for modularity: Development and design of handling and ergonomics for a modular battery system in different application scenarios and conception of a manufacturer-independent, specifiable design.	Universität Stuttgart, Fakultät 7 Konstruktions-, Produktions- und Fahrzeugtechnik - Institut für Konstruktionstechnik und Technisches Design	2016-2019	10.B
BatCon	Function-integrated high-current connectors for battery modules using cost-optimized manufacturing technologies	Fraunhofer-Institut für Werkstoff- und Strahltechnik (IWS)	2013-2015	11
BatMan	Research, development and integration of a novel, scalable and modular battery management system.	Leibniz Universität Hannover	2010-2013	10
BatteReMan	Increasing resource efficiency in the LIB life cycle through remanufacturing	PEM der RWTH Aachen	2016-2019	14
Cell-Fi	Acceleration of electrolyte absorption through optimized filling and wetting processes	IWF der TU Braunschweig, IWB der TU München, MEET Batterieforschungszentrum der Uni Münster	2016-2019	7
Cell-Fill	Process-structure-property relationship for filling and wetting processes of large format lithium-ion batteries.	IWF der TU Braunschweig, IWB der TU München, MEET Batterieforschungszentrum der Uni Münster, Fraunhofer-Institut für Techno- und Wirtschaftsmathematik (ITWM), Fraunhofer-Institut für Keramische Technologien und Systeme (IKTS), Fraunhofer-Institut für Silicatforschung (ISC), PEM der RWTH Aachen	2019-2022	6, 7, 13
cyberKMU²	Developing an online platform to help manufacturing SMEs identify cyber physical systems to address manufacturing vulnerabilities	FIR e. V. an der RWTH Aachen, WZL der RWTH Aachen	2016-2019	13
DaLion	Data mining in the production of LIB cells	Battery LabFactory (BLB) und TU Braunschweig	2015-2018	13
DaLion 4.0	Data mining as the basis of cyber-physical systems in lithium-ion battery cell production.	TU Braunschweig IWF, TU Braunschweig iPAT, TU Braunschweig ifs, TU Braunschweig InES, TU Braunschweig elenia, TU Braunschweig IÖNC	2019-2021	1, 2, 3, 5, 6, 7, 8, 9, 10, 11, 13
DataBatt	Integration of horizontal data structures in battery production	Fraunhofer-Institut für Produktionstechnologie (IPT), HIU des KIT, wbk des KIT, IMA der RWTH Aachen, PEM der RWTH Aachen	2020-2023	12
DigiBatMat (ProZell 2; Material Digital)	Digital platform for battery material data, knowledge and their linkage	INM (Leibnitz Institut für Neue Materialien), Hochschule Aalen, AWS-Institut für digitale Produkte und Prozesse gGmbH, KIT (Institut für Angewandte Informatik und Formale Beschreibungsverfahren), TUBS: iPAT und IWF	2021-2024	12,13
EcoBatRec	Demonstration plant for cost-neutral, resource-efficient processing of spent lithion-ion batteries used in electromobility	IME Metallurgische Prozesstechnik und Metallrecycling der RWTH Aachen	2012-2016	14
ecoLiga (greenBat)	Recycling and resynthesis of carbon materials from lithium batteries	TU Braunschweig IWF, IME (RWTH), HZDR, Fraunhofer IWS	2020-2023	13, 14
Effi.Com	Development of a camera- and ultrasound-based sensor and diagnostic system (coating process)	PEM der RWTH Aachen, ISEA RWTH Aachen	2016-2017	2
EffiForm	Efficient forming strategies to increase service life, reliability and safety, and reduce costs	Fraunhofer-Institut für Keramische Technologien und Systeme (IKTS), MEET Batterieforschungszentrum der Uni Münster, TU München	2016-2018	9

