Battery Production

Roadmap
Battery Production Equipment 2030

Update 2020

Are you looking for strong solutions for battery production? Do you want to set up a production line or are you looking for partners for process development?

Our industry guide provides an overview of which companies offer which technologies along the process chain and helps you find the right partners.

„Picture Key to Battery Production“

VDMA Battery Production: Key to Battery Production

Roadmap
Battery Production Equipment 2030
Update 2020

In cooperation with

Fraunhofer Institute for Systems and Innovation Research ISI

Chair of Production Engineering of E-Mobility Components PEM

Battery LabFactory Braunschweig and TU Braunschweig

Content

Executive summary

References and unique selling points of the 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 solution partner worldwide. Production research in mechanical engineering provides the basis for competitive cell production. It is the key to process innovations and to the strategically important development of unique selling points. The roadmap process makes a valuable contribution to this by specifying production requirements up to 2030 and formulating initial proposals for solutions.

The VDMA Roadmap Battery Production Equipment 2030 addresses the further development of production technology (not product development). Since its first 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 the mechanical and plant engineering industry, also drawing on experience with foreign experts. 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 supply potential worldwide is updated. In recent years, the focus has shifted to Europe and Germany in particular. Proximity to the automotive industry as an end customer plays a key role here. Besides Europe, China remains the most important sales market. The Chinese machine and plant construction industry has developed from its strong domestic market into a world leader. For European production suppliers to participate successfully here, they must face this competition. To this end, turnkey solutions should be planned more intensively in Europe and the industry should be empowered through measures and projects.

The roadmapping methodology introduced in 2014 has been retained. An evalution of the necessary technology breakthroughs ("Red Brick Qalls") identified in 2018 formed the starting point for the update. Subsequently, the future requirements for battery machines were discussed from today's point of view and solutions for mechanical and plant engineering were compiled. Red brick walls were identified in a total of 14 technology chapters and revised according to the current state of the art in technology.

All Red Brick Walls can be traced back to core challenges. **Cost savings** through increased throughput (scale-up or speed-up) and increased productivity (minimization of scrap) represent one of the Grand Challenges. Other challenges are **quality improvement** and **sustainability**. Quality stands for both process stability and product performance.

The research requirements identified in our roadmap should be addressed in a targeted manner through collaboration between industry partners and research organizations. The issue of sustainability is becoming increasingly important. It is critical not to lose sight of the reduction of the CO_2 footprint as an overriding goal. Access to series production is still essential to qualify developments directly in large scale production and to obtain references. It is important to create positive publicity and encourage investment in battery production. Success in battery production requires courage and a willingness to take risks.

Introduction

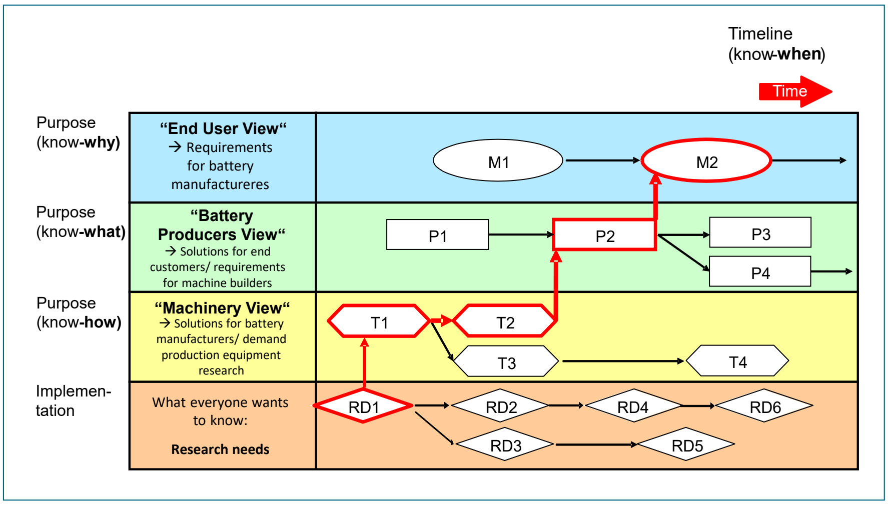
Roadmaps are a proven method of creating clarity: they provide a coherent picture of a future vision, ideally represent consensus across a broad industry field, act as an investment guide. They encourage pre-competitive cooperation between all the actors concerned.

After the first publication of the Roadmap in 2014, VDMA Battery Production has continuously maintained and encouraged dialog between all the actors involved. For the purposes of this 2020 publication, the contents of the 2018 roadmap were reviewed, completely revised and expanded to include new material. The fundamental methodology has remained unchanged

Roadmapping: the complete picture

Technology roadmapping is a strategic tool in innovation management. Forecasts of future megatrends and markets[1] ("know why") can benefit everyone who is able to generate specific requirements for products ("know what"), the technologies to be deployed ("know how") and the required research and development programs over a defined period of time ("know when") [Phaal2003a].

This generates separate "travel routes" which can be considered in each case with separate but related roadmaps[2]: Requirements are formulated by working from top to bottom, while solutions are created working from bottom to top. The overall roadmapping process accordingly leads from an overarching scenario through to products and feasibility and on to specific needs for research, which can be visualized in a **milestone chart**[3] [Phaal2003b].



Roadmapping: From overarching scenario to products and feasibility to research needs. Development paths in milestone diagram. [Phaal2003b]

[1] Popular examples include digitalization, urbanization, climate change, individualization etc.
[2] Identified by different colors in the milestone chart
[3] Strictly speaking, our roadmapping follows the development path shown in the milestone chart in reverse.

If we adapt this to our present case, the following picture emerges: End customer markets such as the automotive industry, electricity suppliers, and mobile machinery represent the blue “Market” route. The green “Product” route is the battery. The yellow route specifies the production technology, and the red route designates production research.

Technology roadmapping in mechanical and plant engineering

User markets and battery technologies have already been studied worldwide in numerous roadmaps [NPE2016, LIB2015, BEMA2020]. Although they also emphasize the importance of production for the sector’s progress, they are not technology roadmaps for production technology in the truest sense.

In 2014, VDMA Battery Production published a first technology roadmap [Maiser2014] that focused on the further development of production technology and not on product development itself. The dialog oriented to this objective between battery producers, production researchers, and the mechanical and plant engineering industry remained the basis of further discussion and has been continued ever since.

Starting point, goals and target groups

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

Companies benefit from the experience gained in related industries[4]. This is why new paths can be taken and revolutionary ideas can be introduced.

The goals of the roadmapping process were described in detail in our roadmap published in 2014 [Maiser2014]. They still apply:

- **Positioning of** the mechanical and plant engineering industry: current progress and future challenges
- **Comprehensive identification of production technology research**.
- **Benchmarking, expanding product portfolios, and initiating consortia** for new and established players.
- **Recommending actions for** all stakeholders. Essentially, those who actively engage in the dialogue benefit the most. [Groenveld1997, Phaal2009].

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

Methodology

VDMA's experience with roadmapping [ADRIA2005, VDMA-PV2010] has underlined the importance of clearly specified methodology for the roadmapping process. We have adapted the roadmapping process used in the semiconductor industry to the needs of battery production. At the heart of this method is the concept of formulating roadmaps separately for customers and production equipment manufacturers. This prevents a situation in which customers make their requirements dependent on the feasibility of process technology and technology suppliers make statements about process solutions only when there is a prospect of volume production.[5]

The importance of "Red Brick Walls"

Compiling the requirements placed on battery manufacturers and on feasibility from the point of view of process development within the defined time grid reveals the following for each individual process step:
(1) Process solutions are already available in the field
(2) Process solutions are available only at a pilot stage
(3) Process solutions have been demonstrated or exist as temporary solutions
(4) Process solutions are currently unknown

If solutions are unknown in several process steps that are required to meet a manufacturer requirement, a metaphorical "Red Brick Wall" arises. This indicates that technological breakthroughs are necessary.

Research efforts must now be targeted at overcoming the Red Brick Walls in order to fulfill the manufacturers' requirements. The identification of Red Brick Walls is thus a core task within the roadmapping process. From this it is possible to derive specific and clearly defined research requirements.

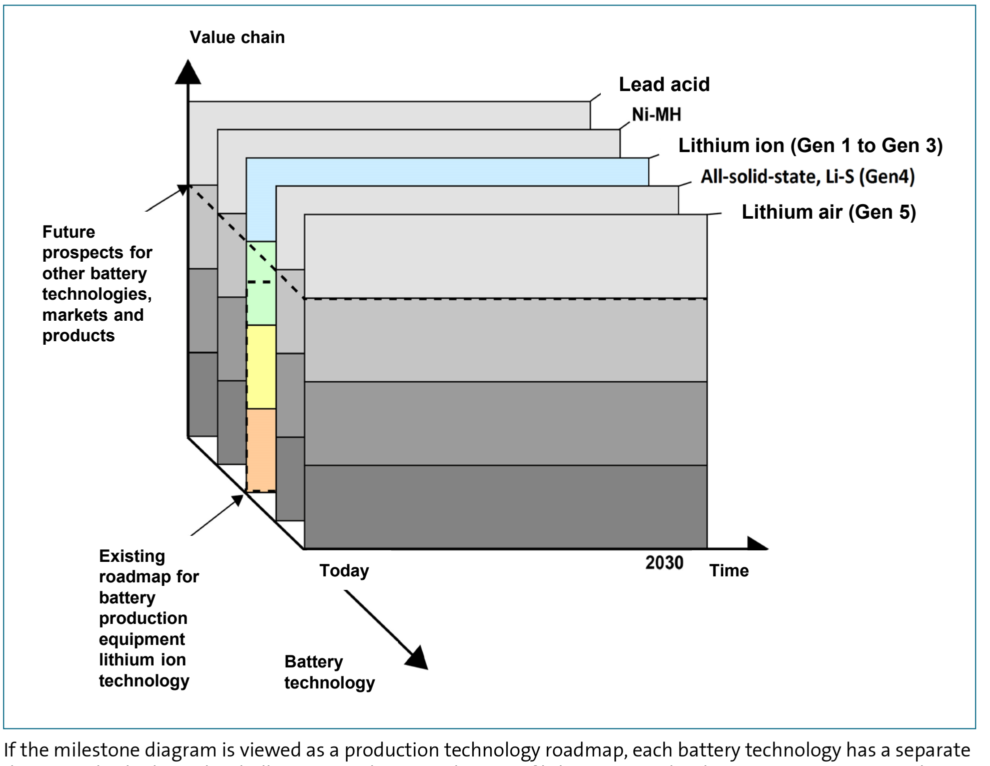
Multidimensional roadmaps - Focus on mechanical and plant engineering

The milestone chart shown above effectively results in a separate chart for each battery technology. This makes our roadmap multidimensional (see illustration) and it would be too complex to discuss production technology in the necessary depth.

To allow an intensive study of the process chain, we have accordingly focused on the battery technology that has already been introduced on an industrial scale: **lithium-ion technology** (LIB, shown in color in the chart).

As production research requires technologies that are ready for series production, our roadmap addresses the lithium-ion generations 1 to 3 (see table). Within these generations, the production technology is upwards-compatible. This means that any conclusions can be applied directly to the next generation, since the changes primarily affect the chemical composition of the active components.

[5] A more detailed description can be found in the roadmap published in 2014 [Maiser 2014].



If the milestone diagram is viewed as a production technology roadmap, each battery technology has a separate diagram. This looks at the challenges to volume production of lithium-ion technology generations 1 to 3. The generations were defined according to the current roadmap of the National Platform for Electromobility. Source: VDMA

The term "generation 4" is used to designate all-solid-state and lithium-sulfur (Li-S) technologies, while generation 5 indicates lithium-air. These technologies are still at the development stage. Changes would be needed to some sub-sections of production for these generations. Detailed information can be found in the all-solid-state process flyer.

In view of the competitive environment for German companies, we shall also limit ourselves to considering large-scale cells for high-capacity and high-energy applications.

Reference scenario: lithium-ion technology

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 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 anode are the most widely used. Average cell voltages of 3.6 to 3.8 V can be achieved with these cell types. In industrial applications or stationary storage systems, lithium iron phosphate (LFP) cathodes are also used, but these have a lower cell voltage of 3.1 V. The manufacturing processes of the above-mentioned battery technologies are all very similar.

Large-format cells for mobile and stationary applications will continue to be based on the LIB technologies described above. The general view of battery research shows that the potential of established large-format lithium-ion batteries is far from exhausted: for example, improvements can be achieved by using high-voltage cathodes or graphite-silicon composite anodes. Even the potential transition to solid-state batteries with metallic Li anodes will maintain key parameters such as cell voltage, and large parts of the manufacturing process will remain similar to today's technology.

The LIB technology described above will continue to be the reference system for many years to come based on its design breadth and the associated versatility of use.

VDMA workshops

The roadmap is revised every two years to ensure that it remains up-to-date. In doing so, the existing RBWs are first evaluated using a questionnaire and subsequent workshops (which can take place both physically and virtually). The following criteria are considered: current status, relevance for battery manufacturers, cost-benefit ratio, and the timescale for achieving the particular goal. Comments and suggestions can also be added. The results are then discussed in plenary sessions or web workshops.

In 2020, we further broke down the RBWs for each technology into several challenges. This enabled a deeper discussion and evaluation.

To capitalize on the expertise of VDMA member companies, topic mentors and other technical supporters were involved in the preparation of the respective technology chapters in this update.

To summarize, this roadmap formulates solutions offered by the European mechanical and plant engineering industry as well as research requirements for the large-scale production of lithium-ion high-performance energy storage systems by 2030.

Markets

This update of the "Roadmap Battery Production Equipment 2030", which was published in 2014, 2016 and 2018, started by looking at the developments on the battery market and in production capacities. What is the outlook from today's point of view, both in general terms and in specific applications such as electric vehicles, industrial applications and stationary energy-storage? Which battery technology will be the main driver of market growth in the coming years or decades and will therefore generate the greatest demand for corresponding production solutions? Who are today's and tomorrow's producers, and what factories are planned worldwide? What drives the requirements that battery manufacturers place on their suppliers?

These questions can be answered by looking at markets, supply and demand 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 [Thielmann2020a]. The data documented in the following were updated to the year 2020 compared to the roadmap published in 2018 [Michaelis 2018], and continue to confirm the trends and dynamics that were already apparent at that time.

Markets, supply and demand

The potential applications for electrical energy storage technologies in general and lithium-ion batteries (LIB) in particular are diverse and range from consumer electronics, electric mobility and stationary energy storage to large-scale batteries used directly in industry [Thielmann2015 a, b, c]. Since their introduction to consumer electronics in the early 1990s,Li-ion batteries have undergone more than 30 years of development. With the intensive further development of large cylindrical cells (in the 21700 format, as well as the 4680 recently announced by Tesla[6]), large-format pouch cells and prismatic cells, they are being transferred to various specific applications. All these cell formats have their advantages and are used in electric vehicles as well as industrial and stationary applications [Hettesheimer 2017]. It can still be assumed that lithium-ion battery technology will be developed to full maturity in the next 10 to 20 years. This means that this technology still has great development potential over the next two decades, and will be optimized step by step over the next few years.

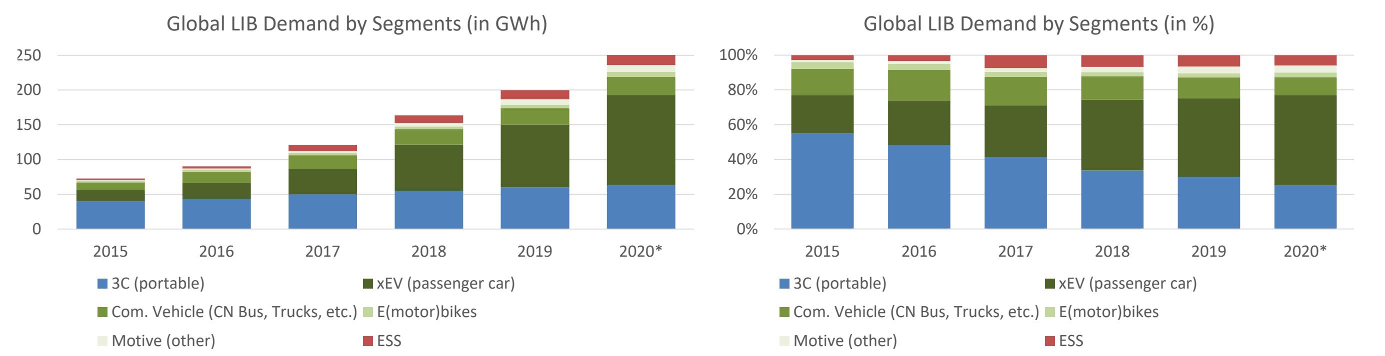
LIB cells: global demand

Global demand for LIB cells was around 200 GWh in 2019. About 126 GWh of this is attributable to[7] the electric mobility sector and around 13 GWh to stationary applications. In portable/mobile applications, [8]the LIB market was around 60 GWh in 2019. Uncertainties result depending on the source and market study as well as differences in determining the number of specific products sold and average battery sizes. Over the last few years, the LIB market has grown annually by 25% percent on

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

[7] Passenger cars, commercial vehicles, etc.

[8] portable or 3C consumption, communications, computer



Global LIB demand by segment (in GWh on the left and market share on the right): the 3C market includes small-format pouch, prismatic, and cylindrical cells up to (and including) size 18650. Demand in this segment is not included in further analyses, only LIB demand in electric mobility and stationary applications, which use large-format pouch and prismatic cells, as well as cylindrical cells of size 21700. Source: Fraunhofer ISI [based on own data and various market studies, including Avicenne2020, Takeshita2020].

average (until the beginning of 2020). The biggest demand and dynamics are generated by electric mobility applications. Growth rates here have been around 40 percent in recent years¬ and are likely to remain at an average¬ of 30-40 percent in the ¬next few years. As a result, demand is ¬now significantly higher in this sector than for 3C ¬applications (see figure above).

LIB Markets – electric mobility

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

By 2019, sales of electric vehicles (PHEVs and BEVs) had risen to 2.2 million (around 90 GWh). At the beginning of 2020, there were already - well over 7.5 million e-cars on the roads worldwide. In the first half of 2020, production of e-vehicles slumped by around 15 percent compared to 2019 due to the Corona pandemic. However, since July 2020, it has been recovering and significantly more e-cars are being produced than in the same period last year. In 2020, sales could increase to 2.8-3 million BEV/PHEVs leading to demand of over 130-150 GWh (220-250 total global LIB demand).

The BEV market for LIB is by far the most important one from the viewpoint of cell demand development. The terawatt-hour (TWh) limit of LIB cell demand for electric vehicles could be reached as early as 2025 assuming an optimistic development of electric mobility [Thielmann 2017, Thielmann 2020b[9]].

Commercial vehicles (e.g. vans, buses) and **mobile machines** (e.g. forklifts) are expected to show similar dynamics and thus open up a growth market for LIB that is just as attractive as the electric passenger car sector. The batteries installed in commercial vehicles range between 50 kWh and over 400 kWh. Although the number of units only accounts for one third of the passenger car market, the growth in market volume could be similar due to the double to triple capacity of the batteries.

Most battery cells for **buses** and commercial vehicles are currently used in the **Chinese** market. In 2019, demand was around 24-29 GWh.[10] This trend means the Chinese market is likely to be fully converted to electric buses in the next few years. Market forecasts see

[9] AABC 2018/2019/2020: Axel Thielmann, The Emerging Battery Markets Beyond xEV, Fraunhofer ISI.

[10] In each case, the lower figure applies only to CN E buses, while the upper figure applies to CN E buses and commercial vehicles.

sustained annual demand in the range of 100,000-300,000 electric buses in China (10-30 GWh). However, the Chinese government's cutbacks in subsidies for manufacturers of electric vehicles show that neither the dynamics nor the stability of this market demand can be regarded as certain in the next few years.

Outside China, sales of commercial e-vehicles such as delivery trucks, postal trucks, garbage - transporters, trucks, etc. are around 100,000, resulting in a demand of a few GWh. The momentum is likely to increase significantly in the next few years.

In the meantime, demand is also increasing in other countries and with it the prospect of a - spread of electric mobility with light and heavier commercial vehicles. This represents an opportunity for Chinese cell manufacturers in particular such as BYD, CATL, etc. to expand into markets outside China.

The demand for electrically powered **two-wheelers (e-bikes)** with LIB cells amounted to over 10 million (approx. 5 GWh) in 2019. [Thielmann2020b[11]]. The sales figures for **e-scooters and e-motorbikes** are currently still far below this, at around 50,000 (1-1.5 GWh). However, battery capacities from 2 to more than 15 kWh are likely to create an interesting market here 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, self-sufficient systems are often the only way to - provide energy.

There are different estimations of the demand and dynamics for LIB cells for stationary applications depending on the market study - [Thiel mann2017, Thielmann 2020a]. In 2019, global demand was 10 GWh with growth rates between 15 and 30 percent.

There is a diverse market in terms of applications, from off-grid to on-grid[12][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 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 come under pressure or even be displaced due to 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. In addition, the grid connection (V2G, G2V) of electric vehicles will require a new or precise definition of stationary storage systems (ESS).

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

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

LIBs are an enabler for the use of renewable energies in the stationary storage market. From an economic perspective, significantly better margins can be achieved in this market than in the e-car market with its high volume - production. The costs for home storage systems, for example, are still around 1200-1500 €/kWh. [13]

LIB supply: production capacities

In order to make reliable statements on how well producers are meeting this demand, it is essential to have a realistic estimate of global production capacities Based on this, it is then possible to determine whether and when new factories need to be built and, more precisely, whether investment in a factory is worthwhile.

The installed global LIB production capacities for electric mobility, industrial and stationary applications were determined based on various studies, press releases and information from the cell manufacturers themselves (see figure on p. 14): According to this information,360 to 730 GWh could be built up by the end of 2020. [14]In the next few years, an average annual increase of 100-300 GWh is expected (see table on page 17). This figure is expected to be even higher from 2025.

Comparison of LIB supply and demand: The comprehensive view

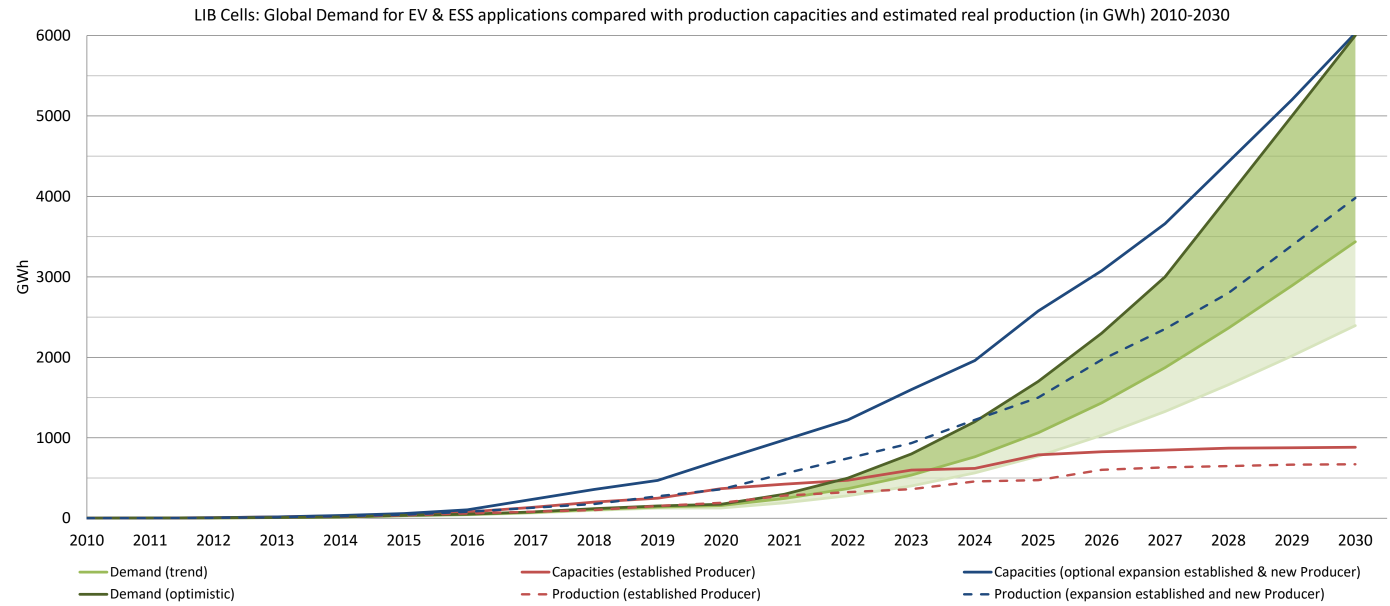
Continuing the comparison of LIB production capacities and LIB demand [Michaelis2016, Thielmann2017, Michaelis 2018], we compare the cell production capacities announced up to October 2020 with global LIB demand in the figure on page 14.

Ideally, demand should take into account not only the units actually installed, but also the **stock in** factories or at customers. If there is an oversupply, customer stocks remain empty and orders are placed late. In the case of undersupply, often more is ordered than is actually needed. Demand is "inflated" unrealistically and possibly cancelled later.

Price development is a key factor in demand dynamics. **Average prices** (Av er age Sales Price, ASP) have always been monitored in the - semiconductor industry. They are closely linked to production costs. In the battery industry, forecasting models have now also been - developed [Maiser2015, Michaelis2016, Thielmann 2017].

[13] cf. CARMEN e.V. 2020: https://www.carmen-ev.de/sonne-wind-co/stromspeicher/batterien/813-marktuebersicht-fuer-batteriespeichersysteme

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



LIB cells: Comparison of global demand for electric mobility, industrial and stationary applications (forecast from 2020, 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].

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. The full capacities cannot be manufactured in the year in which the start of production is announced, especially since the start date is not necessarily at the beginning of a year.

Building a factory, qualifying the production and products and reaching full operation takes between one-and-a-half years for a so-called "copy & paste" facility up to four years for a factory with new production technology. Cell manufacturers are therefore only able to react to rapidly changing demand after some delay. They are dependent on reliable forecasts. Many producers plan several expansion stages of a factory from the outset.

The interplay of supply, demand and delayed reaction produce the typical patterns of the so-called "hog cycle", also seen in other industries.

The **capacity utilization of** a factory is never 100 percent. If the capacity utilization rate is permanently over 85 percent, manufacturers usually start thinking about expansion. The rest is used as a buffer. It is therefore advisable to use values of around 85 percent to calculate the actually used production capacity. In the case of the extremely dynamic LIB market, however, it is apparent that (especially Chinese) battery producers already plan further expansion at significantly lower capacity utilization rates.

A factory never produces only good parts. Well-established factories in the semiconductor industry have a **yield of** over 90 percent. Today, the yields in battery production are significantly lower in some cases. 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: customer requirements and acceptance may vary depending on the specific application involved. Depending on the quality, costs, choice of cell chemistry and format, not all cells produced are suitable for customers. Not every product can be substituted at will.

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. This is all strongly affected by the mood in industry as well as state location and funding policy measures.

In the above chart, we have depicted both the nominal factory capacities (blue, red solid lines) and the [15]more realistic values due to the dampening effects described (broken lines). The development of demand is shown in green in a conservative, a trend and an optimistic scenario. If the lines run above the green areas, there is a calculated overcapacity; if they run below, there is a shortage of production capacity.

The red lines show the expansion of production capacities in the base scenario[16]. The blue lines show the expansion when taking into account optional expansions of production by established and new cell manufacturers (new market participants).

LIB demand (excluding 3C applications) will increase from 2019 (around 140 GWh) to 2020 (around 160-190 GWh). The continued massive growth in demand between 2020 and 2030 is likely to increase to less than 2.5 TWh (pessimistic scenario, lower green line), more than 3 TWh (trend scenario, middle green line) or even to more than 6 TWh in the optimistic - scenario (more than 10 TWh can be expected in the long term[17]).

The production capacities of established cell manufacturers (red lines) will cover this demand for another two years at best and possibly four years if capacity utilization increases. Between 2020 and 2025, established cell manufacturers will therefore need to further expand their production capacities. New cell manufacturers will ramp up in the years around 2025 and compete with established cell manufacturers.

The table on p. 17 lists the cell production capacity expansions planned or announced for 2020 to 2030+ by cell manufacturers, their headquarters and planned location. Minimum and maximum values are given for the three periods due to the high degree of uncertainty concerning which planned capacities will - actually be built and commissioned in the - corresponding year.

The future expansion plans of the leading cell manufacturers CATL, BYD, Panasonic, Samsung SDI, LG Chem, and SK Innovation are increasingly being matched in 2020 by further announcements from cell manufacturers as well as OEMs, which now also want to enter volume production. Such established players, but also new market players, will target the growing market in Europe in particular in the coming years.

The announced cell factories are typically expected to reach sizes between 10-30 GWh. Some cell manufacturers are targeting up to 50 GWh cell factories. Tesla plans to start its own cell production with the new cylindrical 4680 format, to reach up to 3 TWh by 2030, and to

[15] This considered a capacity utilization rate of 85 percent. The average yield of today's factories is assumed to be 90 percent. Announcements by manufacturers on gradual expansion and the ramp-up of factories are included. The remaining effects are difficult to almost impossible to quantify and have not been taken into account.

[16] Base scenario: production capacities in the planning phase for several cell manufacturers

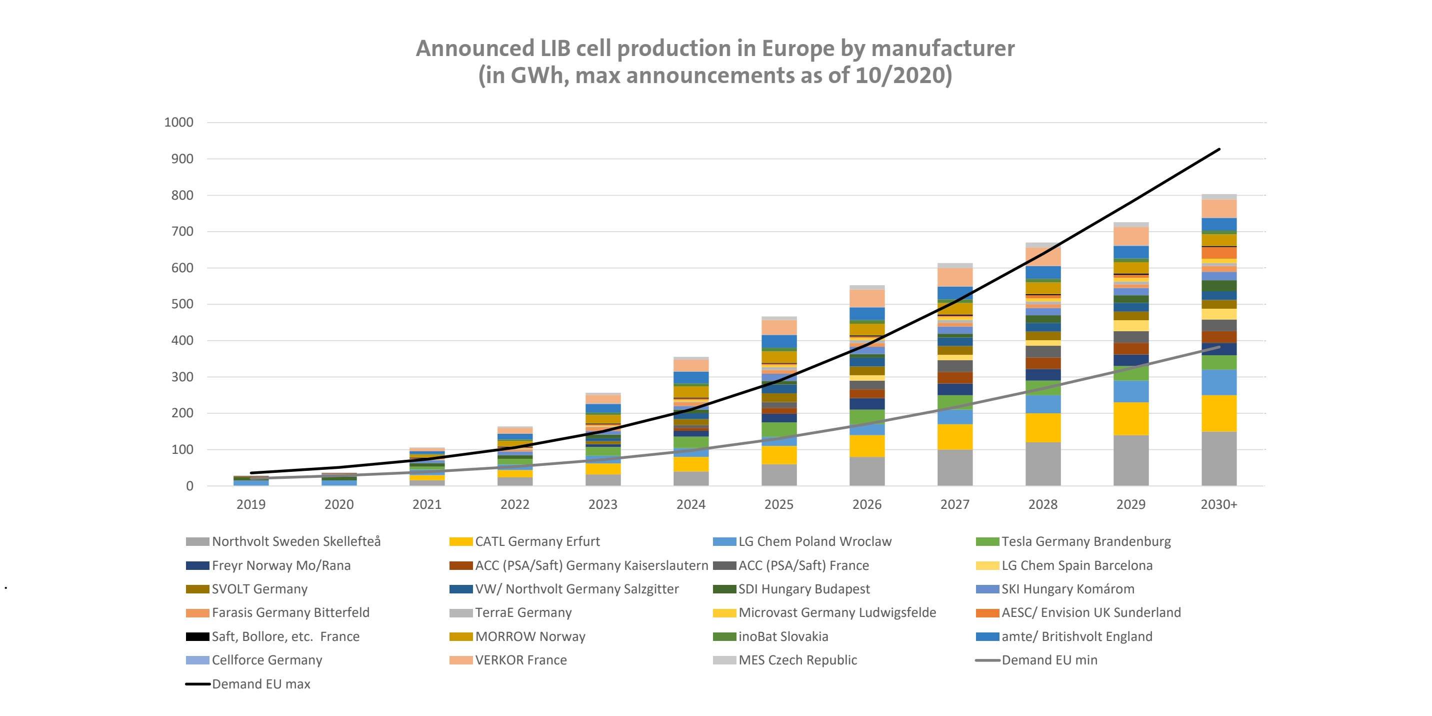
[17] Elon Musk/Tesla even assumes 20-25 TWh by 2040: https://www.onvista.de/news/elon-musks-gigantischer-akku-plan-und-2-weitere-tesla-aktien-news-397436777

achieve this with smaller, more flexible cell production.

Thus, Elon Musk obviously expects the battery market to reach the 10 TWh range beyond 2030. Due to sales of e-cars, Tesla had already reached about 30% demand for e-car battery cells in the period 2017-2019. Assuming that Tesla maintains this demand over the next 10 years, the planned 3 TWh would be considered a realistic extrapolation. The currently announced additional production capacities of 3 TWh from Tesla are likely to be followed by other announcements of up to 3-4 TWh by 2030+ (i.e. from 2030 onwards). In fact, in 2020, CATL announced an expansion of capacity to 1.2 TWh by 2025, which should increase further by 2030 if realized. By the end of 2020, global announcements thus added up to about 7.3 TWh by 2030+ (see Figure p. 14 and Table p. 17).

Cell manufacturer	Headquarter	Production location	2020 (min)	2020 (max)	2025 (min)	2025 (max)	2030+ (max)	2030+ (max)
BAK Battery	China	China	8	15	15	20	15	20,5
Beijing Linkdata Technologies	China	China	0,2	0,2	0,2	18	0,2	24,1
BPP (Bejing Pride Power) to BAIC	China	China	0,31	7	0,31	7	0,31	7
BYD	China	China	24	60	30	70	30	110
BYD	China	**Europe**						
BYD & Changan (JV)	China	China	5	6	10	15,7	10	20,5
CALB (China Aviation Lithium Battery)	China	China	6	13,5	6	200	6	200
CATL	China	China	40	110	50	380	50	380
CATL	China	**Germany**			50	450	60	450
CATL	China	Indonesia, Japan, USA				370		370
CENAT	China	China	1	5	1	5	1	5
CNM Power	China	China	3	15	3	15	3	15
Coslight	China	China	5,25	12,5	5,25	12,5	5,25	12,5
DFD	China	China	1,9	1,9	1,9	1,9	1,9	1,9
Dongfeng Amperex (JV CATL & Dongfeng)	China	China	9,6	9,6	9,6	9,6	9,6	9,6
Dynavolt	China	China		25		25		25
etrust	China	China	0	4	0	7	0	7
EVE	China	China	9	13	9	13	9	15
Evergrande	China	China			30	100	60	500
Funeng Technology	China	China	0	10	0	24	0	36
Great Power	China	China	0,4	10	0,4	10	0,4	13,5
Guoneng	China	China	4	20	4	20	4	20
Guoxuan High-Tech	China	China	17	28	23	100	23	100
Lishen	China	China	17	20	25	70	25	70
Lithium Werks	China	China		0,1		3		9
Narada	China	China	2	2,5	2	2,5	2	2,5
National Battery Tech, Bejing	China	China	11,2	25,2	11,2	25,2	11,2	25,2
OPTIMUM	China	China	18	36	22	36	22	36
Phylion	China	China	3	3	3	3	3	3
SK &EVE	China/ Korea	China			20	25	20	25
SVOLT	China	**Germany**			24	24	24	24
SVOLT/ Great Wall	China	China		4		18		24,2
Tianneng	China	China	1,5	11	1,5	11	1,5	11
Vision	China	China				20		30
Wanxiang (A123)	China	China	5	10	80	80	80	80
Wina Battery	China	China	2,2	2,2	2,2	2,2	2,2	2,2
Zhihang Jiangsu New Energy	China	China	3,5	3,5	3,5	3,5	3,5	3,5
時代上汽動力電池 (JV of CATL and SAIC)	China	China	18	18	18	50	18	50
China (andere)	China	China	6,9	37,4	6,9	37,4	6,9	37,4
LG Chem 1	Korea	Korea	18	18	18	20	18	21,3
LG Chem 2	Korea	China	8	20	8	45	8	62,9
LG Chem 3	Korea	USA	3	5	3	18	3	26
LG Chem 4	Korea	**Poland**	5	15	15	25	15	70
LG Chem 5	Korea	China	0	8	0	32	0	32
LG Chem 6	Korea	**Spain**	0		0	0	0	30
Samsung SDI 1	Korea	Korea	5	5	5	20,8	5	24,1
Samsung SDI 2	Korea	China	4	5,6	4	24,1	4	28,8
Samsung SDI 3	Korea	**Hungary**	2,5	2,5	2,5	10	2,5	30
SK Innovation 1	Korea	Korea	3,9	10	10	15	10	15
SK Innovation 2	Korea	**Hungary**	7,5	7,5	10	20	10	23,5
SK Innovation 3	Korea	China	7,5	7,5	10	20	10	20
SK Innovation 4	Korea	USA			25	45	45	45
Korea (andere)	Korea	Korea	1	1	1	1	1	1
AESC	Japan	China		20	7,5	20	18	20
AESC	Japan	Japan	2,2	3,3	2,2	3,3	2,2	3,3
AESC / Envision	Japan / China	USA	4	4	4	4,5	4	9,62
AESC/ Envision	Japan / China	**UK**	2	2	2	3,44	2	32
GS Yuasa	Japan	**Europe**						
Lithium Energy Japan/ GS Yuasa	Japan	Japan	2,3	2,3	2,3	2,3	2,3	4,7
Panasonic	Japan	China	2,3	6	2,3	8,9	2,3	22,6
Panasonic - Tesla 1	Japan	USA	35	35	39	105	39	150
Panasonic - Tesla 3	Japan	China				35		35
Panasonic (18650)	Japan	Japan	7	10,1	7	19,6	7	19,6
Panasonic (large format)	Japan	Japan	1	4,2	1	16,3	1	37,8
Panasonic /Toyota JV: Prime Planet	Japan	Japan			1	10	1	10
Toshiba	Japan	India		1		1		1
Japan (andere)			1	1	1	1	1	1
Boston Energy	USA	Australia		3		15		15
Boston Energy	USA	USA		3		15		15
Boston Power	USA	China		11		11		11
JCI	USA	USA	1,65	1,65	1,65	1,65	1,65	1,65
Tesla 4	USA	**Germany**				40		40
Microvast	USA	China	2	15	2	15	2	15
Farasis	USA	China	5	8	5	32	5	32
Farasis	USA	USA			10	10	10	10
Farasis	USA	**Germany**			10	10	10	16
Microvast	USA	**Germany**			6	6	6	12
Tesla X	USA	World				500		3000
USA (andere)			1	1	1	1	1	1
Energy Absolute	Thailand	Thailand		1		25		50
Energy Renaissance	Australia	Australia		1		1		1
Exide & LeClanche (JV)	India	India		1	1	5	1	5
Foxconn	Taiwan	China				15		15
LIBCOIN/ Magnis	India	India		1		30		30
Reliance	India	India				25		25
ACC (PSA/Saft)	France	Germany			16	16	32	32
ACC (PSA/Saft)	France	France			16	16	32	32
amte/Britishvolt	UK	UK				35		35
Cellforce	Germany	Germany				1		1
Freyr	Norway	Norway			32	24	32	34
inoBat	Slovakia	Slovakia				10		10
MES	Czech Republic	Czech Republic				10		15
MORROW	Norway	Norway				32		32
Northvolt	Sweden	Sweden		0,5	32	60	33,6	150
TerraE	Germany	Germany				8		8
VERKOR	France	France				40		50
VW/ Northvolt	Germany	Germany			16	24	24	24
EU andere: Saft, Bollore, LeClanche, etc.	Europe	Europe	2	2	2	3	2	4
World in total GWh			**357**	**782**	**799**	**3847**	**912**	**7273**

LIB cell production capacities in GWh for electromobile, industrial, and stationary applications (large-format pouch, prismatic, and cylindrical cells of size 18650/21700) in 2020 and announced expansions of established and new manufacturers until 2025 and 2030+ by cell manufacturers, their headquarters, and cell production locations; baseline scenario (min) of today's existing and known planned production capacities; manufacturers <1 GWh cell production are totaled under "other" and listed by country. Some assumptions were made in the distribution of capacities among countries, such as for CATL. Source: Fraunhofer ISI database.



With CATL's latest expansion plans (not shown in the figure), production capacities could be well above 1 TWh by 2030+. Source: Fraunhofer ISI.

Hotspot Europe

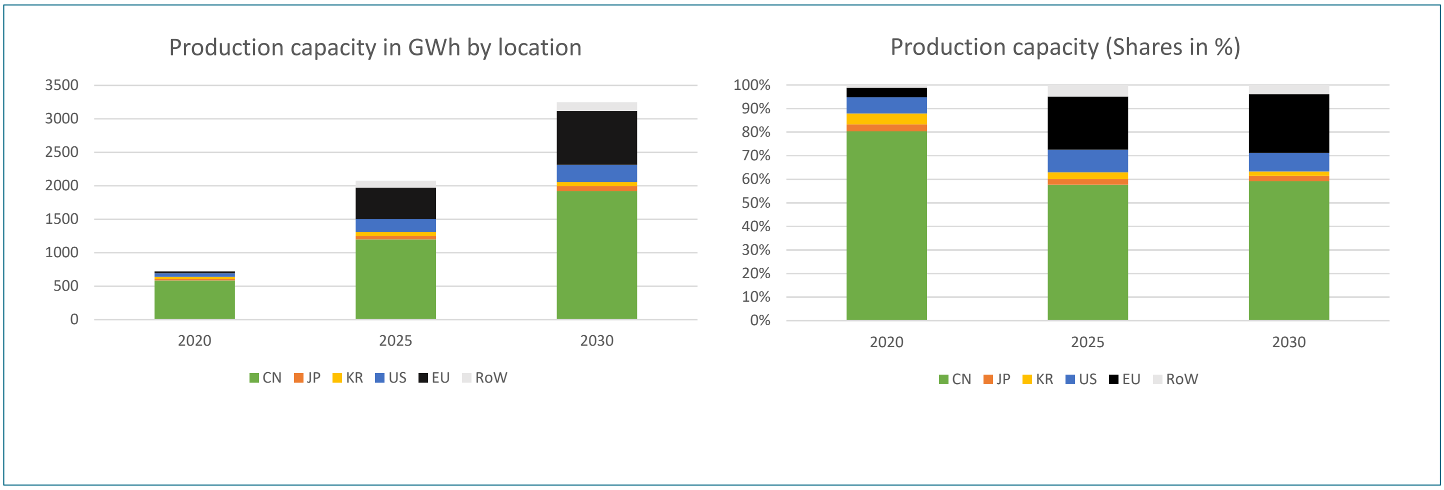
Demand for LIB cells in Europe could be 150-300 GWh by 2025 (conservative to optimistic scenario) and 400-1000 GWh by 2030. Expansion plans by Asian and European cell manufacturers approach 500 GWh after 2025 and 800 GWh by 2030. With the production of cylindrical cells (e.g. Northvolt), growth markets beyond the automotive market are also being addressed (e.g. power tools, e-bikes).