Project	Brief description	Research Institutes	Runtime	RBW
EMKoZell	Results database, model and communication management for the battery cell production competence cluster	Technische Universität Carolo-Wilhelmina zu Braunschweig, Battery LabFactory Braunschweig	2016-2019	13
eKoZell	Results database, model and communication management for the competence cluster battery cell production (successor EMKoZell)	Technische Universität Carolo-Wilhelmina zu Braunschweig, Battery LabFactory Braunschweig	2019-2023	13
Epic (ProZell 2)	Increasing the throughput rate in electrode production through innovative drying management	TU Braunschweig iPAT, TU Braunschweig Ifs, KIT (TFT - TVT), KIT (wbk), ZSW (ECP)	2020-2023	2
EVanBatter (greenBat)	Development of a resynthesis route of active materials for lithium-ion batteries that is robust against impurities.	TU Braunschweig iPAT, Fraunhofer Institut für Schicht- und Oberflächentechnik (IST), TU Clausthal, Fraunhofer-Institut für Keramische Technologien und Systeme (IKTS)	2018-2022	13,14
EVOLi2S	Evaluation of the technical economic advantages of the open cell module for lithium-ion and lithium-sulfur batteries with regard to stationary and mobile applications.	TU Braunschweig iPAT, MEET Batterieforschungszentrum der Uni Münster	2018-2021	1, 2, 3, 5, 6, 7, 8, 11
ExLaLIB	Increased energy and material efficiency through the use of extrusion and laser drying technology (electrode production LIB)	PEM RWTH Aachen, WWU Münster, MEET Batterieforschungszentrum der Uni Münster	2016-2019	1, 2
E-Qual	Data-based process and method development for efficiency and quality improvement in lithium-ion cell production	Zentrum für Sonnenenergie- und Wasserstoff-Forschung Baden-Württemberg – Standort Ulm	2020-2023	13
Fab4LiB	Research into measures to increase material and process efficiency in LIB production across the entire value chain.	PEM RWTH Aaachen, MEET Batterieforschungszentrum der Uni Münster	2018-2019	5, 6
FastChargeLongLife	Development of optimized fast charging methods	Battery LabFactory und TU Braunschweig (iPAT, elenia, InEs)	2020-2023	5, 6
FesKaBat	Solid cathodes for future high-energy batteries	Universität Münster, Institut für Anorganische und Analytische Chemie, Battery LabFactory (BLB) und TU Braunschweig	2016-2019	1, 2, 3
FlexBatt	Flexible assembly concepts for modular battery systems	Battery LabFactory und TU Braunschweig (BLB, IWF)	2014-2016	12
FlexJoin	Process-safe system and joining technology for the flexible production of battery modules	Fraunhofer-Institut für Lasertechnik ILT	2016-2018	11, 12
FormEL (ProZell2)	Determination of process-quality relationships of formation and end-of-line testing for function-integrated overall process optimization	elenia der TU Braunschweig, InES der TU Braunschweig , MEET Batterieforschungszentrum der Uni Münster, EES der TU München, PEM der RWTH Aachen	2020-2023	9
GranuProd	Granule-based single-step electrode production system with intelligent production control	TU Braunschweig iPAT, KIT (TFT), TUM (iwb)	2021-2023	5,6
HEBEL	High energy battery with improved electrolyte separator composite ceramic separator/electrolyte	FAU Erlangen, Lehrstuhl für Chemische Reaktionstechnik	2009-2012	4
HEMkoop	High-energy materials processed cost-efficiently and ecologically	BatteryLabFactory (BLB) und TU Braunschweig, MEET Batterieforschungszentrum der Uni Münster	2018-2021	1 2, 3, 5, 6, 7, 9, 11
HighEnergy	Manufacturing of high-capacity, structured electrodes	KIT, Institut für Produktionstechnik, TU Braunschweig, Universität Ulm, Institut für Stochastik, Zentrum für Sonnenenergie- und Wasserstoff-Forschung (ZSW) Baden-Württemberg	2016-2019	2, 3
HiStructures (ProZell 2)	Hierarchical structuring of high-capacity electrodes	TU Braunschweig iPAT, TU Braunschweig Ifs, TU Braunschweig InES, ZSW (ECM), KIT (TFT), UU, DLR-HIU, KIT (IAM-WET)	2019-2022	1, 2, 3
HoLiB	High-throughput processes in the production of lithium-ion batteries	TU Braunschweig IWF, TU Braunschweig ifs, TU Berlin IWF, Fraunhofer ILT	2019-2022	5, 6, 11, 12
HVBatCycle	HV Battery Recycling and Resynthesis Processes for Sustainable and Functionally Preserved Material Cycles	TU Braunschweig iPAT, Volkswagen AG, TANIOBIS, Schmalz, Viscom, RWTH Aachen, Fraunhofer Institute for Surface Engineering and Thin Films IST	2022-2024	13,14
EMKoZell	Ergebnisdatenbank, Modell- und Kommunikationsmanagement für das Kompetenzcluster Batteriezellproduktion	Technische Universität Carolo-Wilhelmina zu Braunschweig, Battery LabFactory Braunschweig	2016-2019	13
eKoZell	Ergebnisdatenbank, Modell- und Kommunikationsmanagement für das Kompetenzcluster Batteriezellproduktion	Technische Universität Carolo-Wilhelmina zu Braunschweig, Battery LabFactory Braunschweig	2019-2023	13

Project	Brief description	Research Institutes	Runtime	RBW
IKEBA	Integrated components and integrated design of energy-efficient battery systems	Fraunhofer-Institut für Integrierte Schaltungen, KIT - Institut für Angewandte Materialien - Angewandte Werkstoffphysik	2013-2016	10
InnoCase	Research and development of innovative housing concepts for large-format lithium-ion batteries	ElringKlinger AG, Futavis GmbH, Manz AG, TRUMPF Gruppe, PEM der RWTH Aachen, IWB der TU München , EES der TU München	2019-2022	10
InnoDeLiBatt	Innovative production technologies for the manufacture of disassembly-ready lithium-ion battery storage systems	KIT, Institut für Produktionstechnik (wbk)	2016-2018	11, 12, 14
InnoRec (ProZell 2)	Innovative recycling processes for new lithium cell generations	TU Braunschweig iPAT, TU Clausthal (IFAD), RWTH Aachen (IME), TUBAF (MVTAT), MEET Batterieforschungszentrum der Uni Münster	2019-2022	14
InTenz	Intensive post-drying of components for lithium-ion cells in discontinuous drying ovens	TU Braunschweig, Hoschule Landshut	2018-2020	2
InteKal (InZePro)	Intelligent calendering	TU Braunschweig iPAT, wbk Institut für Produktionstechnik (KIT), iwb Institut für Werkzeugmaschinen und Betriebswissenschaften (TUM); assoziierte Partner: Siemens AG, BREYER GmbH Maschinenfabrik	2021-2024	2,3
IntelliPast (InZePro)	Development of an intelligent and autonomous paste manufacturing process	TU Braunschweig iPAT, Institute of Mechanical Process Engineering and Mechanics (MVM), Karlsruhe Institute of Technology (KIT), Institute of Production Science (wbk), Karlsruhe Institute of Technology (KIT)	2020-2023	1
IQ-EL	Inline intermediate product analysis and derivation of a quality gate concept for electrode production	TU Braunschweig iPAT, Karlsruher Institut für Technologie (KIT): IAM–WK, IAM-ESS, MVM, TFT, Zentrum für Sonnenenergie- und Wasserstoff-Forschung Baden-Württemberg (ZSW)	2021-2024	1-6
InTreS	Innovative carrier materials for optimizing the current conductors of electrical storage systems	PEM der RWTH Aachen, ISF der RWTH Aachen	2017-2019	11
KonSuhl	Continuous suspension production	Battery LabFactory (BLB) und TU Braunschweig	2016 - 2019	1
LCA-Li-Bat-Recycling	Life cycle assessments of the LithoRec II and EcoBatRec recycling processes for lithium-ion batteries	Öko-Institut - Institut für angewandte Ökologie e. V.	2012-2016	14
LeiKonBin	Development of battery materials and contacting technologies for the production of battery cells based on electrically conductive adhesives	TU Braunschweig Ifs, IÖNC	2018-2020	1, 2, 11
LiBforSecUse	Quality assessment of Li-ion batteries for electric vehicles for second use applications	Physikalisch-Technische Bundesanstalt (Projektpartner: CMI, LNE, METAS, NPL, RISE, Aalto Univ, ACE, NIC, BRS, HIOKI, JRC, Li.plus)	2018-2021	13, 14
LiBEST2	Development of high capacitance silicon anodes	HI MS (Helmholtz Institute Münster), TU Braunschweig iPAT, MEET Münster, Fraunhofer IWS (Institut für Werkstoff- und Strahltechnik), NTU (National Taiwan University), NTUST (National Taiwan University of Science and Technology)	2020-2023	1,2,3
LiOptiForm	Power electronic optimization of forming equipment for LIBs	WHS Zwickau, Fakultät Elektrotechnik, Fraunhofer IKTS	2016-2018	9
LithoRec II	Recycling of lithion ion batteries from electric vehicles	TU Braunschweig, MEET Batterieforschungszentrum der Uni Münster	2012-2015	14
LiBforSecUse	Quality assessment of Li-ion batteries for electric vehicles for second use applications	Physikalisch-Technische Bundesanstalt (Projektpartner: CMI, LNE, METAS, NPL, RISE, Aalto Univ, ACE, NIC, BRS, HIOKI, JRC, Li.plus)	2018-2021	13, 14
IKEBA	Integrated components and integrated design of energy-efficient battery systems	Fraunhofer-Institut für Integrierte Schaltungen, KIT - Institut für Angewandte Materialien - Angewandte Werkstoffphysik	2013-2016	10
InnoCase	Research and development of innovative housing concepts for large-format lithium-ion batteries	ElringKlinger AG, Futavis GmbH, Manz AG, TRUMPF Gruppe, PEM der RWTH Aachen, IWB der TU München , EES der TU München	2019-2022	10
InnoDeLiBatt	Innovative production technologies for the manufacture of disassembly-ready lithium-ion battery storage systems	KIT, Institut für Produktionstechnik (wbk)	2016-2018	11, 12, 14