Europe is currently following the previous hot - spot of China due to the rapidly growing - demand for electric mobility and thus LIB cells. In the coming years, cell production capacity is to be built up in Europe, comparable to that established in China over the last few years and further expanded in the coming years.

The share of around 80 percent of global production capacity currently held by China is therefore likely to fall back below the 50-60 percent mark in the coming years.

The U.S., Europe and other countries will build up corresponding production capacities from 2025 to 2030 - but these will also come from Chinese companies such as CATL and BYD as well as established Korean and Japanese manufacturers.

The scenario shown in the figure on page 16 for the European announcements (bar) assumes that all announced capacities will be realized. In the Chinese market, it can be assumed that the number of cell manufacturers, estimated at over 100, will consolidate again in the next few years and that not all of them will succeed in entering volume production. In Europe, too, it is unlikely that all manufacturers will succeed in gaining a foothold in the highly competitive market and - establishing themselves in volume production. The Asian companies now expanding worldwide therefore have the best chances of transferring the production know-how acquired in their domestic markets to export markets. The quality of Chinese cells is already seen as being on a par with that of Japanese and Korean cells. European companies must therefore be able to compete on price or have a unique selling proposition.



Global demand in GWh by location (left) and % shares of production capacities by country of manufacturer (right). Excluding the Tesla 3TWh announcement by 2030 and the CATL 1.2 TWh announcement by 2025, as the location breakdown would still be speculative today, source: Fraunhofer ISI.

What makes a site suitable?

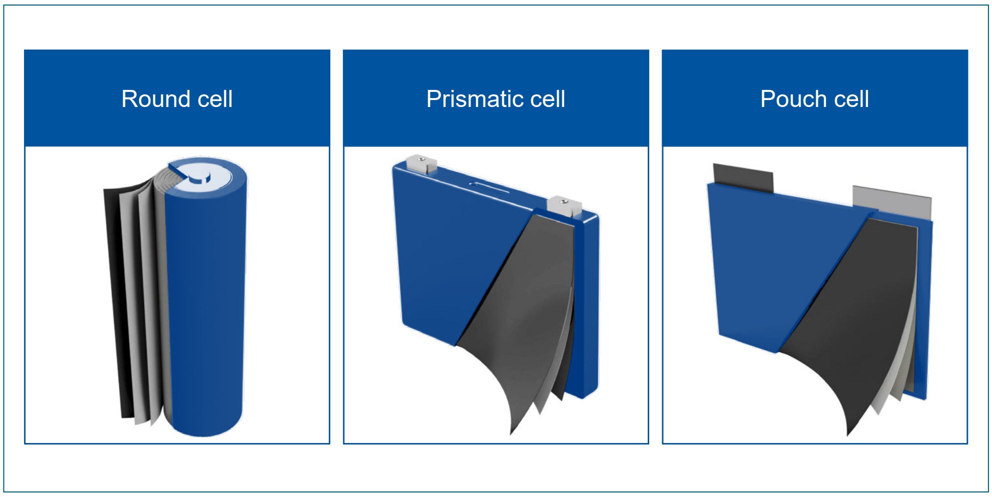
The above figure shows that, in addition to CATL as the Chinese manufacturer, Korean cell manufacturers in particular are increasingly setting up sites in Europe (and the USA). Panasonic, the Japanese manufacturer, is currently still expanding with Tesla and in the Chinese market and is thus following the location of demand (i.e. the locations of the OEMs).

Chinese manufacturers are primarily serving the enormous and growing domestic market but are secondarily trying to gain a foothold in Europe as well. After CATL, BYD and other manufacturers from China are likely to follow (e.g. SVOLT).

Between 2020 and 2030, a global relocation of cell production will emerge to locations where the cells can be transported as easily as possible to their user markets: primarily to OEMs.

The particular relevance of the proximity of cell production to the sales market becomes clear when considering the need and the potentials for reducing the costs of battery cells and packs:

- Transportation costs (especially at future GWh scales) and thus logistics costs can be reduced by locating production capacities 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 LG Chem, SDI, and SKI choosing to locate in Poland and Hungary.
- Costs for **infrastructure** (land, buildings, etc.) represent a significant part of the initial investment and must be allocated through depreciation. The settlement policies of states, regions, municipalities and cities play an important negotiating role here in order to make their location attractive to cell manufacturers.
- In addition to the pure "economy of scale", **automation is** an important lever for further optimizing process steps, quality, yield and throughput. The proximity of cell manufacturers to equipment suppliers and the supply chain, which gives them the opportunity to achieve a unique position in terms of **material and process quality**, can contribute to location decisions. European mechanical engineering could offer Asian and European cell manufacturers added value in this area in particular and could build up future references.



- Last, but not least, "green battery production" and the reduction of CO2 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.

Germany's location may have been decisive for some of the cell manufacturers due to its combination of several factors: energy mix, proximity to OEMs, and access to skilled labor. However, locations in several European countries are also becoming more important as demand from OEMs grows (e.g. France, Spain).

Cell formats: advantages and disadvantages of specific formats

Comparison of cell formats

In practice, the applications of lithium-ion cells range from consumer electronics to commercial vehicles and the automotive industry. The great diversity of applications also leads to a high variance of both pure cell size and cell formats.

Three primary cell formats are currently distinguished, as shown in Fig. p.20: pouch cells, cylindrical cells, and prismatic cells. The process steps required for the production of the different cell formats are fairly similar; however, the individual cell formats require precise coordination and optimization of specific - equipment. One significant production difference is that the electrodes and separators of cylindrical cells are wound. In comparison, the components of pouch cells are brought together in a stacking process. The components of a prismatic cell can now be wound into a flat coil or stacked.

The advantage of winding is the high process speed. Advantages of stacking are comparatively better utilization of space within the cell and simultaneous material protection. A central disadvantage of stacking is a significantly lower process speed. An additional process step can speed up the process: direct lamination of the separator with the electrode material, so that this composite can then be stacked. This means that fewer, stiffer objects have to be stacked, which increases the possible stacking speed.

Due to the differences in cell formats, almost no flexibility can be implemented in cell production for series production. Cell manufacturers have to commit to a specific format on a cell production line.

The **energy density** is one of the most important technical parameters of the energy storage system in mobility applications, as there is limited space available in the vehicle and weight is crucial for the subsequent energy consumption. The more energy that can be stored in the traction battery, the greater the - range of the vehicle. One of the key factors here is the ratio between the active and inactive materials of the various cell formats at the cell and module level. Due to the geometry, the volumetric energy density of cylindrical cells is the highest, but the energy density of large-format pouch cells has approached that of small-format lithium-ion cells in recent years. Due to the module design, cylindrical cells lose - some of their advantage over prismatic and pouch cells at the module level due to the packing density of cylinders. The energy density of prismatic cells is generally somewhat lower at the cell level due to the heavier housing.

Each of the cell formats mentioned is available in a large number of variants with different dimensions. The aim is always the optimal adaptation of the battery cell to the available installation space and the application characteristics of the battery system.

The high diversity of cell variants must also be addressed in applicable module concepts. Here it is important, for example, to also utilize the stiffness of the cells. In addition to functional integration**,** high **rigidity** is also necessary for both safe installation and good handling. It is therefore one of the core requirements of automotive manufacturers for the cells.

The cylindrical cell has an advantage over the other cell formats due to its high stiffness, but it also has many more joints and is therefore more complex to assemble. However, it does not need to be braced in the radial direction, as very little volume change occurs [Warner2014]. For round cells, the so-called 21700 format has become established in the automotive sector in contrast to smaller formats such as the 18650 cell. The capacity as well as the volumetric energy density of the 21700 cell is higher, and the cells are easier to integrate into the battery system. This results in a significant cost reduction. Due to its format and size, the prismatic cell is particularly well suited for the production of modules with less support structure. Bracing is possible, for example, using a tie rod. The pouch cell is less rigid due to its film envelope and requires the assistance of a plastic frame for positiong.

In all cell formats, the trend is toward ever larger cells in order to achieve more energy content and improved high-current capability. The latest example is the newly introduced 4860 round cell format from Tesla. [18]

[18] https://www.electrive.com/2020/09/23/tesla-battery-day-tabless-4680-cell-and-in-house-production/

In some cases, this leads to the production of cells so large that the module level is completely eliminated and the cell level is moved directly to the battery pack level (see the following section "Cell to Pack").

In principle, all cell formats can be tempered with suitable cooling systems. The main differences are the required **cooling effort** and the possibilities for supplying and dissipating **heat**. In electromobility, the greatest thermal load is typically induced in the cell by fast charging. The goal of cooling is to produce a uniformly low temperature in the cell. The homogeneity of the temperature distribution has a significant influence on the aging of the cell, as the processes cannot take place uniformly within the cell otherwise. Liquid cooling is typically used.

In cylindrical cells, the heat generated during charging processes, especially in the core, can best be dissipated via the outer surface of the cylinder. However, the geometry makes it difficult to achieve uniform temperature distribution. Due to the cylindrical shape and the distance of the cells from each other during assembly to the module, a cheap but low-performing air cooling system may also be used in some cases.

Pouch cells allow good heat dissipation through the current conductors as well as the sides of the cell, since the electrode material is thermally bonded directly to the cell walls. This provides the best cooling performance.

Prismatic cells are usually cooled via the bottom, which has the disadvantage of a long cooling distance. This can lead to undesirable temperature gradients in the system, since the top of the cell is quite far away 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 concept. Ever-increasing charging currents, which generate more heat, make high-performance cooling systems increasingly necessary.

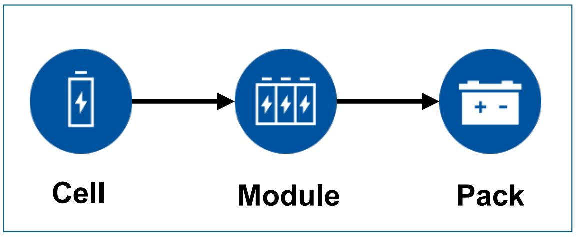
The **service life is** difficult to compare across the cell formats. It depends strongly on additional factors such as the cell chemistry or the stress on the lithium-ion cell. The lifetime of the cell is mainly determined by cycle life and cycle stability. The cycle life is dependent on the design of the cell chemistry and the operating strategy. During cyclic loading, the swelling of the cell stresses the active materials, which contributes to aging.

The overall trend in the automotive industry is toward increased use of large-format pouch and prismatic cells, partly because these can be produced into a module or system with less manufacturing effort.

Category	Pouch cell	Round cell	Prismatic cell
Volumetric energy density at cell level	Medium energy density at cell level	Currently highest energy density at cell level	Currently lowest energy density of the three cell formats
Volumetric energy density at module level	High energy density similar to round cell	High energy density similar to pouch cell	Currently the lowest energy density of the three cell formats
Lifespan	Independent of format	Independent of format	Independent of format
Housing	Aluminium-plastic composite foil	Mainly nickel-plated steel	Predominantly aluminium
Dimensions	• Many sizes • Efficient use of space due to rectangular shape • Opposite or next to each other cell contacts	• Typical size 21 x 70 (D x L, mm) but other formats also possible • Low packing density due to space utilisation	• Less diversity than the pouch cell • Efficient packing of the cell compound • Tendency towards more elongated housings
Mechanical strength	• Unstable housing • Inflates when pressure builds up	• High leak tightness • High stiffness • Mechanically robust • Robust under internal pressure due to degassing	• High leak tightness • High stiffness • Lower mechanical stability than the round cell
Thermal regulation	• Good surface to volume ratio • Efficient temperature control	• Low heat dissipation	• A high volume compared to the surface area • Heat conducting surface
Typical energy content	65 – 300 Wh	10 – 18 Wh	80 – 450 Wh

Comparison of cell formats, source: PEM of RWTH Aachen University

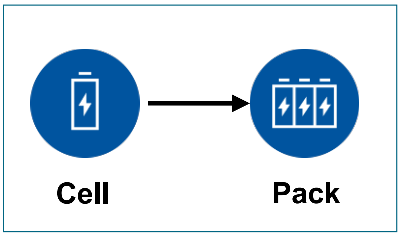
"Cell to Pack" - a new system concept



Source: PEM of RWTH Aachen University

Designs of battery systems for electric vehicles have always used the same structure: the cell, module, and pack levels.

Previously, battery cells have largely been developed and produced separately from the battery module and battery pack. The goal of system development is to design modules and finished systems from suitable battery cells. Recent announcements, for example by the Asian manufacturers CATL and BYD, suggest that the previously separate cell and pack levels can be directly combined. This would make the intermediate module level unnecessary, allowing for a battery system with a simpler structure and higher volumetric and gravimetric energy density.



Source: PEM of RWTH Aachen University

To be able to skip 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 cell design with elongated dimensions makes the most sense, as a very thick cell would have poor heat dissipation, and a tall cell cannot meet the tight installation space requirements in the vehicle.

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 safe cell chemistry, such as lithium iron phosphate, which has the disadvantage of lower energy density.

In current battery systems, the cells take up about one third of the volume of the entire battery pack. In electric vehicles, the weight share of the cells is over 70 percent of the overall system. The rest of the volume and mass is distributed among dead volume, other components such as the battery management system, the housing components, and the cooling system.

Eliminating the module level would greatly reduce the number of structural components, which would also reduce assembly efforts. The energy density could also be increased, in both volume and mass. A very long, sufficiently rigid prismatic cell mounted transversely in the vehicle could even take on a load-bearing function in the vehicle structure.

The first announcements from battery manufacturers promise that the system energy density can be increased by 15 to 20 percent, despite the use of cell chemistries with lower energy density. Costs are also expected to drop sharply, as the iron phosphate cell chemistries used are less expensive and fewer parts and manufacturing steps are required in system production. [19]

This concept seems coherent from a product perspective, but it increases the demands on cell production. The stacking or winding of extremely long electrode assemblies and results in elongated cells. This makes the handling of the electrolyte sheets very complex, as positioning inaccuracies lead more quickly to safety or quality-critical errors. The uniform distribution of the electrolyte in a very large cell also increases the filling time and requires new filling concepts. From a quality assurance perspective, it is also much more expensive to reject individual large-format cells at the end-of-line test, as required by the "cell to pack" approach, as much more value is lost than with a small cell. Despite increased 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 the cell production process can be implemented economically in the long term. Here, too, cell producers are dependent on innovative solutions from mechanical and plant engineering.

[19] https://www.electrive.net/2020/03/30/byd-kuendigt-neue-blade-batterie-mit-lfp-technologie-an/

Product requirements and specifications

Key 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 energy density [W/kg] also called specific power and volumetric power density [W/l] as well as the fast charging capability derived from it in the size range above 1 C
- Cycle life and calendar life
- Ambient conditions such as tolerated temperatures in [°C] or vibrations
- Safety according to EUCAR level
- Cost [€/kWh]

Other relevant criteria are the voltage stability during the discharge process or the effort involved for integrating the battery in the application. In addition, there are increasing specifications such as the environmental - compatibility of the production process and the need for cost-effective, environmentally-friendly disposal or the growing interest in re-manufacturing and recycling the components.

The central issue is the reduction of battery storage costs at system level. This can be achieved, among other things, by further developing the energy density at cell level, which can also increase the range of electric vehicles and improve their competitiveness compared with internal combustion engine vehicles. For plug-in hybrid electric vehicles (PHEV) and hybrid electric vehicles (HEV), power density is particularly important. In the case of purely electric vehicles (EVs), the requirements of automobile manufacturers (OEMs) for volumetric energy density in particular have increased sharply in recent years, since the dimensions for installing the battery in the vehicle are usually fixed and the achievable energy density at pack level is decisive for the range. The electric vehicles available today have a maximum range of more than 500 km.

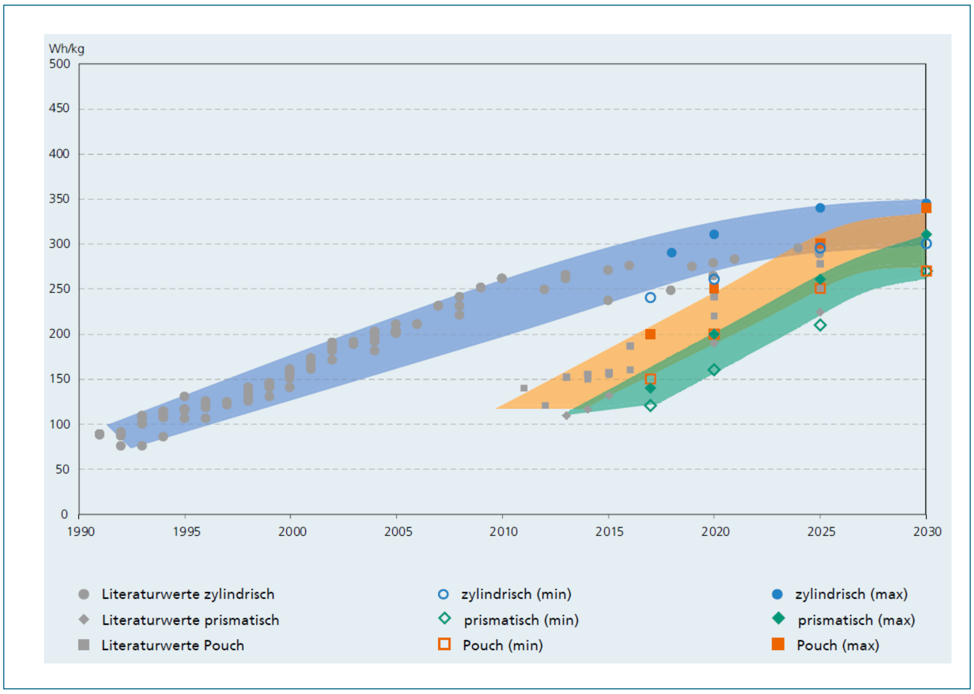
Recent developments clearly show that the lithium-ion cell is a suitable technology for realizing electric mobility, whose potential is far from exhausted.

Performance parameters for electromobility applications

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

The **gravimetric energy density of** the best cylindrical cells is currently around 270 Wh/kg and is expected to rise to over 300 Wh/kg in the future. In recent years, large-format pouch cells have approached the energy density of the small-format Li-ion cells and achieve similar values. The prismatic hard-case cell currently achieves lower energy densities of around 200-230 Wh/kg.

In the future, the gravimetric energy densities of the different cell formats are expected to converge, which is why a potential of more than 300 Wh/kg is assumed for the large prismatic and pouch cells in the future.



Development of gravimetric energy density of LIB cells by cell format [Thielmann 2017].

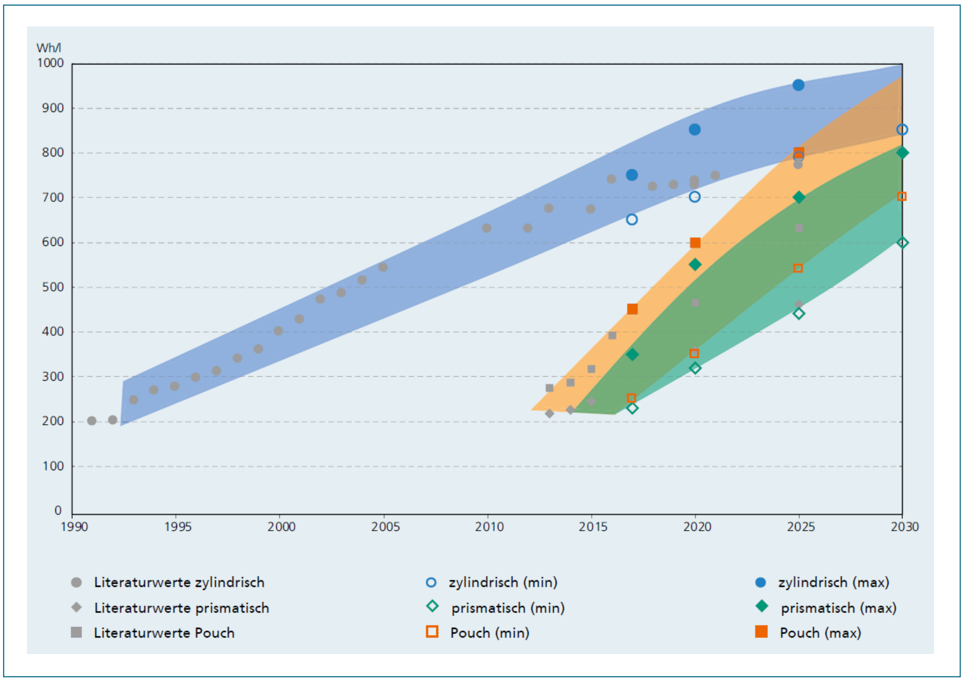
There are currently also major differences in **volumetric energy density** between small- and large-format lithium-ion cells (see figure on page 27). Cylindrical cells currently reach over 750 Wh/l and will reach up to 1000 Wh/l in the future, while prismatic and pouch cells are expected to increase from currently over 500 Wh/l to up to 800 Wh/l (prismatic) and up to 1000 Wh/l (pouch) in the long term.

Compared to the cell level, volumetric energy - density at the module level in the designs available so far decreases by 20-22 percent for the pris ma tic cell, 30-50 percent for the pouch cell and about 50 percent for the cylindrical cell. Many of the current developments in the automobile sector are therefore aimed at more efficient integration of the battery cells in the battery pack. This can be achieved by eliminating the module plane or by more efficient arrangement of cooling and safety systems.

The **power density of** batteries is of varying relevance for different powertrains. In contrast to purely electric vehicles, where volumetric energy density and high charging power are the decisive criteria, the power density of batteries is more important for purely electric vehicles.

In hybrid drive concepts, a high power output of the lithium-ion cell is of particular relevance 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 remain at least on the same level with an increase in the remaining performance parameters. The requirements of the surrounding setting **are** taken into account by specifying the power density at a low temperature of -20°C. The power density is about five times higher than the power density **for HEV.** It is about five times lower than the gravimetric power density at room temperature of the respective electric vehicle type.

The **calendar life** varies for all types of electric vehicles, as it depends on the load on the battery. Manufacturers' warranties for today's EVs typically exceed 10 years with mileages in excess of 150,000 km. To achieve the useful life of today's internal combustion engine vehicles, which often spans several phases from initial



Development of volumetric energy density of LIB cells by cell formats [Thielmann 2017].

registration to used markets, lifetimes of 15 to 20 years must be realized. In this period, mileages of several 100,000 kilometers can be achieved, which are translated into requirements for the cycle-life of the batteries. The driving and charging profile of the vehicle batteries represents a large influencing factor. For instance, it can be assumed that EV batteries in particular will only be fully and continuously discharged on infrequent long journeys. Battery use in partial-cycle operation leads to low degradation, so that even high mileages with more than 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 thousand cycles.

As fast-charging capabilities increase, so do the loads on the cell. This results in 60-120 W/kg for BEVs, 100-300 W/kg for PHEVs and 200-400 W/kg for HEVs.

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 break-proof, fire-proof and explosion-proof.

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

In addition to the cell chemistry, the design of the Li-ion cell as well as the battery modules and 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 power circuit can be - interrupted by thermal fuses to prevent the cell overheating. The mechanical stability of the cell is provided 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 is involved. A rough classification can be made - based on the application as energy or power storage [Kaschub2017].

Power storage units, which have to deliver and absorb high currents in the short term, have particularly high cycle-life criteria, while energy storage units with large storage volumes require a long calendar-life.

For both types of storage, it is usually assumed that the cost requirements are high, which must be considered in macroeconomic calculations over the entire life cycle. The level of investment and operating costs is significantly influenced by the service life 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 achieve a sustainable energy supply.

Decentralized PV battery systems, peak shaving, direct marketing of renewable energies, - provision of control power and so-called "multi-purpose" design are the most important applications for stationary energy storage. 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. Provided that the power - parameters meet the respective requirements of stationary applications, they are likely to be increasingly used there as well. "Second-use" concepts are also being discussed in this context [Fischhaber2016].

Requirements for battery manufacturers

Product requirements and the performance parameters derived from them for high-energy and high-power applications are documented in existing sources and have been incorporated into the road mapping process. Detailed specifications of the battery manufacturers for the production technology are often subject to NDAs and only accessible to a limited extent. The customer's point of view and their requirements for machine and system construction were ensured by including battery manufacturers and the automotive industry. Dialog and discussions on this topic at international events and the presentation of the roadmap at the VDMA roadshows in South Korea, China and the USA provided equally important input for the roadmap.

Cell production

Battery manufacturers continue to demand the most cost-efficient cell production possible. Possibilities for machine and plant manufacturers to achieve cost degression are described in the following chapter. These must still comply with the high quality standards for stationary and mobile applications. Prerequisites are stabilizing production processes and avoiding overengineering by optimally adapting the machines to the relevant application.

For European locations in particular, the focus is shifting to the development of sustainable and energy-efficient processes, which can be improved, for example, by reducing solvent content and further developing the drying and forming processes. The development of so-called "micro-environments" is intended to reduce energy consumption and operating costs of the clean and dry rooms. Another customer wish is high production precision. This can reduce rejects and costs through a higher degree of automation. Finally, higher energy densities or larger cell formats help to further reduce the manufacturing costs per kilowatt hour.

Battery safety 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 help to increase the safety of production.

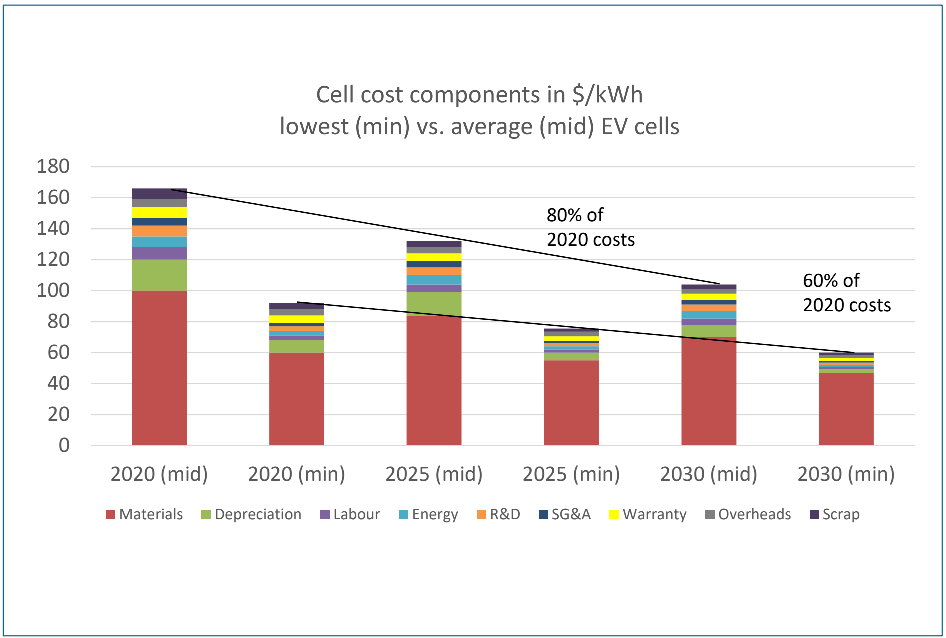
The great potential for optimization through the automation and digitalization of factories is well known among manufacturers and is increasingly in demand (Industry 4.0).

Module and pack production

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

Battery recyclability is another requirement. Legal requirements and the lack of primary - sources of the essential raw materials in Germany increase the desire to recover the materials as completely as possible. There is a demand for disassembly technologies and repair options or the initiation of battery service facilities. [CEID2020]

Finally, the battery is to become a "smart product". These are products that collect data about their own manufacturing process and pass this on to further processing steps. This means that business models based on data analysis should be developed. To this end, machine and plant manufacturers must provide possibilities for the product to communicate data about the production process.



Forecast battery cell cost structure in dollars per kWh, source: Fraunhofer ISI

LIB cell cost structure and development

Key and competition relevant levers for the costs of LIB cells are volume production and thus highly scaled cell production in conjunction with location factors[20].

Meta-analysis on cost development

A meta-literature analysis of market studies from different suppliers [21]helps us to better understand the current and future changing cost components of LIB cells and their reduction potentials. We analyzed about 30-50 specific cells (pouch, prismatic, cylindrical) of cell manufacturers (including CATL, Panasonic, LG-Chem, SDI) with information about the cost structures expected for 2020, 2025 and 2030. In addition to the most competitive cells (indicated as min. in Fig. p. 30), typical average cell costs (averaged over the cell forms) were also identified (indicated as mid.).

Compared to 2020, cost reduction potentials are shown to be about 80 percent by 2025 and about 60 percent by 2030 from current costs of less than $100[22] to more than $150/kWh.

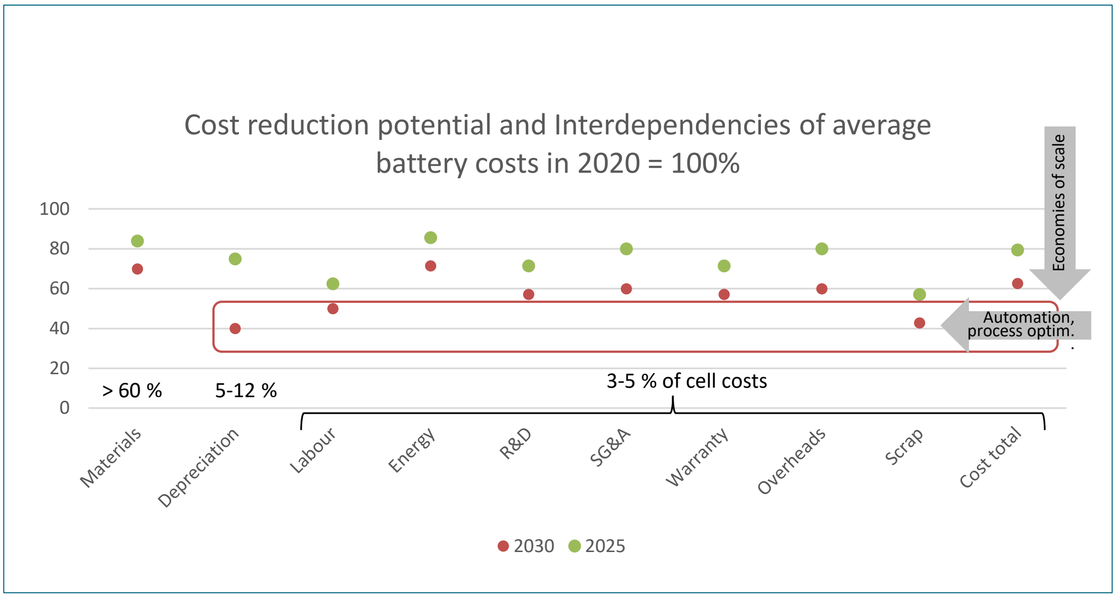
The material costs have a cost share of over 60 percent, which is expected to rise to 70 percent or more in the next ten years. According to the results of the market analysis, the maximum potential for a cost reduction of LIB cells in the long term is about $60/kWh. This means that the currently known technologies or foreseeable technology developments would only cover the costs of the material at most.

The meta-analysis provides interesting insights into the developing cost structure. While the material costs per kWh can still be reduced by 25 percent in absolute terms compared to 2020, in particular through higher capacities of the active materials, a total reduction potential of 50 percent is expected for the cost factors relevant to cell production.

[20] Indirect: transportation costs, infrastructure costs, energy costs, employment, etc.

[21] esp. Avicenne, Anderman, Takeshita 2015-2020

[22] Some studies also place the Tesla cell, which sets the price for the 2020 lower bound, at over $100/kWh



Cost reduction potentials & interdependencies of average battery costs, source: Fraunhofer ISI

The costs incurred in the context of cell production, such as R&D, sales overheads (SG&A), warranty, etc., can be reduced by corresponding economies of scale in volume production. Material costs do not follow these economies of scale.

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 rejects and the number of skilled workers required (given the size of the plant). In addition, process innovations with relevance for the plant investment can contribute to cost reduction.

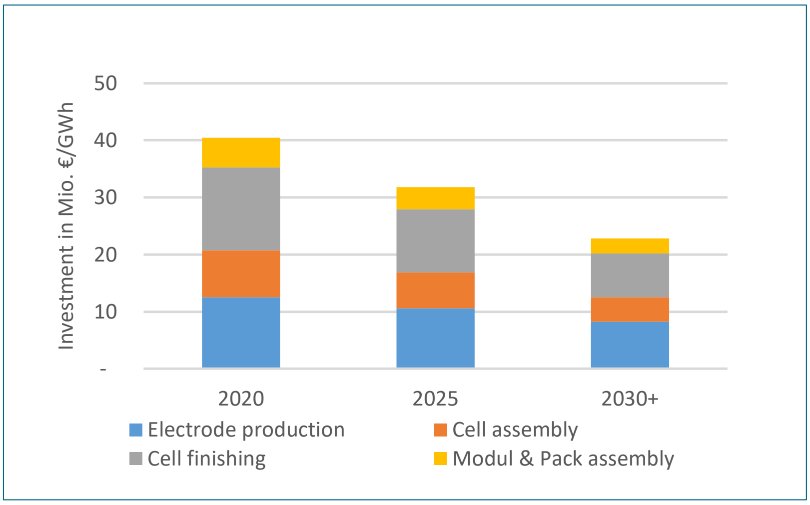
The evolution of the cost share of production facilities can be identified through depreciation: While today this accounts for $10 to $20 million/GWh per year and thus amounts to $40 to $160 million/GWh over a useful life of 4 to 8 years (depending on the scaling of production), plant investment is expected to halve to $20 to $80 million/GWh in the next 10 years (due to economies of scale as well as process innovations).

The most important cost components are discussed in more detail below: material and production costs. In addition to the "top-down" analysis of meta-market data, the identified cost factors are evaluated and their plausibility is checked "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]. Different material- and energy-intensive process steps are necessary starting with the mining of the metal ores, their purification and deposition as metal salts, e.g. as sulfates or carbonates. The production of the actual active materials in "battery quality" is carried out on industrial scale using high-temperature processes.

Due to this process chain, the costs for the finished active materials are between 40 percent (for an expensive material such as LCO) and 200 percent (for an inexpensive material such as LFP) above the pure metal prices. Accordingly, the NMC group of materials in particular can be strongly dependent on raw material prices. These are sometimes very volatile. In mid-2018, for example, the price of cobalt was almost three times the current market price (end of 2020). The trend toward nickel-rich materials has already significantly reduced the impact of cobalt price developments on material costs. However, these now depend all the more on the



Investments in production facilities in € million/GWh, source: Fraunhofer ISI

nickel price. In
the long term, no further cost savings can be expected from the transition to even more nickel-rich materials beyond NMC 622 or 811, since the reduction in expensive cobalt also means that less manganese is used, which is one of the less expensive components. In addition, the cost of the Li precursor increases for nickel-rich materials.

A significant reduction of the cathode cost - would thus enable a transition to other materials such as LFP (lithium iron phosphate) or manganese-based compounds. With a cathode material such as lithium-rich high-capacity NMC, which is still in the research stage today, the cost of the cathode could be reduced from over $40/kWh today (NMC materials) to under $30/kWh.

The most commonly used anode material is still natural graphite obtained from mines, and increasingly also synthetically produced graphite. Natural graphite is inexpensive to extract, but additional costs are incurred due to the downstream steps. Synthetic production offers good control of material parameters from the outset. Today, suitable graphite from both processes is available for about $10/kWh.

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

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

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

The situation is similar for the separators, whose main component is a polypropylene or polyethylene film that is basically inexpensive to manufacture. The additional coating with ceramic nanoparticles improves the safety properties, but significantly increases the costs.

The costs of other components such as housing and lid are essentially dependent 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.

Material costs and, ultimately, raw material and energy costs form a lower limit for the future cost development of LIB. Against this background, price forecasts based solely on the extrapolation of cost reductions achieved in the past should be treated with caution. Today's

most cost-efficient, high-energy battery cells can be produced at a material cost of about $80/kWh. With the technological advances described above, costs of $70/kWh are conceivable. With the technologies known today, it is very unlikely that costs will fall below $60/kWh at cell level [Thielmann2019]. However, if material prices dominate the overall price, experience from related industries such as photovoltaics shows that material savings or alternative materials are used and prices do not usually settle at one level [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 in machinery and equipment are allocated to their useful life (usually between 4-8 years). To date, the share of depreciation for machinery and equipment has been between 15 and 20 percent of the cell costs. The precise share depends, among other things, on the respective cell format and the size of the factory, i.e. economies of scale. Cost - degression is therefore one of the main drivers behind the current trend towards building the largest possible cell production facilities in the sense of "giga" and "tera" factories.

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

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

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

The effect of economies of scale on specific investments in production plants under these conditions is shown in Fig. p. 33 (taking into account increasing battery capacities and changing cell chemistry). The figure clearly - shows that the specific investment of approx. 40 million €/GWh is expected to decrease by approx. 40 percent over time. A look at the specific investments in equipment for cell production and module & pack manufacture shows that investments in machinery and equipment for cell production account for the largest share of more than 85 percent.

Cell production can be divided into the areas of electrode production, cell assembly and cell finishing. While electrode production is still strongly characterized by continuous production processes, such as coating or calendaring, cell - assembly and cell finishing are predominantly individual processes. A look at the 2020 investments at this process level shows that the highest investments per GWh will be in the area of cell finishing (approx. 35 percent) and - electrode production (approx. 30 percent). However, this share will not remain constant over the coming years.

In principle, the trend towards larger battery capacities can be realized in two ways: By increasing the number of cells in the battery -

system or by keeping the same number of cells with higher energy densities. Since installation space in vehicles is limited, the second option will probably be the most widely used(at least in the vehicle sector).

Assuming a higher energy density [23]with the same number of cells, the specific share of electrode production could increase from 30 to 35 percent in the future, while the share for assembling and finishing the cells would be minimally reduced.

In summary, production costs are very strongly dominated by depreciation and amortization for machinery and equipment. Specific investments (in $ million/GWh) will continue to decline in the future. The main drivers are innovations at product and process level and, in particular, the realization of economies of scale. Investments in cell production are significantly higher than those in module and pack production. At the process level, the highest specific investments are currently being made in electrode production and cell finishing.

Both the amount and the relative share of the specific investments in a complete PHEV battery system are strongly dependent on the product to be manufactured. When producing a PHEV battery system, for example, the specific investment per GWh in 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 somewhat different production structure, such as solid-state batteries. The results of such considerations must therefore always be -interpreted against the background of the product to be manufactured. A transparent presentation of the assumptions made here can be found in Hettesheimer et. al [Hettesheimer2018].

[23] due to the use of better materials at a constant coating thickness, so that the number of cells per kWh can be reduced while maintaining the same coating capacity

Mechanical and plant engineering solutions

Cost degression

It is known from numerous other industries, such as semiconductors or photovoltaics, that increasing quantities leads to cost degression from corresponding learning effects. In addition to technical innovations, improved yields, economies of scale, a higher level of automation, and knowledge of the process-quality correlations can be levers for this. These points are discussed in more detail below. Energy and resource efficiency, which can also have a significant influence on cost reductions, are - considered under sustainability.

Improved yields

Due to the high material costs of 60-70 percent today, increased yield is essential to strengthening competitiveness [Chung2018, Kwade2018b]. Even with speed increases, yields must at least remain equivalent. Otherwise, the benefits of increasing throughput through process integration and intensification would be moot.

Production yields for Li-ion cells are approx. 90 percent in established factories in [Brodd2013]. The number of process steps is directly related to the overall yield, as scrap multiplies with each individual production process step. Cost reductions can therefore be achieved by reducing the number of unnecessary production steps.

Causes for reduced yield include a lack of stable, robust production processes and the resulting product deviations or defects (e.g. surface mass deviations, edge overhangs, positioning errors, foreign particles). Further development and optimization of production processes, as described in the Red Brick Walls, can make a significant contribution to increasing the yield.

Early detection of quality defects in the intermediate products of electronics production is crucial. One example is using camera technology for inline detection and rejection of defective electrodes. Quality controls can be performed with the help of inline measurement technology at strategic points in the process to monitor intermediate product properties and evaluate process variants and reliability.

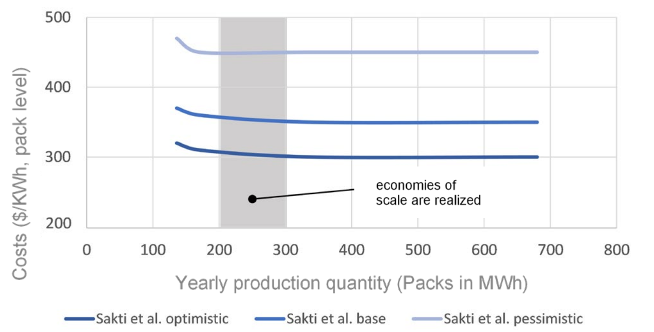
The benefits of using inline measurement technology must be evaluated individually for each system from the perspective of increasing quality, detecting rejects, and the costs incurred [Schmitt2008]. The evaluation of measurement data can also be used to identify internal and external effects of the process, which can reduce the learning curve. Knowledge of the influence of process parameters on the quality of the intermediate product can identify potential for optimizing processes and products. This can be used to adjust the position, number, and content of quality controls accordingly to achieve an interactive and self-optimizing control system for cell production quality management [Schnell2016].

Economy of Scale

Growing demand for LIB will lead to an expansion of production capacities. This can be achieved by increasing the number of machines ("numbering-up") or the capacity ("scaling-up"). Scaling makes a significant contribution to 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"

Simulation of costs in relation to annual production in MWh



Source: SU based on [Sakti2015].

[Voigt2018]. This means that production systems do not need to be increased as output quantity multiplies. Scaling up can be achieved in many different production steps, and is therefore addressed in many RBWs.

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

Therefore, economies of scale can be achieved in Li-ion battery production at smaller production sites with an annual output of 1-1.5 GWh/a as well as at large production sites with an output of 35 GWh/a [Panasonic2015].

Increased automation

For the continuous improvement of lithium-ion batteries, highly automated battery production concepts are being developed to reduce costs and increase quality. These concepts feature process intensification (time reduction), integration, optimization, and process substitution.

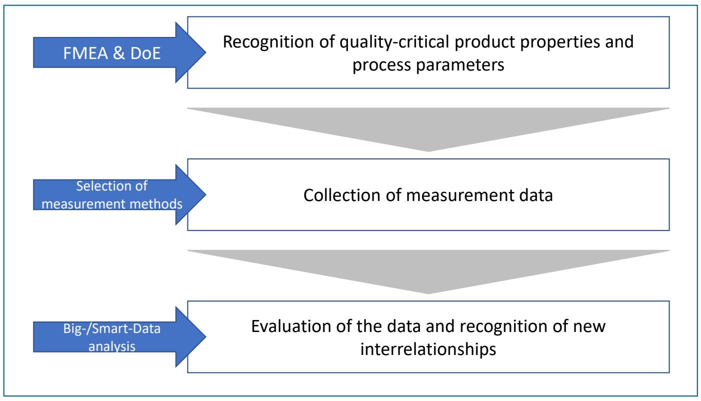
In industrial cell production (conversion to final cell sealing), fully automated individual processes are already in place. These are usually rigidly linked to one another in order to achieve the lowest possible cycle times and highest throughput.