Project	Brief description	Research Institutes	Runtime	RBW
LiMeS	Lightweight lithium-metal-sulfur battery system based on structured hybrid electrode concepts for aerospace applications	TU Braunschweig iPAT, Fraunhofer IPA, LUH (IfES), Airbus S&D, GKD, GS GLOVEBOX, Stercom, Lödige, FutureCarbon	2019-2022	1,2,3
LiVe	Fabrication and targeted nanostructuring of electrode structures for high-power lithium batteries.	IME der RWTH Aachen, IPAT der TU Braunschweig, Universität Duisburg-Essen, Universität Erlangen-Nürnberg, Justus-Liebig-Universität Gießen, Leibniz-Universität Hannover, MEET Batterieforschungszentrum der Uni Münster	2009-2013	2
LoCoTroP	Low-cost dry coating of battery electrodes for energy-efficient and environmentally friendly production processes	Fraunhofer-Institut für Produktionstechnik und Automatisierung, Hochschule für angew. Wissenschaften Landshut, TU Braunschweig	2016 - 2019	1,2
LOWVOLMON (greenBat)	Monitoring of low-volatile electrolytes in the mechanical recycling process chain	TU Bergakademie Freiberg (MVTAT), TU Braunschweig (iPAT), Karlsruher Institut für Technologie (TVT), Fraunhofer-Institut für Werkstoff- und Strahltechnik, TU Clausthal	2021-2024	
MiBZ	Development of a multifunctional intelligent battery cell	Technische Universität München, Fraunhofer-Institut für Integrierte Systeme und Bauelementetechnologie	2015-2018	10
MiKal (ProZell 2)	Optimum electrode structure and density through integrated design of mixing and calendering processes	TU Braunschweig iPAT, TUM (Iwb), MEET, ZSW (ECP), KIT (IAM-WET)	2019-2022	2, 3
MultiDis	Multiscale approach for the description of soot decomposition in the dispersion process for process- and performance-optimized process control	Battery LabFactory (BLB) und TU Braunschweig , Karlsruher Institut für Technologie, Institut für Mechanische Verfahrenstechnik und Mechanik (MVM) Institut für Angewandte Materialien – Werkstoffe der Elektrotechnik (IAM-WET)	2016-2019	1
MultiEx (ProZell 2)	Development of a methodology for the design and scaling of continuous dispersing processes in lithium-ion battery production by means of simulative and experimental investigations".	TU Braunschweig iPAT, KIT (MVM)	2019-2022	1, 2
NeW-Bat	New energy-efficient recycling of battery materials	Fraunhofer-Institut für Silicatforschung	2016-1019	14
Newbie	Development of sustainable, safe, and fast-charging next-generation lithium-ion batteries (LIBs) with long lifetimes in electromobility applications.	TU Braunschweig (iPAT, ifs, iwf, elenia), Mercedes-Benz AG, MAHLE International GmbH, TRUMPF GmbH & Co. KG	2021-2024	1,2,3
NextGenBat	Expansion of existing facilities to also include novel materials and cell concepts and research on potential industrialization	RWTH Aachen, Forschungszentrum Jülich GmbH, Fraunhofer-Institut für Lasertechnik (ILT)	2018-2020	12
NP-LIB	Sustainable core process technologies for the mass production of Li-ion batteries	Manz AG, SW Zentrum für Sonnenenergie- und Wasserstoff-Forschung Baden-Württemberg	2013-2015	5, 6, 9
Oekobatt 2020	Ecologically and economically produced LIB for "Battery 2020	Zentrum für Sonnenenergie- und Wasserstoff-Forschung Baden-Württemberg Ulm	2016-2018	14
OekoTroP (ProZell 2)	Ecologically gentle dry coating of battery electrodes with optimized electrode structure	TU Braunschweig iPAT, HAW-Landshut, Fraunhofer IPA, Fraunhofer-ISIT	2019-2022	1, 2, 12
ÖkoMatBatt	Ecologically and economically sustainable materials for cathode and anode coating in the lithium-ion battery.	VARTA Microbattery GmbH, ARLANXEO Deutschland GmbH,Hobum Oleochemicals GmbH, Fraunhofer Institut (IST), TU Braunschweig (iPAT, ifs)	2021-2024	1,2,12
OptiFeLio	Optimized design and production concepts for the manufacture of lithium-ion battery housings	Fraunhofer-Institut für Chemische Technologie, KIT - Fakultät für Maschinenbau - wbk , ZSW	2014-2017	10
OptiKeraLyt	Material and production process optimization for lithium-ion batteries with ceramic solid-state electrolytes.	PEM der RWTH Aachen , Forschungszentrum Jülich GmbH, Institut für Energie- und Klimaforschung, Werkstoffsynthese und Herstellungsverfahren (IEK-1), Fraunhofer-Institut für Lasertechnik (ILT), Deutsches Zentrum für Luft- und Raumfahrt (DLR), Helmholtz-Institut Ulm (HIU), Universität Duisburg-Essen	2019-2021	6, 7
Optilyt	Development of customized separator/electrode systems for optimized electrolyte filling of LIBs	Fraunhofer-Institut für Keramische Technologien und Systeme IKTS	2014-2017	4, 7
OptiZellForm	Acceleration and energetic optimization of cell formation	PEM der RWTH Aachen, elenia - Institut für Hochspannungstechnik und Elektrische Energieanlagen, MEET Batterieforschungszentrum	2016-2019	9