Digitalization is closely related to the level of automation. The aim is to increase product quality and minimize rejects in production through intelligent manufacturing. The principles of Industry 4.0 are applied for this purpose, such as the use of cyber-physical systems, networked processes, data feedback, and active, measurement-based machine control. The foundation for networking of the production line is an integrated 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].

Another goal is to create a digital twin or shadow for each battery cell produced in order to record and verify all physical relationships and parameters, as well as maintain specific fault tolerances and cell quality [Schuh2020]. This topic is considered in more detail in RBW 13.

Sustainability

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. The use of batteries in electrical energy storage systems is equally important. The use of renewable energies and their storage capabilities is essential for a sustainable energy supply.



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

Energy efficiency

Energy-intensive processes are required for the production of batteries, especially in cell production. The most energy-intensive process steps are coating and drying, forming, and supplying conditioned drying room atmospheres. Together, they account for the - majority of the energy consumption in cell production [Pettinger2017]. These topics are discussed in more detail in RBW 2, 3, and 9.

Energy costs during production are a significant factor from a business perspective, accounting for up to 5 percent of the production costs of a Li-ion cell [Schünemann2015]. Energy consumption in battery production is also particularly relevant from an ecological perspective. The production of an Li-ion battery generates about 145 kg of greenhouse gas emissions per kWh of battery capacity, according to modeling by Agora Verkehrswende. This corresponds to about 40 percent of the total greenhouse gas emissions from the production of a BEV. It also states that 75 percent of the greenhouse gas footprint of battery manufacturing comes from cell production. Over 50 percent of this comes from electricity consumption. The cathode and anode materials, as well as the housing and the battery management system also make significant contributions [Meyer2018].

Overall, the CO_2 balance of battery production is strongly dependent on the electricity mix of the respective country of production.

Resource efficiency

Materials account for up to 70 percent of the costs of a Li-ion cell, which provides motivation for achieving a high level of resource efficiency in production from a purely economic point of view [Schünemann 2015]. The aim is to minimize the production waste that arises throughout the process chain; e.g., through start-up losses during coating and calendering, or offcuts during conversion. Increasing the yield also leads to better resource efficiency.

In particular, the materials copper, cobalt, and nickel, 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 the mechanical and plant engineering sector, this means that resource-efficient plants will become more attractive in the future as production capacities increase.

Recycling

Battery recycling and remanufacturing [Kwade2018b] is another important factor that can contribute to increasing both resource efficiency and energy efficiency. These have the potential to positively influence the CO_2 balance of the battery, its costs, and the supply of raw materials. Recycling refers to the process of recovering material components of the battery. Recycling may become the most important source of raw materials for Europe, as natural - resources are very scarce or non-existent - [Miedema2013]. The remanufacturing of batteries includes all methods for use in Second Life applications. A significant increase in used

Li-ion batteries is expected due to the ramp-up of electromobility and stationary storage [Hoyer2015]. Significant investments have been made into research and development of efficient recycling processes in recent years. More detailed information is available in RBW 14.

Improved quality

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, which command 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. An increase in the level of automation can also contribute to quality improvement. For example predictive engineering or maintenance can increase process reliability and provide the ability to directly adjust production parameters.

Measuring and testing technology

The battery production chain is a complex interaction of many disciplines. The three cell formats and variety of cell chemistries, some of which are still under development, leads to a large overall variation in production processes. This results in a large number of unknown interactions between process and product - parameters. This, combined with the high number of process steps, can lead to high scrap rates. Consistent and intelligent measurement technology enables early reaction, and thus the opportunity 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 in low tolerance - ranges must be identified. Processes can be optimized with quality inspection equipment and suitable adjustments to product and process parameters.

In general, analysis methods must be resistant to environmental conditions. Stable control circuits can provide many process benefits:

- Fast response due to small control circuits
- Stabilization of the manufacturing process
- Increased quality
- Reduced costs

The measurement technology used should also be non-destructive and contribute to earlier defect detection.

Quality assurance for complex process chains is described in the figure above. First, quality-critical product and process properties must be identified and evaluated by their relevance. Common evaluation methods include FMEA (Failure Mode and Effects Analysis) and DoE (Design of Experiments) [Westermeier2013]. The table on p. 41 shows quality parameters for cell production and possible measurement methods. The second step is the selection of measurement methods and the collection of process data. Finally, the measurement data must be evaluated. In the best case, this can be used to identify new cause-and-effect relationships - between individual production steps (machine/process-structure property relationships). Digitally networked production lines and Big Data applications are used to collect data and identify these quality-structure relationships. Process parameters are then adjusted based on the evaluation of the collected data. This results in an increase in the quality of the LIB, which leads to reduced reject rates, and ultimately the profitability of the production is increased. Among others, processes following this procedure have been developed by Schnell et al. for the production of entire batteries, and by Kölmel et al. for battery module and battery pack assembly [Kölmel2014, Schnell2016].

Level of automation

Automated processes are generally less prone to errors than manual production steps. This makes automation an important instrument for increasing quality and minimizing rejects. The basic objective is to increase the degree of automation to a reasonable level and prevent over-engineering:

- Avoid excessive automation
- Establish sensitive, flexible automation that can be easily adapted
- Link information processes
- Intelligent production through the use of learning systems.

Automation enables machines to be adjusted to possible quality fluctuations, and measured process data to be evaluated via software. Process results can also be compared with the target quality to determine which process control variables need to be changed [Linke 2017]. Further development of this evaluation process can potentially link of all the plants in a production line together, as upstream and downstream processes have a direct influence on intermediate processes.

Interfaces are used to provide information that is relevant for further processing and quality assurance along the process chain or for process control, especially with measurement and testing technologies. Data mining and big data analysis can be used to recognize new relationships between process and quality parameters (see RBW 13). Production parameters can be automatically adjusted during the production process based on measured material and component parameters. This leads to significantly lower scrap rates.

Process reliability

A large number of factors influence the performance of the battery cell in the production process. Detailed knowledge of product and production-relevant parameters and their interactions is required to improve the energy and power density, costs, and the cycle stability and the service life of battery cells. Process reliability and robustness should guarantee consistent product quality over months and years. As already described, quality-relevant plant and product parameters must be recorded for this purpose.

Predictive engineering or maintenance should be used to increase process reliability by keeping machine and equipment failures as low as possible. A high number of failures usually occur as production is established, which must be kept to a minimum via the mechanical engineer's learning curve along with identification of machine/process structural relationships. Random failures that occur in continuous operation due to the effects of wear should determine the type and extent of the quality controls. For random failures, it is difficult to identify safety-relevant process parameters and record them with sufficient accuracy. Control circuits are required to compensate for wear and maintain process robustness. For data mining in the production of LIB cells, suitable quality parameters are identified and tolerable fluctuations are determined via targeted variation of parameters along the process chain, without influencing the cell performance [Heins2017].

This sets the foundation for new product and production strategies and more powerful battery cells, which can be used as a basis for active control of production processes. In the future, intelligent database systems can make a significant contribution to process safety. They will make it possible to optimize various battery criteria, recognize causal relationships, and define meaningful tolerances..

		Important quality parameters	Important measurement methods in production
Electrode manufacturing	Mixing	• Purity • Suspension density • Solids content • Homogeneity • Viscosity • Carbon black agglomerate size • Temperature	• Magnetic separator, microscopy, ICP • Solid balance, TGA • Rheometer • Laser diffraction spectrometer • Rheometer, viscometer • Microscopy • Thermometer
	Coating	• Surface finish • Wet film thickness and accuracy • Edge geometry • Adhesion	• Chrome. White light sensor, camera • Laser triangulation • Camera • Mechanical (including forehead trigger test, etc.)
	Drying	• Material temperature • Surface quality • 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 (e.g. forehead pull-off test, etc.) • EDX
	Calendering	• Layer thickness, density and porosity • Surface roughness • Fractures in the material • Weight distribution • Pore size distribution	• Layer thickness, density and porosity • Surface roughness • Fractures in the material • Weight distribution • Pore size distribution
	Slitting	• Burr quality • Geometry of cut edges • Foreign metallic particles • Deformation of the microstructure	• Chrome. White light sensor, camera • Laser triangulation • Ultrasonic sensor • Camera
Cell assembly	Stacking/Winding	• Positioning • Foreign particle concentration • Electrical charge	• Laser triangulation • Camera
	Contacting	• Contact resistance • Mechanical stability • Weld quality	• Resistance measurement • Short circuit test • Weld monitoring, current measurement
	Insertion & Closure	• Electrical insulation • Tightness	• Measured after electrolyte filling
	Electrolyte filling	• Tightness • Electrical insulation • Electrolyte temperature • Dosing accuracy • No residues in the sealing seam	• Pressure test, optical coherence tomography • Insulation measurement • Temperature sensor • Measure
	Sealing	• Tightness	• Pressure test, optical coherence tomography
Formation and Aging	Press Rolling	• Homogeneous distribution of the electrolyte • Optimal formation of the SEI layer • Capacity of the cell after formation	• X-ray • Only measurable after formation
	Formation	• Cell internal resistance • Capacity • Cell temperature	• Calculation • Temperature sensor
	Degassing	• Tightness	• Pressure test, optical coherence tomography
	Aging & EOL-Test	• Self-discharge • Capacity • Cell internal resistance	• Measuring the open circuit voltage • Calculation • Electrochemical impedance spectroscopy

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

Frugal innovation vs. full digitalization

The frugal innovation approach targets the essential core functionality of a product. The term frugal stands for less is more. In contrast to current practices 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 provide the best possible benefit relative to the price [Radjou2014]. The focus is on target group-specific or application-oriented functions [Zeschky 2010]. Frugal innovation can also be based on a new idea or invention that is successfully applied and achieves market penetration if implemented and applied in the product, service, or procedure (diffusion) [Dörr2011].

Frugal innovation addresses the battery as a product design. From a mechanical engineering perspective, frugal innovations concern the machines and equipment within the "production system."

Battery production is characterized by a complex process chain in which a large number of process-structure-property relationships must be understood and controlled using process technology. Both the frugal innovation and full digitization approaches can be used to meet this challenge.

Industry 4.0 seeks optimization through - networked production lines with continuous data recording and artificial intelligence. Current hardware and software solutions that introduce more functionality and intelligence into the production system, machines, and plants make digitalization possible. This results in increased complexity and susceptibility to errors in the system. The frugal innovation approach aims to reduce this complexity. This can be achieved in different ways, including the targeted, effective use of advanced technologies in frugal products and solutions [Hitech 2018]. Therefore, Industry 4.0 solutions can also be used specifically for frugal innovation.

The topic of overengineering came into sharp focus in the 2018 roadmapping process. Excessive process requirements often 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 frugal innovation approach counters this. However, it presupposes a sufficient understanding of the process. Continuous data acquisition and evaluation within the context of Industry 4.0 can make a significant contribution to this. Based on the process understanding gained, additional but useful functions can be - incorporated into the manufacturing process or processes can be simplified, depending on the issue.

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 increased throughput for comparatively lower costs. Both approaches should be pursued and combined to fully take advantage of the potential in the battery production chain.

Challenges and necessary 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 variety of existing technology alternatives in cell production leads to diversity in battery production lines [Heimes2014]. At the same time, different interlinked technologies are required in the individual production processes [Kwade2018b]. In the roadmapping process, this manifests itself in a significantly higher number of challenges in cell manufacturing than module and pack assembly. At the same time, cell production also holds the higher revenue potential.

Roadmapping identifies challenges based on existing and future requirements for the entire process chain. The necessary technology breakthroughs (Red Brick Walls) are derived from this.

The foundations for the quality of the cell 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 there.

Cell production is further subdivided into cell assembly and cell finishing. The primary bottlenecks in the production process are stacking, electrolyte filling, forming, and maturing, which also have a considerable influence on the quality of the end product. The environmental conditions to be maintained in cell production also require working in dry and clean room atmospheres. Along with forming, operating dry and clean rooms in cell production is the most energy-intensive.

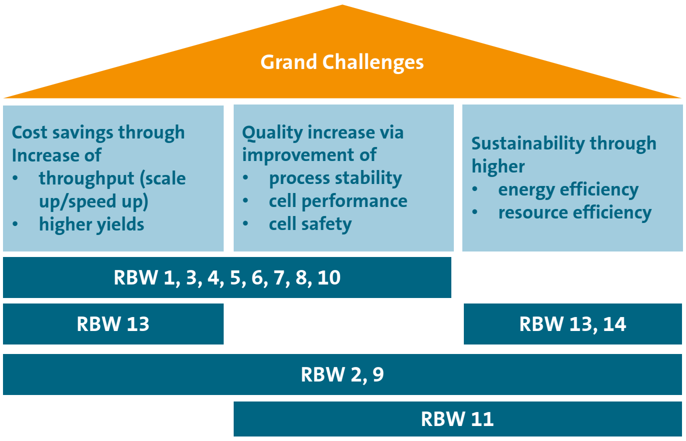
Housings are subject to strong cost pressure in both the cell and module sectors. The challenges lie in saving material and avoiding redundancies, as well as efficient production. It may also be necessary to “think out of the box" and develop new battery module and packaging concepts - that are more cost-effective to produce.

The only way to successfully prevent over-engineering is to recognize the interdependencies between process and quality parameters. This is becoming increasingly important for the entire cell manufacturing process, including electrode production.

Lower investments are required in **battery module and battery pack assembly** than in cell production, but process alternatives are highly concept-dependent [Kampker 2015b]. Production that is flexible with regard to variants and quantity is a key challenge for applications outside the electromobility market (e.g., commercial vehicles, stationary applications, power tools). The Red Brick Wall for contacting technology, which was already addressed in 2016 and 2018, still exists. Fast-charging capability and the associated handling of higher currents still require high-voltage - connectors that are suitable for mass production but can also be disassembled 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 chapter.

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



The biggest challenges to battery production and their relation to the identified Red Brick Walls (RBW).

The 14 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 is largely determined by the point in time at which all Red Brick Walls are reached, individual production equipment providers must still be concerned about effort and benefit. The Red Brick Walls are evaluated using a corresponding portfolio matrix.

Grand Challenges

The term "Grand Challenges" was already introduced in 2014. These are the challenges that are central to all of the Red Brick Walls.

The first Grand Challenge **is cost savings** through increased throughput (scale-up or speed-up) and increased productivity (minimization of scrap). Scale-up, speed up, and scrap minimization are aimed directly at reducing costs. However, cost savings are also the indirect driving force behind improved quality and sustainability.

The second Grand Challenge is improving quality. This refers to process quality in the form of process stability and high yields as well as addressing 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. Increasing the process speed can have a negative impact on process stability. Demand-optimized plant technology, quality-optimized handling, and standardized cutting - points in the production cycle that are suitable for mass production all allow higher speeds with the same process stability and low reject rates.

The third Grand Challenge is s**ustainable** battery production. “Green production" refers to the environmentally friendly and safe processing of raw materials throughout the entire manufacturing process, as well as the processing and use of environmentally friendly and safe materials. This also includes energy and resource-efficient production. This is supplemented by the so-called closed-loop - economy, which ensures that as many battery - raw 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 and more relevant due to increasing environmental regulations. The combination of efficient manufacturing processes, resource-conserving production, and sustainable value chains provides the opportunity to play a pioneering role in battery production along with significant cost benefits.

Red Brick Walls 2020 in detail

The following technology chapters were updated and developed, building on the RBW assessments presented in 2018. The RBWs from 2016 were broken down further to examine the challenges of the process steps in more detail. The primary RBWs for the process step are listed in tabular form in order of priority at the beginning of each chapter.

The **milestone diagram** with parallel "lanes" is used to visualize and analyze projected - technology development paths.

The subsequent diagrams only show requirements for the battery manufacturers for which no production solutions exist today - these are Red Brick Walls by definition. A milestone diagram has been prepared for the highest-priority Red Brick Wall in each technology chapter to maintain clarity.

The starting point in the milestone diagram is "2020," which represents the current state of production technology for volume production.

Four symbols are used to represent milestones in the development path, which can be seen in Figure 1. 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 demonstrable solutions. Technologies suitable for mass production are represented by a rectangle with pointed corners.

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

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

There are already a large number of research projects related to production research and the Red Brick Walls presented in this roadmap that have addressed or are addressing open questions in battery production. An overview of these can be found at the end of this chapter.

Technical support in the field of electrode and separator production

Industry support from:	Mixing	Coating	Calendering	Separator production	Singulation
ACHENBACH BUSCHHÜTTEN GmbH & Co.KG Thomas Dornseifer, Thomas Timmer		x	x		
AZO GmbH + Co. KG Jochen Weimer	x				
Brückner Maschinenbau GmbH & Co. KG Karl Zimmermann, Dr. Thomas Knoche				x	
BST GmbH Klaus Hamacher, Florian Kortekamp		x	x	x	x
Dr.Ullmann Consulting Dr. Bernd Ullmann					x
Dürr Systems AG Andreas Keil		x			
Erhardt + Leimer GmbH Herbert Bobinger, Dirk Schröder		x	x	x	
Festo SE & Co.KG Marthinus Venter					x
Freudenberg Performance Materials SE & Co KG Dr. Christoph Weber				x	
Gebr. Becker GmbH Marc Franzbäcker	x	x	x		
GEBR. LÖDIGE Maschinenbau GmbH Dr. Dirk Jakobs	x	x	x	x	
GROB-WERKE GmbH & Co.KG Joachim Szaunig					x
Industrie-Partner IP PowerSystems GmbH Ulrike Polnick					x
KROENERT GmbH & Co KG Christian Werner		x		x	

Technical support in the field of electrode and separator production

Industry support from:	Mixing	Coating	Calendering	Separator production	Singulation
MainTech Systems GmbH Dr. Jens Michael Hager		x			
Manz AG Maximilian Wegener					x
MARPOSS GmbH Michael Klenk					x
Maschinenbau Kitz GmbH Rainer Forster	x	x			x
Maschinenfabrik Gustav Eirich GmbH & Co. KG Dr. Stefan Gerl	x			x	
Matthews International GmbH Frank Bogenstahl			x		
NETZSCH-FEINMAHLTECHNIK GMBH Dr. Florian Schott	x			x	
OMRON ELECTRONICS GmbH Henry Claussnitzer, Marc Woerner					x
PIA Automation Bad Neustadt GmbH Dr. Hubert Reinisch					x
Robert Bosch GmbH Bernd Feirabend					x
SCHUNK GmbH & Co.KG Michael Bartl					x
SICK AG Philipp Mutz					x
SIEMENS AG Alina Rost		x	x	x	
Smit Thermal Solutions B.V. Michael van der Gugten		x			

Technical support in the field of electrode and separator production

Industry support from:	Mixing	Coating	Calendering	Separator production	Isolation
TRUMPF Laser- und Systemtechnik GmbH Marc Kirchhoff, Johannes Bührle		x	x	x	x
VITRONIC Dr.-Ing. Stein Bildverarbeitungssysteme GmbH Oliver Meister, Richard Moreth	x	x	x	x	x
Zeppelin Systems GmbH Peter Schmäling	x				

Technical support in the field of cell production

Industry support from:	Stacking	Electrolyte filling	Dry and clean rooms	Formation	Housing (cell)
ACHENBACH BUSCHHÜTTEN GmbH & Co.KG Rainer Neukant					x
bielomatik GmbH Dr. Tobias Beiß					x
Bosch Rexroth AG Andreas Gryglewski	x				
BST GmbH Klaus Hamacher, Florian Kortekamp	x		x		
COLANDIS GmbH Michael Habe not, Joachim Ludwig			x		
Dr.Ullmann Consulting Dr. Bernd Ullmann	x				x
Erhardt + Leimer GmbH Thomas Grimm	x				
Festo SE & Co.KG Marthinus Venter	x	x	x	x	
Gebr. Becker GmbH Marc Franzbäcker		x	x		
GROB-WERKE GmbH & Co.KG Moritz Glück, Joachim Szaunig	x	x	x		
HESSE GmbH Dirk Siepe					x
HIGHYAG Lasertechnologie GmbH Marc Hübner					x
H&T Battery Components Volker Seefeldt					x
Industrie-Partner IP PowerSystems GmbH Ulrike Polnick	x	x	x	x	x
KUKA Systems GmbH Dr. Joachim Döhner	x				
Leybold GmbH Dr. Sina Forster, Dr. Tom Kammermeier		x	x		

Technical support in the area field cell production

Industry support from:	Stacking	Electrolyte filling	Dry and clean room	Formation	Housing (cell)
Liebherr-Verzahntechnik GmbH Thomas Mattern	x				
Manz AG Randy Bedsaul, Andreas Schaal, Maximilian Wegener, Matthias Werner	x	x			
Maschinenbau Kitz GmbH Rainer Forster	x			x	
mkf GmbH Christian Voigt, Dirk Möder			x		
OMRON ELECTRONICS GmbH Henry Claussnitzer, Marc Woerner	x				
PIA Automation Bad Neustadt GmbH Dr. Hubert Reinisch	x				
SCHUNK GmbH & Co.KG Michael Bartl	x				
SICK AG Philipp Mutz	x	x			
ThyssenKrupp System Engineering GmbH Tobias Grobe, Toni Wolfgang, Andreas Kulisch von Ahlften				x	
TRUMPF Laser- und Systemtechnik GmbH Marc Kirchhoff, Johannes Bührle					x
VITRONIC Dr.-Ing. Stein Bildverarbeitungssysteme GmbH Oliver Meister, Richard Moreth	x	x			x
WEISS GmbH Yifan Lu	x				
ZELTWANGER Dichtheits- und Funktionsprüfsysteme GmbH Andreas Baur, Patrick Reich					x
ZELTWANGER Automation GmbH Anthony Nobel					x

Technical support in the field of module/pack production and other topics

Industry support from:	Housing (module)	Contacting	Flexible production	Cause-effect relationships	Circular economy
ACHENBACH BUSCHHÜTTEN GmbH & Co.KG Rainer Neukant	x				
Balluff GmbH Tobias Hörsch			x	x	
bielomatik GmbH Dr. Tobias Beiß	x	x	x	x	
Bosch Rexroth AG Andreas Gryglewski			x		
COLANDIS GmbH Michael Habenicht, Joachim Ludwig			x		
Dr. Ullmann Consulting Dr. Bernd Ullmann	x	x	x		
Festo SE & Co.KG Oliver Klein, Martin Schaupp Marthinus Venter		x	x		x
F&S BONDTEC Semiconductor GmbH Stefan Berger, Dr. Josef Sedlmair		x	x	x	
Gebr. Becker GmbH Marc Franzbäcker					x
GEBR. LÖDIGE Mechanical Engineering GmbH Dr. Dirk Jakobs					x
HESSE GmbH Dirk Siepe	x	x	x	x	
HIGHYAG Laser Technology GmbH Marc Hübner	x	x			
H&T Battery Components Volker Seefeldt	x	x			
Industrie-Partner IP PowerSystems GmbH Ulrike Polnick	x		x	x	x

Technical support in the field of module/pack production and other topics

Industry support from:	Housing production	Contacting	Flexible production	Effect relationships	Circular economy
KROENERT GmbH & Co KG Christian Werner			x		
KUKA Systems GmbH Dr. Joachim Döhner		x	x	x	x
Liebherr-Verzahntechnik GmbH Viktor Bayrhof			x	x	x
Manz AG Maximilian Wegener	x	x	x	x	
MARPOSS GmbH Michael Klenk	x		x		
Maschinenbau Kitz GmbH Rainer Forster	x	x	x	x	x
OMRON ELECTRONICS GmbH Henry Claussnitzer			x	x	
Pfeiffer Vacuum GmbH Dr. Stefan Zabeschek	x				
PIA Automation Bad Neustadt GmbH Dr. Hubert Reinisch		x	x	x	x
pro-beam GmbH & Co.KGaA Marcus Will	x	x			
Robert Bosch GmbH Bernd Feirabend			x	x	x
Schuler Pressen GmbH Markus Roever	x				
SCHUNK GmbH & Co.KG Michael Bartl			x		
SICK AG Philipp Mutz	x		x	x	
SIEMENS AG Mathias Altmannshofer, Alina Rost			x	x	x

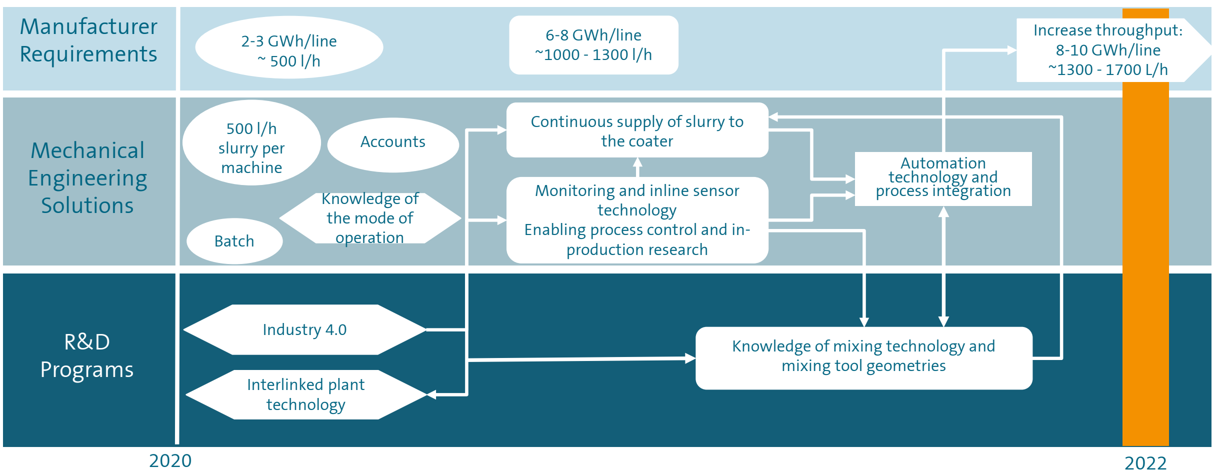
Technical support in the field of module/pack production and other topics

Industry support from:	Housing production	Contacting	Flexible production	Effect relationships	Circular economy
ThyssenKrupp System Engineering GmbH Tobias Grobe			x	x	
TRUMPF Laser- und Systemtechnik GmbH Marc Kirchhoff, Johannes Bührle	x	x	x		
ULT AG Dr. Stefan Jakschik					x
VITRONIC Dr.-Ing. Stein Bildverarbeitungssysteme GmbH Oliver Meister, Richard Moreth	x	x		x	
WEISS GmbH Yifan Lu			x		
ZELTWANGER Dichtheits- und Funktionsprüfsysteme GmbH Andreas Baur, Patrick Reich	x				
ZELTWANGER Automation GmbH Anthony Nobel	x	x	x		

Mixing

No.*	Red Brick Wall	Current status compared to 2018	Relevance**	Timeline***
1.1	Increase throughput/reduce mixing time	Progress made	High	2022
1.2	Increase quality/improve cell performance	Progress made	High	2030 (update every 2 years)
1.3	Structuring/ functionalization of active materials	Progress made	High	2023
1.4	Flexible adaptation to "next-generation" - materials: increase nickel content	Progress made	High	2025
1.5	Flexible adaptation to new materials: aqueous processing of cathode materials	Progress made	High	2025

RBW 1.1: Mixing - increase throughput / reduce mixing time
More efficient, process-integrated suspension production (e.g., the use of alternative machine technology, interlinking with metering systems and coaters) with the goal of continuous just-in-time coating process supply. Higher yield through minimization of residual quantities and rejects along with simultaneous reduction of inactive materials (binders, conductive additives, solvents) and increase in quality (suspension, cell properties). Monitoring of quality parameters in the mixing and dispersing process to establish connections between operating parameters and modes with raw material and cell properties, to ensure and monitor quality at an early stage.



Legend: State of the art, Research methods/projects, Pilot plants, concrete 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 (timeline considered is through 2035).

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

Mixing

Basics
Battery cell production begins with dry and wet mixing processes of powdered source materials to obtain suitable suspension viscosity and structure of the conductivity additives for the coating process. This consists of active materials as well as inactive components (conductive carbon blacks, conductive additives, binders) and a solvent. The aim of mixing is to homogeneously blend the powdered components and to structure composites of conductive carbon blacks/active materials and conductive carbon blacks/binder polymers. This is the foundation for producing electrode coatings with good electrical conductivity or homogeneous current and ion density distribution and good performance and energy properties, especially for future large-format cells with a width of approx. 500 mm [Kwade 2018b].

Challenges
Due to the construction of so-called "giga factories" (8-10 GWh/line, with a final planned total capacity of approx. 30 GWh), a competitive, stable, robust, and process-integrated production of the battery suspension with the aim of a continuous just-in-time supply of the coating process will be essential in the future. Increasing the throughput/reducing the mixing time is therefore a top priority for this process step. Continuous or quasi-continuous mixers and mixing processes have already been developed for this purpose and introduced into production for output in the range of several hundred liters of suspension per hour.

For an efficient process, dry and wet mixers can also be used in combination; e.g., in a one-pot process. It is also possible to combine a dry and batch mixing process for high throughput with a continuous mixer for wet dispersion. Ideally, a well-founded process can be combined with machine know-how to create a targeted structure of the conductivity additives and viscosity, making it possible to quickly and flexibly adapt to new (active) materials or scale-up to increased throughput and efficiency.

Furthermore, improved quality can lead to increased electrode homogeneity, especially in the early dry and wet mixing processes of battery cell production. This can have a significant influence on the subsequent cell performance, and is relevant for both mixing equipment and battery manufacturers.

Through optimized process control during mixing and dispersion, the amount of suspension produced per unit of time can be maximized and the time and energy required can be minimized, in both continuous and batch operation. Fully automated dosing of powders and liquids and the use of alternative machine technology and mixing tool geometries are becoming increasingly important for more efficient and process-integrated suspension production.

The objective of the mixing process is to achieve homogeneous and efficient material distribution as well as to generate specifically structured composites of active materials and binder polymers with conductive carbon blacks (RBW 1.3). This is a challenge in its own right, but makes a significant contribution to improving cell performance (RBW 1.2).

Furthermore, mixing processes for next-generation battery electrode production with reduced or no solvent use must be actively promoted (RBW 1.5). The comparatively high sensitivity of nickel-rich active materials to moisture and CO_2 also places new demands on the process. Due to the high material costs (60-70 percent of the total cell costs), it is essential to reduce production scrap, and ideally to avoid it completely.

Possible solutions

One important aspect is the development of suitable quality management strategies for the electrode suspension. The combination of various inline sensor systems and derived quality controls is crucial. In addition to the production parameters, machine and process parameters for control/regulation as well as inline detection of production anomalies and errors must be included. This seamless inline process and product monitoring makes it possible to determine machine and process capability indicators.

Strong linking and combination of existing system technologies can increase quality and improve subsequent cell performance, thus ensuring the required just-in-time supply of the coating process. Continuous or quasi-continuous mixers and blending processes make it possible to realize high throughput while simultaneously reducing space requirements.

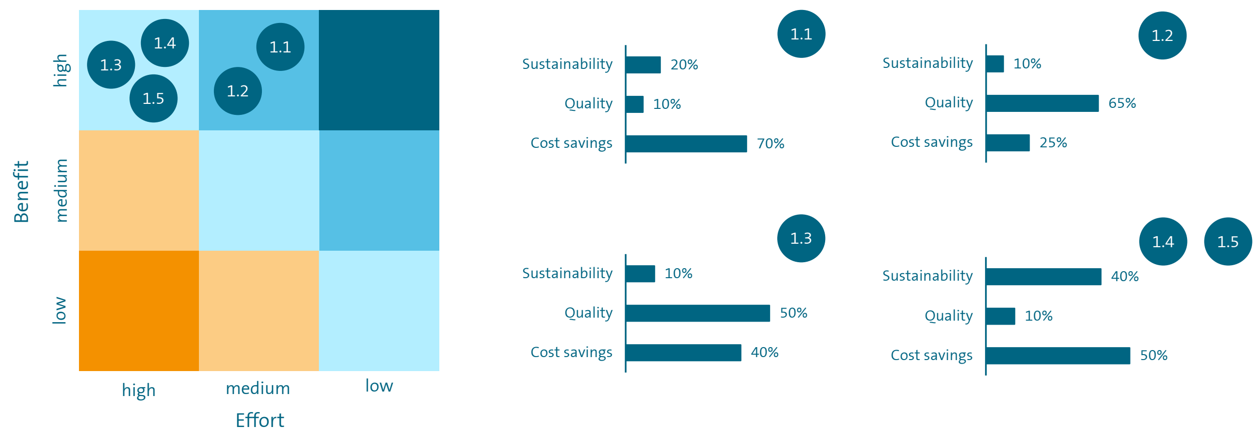
Dry mixing processes can be used to achieve good mixing homogeneity in a short processing time, set advantageous conductive carbon black agglomerate sizes, and incorporate targeted conductive carbon black fractions on the active material surfaces (to achieve efficient electron distribution on the active materials) and in binder polymers. They are an optimum starting point for further processing in dry electrode manufacturing methods or for subsequent preparation into extrusion or coating compounds.

Inline measuring methods in the various process steps enable the feedback of measured variables for automated process control and error compensation, including using artificial intelligence, and thus continuous improvement of electrode quality through "in-production research" concepts. Incoming goods, intermediate, and final product controls should also be performed to ensure compliance with final product requirements and a low variance in the electrochemical parameters of subsequent cells. 6-sigma processes are required.

In the future, a reduction of the solvent content will be relevant for the wet blending process. Efficiency with the lowest possible solvent content can only be achieved in close cooperation with the development and identification of new binders and processing machines (film extruders or calenders instead of coaters), whose processing must be responded to on the machine side. In addition to lower solvent content (approx. 50 percent), continuous extrusion processes make high throughput suitable for mass production. Another - significant advantage is the high reproducibility of the process, without time-consuming intermediate cleaning of machine and system parts. The integration of inline quality control is simplified, as is direct connection to a laminating line. For dry, solvent-free electrode manufacturing processes, direct pressing of the electrode mass is also conceivable, for example, in a calender. In all cases, a stable upstream mixing process is required.

When processing cathodic active materials with high nickel content (NCM811 and higher), structural damage due to pronounced moisture absorption and reaction with CO_2 must be taken into account. Therefore, it is necessary to perform controlled moisture and CO_2 mixing processes. Wet dispersion can be completely - eliminated if dry powder coating or pressing processes are developed. Here, powder pre-treatment and homogenization (dry mixing) and, if necessary, structuring (e.g., fibrillation) are required to break down conductive carbon black particles and structure them together with the active materials and binders. Another possible solution is the aqueous preparation of cathode materials, which has already been demonstrated for NCM111 and is under development for NCM622.

Effort Benefit Diagram and Impact on Sustainability, Quality and Cost



1.1 Increase throughput 1.2 Increase quality 1.3 Structuring/functionalization

Effort and benefit assessment
Future demands on the mixing process (8-10 GWh/line) will require a significant increase in throughput (1.1). This more efficient and process-integrated suspension production requires a great deal of effort due to the required in-depth process and machine knowledge, but also offers substantial benefits.

Continuous or quasi-continuous mixing and dispersing processes are generally considered to be very relevant for the future, as they offer significant benefits at a moderate cost. For efficiency reasons, combinations of different mixing processes (e.g., dry mixer with extruder) are also a possible solution. Extensive process integration and plant interlinking comes with a high initial cost; however, the benefits can also be significantly higher, as reduced mixing times and improved electrode quality can lead to an increase in throughput, which is associated with significant cost savings (1.1).

A promising approach for improving quality - (1.2.) is the implementation of inline sensor technology, which requires moderate to high effort but brings a very high benefit.

Continuous or intermittent in-line process monitoring is essential for the successful development of appropriate quality - management strategies and an increase in quality, as well as reduction of costs through minimization of scrap.

The adaptation and development of existing processes to novel structured (active) materials requires moderate effort in terms of plant engineering, as formulation strategies have to be adapted to the new materials (1.3). However, the benefits of such materials can be very high, depending on the desired properties of the cell, as they allow a reduction of inactive materials (1.4) and result in an improvement in cell performance (1.2) via increased volumetric cell capacity. Further development of suspension quality is also driven by "in-production research" concepts.

The reduction of solvent content and aqueous processing of cathode materials (1.4; 1.5) are challenges that are associated with a high benefit. Reduced-solvent/solvent-free production has both economic and ecological advantages. Costs can be saved in both drying and subsequent condensate treatment, which can also make a significant contribution to more sustainable battery production.

Professional support

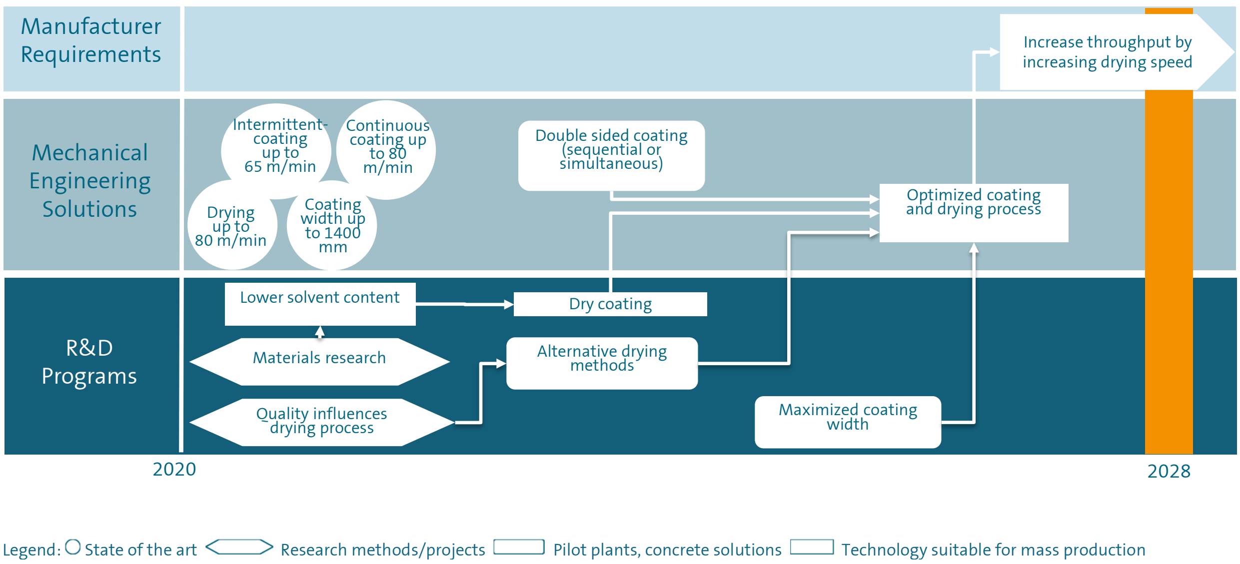
Topic sponsor:
Dr. Stefan Gerl, Head of Process Engineering,
Maschinenfabrik Gustav Eirich GmbH & Co KG

With additional support from:
AZO GmbH + Co. KG
Bosch Rexroth AG
Gebr. Becker GmbH
GEBR. LÖDIGE Maschinenbau GmbH
Hesse Mechatronics GmbH
Maschinenbau Kitz GmbH
NETZSCH-Feinmahltechnik GmbH
VITRONIC Dr.-Ing. Stein Bildverarbeitungs-systeme GmbH
Zeppelin Systems GmbH

Coating and drying

No.*	Red Brick Wall	Current status in Comparison to 2018	Relevance**	Timeline***
2.1	Increase throughput	Progress made	High	2028
2.2	Increase/improve quality	Progress made	High	2020-2024
2.3	Increase energy efficiency and avoidance of critical materials	No progress made	High	2022

RBW 2.1: Coating, drying - increase throughput
Lower coating solvent content increases throughput, and long drying lines can be avoided or production output can be increased. Drying is a key factor in determining speed and quality, but a high-quality coating application must be ensured at high web speeds (ideally on web widths of up to 1.4 m and on both sides simultaneously). Alternative drying technologies or combinations thereof are increasingly coming into focus for increased energy efficiency and faster drying.



*RBW priority decreases from top to bottom.

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

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

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

RBW 2: Coating, drying

Basics
In the coating process, the suspension is applied to a carrier film with an application tool, either continuously or intermittently (i.e., with interruptions). Slot-die coating is currently the most common industrial practice.

Typical energy electrode wet film thickness values are between 200-250 µm. With several or so-called multi-chamber nozzles the coating width can be up to 1400 mm (anode, Cu and cathode, Al), as substrate manufacturing technologies have improved significantly in recent years. Coating application and drying can influence the quality of the coating on both sides.

However, drying has a greater influence on the speed than the coating application. An approximate guide value for the drying time is 40-80 s, depending on the wet film thickness, the solid content of the suspension, and the solvent used. As a result, the throughput is largely restricted by the length of the dryer, and the throughput of future production processes may be significantly influenced by the drying technology.

Today, recirculating air dryers are generally used, sometimes in combination with IR dryers [Kwade 2018b]. Science and industry are currently focused on alternative drying processes.

Depending on the system, the top and bottom sides of the film may either be coated on both sides simultaneously or, as is the rule today, sequentially (tandem coating). For one-sided coatings, carrier rollers can be used at the start of the drying process instead of air bearing floatation nozzles. These allow the coating to be heated more gently. Further demands on the process are the avoidance of cracking in the coating material and the minimization of binder migration to the coating surface [Kwade 2018b]. These occur at high drying rates when the coatings are dried too quickly. Thus, there are optimization issues between cost/throughput and the achievable quality (e.g. energy, power density) for the drying processes, which can be significantly influenced by the machine technology, and especially the drying technology.

Suitably gentle drying is achieved and surface defects are prevented using temperature profiles/air speeds with different zones.

A suspension line is required for simultaneous double-sided coating, as contact between the wet/damp coating and the carrier rollers must be avoided. The advantage of simultaneous coating over sequential coating is that dishing of the electrode can be avoided. Dishing refers to the tilting up of the film edges due to stresses between the substrate and the coating induced by drying, which leads to shrinkage of the film.

Challenges
Increasing throughput (cost efficiency) is currently one of the most important challenges to competitive mass-scale electrode production. Planned large-scale giga factories must achieve high throughput to meet market demand. Standard scale-up processes for conventional dryers face high initial costs and manufacturing issues. For example, increasing the size of the drying section leads to web guiding challenges, which can lead to wrinkles in the substrates. This means that current dryer lengths today are primarily restricted by substrate properties.

In addition to increasing throughput, another challenge is improving quality. Solutions must be actively pursued here, especially with regard to high material costs and consistent electrode quality.

On one hand, identifying quality controls can be decisive for the economic efficiency of the coating process by reducing rejects. Due to the direct influence of the coating and drying process steps on the electrode structure, technologies are required which, for example, monitor and measure the homogeneity of the coatings in-line, as well as actively intervene in the process if set limit values are exceeded or not reached, such as defining/marking the electrode as a second or reject.

On the other hand, in addition to reducing rejects, active intervention in the process can prevent quality fluctuations and achieve the desired cell properties. This requires preliminary and intermediate product characterization to detect product fluctuations as early possible and avoid rejects.

In addition to increasing throughput and improving quality, the responsible use of materials is a key issue in terms of sustainability. The aim here is to find alternatives to the toxic and expensive solvent NMP for cathode coating, optimize equipment, and avoid rejects. Until solvent-free electrodes are market-ready, it is imperative to focus in parallel on optimizing recovery and exhaust air purification systems. This plays a significant role with regard to our responsibility to the environment and future generations.