Project	Brief description	Research Institutes	Runtime	RBW
PErfektZell	Process quality improvement through a novel extension on the calender for the processing of battery electrodes for cell production	Karlsruher Institut für Technologie - Fakultät für Maschinenbau - wbk Institut für Produktionstechnik	2019-2021	3
PräLi (ProZell 2)	Coating and prelithiation of anodes	TU Braunschweig iPAT, TU Braunschweig Ifs FzJ-HIMS, MEET	2019-2022	1, 2, 7, 9
ProfiStruk (ProZell 2)	Process and equipment development for process-integrated in-line structuring of lithium-ion electrodes	TU Braunschweig iPAT, TU Braunschweig Ifs, TUM (iwb)	2019-2022	1, 2
ProBat	Project planning of quality-oriented, series-flexible battery production systems	WBK KIT	2012-2015	6, 12
ProKal	Process modeling of the calendering of high-energy electrodes	Battery LabFactory (BLB) und TU Braunschweig, TU München, iwb, Westf. Wilhelms-Universität (WWU Münster), Institut für Physikalische Chemie (MEET)	2016 - 2019	3
ProLiMA	Lithium metal anode processing	TU Braunschweig ifs, TU Berlin IWF	2019-2021	5, 6, 11
ProTrak	Throughput-optimized forming processes: Production technology for the manufacture of lithium-ion cells	TU Berlin, Fakultät V - Verkehrs- und Maschinensysteme - Institut für Werkzeugmaschinen und Fabrikbetrieb, Fraunhofer-Institut für Solare Energiesysteme (ISE)	2012-2015	9
PolySafe	Increasing the safety of lithium-ion batteries through metal-polymer composite current collectors.	TU Braunschweig (iPAT, IWF, ifs, elenia) Fraunhofer IST, von Ardenne, Maschinenbau Brückner, Fraunhofer FEP, VARTA Microbattery	2021-2024	1,2,3,8,9
ProLiT	Dry coating of LFP & NCM cathodes for LIB	TU Braunschweig iPAT, Custom Cells, Daikin, Ibu-tec, Saueressig, Coperion K-Tron, Eirich, Umicore, BMW	2021-2024	2
QS-Zell	Development, integration and validation of innovative processes and QA methods in the production of large-format lithium-ion cells.	ZSW – Produktions- und Prozessforschung	2016-2019	13
Recycling 4.0	Digitization as the key to the Advanced Circular Economy using the example of innovative vehicle systems	TU Braunschweig IWF, TU Clausthal, Ostfalia	2018-2021	13, 14
ReDesign	Development of design guidelines for the recycling-friendly design of battery systems in the context of the circular economy.	TU Braunschweig IK, TU Braunschweig IWF, Fraunhofer IKTS, LUP der Universität Bayreuth	2020-2023	14, (10, 11)
RollBatt (ProZell 2)	Further development of winding processes and cylindrical cells	TU Braunschweig IK, ZSW (ECM)	2019-2022	10, 11, 12
Roll-It	Investigation of the relationship between cell properties and moisture and mapping by a computational model.	Technische Universität Braunschweig, Karlsruher Institut für Technologie - Institut für Thermische Verfahrenstechnik	2016-2019	2
SiGgI	'Silicon Graphite goes Industry' Material refinement approaches for the production of continuous silicon-based anodes.	EL-Cell GmbH (Hamburg), Technologiezentrum Elektromobilität der Volkswagen AG, Custom Cells Itzehoe GmbH, Sili Technolgies GmbH, M. Braun Inertgas-Systeme GmbH, Battery LabFactory Braunschweig (IPAT, iwf, ifs)	2016-2022	1,2,3,8,9
SiKo	Material development and production of silicon composites	TU Braunschweig iPAT, Varta Microbattery, Glatt, SGL	2020-2023	1,2,3
Sim2Pro	Multi-Level-Simulation von Produkt-Prozess-Wechselwirkungen	Technische Universität Carolo-Wilhelmina zu Braunschweig - Institut für Werkzeugmaschinen und Fertigungstechnik	2016-2019	13
Sim4Pro (ProZell 2)	Sim4Pro Digitization Platform - Simulation for Battery Cell Production	TU Braunschweig IWF, TU Braunschweig iPAT, TU Braunschweig INES, KIT (MVM), KIT (TFT), KIT (wbk), TUM (iwb)	2019-2022	13
S-PROTRAK	Separator coating within the framework of the project Production technology for the manufacture of LIBs	Fraunhofer ISIT, Battery LabFactory (BLB) der TU Braunschweig	2013-2014	4
SUSTRAB	Sustainable and transparent value chains for battery materials for a circular battery economy.	BASF SE, TU Braunschweig (iPAT), Fraunhofer-Institut für Schicht- und Oberflächentechnik (IST), Karlsruher Institut für Technologie, Battery and Electrochemistry Laboratory (BELLA)	2021-2024	1,2,3,13,14
SulForFlight	Development of optimized lithium-sulfur batteries for aerospace applications	TU Braunschweig (iPAT), Frauenhofer IWS, DLR	2022-2025	1,2,3