Possible solutions

In all approaches, the achievable increase in throughput is always offset by quality issues. Stable processes must be established and optimized in order to maintain the necessary cost structures and keep rejects low. This, and the acceleration of drying in general, requires optimized processes and equipment configuration, along with 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).

The speed of the drying and coating process can be significantly increased by reducing the time spent in the drying process. This is the aim of efforts to produce suspensions with higher solid contents and to enhance the drying process with combined energy applications; e.g., convective with IR. This requires the coating equipment application tools to be adapted for processing extremely high-viscosity suspensions.

Solvent-free coating processes have already been successfully implemented, at least on a pilot plant scale. Instead of a suspension, these processes use powder, which can be pressed by hot calendering to form a film that is applied directly or laminated to the carrier film.

Other alternatives are PVD processes or electrostatic coating approaches. Further development of binder materials is essential for both high viscosity and dry coating, and must be adapted to the machine concept. In general, extensive material research is required for both the reduction of the solvent content and dry coating [DryLIZ 2016]. Survey partners expect dry coating to be suitable for the mass market from 2025-2030.

The ability to achieve high process speeds of more than 80 m/min without compromising quality is a fundamental contribution to increasing the throughput of wet film coatings. The achievable process speeds are directly related to the coating processes: double-sided sequential or simultaneous, either intermittent or continuous. Plant manufacturers expect process speeds to increase by 50 percent by 2025.

In addition to established processes, new approaches could include screen or gravure printing. The inclusion and development of new drying processes, such as infrared or laser drying, is also essential. By combining drying processes, drying speeds can be increased and dwell times can be shortened. Research results show that laser drying can achieve a more efficient energy input, and thus lower energy consumption, compared to conventional drying ovens. Furthermore, switched laser drying upstream of the convection dryer is also conceivable, for example using VCSEl lasers.

Sequential coating offers further potential. This refers to the slight drying" of the first side, so that carrier rollers can be used for transport. After the subsequent coating of the second side, both sides can be fully dried simultaneously. Another alternative is the direct, simultaneous, double-sided coating of two wet layers, which offers the advantage uniform coverage of both sides without the "keying" effect described above.

Further demands on the coating process arise when the coating width is increased to increase throughput. This requires the further development of 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). Multi-strip coating in these widths can be implemented on both sides almost simultaneously, as well as intermittently for certain electrode formats.

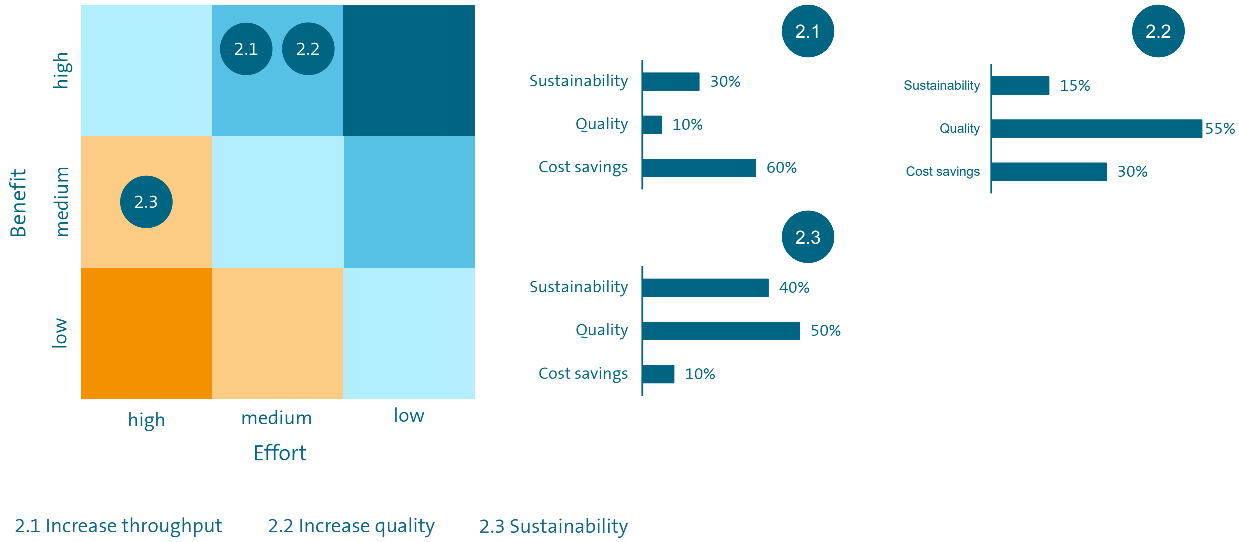
Technologies for precise metering of the suspension volume flow and nozzle venting are crucial for setting exact edges in intermittent coating, both for simultaneous and sequential coating. Uniform coating of the edges can be achieved, for example, by optical methods for automatic web control.

Multilayer coatings are being more widely applied for further development of future electrodes that combine very good charging performance with outstanding energy properties (range). Multi-slot nozzles can be used for this purpose. Previous drying processes have primarily used conventional convective drying.

A reasonable combination of different drying processes (e.g. convection and infrared) to increase the drying speed is a challenge. The dryer length is limited by the carrier film, so it cannot simply be extended.

Optical systems can also be used to detect surface defects at an early stage and trace them to their sources. For example, stripes on the coating can be attributed to an agglomerate in the die gap. Furthermore, it is necessary to assess the extent to which the detected defects reduce the quality. By dividing the defects into categories, it can be determined whether defects lead to cell rejection or to a reduction in quality (seconds).

Effort Benefit Diagram and Impact on Sustainability, Quality and Costs



Furthermore, quality controls must be determined to detect potential quality-degrading fluctuations as early as possible and intervene in the process accordingly. Cyber-physical systems can be established to directly evaluate inline measured data and recommend actions, or the data can be used as a predictor for the creation of a digital twin.

Responsible use of materials is a crucial issue in terms of sustainability. Due to the high cost of materials and the poor environmental footprint, the avoidance of scrap is essential. For example, camera-based control systems can be used when setting up the coating lines to ensure that the coating positions relative to the substrate as well as to each other (top to bottom) are automatically positioned and further regulated in subsequent production processes.

The surface inspection described above can also be used to classify defects and quickly intervene in the process to avoid rejects. An additional automatic closed-loop layer thickness measurement would make it possible to setup an almost entirely automated coating line.

The use of NMP as a solvent for cathode coating, which is associated with high costs in addition to its high toxicity, has the logical consequence of reducing or even avoiding solvent content, - which in turn reduces energy costs and minimizes the CO2 footprint. If NMP is to be used, the goal should be energy-efficient, almost complete recovery of the solvent.

Effort and benefit assessment

The effort required to optimize throughput is estimated to be "moderate," with high benefits. Increasing throughput plays an increasingly important role in battery production and can significantly reduce costs. The use of innovative drying technologies (IR, laser, or contact drying), as well as dry coating and the further development of simultaneous coating processes, offer an opportunity to increase throughput and reduce costs, but with increasingly high development effort.

Quality assurance measures are generally considered very relevant and can reduce costs and serve as a predictor of the tolerance ranges for the finished product. The benefit is estimated as high and the effort as moderate due to the availability of many technologies from other industries.

Ideas for alternative drying processes along with dry coating for solvent reduction or avoidance were discussed to increase sustainability. The implementation costs are estimated to be high, with moderate benefits. High cost savings are assumed for increased sustainability. Above all, this can be achieved by reducing scrap and energy costs.

Professional support

Topic Sponsors:
Christian Werner, Regional Sales Director, KROENERT GmbH & Co KG;
Andreas Keil, Director Business Development, Dürr MEGTEC Systems SAS

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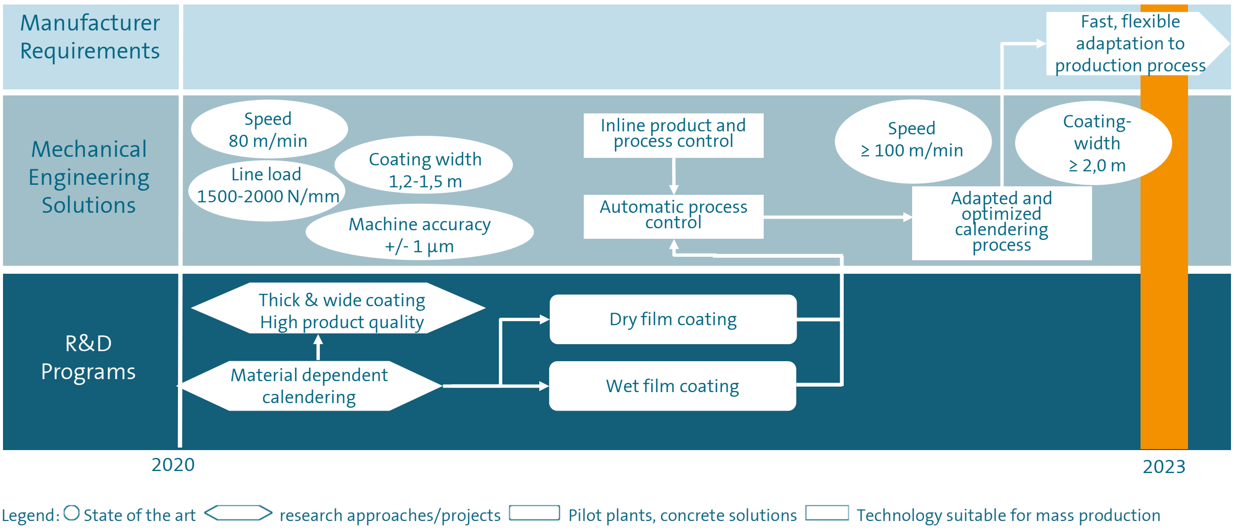
Calendering

No.*	Red Brick Wall	Current status in Comparison to 2018	Relevance**	Timeline***
3.1	Fast flexible adaptation to new materials	Progress made	High	2023
3.2	Increase throughput: increase speed without impacting quality	Progress made	High	2025
3.3	Ensure homogeneous electrochemical properties and uniform layer structures for increasingly large web widths	Progress made	High	2025

RBW 3.1: Calendering - Fast, flexible adaptation to new materials
Gain process understanding, especially of process-structure-property relationships for optimal system¬ ¬design (e.g., calendering of thick electrodes). Simultaneously increase density and energy density (el. vs. ionic conductivity). Consider interaction with other process steps to ensure optimal downstream processing. Monitoring of process parameters (e.g., force instead of gap-controlled calendering). Direct continuous calendering , e.g., after dry coating.



*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

RBW 3: Calendering

Basics

Calendering (continuous roll compaction) is the final process step in electrode manufacturing, and is therefore an important quality control for the transfer to the cell manufacturing processes. During the calendering process, the particles of the porous coating are rearranged by pressure and shear forces. The electrical percolation paths and mechanical polymer-binder linkages (solid phases of the electrode) that are initially established after the coating dries are broken, and particle-particle and particle-binder contacts are re-established, which defines the final pore structure distribution. As a result, there are interactions with the upstream processes of suspension preparation and layer formation.

The compaction process generally defines all central electrode properties, such as energy and power density, the cycle stability, and the correlating physical coating properties such as structural and electrical properties, which determine the electron and ion transport processes. The key requirement for classic liquid electrolyte batteries for electric cars is achieving the highest possible energy density (range) with simultaneous fast charging capabilities - (densities: cathode > 3.2 g/cm³; anode ≥ 1.3 g/cm3). As significantly higher capacities are introduced on the materials side, high energy densities are not as decisive for graphite anodes (especially graphite-silicon anodes) as for the cathode. Moderate densities are often used to - avoid the limitations of ion diffusion. An important goal of densification is to achieve mechanically advantageous coating properties to compensate for stresses in the manufacturing processes or the layer breathing of the anodes during electrochemical cyclization.

Challenges

Understanding of material-process interactions is crucial to enabling fast, flexible adaptation to new materials and prediction of electrode performance after calendering. The process interactions of calendering with upstream processes are in turn dependent on these material dependencies. The conductive carbon black structures, their degree of dispersion, and the structuring of the conductive carbon black with active material and the binder polymer are defined during dry and wet mixing (see figure below). This has a direct influence on the achievable coating structure, the charge transport, and the line load absorption of the electrode in the calibration process. The mechanical properties of the electrodes (adhesion to the substrate, coating homogeneity, deformability, elasticity, residual stresses) are also significantly changed, which is relevant for the lifetime of the cell and the processing properties in cell construction. These types of relationships must be transformed into generally valid material/process structure property relationships in order to be able to create optimal functional structures for specific applications for new materials more quickly in the future (RBW 3.1).

Another major challenge is to increase the speed without affecting the quality (RBW 3.2). The gap width or the line load to be applied are the central process parameters of calendering, which are used as control variables. The influence of the web speed, 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, must also be considered. Large roller diameters are associated with gentler compaction processes. Furthermore, with a constant roller diameter, high surface loads increase the catchment area (and thus the stress surface) and compaction intensity . High throughput speeds increase the necessary compaction performance per unit of time in the catchment area, although this may not affect the quality. With regard to maintaining quality, increasing the roller temperature can promote binder polymer deformation and reduce the required cathode line loads. This can minimize electrode deformation ("dishing") as a consequence of mechanically-induced residual stresses at the interface with the substrate. Another approach for limiting residual stresses and ensuring high quality is to pre-stretch the substrates to avoid significant stretching during calendering. A key quality feature of a calender is the consistency of the nominal gap size at high throughput rates. Thick electrodes and high line loads for cathodes can cause the actual gap to widen due to high mechanical compaction stresses and the associated deformation of the roller frame, thus limiting the densification capability of a calender.

In addition to the appropriate conductive carbon black structure discussed above, the smallest possible deviation between the actual and nominal gap is also decisive in ensuring homogeneous electrochemical properties (RBW 3.3), as the homogeneity of the layer structures on both sides is influenced at the microlevel. The objective is a homogeneous distribution of electron and ion current densities, even with large electrode widths. Specifically, a low variance of the ion transport host (the electrolyte-filled cavity structure) and thus an effective diffusion coefficient of the electrode material is aimed for. This is challenging in terms of machine technology with high coating widths of 1.5 m (anode) and up to 2.2 m (cathode), as large roller diameters are required and the deflection of the rollers must be kept as low as possible. Deviations due to deformation - in the bearings or the roller stand also contribute. The general goal is a machine accuracy of +/- 1 µm. The achievable accuracy in the product should simultaneously be monitored in parallel in-line and used as a continuous quality control. It should also be used for intelligent process control in the near future; if possible, by establishing methods for using artificial intelligence (AI). Additional quality parameters at the micro level (e.g. pore distribution) should be included in the overall concepts along with the layer thickness to achieve the most accurate and precise quality measurement and process control possible at the transition to the cell production processes

Possible solutions

High product quality and product-oriented process and machine development can only be achieved by systematically generating expertise in the field of material/process-structure-property relationships. Understanding the interaction of the mixing processes with calendering is crucial. With sufficient expertise, process and machine technology can be adapted to new material and cell generation types in the industry faster and more economically. The development of calendering lines with advanced in-line measuring technology is essential for acquiring material knowledge and maintaining high product quality.

Mechanical pre-stressing of the substrates and temperature-controlled calendering with a pre-heating section and/or heated rollers is essential for increasing throughput without affecting quality, ensuring homogeneous electrochemical properties, and avoiding effects such as "-dishing" (deformation and tilting up of the electrode due to residual stress) at high cathode line loads. The influence of temperature can be used to reduce the required line loads for -generating consistent electrode densities, but the increased machine deformations and changes to the actual gap must be taken into account.

Another approach for avoiding dishing, especially with very thick electrodes, is a 2-step densification process, which can conveniently be implemented in a single machine unit. The coating film can be densified on a polymer film and then transferred to a metal foil via a lamination process. The same machine can also be used to laminate a separator to the electrode coating to further increase cell construction production efficiency by reducing the number of individual parts.

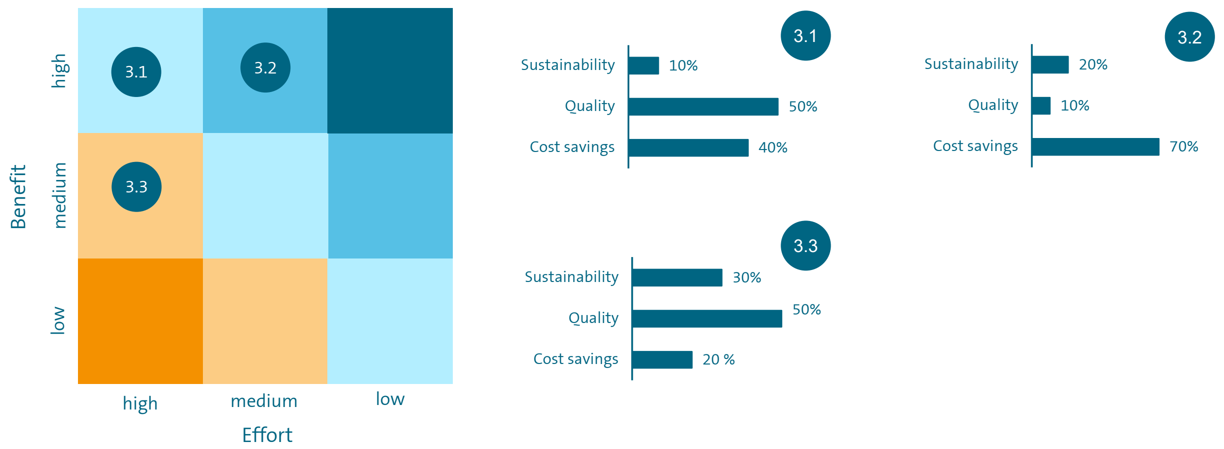
Low deformation of the calender (seat and rollers) is absolutely essential on the machine side to ensure the smallest possible difference between the nominal and actual gap dimensions. Continuous recording of the actual gap dimensions directly between the calender rollers is an important measure that should be implemented first. This measured variable should then be used as a process quality and process control variable. The line load and the accuracy of the layer 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; if possible, using established methods, real-time capable models, and artificial intelligence (AI). If this is the case, "in-production research" concepts emerge for continuously improving the production process and the specific product. Additional quality measurement variables - should be included in the overall measurement concept along with the layer thickness and line load to achieve the most accurate and precise quality measurement and process control possible at the transition to the cell production processes. Defect detection should be performed after coating and after the calender gap. This should be linked to a tracking system so that coating defects can be rejected directly or after they become evident in the calendering process. Rollers that can be locally and specifically depressurized based on information from the upstream analysis processes could offer a competitive advantage. - Immediate benefits would include long roller service life (die protection) and avoidance of downtime.

Achieving homogeneous electrochemical properties and uniform layer structures with ever larger web widths and a robust and stable compaction process requires targeted conductive carbon black structuring with active materials and binders. However, intelligent machine and plant design is also necessary to minimize deformation during densification at high line loads. Roll bending systems could be a practical approach to effectively dissipate forces.

Another key issue is the suitability of the calenders for emerging electrode widths of 1.5 m and possibly > 2 m. The width and diameter of the rollers must be increased while maintaining accuracy. Design measures must be implemented to minimize roller deflection and machine deformation in order to be able to gently densify thick layers of high-capacity electrodes.

Effort and benefit assessment
The development effort for suitable plant design and machine construction is classified as high. This is exacerbated by the design of the plant technology, which is dependent on the material, formulation, and process-induced electrode structure (conductive carbon black structure, mixing processes). Expertise on material/process-structure property relationships and in-depth in-line process control can therefore be considered very relevant to machine development. Since this is a prerequisite for fast and flexible adaptation to new materials, the effort for RBW 3.1 is considered high.

Effort Benefit Diagram and Impact on Sustainability, Quality and Costs



3.1 Fast, flexible adaptation   3.2 Increase in throughput   3.3 Ensuring homogeneous electrochemical properties

Increased throughput can be achieved without affecting quality (RBW 3.2) as well as the assuring homogeneous electrochemical properties and uniform layer structures with increasingly larger web widths (RBW 3.3) by suitable machine design and force absorption, as machine deformation (rollers, roller stand, bearings, etc.) can be avoided and the target roller gap can be better maintained. Based on existing studies, speed and therefore throughput can be increased relatively easily without influencing quality, which is why the RBW is rated as moderate effort with high benefit.

RBW 3.3, ensuring homogeneous electrochemical properties and uniform layer structures with ever larger web widths, requires greater effort and is difficult to measure continuously in production. Direct gap measurement and its use as a process quality and control parameter, as well as in-production research concepts, can therefore be considered effective in this respect. The design effort associated with wider calender rollers is also significantly higher; therefore, after evaluation of the two criteria, the result is high effort with moderate benefit. In conclusion, more competitive calender system technology can be achieved with suitable design and force absorption.