Project	Brief description	Research Institutes	Runtime	RBW
STACK	Fast stacking for mass production of low-cost and safe lithium-ion cells and further development of electrode and separator materials	ZSW, Fraunhofer-Institut für Chemische Technologie Bayerisches Zentrum für angewandte Energieforschung e. V.	2018-2020	6
TempOLadung	Optimization of charging procedures of a lithium-ion battery with special consideration of the temperature behavior.	Hochschule Offenburg	2018	9
TopBat	Development of temperature-optimized battery modules with instrumented cells	Fraunhofer-Institut für Techno- und Wirtschaftsmathematik	2013-2016	10
TrackBatt (InZePro)	Tracking and tracing in battery production	TU Braunschweig IWF, TU Braunschweig iPAT, TU Braunschweig ifs, TUM (iwb), ZSW	2020-2023	12, 13
ViPro	Development of virtual production systems in battery cell production for cross-process production control	Fraunhofer IPA, TU Braunschweig IWF, KIT wbk, ZSW	2020-2023	12, 13

Lithium-ion batteries of tomorrow -Where is the journey heading?

Following the technology chapters, central developments in energy storage technologies beyond Li-ion batteries have been considered since the first roadmap on Battery Production Equipment [Maiser 2014]. Since the focus of this updated roadmap is also on optimized lithium-ion batteries, the following section briefly discusses emerging and possible future battery technologies based on the high-energy lithium-ion batteries considered centrally in this roadmap (see also [Thielmann 2017]).

Lithium-ion technologies

High energy lithium ion batteries

For the further technology development of high-energy LIB, a successive change of cell components will take place. Starting from lithium-ion batteries established on the market, the future use of high-energy active materials (e.g. Si/C composites) and finally Li-metal anodes, which could be enabled by solid-state electrolyte, is emerging. An evolutionary further development and coexistence of lithium-based battery technologies is expected.

The current state of the art for cathode materials is NMC811, which is used in many electric vehicles, or NCA with a high Ni content. The high Ni content of both materials increases the demands on the manufacturing process and on safety mechanisms at cell and packaging level. Furthermore, LFP is used to a large extent. These and related materials are opposed by high-voltage cathodes, which could permit average cell voltages of over 4 V.

However, such cells require adapted electrolytes that are not available on a large industrial scale today. In addition, the higher cell voltage would require a redesign of the BMS. Furthermore, Li-rich high-capacity materials are under development. Challenges exist in particular in the still poor cycle stability of the materials. Due to their favorable chemical composition, they are nevertheless considered as possible candidates for cost-effective LIBs.

Graphite is the most commonly used anode material today and will continue to play a role in the foreseeable future. Layer thickness and structure will always be adapted to the maximum possible optimum. Already today, Si/graphite composites with a proportion of 2 to a maximum of 5 percent silicon oxide are used to increase capacity. In the short term, nano-Si/C materials with a silicon content of 5 to 20 percent could come onto the market. Cells with pure Si anodes are also being tested. Depending on the further development of the energy density of the cathode, the attractiveness of higher silicon contents will increase. For their utilization, there is a particular need for the development of suitable electrolytes and techniques that can contain irreversible side reactions.

The **efficiency** of lithium-ion cells is well over 90 percent and, in addition to the cell design, is largely determined by the cell chemistry. High battery efficiency contributes to the energy efficiency of mobile applications and can thus improve their energy footprint.

Solid state batteries

Many of the safety risks in Li-ion batteries are caused by the use of liquid, highly flammable or explosive electrolytes. Solid-state batteries do not use liquid organic components, which may reduce the safety risks. The hopes for solid electrolytes also lie in the possibility of Li-metal anodes, which would allow high energy densities at the cell level. Announcements by various players point to energy densities beyond of 350 Wh/kg and 1000 Wh/l.

Material-specific limitations, such as the solubility of various cations or the limitation of the voltage window accessible for electro-chemical reactions, are also linked to the properties of the currently used organic solvents and Li salts. In addition, partial material degradation occurs in current LIB cells as the service life progresses, especially with liquid electrolyte. The use of solid electrolytes and thus the realization of solid batteries can break through the aforementioned limitations.

Research is currently being conducted on several groups of solid electrolytes. Polymer-salt complexes (e.g. polyethylene oxide and LiTFSI) can be processed into thin layers and are therefore highly compatible with established manufacturing processes for LIBs. However, the power densities achieved by such batteries do not yet allow their use in electric vehicles without additional treatment. In contrast, ceramic electrolyte systems are available, e.g. based on oxide, phosphate or sulfide materials. In some cases, high energy and power densities are already achieved with these materials. However, the processing of these materials is more complex than that of polymer systems. In addition, the materials with the best kinetic properties often have poor chemical compatibility with the desired active materials. Possible cell formulations must therefore include protective coatings that provide the necessary chemical stability but involve additional production effort.

Compared with conventional LIB, adjustments are to be expected in all areas of cell production. The transition to metallic Li anodes could eliminate the classical particle coating process of the anode. This could be replaced by either the production of functionalized metal foils (initial Li-free anode) or the thin Li coating of carrier foils in electrochemical or sputtering processes (initial Li-coated anode). Particularly when ceramic electrolytes are used, adjustments may also be necessary on the cathode side. The production, compaction and, if necessary, heat treatment of mixtures of active material and electrolyte particles can prove to be very complex. Also in the field of cell assembly, the fracture behavior of the ceramic layers could require a transition from winding to stacking of electrodes. The classical electrolyte filling is no longer necessary.

In terms of cost, the picture is not yet clear compared to conventional LIBs. At the material level, research is being conducted into compounds whose high metal prices make commercial use unlikely. However, there are also solid-state electrolytes being tested which, apart from their lithium, consist of highly available and thus potentially very favorable elements. A clear reduction potential results from the omission of the graphite anode deposited on a Cu foil. Especially solid-state batteries with initial Li-free anodes could translate this cost component into favorable cell prices.

Which materials will ultimately lead to a breakthrough and what exactly the first industrial manufacturing processes will look like is still uncertain today. Various start-ups as well as established companies and OEMs around the world are working on the development of solid-state batteries. In addition to technology development, the challenge lies in setting up supply structures from the material to the manufacturing plant. Despite the high level of interest from the industry, solid-state systems in xEV applications are not likely to become established until 2030 and then diffuse into the market. Before then, applications in niche applications are conceivable.

Beyond lithium-ion technology

Alternative battery technologies with higher energy density?

Based on the performance parameters (usually gravimetric and volumetric energy density and cycle stability) of alternative batteries, it can be seen that even for technologies with theoretically high achievable energy densities of the energy throughput (the product of energy density and achievable number of cycles) is not improved compared with LIB or the optimized high-energy Li-based batteries or Li-solid batteries of the future. Measured against the current requirements of electromobile applications, most alternative battery technologies must be classified as unsuitable at their current stage of development. However, this could change as development progresses.

However, many of these technologies have added value in terms of cost and resource availability and are currently seen as potential options for stationary (ESS) or special applications. Li-S batteries e.g. could be used in flight applications.

Batteries with conversion materials

Conversion materials (e.g. metal oxide anodes or fluoride cathodes) represent an umbrella term for many different materials with very high specific capacities, often with an unsuitable potential for use as anode/cathode in Li-based batteries. Theoretically, material combinations with high energy density are conceivable. Current research topics concern the material design and the nanoscaling of the materials. Challenges are the volume changes of the particles, which lead to a low lifetime and cycle stability. In terms of production technology, no processes have yet been established and further components require adaptation (electrolyte, cell design).

Sodium-ion batteries

Sodium is present in the earth's crust at 2.6 percent and Na2CO3 costs significantly less than Li2CO3 (Li-carbonate). Sodium-ion batteries (SIB) would provide a cost-effective alternative to LIB. The patent landscape is less densely populated. This could facilitate an entry into materials and battery production. The portfolio of possible cathode materials for SIBs is very large (layered oxides, phosphate, Prussian blue analogs). On the anode side, the number of possible materials is significantly limited due to the ionic size of sodium. Graphite, for example, does not allow the direct intercalation of Na-ions. Hard carbons, for example, have to be used. However, with 250-300 mAh/g, these have a lower gravimetric capacity than graphite. The choice of material for the anode is therefore a challenge. Compared to LIB, a parallel development is seen, which takes place with a time delay and is associated in each case with reductions in the performance parameters of 20 to 30 percent. The R&D effort is also comparatively low due to the transferability of the production solutions from LIB (drop-in).

Metal-sulfur (Me-S) batteries

Elemental sulfur shows good electrochemical activity with various metals (Me) and is also able to accept two electrons per sulfur atom. Due to its good resource availability and low extraction costs, the element is considered highly promising for future storage applications. Theoretically, corresponding materials as cathode have a capacity of 1672 mAh/g at complete conversion.

However, sulfur and Me polysulfides have poor electronic conductivity, so that practical applications require the functionalization of sulfur in carbon or other conductive structures. On the materials side, the re- duction potential theoretically allows gravimetric energy densities of over 2000 Wh/kg for Li-S and over 1000 Wh/kg for Na-S and Mg-S. The weakness of the systems is the good solubility of metal polysulfides in many organic solvents, which serve as the basis for electrolytes. This leads to decomposition of the cathode in the course of cyclization. The transport of the dissolved ions to the anode leads to self-discharge of the cells (shuttle effect). The use of solid-state electrolytes could lead to a solution to this problem.

Na-S high-temperature batteries are already used in stationary storage systems. They are operated at high temperatures and with molten sulfur and sodium, which requires a cell structure that is fundamentally different from LIB and does not allow mobile use.

Me air/O_2-batteries

Metal-air/oxygen batteries are the subject of basic research. The prevailing opinion is that rapid commercialization will not be possible. Various steps of the redox reaction are still too poorly understood to prevent degradation phenomena from occurring. So far, it is unclear whether Me-air systems can be produced at competitive prices, since the materials to be used have not yet been determined and the use of a wide range of additives is likely to be necessary. Challenges exist at all levels, from material to system design.

Redox flow batteries

Pilot plants and small series for redox flow batteries (RFB) have been available for some time. The comparatively low energy densities only allow applications in the stationary sector (e.g. peak load buffer). The decisive factor for the further development and widespread use of RFBs is their cost-effectiveness, which is determined by the cost of the stored energy over the lifetime or application period (LCOE). In the medium to long term, 5-10 ct/kWh would have to be achieved. Challenges exist with regard to increasing the service life and reducing the manufacturing costs.

Lead carbon batteries (PbC)

PbC batteries represent a further development of the well-established lead-acid batteries. Therefore, no disruptive changes are expected in terms of price and energy density. On the one hand, the advantage of PbC batteries is the increase in power density compared to lead-acid batteries. On the other hand, the electrode structure enables use and storage of the batterie in a partially charged state. This is particularly essential for buffer applications (e.g. solar or domestic storage). A price advantage over LIBs can also be expected in the long term. There is very good compatibility with existing lead-acid-based applications (drop-in). Challenges exist in the design of the negative electrode and in the production technology.

Organic batteries

Organic batteries, or organic cathode materials, are an example of another storage technology. For their realization, no transition metals are needed and completely different synthesis processes are required. Potentially, such batteries would be extremely cheap. However, it is challenging that no suitable electrolytes are available and the cycle stability is not given. Overall, the lack of suitable electrolytes is very often a barrier to the exploitation of alternative battery technologies and materials. The challenges are manifold and concern e.g. chemical/electrochemical stability, corrosivity and solution properties.

Conclusions and Recommended Actions

Conclusions

Electromobility market penetration is progressing steadily, not least due to political framework conditions implemented in recent years. The demand for lithium-ion batteries (LIB) also continues to grow rapidly. Global demand for LIB cells reached 460-500 GWh in 2021.

The impressive global expansion of cell production capacities underlines global dynamics. Based on factory announcements, the 1.2 terawatt hour (TWh) limit of LIB cell demand for electric vehicles was reached in 2022. However, this TWh limit is not realistically expected to be exceeded until 2024 due to ramp-up curves and project postponements. A corresponding increase in demand can also be assumed in this time frame. Globally relevant cell manufacturers continue to come almost exclusively from the Asian region. However, the locations of production plants are increasingly shifting to where demand is generated. Europe benefits from this as the location with the headquarters of the largest vehicle OEMs. With the Battery Regulation and *Net Zero Industry Act*, Europe has also created political framework conditions that favor local European cell production for the European market. With Northvolt and VW leading the way, European cell manufacturers have also taken on the challenge of becoming suppliers to the automotive market. A strong increase in production facilities in the USA can also be expected in the next few years.

As a result, there is great global business potential for the European mechanical and plant engineering industry in the dynamic electromobility and LIB production markets, both in cell production and in module, pack, and system production. The high innovative capacity of mechanical and plant engineering can help enable the shift to innovative technologies for climate change such as electromobility. This has already been seen in related industries with impressive results.

Baseline for the European mechanical and plant engineering industry

Sustainable, intelligent production technology is a prerequisite for electromobility and stationary storage to contribute to climate protection. The European mechanical and plant engineering industry benefits from strong specialization and experience from other industries. It can draw on existing competencies in digitalization (Industry 4.0) and in environmental protection and sustainability. In module and pack production, Europe also benefits from experience gained since the start of electromobility and local interaction with the customer industry. Asian players continue to have an advantage in cell production and from knowledge gained in many years of equipping factories from an early stage. However, the requirements for the production of large-format batteries for use in electromobility or the stationary sector are high. The hurdles formulated in this Roadmap apply to all market participants.

Focus on large-scale production

This Roadmap focuses on production technology, based on a thorough review of the current state of the art and consideration of the complete process chain, from material preparation to pack assembly. It is important to evaluate all production solutions in terms of their relevance for large-scale production. With the current market ramp-up and the implementation of the first *gigafactories*, many of the challenges are aimed at increasing throughput and maintaining quality and process stability in large-scale production. Due to the high material value and power requirements, eliminating scrap in a 10 GWh cell manufacturing plant could save approximately €5 million and 10.5kt of CO_2 equivalents.

Period in review

Due to high market dynamics, process solutions will primarily become relevant in the next few years. Breakthroughs for many of the RBWs can already be aimed for in 2024, and for almost all of them by 2027. Very few address solutions to the challenges of the following years. Consideration beyond 2030 would be speculative, or could be made in scenarios at best.

Involvement of key stakeholders

The results of this Roadmap are based on open and targeted discussions in the workshops. As with the last updates to the Roadmap, member companies from VDMA Battery Production contributed to the development of the technology chapters. Member companies contributed to the process through sponsorships and technical support. The Roadmap is publicly accessible and attracts worldwide attention, and many suggestions and proposals can be taken up and implemented. The goal-oriented dialog between battery producers, production research, and mechanical and plant engineering will continue on an ongoing basis.

Recommended actions

Target research needs and bring them to industrial implementation

The broad awareness of all actors along the battery production value chain as well as potential private and public investors is necessary to address the identified research needs in a targeted and sustainable manner. Close cooperation between industrial partners and research institutions is essential. BMBF funding measures grouped under the umbrella of battery research already address important topics. Projects that go beyond pilot plants can support the industry in establishing new approaches in volume production and minimizing the investment risk. They should also continue to be supported by funding programs. Clear priorities are being set by the EU: in addition to the IPCEI alliances, which aim to set up gigafactories in Europe, there are also activities within ETIP Batteries Europe and the European Battery Partnership. The *Net Zero Industry Act* is a recent response to the American *Inflation Reduction Act*.

Collaborative industrial research also makes it possible for smaller companies from the mechanical engineering sector to develop basic knowledge in a pre-competitive area, creating the conditions needed for new ideas. The successful VDMA X-MOTIVE network provides an ideal platform for this.

Production research establishes a foundation for the development of competitive cell production and is key to process innovation and the development of unique selling propositions. References and unique features create the best conditions for European battery mechanical engineering to position itself in this future-oriented field sustainably and for the long term, and also to become more attractive as a global solution partner.

In addition to the right research contents, time also plays a decisive role. If Europe wants to continue to hold its own internationally in this area, research ideas must be brought to fruition more quickly. It often takes 1.5 to 2 years from the initial idea to the start of a project. In particular, the regulations on faster approval procedures in the *Net Zero Industry Act* are an important approach. However, it remains to be seen whether this resolution will have a correspondingly strong impact.

Concrete research needs for improving mechanical and plant engineering production technology arise from the following contexts, in particular:

Achieve learning effects: The planning of future factory capacities requires careful consideration of many aspects, including the requirements of the cells to be produced. For economic and sustainable implementation, equipment and production technology must be continuously optimized. This helps to accelerate the ramp-up phase, increase throughput and quality, and master the interplay between supply, demand, capacity utilization, cost and price development, etc. in terms of planning. Therefore, optimized production techniques should quickly achieve learning effects.

Scale-up of processes: As cell factories grow in size, this is an important lever for reducing costs. It represents an alternative to numbering-up, the simple multiplication of lines. To this end, the process technology must be optimized accordingly. Process stability and quality must be guaranteed, even at high flow rates. The understanding of the process must be continuously improved.

Alternative system topologies: The aim of alternative system topologies at the module-pack level is primarily to maximize the battery pack filling level, and thus to increase the energy content. This is possible above all by reducing the amount of housing components, integrating functions, and using standardized modular systems.

Avoid over-engineering: Interdependencies can be unlocked through the targeted development of process knowledge. This requires comprehensive process monitoring, and the collection and evaluation of an extensive data set. This approach of systematically processing large amounts of data is also known as data mining. Each production step has individual process parameters.

Meaningful tolerances can only be defined if the extent to which the quality of the intermediate products and the final battery cells are influenced by the individual process steps is sufficiently understood. Here, it is important to achieve solutions that are both technically and economically practical. Acquired process knowledge should flow into meaningful requirements for machines and systems. Excessively high requirements in the specifications drives up prices unnecessarily.

Early involvement of mechanical engineering

With new materials and processes, manufacturability and readiness for series production are critical for success. Mechanical and plant engineering must be involved in the development of new products at an early stage, especially in new technologies and cell design decisions. This does not only apply to cell production; it is necessary to be flexible with regard to design adaptations to cells or vehicle concepts in the area of module and pack production as well.

Based on current information, it is likely that optimized LIBs will remain the key technology for at least the next 10 years. Nevertheless, it is already essential for mechanical and plant engineering to address the technical process characteristics and challenges in the production of advanced LIBs, as well as advanced battery technologies in general.

Strengthen international competitiveness

References and unique selling points require production research as well as cooperation and interaction along the entire value chain. European machinery and plant engineering are reliable partners who stand for innovation and efficiency with regard to total cost of ownership as well as sustainability. In order to be able to offer cost-effective products, the understanding of costs for individual process steps and the overall life cycle must be strengthened.

To remain competitive in international cell production, it is becoming increasingly important to offer complete systems and entire production lines with corresponding warranties. This requires close cooperation between machine and plant manufacturers along the production chain.

The Corona pandemic and the war in Ukraine have also shown the importance of local suppliers and acted as accelerators for European cell production and supply chains.

Gain access to large-scale production

Manufacturers of production equipment can only gain experience in volume production through direct participation in large-scale projects. This requires direct cooperation with the manufacturer, as this is necessary to quickly identify technical requirements and develop solutions. Trust-based cooperation between cell manufacturers and mechanical and plant engineering will increase in importance and determine success or failure.

Innovation and new approaches

With rapidly growing markets, the focus is on meeting demand. This creates a risk that there is not adequate time for innovation and new approaches. It is important to recognize opportunities and to develop appropriate strategies now. This does not just involve optimizing existing processes, but also thinking "outside the box!"

Sustainable battery production

In the context of alternative mobility technologies and the energy transition, batteries play a key role in reducing negative environmental impacts. Li-ion batteries are a core technology for **decarbonization**. Renewable energy sources such as solar and wind power can only meet demand with suitable storage options.

In electromobility, reducing the **CO_2 footprint** is of critical importance. The production of battery cells, including the required materials, is responsible for the majority of this environmental impact. Increasing the material and energy efficiency of production is therefore essential. **Recycling processes and technologies** must also be developed. Recycling offers opportunities to create unique selling points.

Production solutions that contribute to Re-X capabilities will increase in importance as a competitive advantage, as will those in cell factories with integrated resynthesis or reconditioning of battery materials.

Strength, endurance, and the courage to take risks

Production research is the key to innovation, which is essential for success in battery machine manufacturing. Market access is often not easy. In addition to good production solutions, perseverance and stamina are required when it comes to winning customers. At the same time, it requires a certain willingness to take risks in order to implement new approaches in series production or to establish oneself on the market as a provider of turnkey solutions or a general contractor. This is an increasing customer demand.

Instruments such as tax incentives for research and general degressive depreciation are important for minimizing investment risks.

Making the roadmapping process permanent

Roadmapping is a dynamic, iterative process. With this new edition, VDMA Battery Production has continued the dialog which began in 2014 with the first Roadmap, and will continue to drive the active implementation of the roadmapping process.

Appendix

List of abbreviations

Abbreviation	Meaning
3C	Consumer, Computer, Communication or Portable Devices
ASP	Average Sales Price
BEV	Battery electric vehicle
BMBF	Federal Ministry of Education and Research
BMS	Battery Management System
BoL	Beginning-of-Line
CAPEX	Capital expenditure, for English capital expenditure
COP	Penetration coefficient
C-Rate	Charge (or discharge) current of a battery in relation to its capacity.
Cu foil	Copper foil
DCM	Dichloromethane
DoE	Design of Experiments
EIS	Electrochemical impedance spectroscopy
EoL	End of Life
EOL test	End of Line Test
EMPT	Electromagnetic pulse technology
ESS	stationary storage
EUCAR Level	Hazard classification of the European council for automotive and R&D
EV	Electric Vehicle
R & D	Research and development
FMEA	Failure Mode and Effects Analysis
HEV	Hybrid electric vehicle
HF	Hydrofluoric acid
IPCEI	Important Project of Common European Interest
IR dryer IRA	Infrared Dryer Inflation
AI	Reduction Act Artificial
KIT	Intelligence
	Karlsruhe Institute of Technology
KPI	Key Performance Indicators
LCO	Lithium Cobalt Oxide
LCOE	Levelized Cost Of Electricity
LFP	Lithium iron phosphate
Li	Lithium
LiB	Lithium-ion battery
LiTFSI	Lithium bis(trifluoromethanesulfonyl)imide
Me	Metal
Na	Sodium
Na-IB	Sodium-ion batteries
NCA	Lithium nickel cobalt aluminum oxide
NDA	English: non-disclosure agreement, confidentiality agreement
NIR	Near infrared
	Nickel
	Lithium nickel manganese cobalt oxide

NMP	N-methyl-2-pyrrolidone Solvent
OEM	Original Equipment Manufacturer z. dt. Original Equipment Manufacturer
OPC UA	Open Platform Communications Unified Architecture
OPEX	Operating expenses, for English operational expenditure
Pb batteries	Lead-acid batteries
PbC	Lead Carbon
PE	Polyethylene
PET	Polyethylene terephthalate
PHEV	Plug-in hybrids
PP	Polypropylene
PSA	Personal protective equipment
PV	Photovoltaics
PVDF	Polyvinylidene fluoride
PVD process	Physical Vapour Deposition coating process
RBW	Red Brick Wall
Re-X	Possible recycling processes are summarized under Re-X
RFB	Redox flow batteries
RFID	Radio Frequency Identification
S	Sulfur
SEE	Solid Electrolyte Interface
SG&A	Selling, General and Administrative Expenses
Si/C composites	Silicon/carbon composites
SoA	State of Art
SoH	State of Health, quality of the battery
SPC	Solid state permeability
TCO	Total cost of ownership
TGA	Technical building equipment
UHMWPE	Ultra-high molecular weight polyethylene
V2G, G2V	Vehicle to Grid, Grid to Vehicle
VCSEl laser	Vertical-cavity surface-emitting laser
WEZ	Heat-affected zone
xEV	BEV, PHEV and HEV

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