Professional support

Topic sponsor:
Frank Bogenstahl, R&D Engineering,
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With additional support from:
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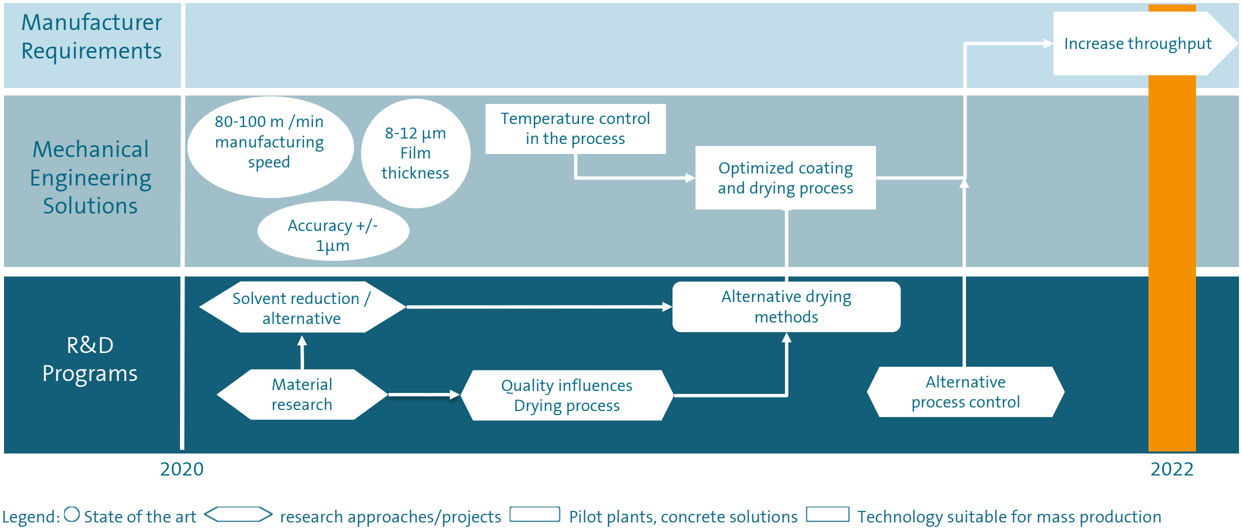
Separator production

No.*	Red Brick Wall	Current status in Comparison to 2018	Relevance for separator manufacturers	Timeline***
4.1	Increase throughput: high volume production	**	High	2022
4.2	Quality control/coating quality	**	High	2025
4.3	Reduce separator film thickness/improve film handling	**	High	2025
4.4	Sustainability and environmental protection	**	High	2022

RBW 4.1: Separator production - high volume production
Faster, high-quality separator production and optimized process control make it possible to increase throughput to meet market demand. Optimized process conditions and minimization of energy consumption during drying accelerate production and reduce the necessary energy demand. Process monitoring for production quality control must be integrated into the processes to guarantee direct control and high-quality products.



*RBW priority decreases from top to bottom.

**Topic was not addressed in the 2018 roadmap

***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

RBW 4: Separator production

Basics

The separator is a crucial component for the production and operation of lithium-ion battery cells (LIB), and has a significant influence on the performance characteristics and safety of a cell.

Modern industrial-scale separator variants are mostly based on polyolefin-based membranes, which consist of polyethylene (PE) or polypropylene (PP) as well as multilayer composites of the above-mentioned polymers, and are manufactured in a so-called "wet process." Additional ceramic layers can be applied to improve the safety and wetting properties. Plants are available with production volumes in the millions of m^2 p.a. (market share of approx. 90 percent in the lithium-ion battery market).

Fully ceramic separators that utilize different technology are also available on the market. These have a production-relevant network of polyethylene terephthalate (PET nonwoven) that provides structure, and are equipped with ceramics of Al_2O_3 or hybrid mixtures of Al_2O_3 and SiO_2. These separators are primarily used for special applications, and production volumes are limited to much smaller quantities.

Separators must fulfill wide-ranging and diverse functions and challenges. With regard to cell function, the primary task is the electrical separation of the positive (cathode) and negative (anode) electrodes as well as ionically connecting them via its electrolyte-filled cavity structure. The separator must also be mechanically and structurally stable in order to withstand the manufacturing processes without mechanical effects or developing of defects. These may include mechanical stresses caused by foreign particles or temperature-induced mechanical loads. Material shrinkage of the separator must also be minimal within the temperature operating range of the application, and temperature stability must be ensured when passing through the cell and its significantly higher temperatures (> 150°C, or better > 200°C).

Separators are usually produced in a two-step process. The base membranes or the PET nonwoven are produced in the first step, and can then be provided with functions such as a second polymer membrane or ceramic coatings.

The base membrane is manufactured in a primarily "wet process." First, the polymers used are melted in a twin-screw extruder using large quantities of mineral oil (70-80 percent), extruded using a slot die, and then cooled. The - cooling must be as uniform as possible over the entire surface. The film is then biaxially stretched to achieve the target film width. Mineral oil is required to be able to process the - high-molecular PE in an extrudable viscosity range. To achieve a product that is as pure as possible, the mineral oil is then removed using dichloromethane (DCM) in an extraction and drying step. DCM is used because of its good mineral oil solubility and low boiling point (39.8 °C). DCM is also non-flammable. However, DCM has a very harmful and toxic effect on the environment. On the other hand, polyester nonwovens are produced from suitable synthetic fibers using a papermaking process. The coating of base film or PET nonwovens with ceramic layers , if required, is applied with an engraving roller. The solvent is later removed in a thermal drying step.

Challenges
Fully automated production processes, high efficiency (low defect rates), a high level of process integration, and knowledge of interdependencies are all essential for competitive production of separators on a mass production scale (millions of m^2 p.a.).

The consistent high quality of the base membrane or alternatively of 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 (RBW4.2). Production volumes of several million m^2 are required to be considered as an established supply source in the global small electric vehicle mass market.

For Germany and Europe to become a leading battery production market, it is essential to increase throughput and attract manufacturing companies. Germany and the European Union's high requirements for sustainable and environmentally friendly processes is also a barrier as well as an opportunity (RBW 4.3).

For this reason, plant technology throughput must be increased in the future to meet battery manufacturers' high production volume requirements (RBW 4.1). Current technologies in the production of base films (e.g. polyethylene) allow speeds of 50 - 60 m/min at production - widths of approx. 4.5 m. In the future, both production parameters must be increased to meet demand.

Functionalized coatings of base films or nonwoven separators (fully ceramic) are produced on a much smaller scale. Production - volumes must also be increased for these technologies to meet market demand on a sustainable basis, especially for special applications.

However, as volumes increase, the increased production speed must not have a negative impact on energy requirements and the high separator product quality requirements.

In addition to strict raw material and intermediate product incoming inspections, real-time inline measurement techniques for product control as well as direct process regulations must be established to achieve this goal.

Current separator base film production processes use solvents with low environmental compatibility, and the recovery rate must be increased further. Separators must also be developed using recycled and renewable raw materials (including polymers).

Film thicknesses must be further reduced to increase the gravimetric and volumetric energy density (< 16 µm [12 µm base film + 4 µm coating], and possibly 8-10 µm [5-7 µm base film + 3 µm coating]). The layer thickness of modern standard separators is approx. 16 µm, consisting as described of several layers or an applied coating. The greatest challenge with thinner films is to guarantee consistently high component quality to achieve high cell safety requirements. The films also become more difficult to handle as their thickness decreases (RBW 4.4).

Possible solutions
Comprehensive process and product monitoring is necessary to achieve sustainable competitive separator production. This includes real-time recording of machine, process, and product parameters for quality control and direct control/regulation of process management. Critical end product controls should be

performed to ensure the highest possible safety and compliance with final product requirements.

Base film production must be increased to a speed of at least 80 m min-1 and widths of > 6m to efficiently increase throughput without affecting quality. This facilitates the production of "parent reels" with greater product capacity for the same roller length.

The coating speed must also be increased for competitive production of coatings for the base film and nonwoven ceramic separators. The width of coating systems should also be extended well beyond one meter so that they can later be effectively converted to narrower roller widths for use in battery assembly.

Target separator requirements for the more efficient cell production lines of the future could be met more sustainably and cost-effectively with increased throughput.

Particular attention should also be paid to the thinner separator thickness requirements for future separator production. Systems must be aligned even more precisely and processes must not cause the separator foil to tear. Electrical charges must be removed or avoided for proper handling.

Another key topic for the industry is the lamination of the separator with an electrode for simplified handling, and particularly an - increase in quality (e.g., alignment or overlap accuracy of the separator between the electrodes) and efficiency from reduced handling of individual parts in cell production.

In the coming years, reduced solvent demands and energy consumption will also play a key role in meeting "green" battery requirements. Process technologies such as extrusion can reduce solvent requirements for coatings and film production. Processes and equipment should also be designed to use non-critical solvents, ideally water.

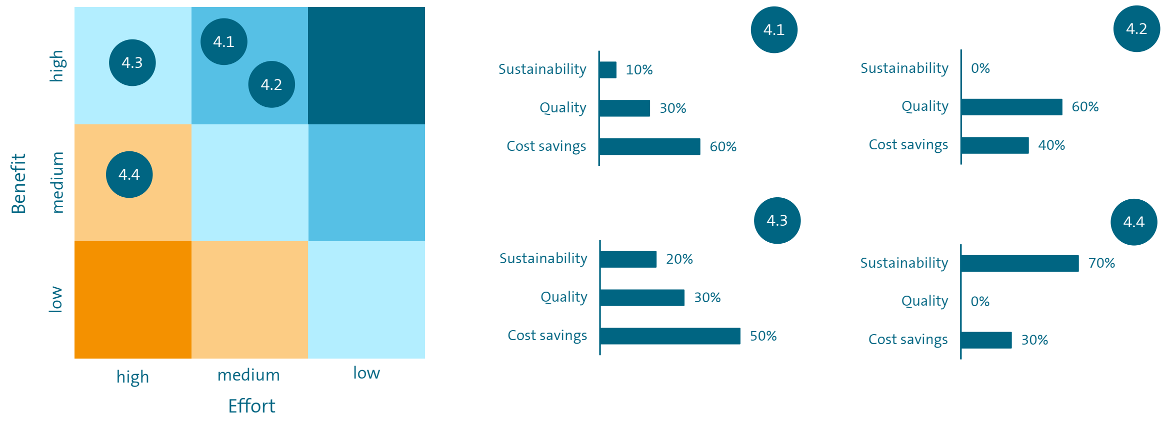
Green polymers produced from renewable raw materials also offer great potential for the production of separators. This branch will become increasingly important in the future and will allow a reduction of the ecological footprint, as separators will be installed in cells in large quantities. Existing plants must be designed to be adaptable and convertible for new separator technologies.

Effort and benefit evaluation

Increasing separator production throughput results in greater economic efficiency as well as stable continuous production, which can both reduce costs and increase quality due to fewer product changes. This has a high benefit with a moderate cost for production or producing companies.

Quality control of coating quality and other product parameters is generally considered to be very relevant for the future, as it offers a high benefit at moderate expense due to the advantages mentioned above. The integration of inline process and product monitoring represents a moderate to high outlay, depending on the parameters being monitored. However, critical quality parameters can be checked during the manufacturing process or materials input to maintain final cell requirements and especially cell safety. The benefit of these process steps can be rated as very high, as rejects and efficiency are improved as a result.

Effort Benefit Diagram and Impact on Sustainability, Quality and Costs



4.1 Increase throughput 4.2 Quality control 4.3 Reducing the film thickness 4.4 Environmental protection / sustainability

The most important parameters to be monitored are temperature, coating thickness and coating quality. The main purpose is to reduce the cost of the product and to increase the quality or to keep it at the same level.

For future cell technologies, the aim is to reduce separator film thickness and improve film handling. This improvement will lead to an increase in volumetric and gravimetric energy density. The effort required for implementation is estimated to be high, but the benefits are high at the same time. This technology of reducing the film thickness allows both to significantly reduce the cost and to increase the quality of the membrane, since membrane defects can have a stronger impact on the cell performance. In addition, less material is used, which generally improves sustainability and resource efficiency.

As experience with the battery product grows and generally applicable legal requirements become more stringent, the focus is shifting to sustainability and environmental protection in production processes. Complex and sometimes critical production processes must be replaced by alternatives and alternative process routes with non-critical reactants. The use of organic solvents should be reduced or avoided altogether. The effort required for realization is estimated to be high, whereas the benefit for the separator manufacturer is to be seen in the medium range. The primary benefit is a significant increase in sustainability. If expensive reactants are replaced, it is also conceivable that the production costs of the separator product can be reduced.

Professional support

Topic Sponsors:
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Karl Zimmermann, Director Sales & Marketing
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Brückner Maschinenbau GmbH & Co. KG

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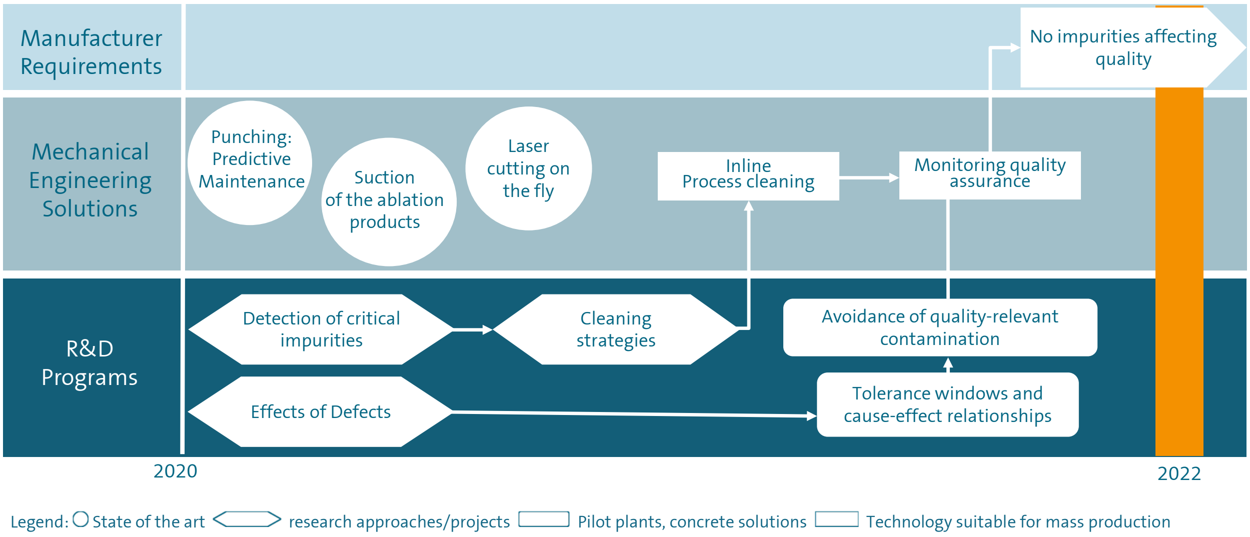
Separation

No.*	Red Brick Wall	Current status in Comparison to 2018	Relevance**	Timeline***
5.1	Quality and reliable monitoring	Progress made	High	2022
5.2	Improving cycle time through more productive handling systems	Progress made	High	2023
5.3	Quality-assured separation of electrodes with a high coating thickness	Progress made	High	2024
5.4	High cut edge quality	Progress made	Medium	2022

RBW 5.1: Separation - quality and reliable monitoring
Residues generated in the separation process can cause short circuits in the cell due to their size. Particle size varies by separation technology. Quality optimization is currently achieved through filter techniques and predictive tool maintenance. 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).

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

RBW 5: Separation

Basics

In the separation process, individual anode, cathode, and separator sheets are separated from the electrode/separator coils. This process is performed by punching using shear knives or cutting using laser radiation. Very clean cut edges can already be achieved using the punching process. However, the tool wear can lead to mechanical deformation of the cut edges. In the worst case, particles of the coating can even become detached.

Laser cutting of electrodes is now state-of-the-art. It meets the requirements of cutting speed, minimum burr formation, and a heat-affected zone (HAZ). The high flexibility of the laser guidance system also makes it possible to change formats. A disadvantage of separation by laser cutting is that, despite the use of short-pulse lasers, it is a thermal separation process, which leads to a HAZ along the cut edge. The local heating and the different rates of evaporation of the coating and the carrier film can lead to burrs on the cut edge, especially with large thicknesses >250 µm [Schmitz 2014].

Filter technologies and predictive maintenance[1] are already being used to prevent contamination by foreign particles and to detect wear of the cutting tool at an early stage. This means that countermeasures can be initiated in good time. A positive side effect is that this results in longer tool life. One way of minimizing quality-reducing contamination in laser cutting is the extraction of the gases and microparticles produced.

Cutting speeds of up to 0.1 s/sheet can be achieved with punching. In laser cutting, between 1 and 4 m/s can be realized, depending on the electrode thickness. This results in a cutting speed of up to 0.06 sheet/s, depending on the geometry to be cut. However, the gripping and handling process for the electrodes and separator sheets is always the time-limiting factor during separation, which leads to significantly higher cycle times [Luetke 2011], [Korthauer 2013].

Challenges

Quality-critical impurities can be caused by material re-sublimating at the cut edge during laser cutting, coating flaking, burr formation during punching, or loose particles on the active material. In lithium-ion cells, these impurities can cause lithium plating. In the worst case, this could lead to separator damage and a short circuit. Therefore, avoiding impurities is a fundamental challenge. Dependable quality assurance can also significantly reduce rejects in production.

In addition to the improvement of the cut edge characteristics of conventional electrodes as well as thick high-performance electrodes during laser cutting, challenges lie in the fast handling of the materials. Due to the high cutting speeds that can be achieved, the cutting process is no longer the speed-limiting step, but rather the handling or the feeding and removal of the electrode material. Achieving high-speed handling is considered particularly challenging due to the sensitivity of the product and the altered intermediate product state from continuous to discontinuous.

[1] Predictive maintenance based on historical data or quality characteristics available in real time

Possible olutions

Quality measurement makes it possible for companies to precisely control the quality of the cut edge and the sheet surface. Suitable monitoring systems with reliable reject detection must be developed to provide this level of quality assurance. High-resolution optical systems that can identify critical ablation products on the surface are essential. This will make it possible to evaluate the quality of the cut edges and detect tool wear at an early stage. Innovate inline surface inspection imaging techniques from related industries offer further opportunities for process optimization. These technologies can be transferred to battery production and refined in research projects.

Suction must be optimized during laser cutting to avoid the sublimation of particles at the cutting edge. Filter technology is already available on the market that can be adapted to the particle size. However, trends toward increased coating thickness make it difficult to establish the laser cutting process, as greater coating thicknesses require higher energy input. Vaporization increases at the cut edge, which leads to a stronger contamination load [Schmitz 2014]. However, the steadily increasing brilliance and power of the laser beam sources and the associated high Rayleigh length will make it possible to reduce this influence (single mode fiber lasers).

Another approach is to clean the electrode sheets after separation. However, this must not change the properties of the cell material. The additional effort must also be financially viable for cell manufacturers. One solution is CO_2 snow jet cleaning, in which carbon dioxide is used to remove contaminants in a dry process without leaving any residue. Benefits are good automation and the possibility of continuous process control. However, its use depends on the temperature and material compatibility of the carbon dioxide with the coated carrier film.

In general, it is important to research and validate tolerance windows and cause-effect relationships to avoid quality-relevant impurities.

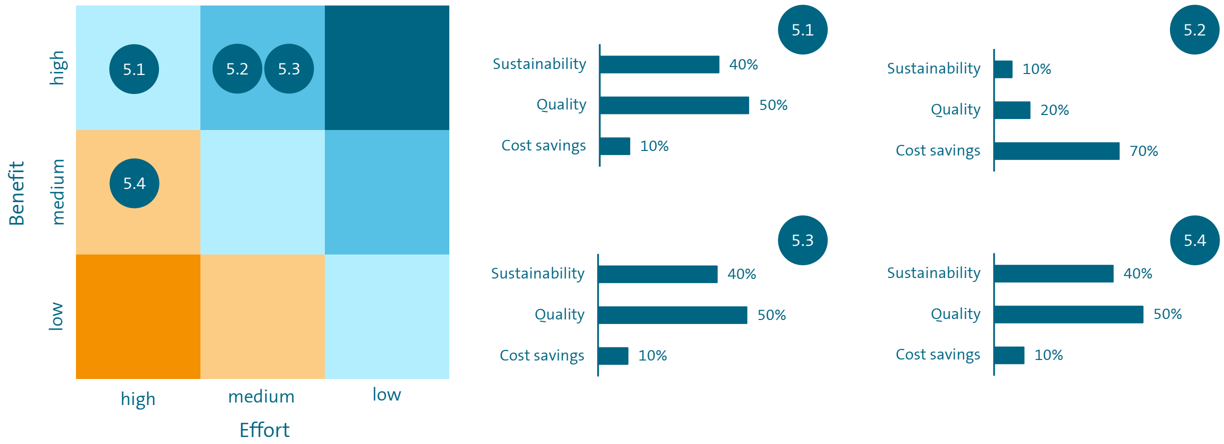
Continuous laser cutting (cutting on the fly) offers the greatest potential for increasing cycle times. Continuous processing is particularly advantageous because it avoids transient stress on the electrode material, thus preventing film - cracks or damage due to high start-up and shutdown speeds. Possible solutions or projects for continuous in laser cutting are currently unknown or not to be found in the German research landscape.

Effort and benefit assessment

Since separation has a significant impact on subsequent cell performance, the benefits are considered to be high. Introducing reliable monitoring methods offers an opportunity to increase quality and reduce scrap. Lower contamination levels due to improved cutting processes or associated quality assurance results in longer lithium-ion cell service life and thus increased sustainability. However, the high cost of implementing the measurement technology and building up the necessary process understanding is a challenge.

Taking the constantly increasing cell output of planned production plants into consideration, future terra factories will offer high cost savings due to higher cycle times from more productive handling systems. The necessary development work is estimated as moderate and the benefit is high.

Effort Benefit Diagram and Impact on Sustainability, Quality and Costs



5.1 Quality and reliable monitoring
5.2 Improvement of cycle time through more productive handling systems
5.3 Quality-assured separation of electrodes with high coating thickness
5.4 High cut edge quality

High-quality separation of electrodes with high coating thickness leads to improved quality and increased sustainability of the cells produced. Cost savings from the reduction of possible cell failures are considered low. The effort is also assessed as moderate and the benefit as high.

Additional improvements to the cut edge quality also lead to increased sustainability and product quality for the reasons mentioned above. The effort is assessed as high with a moderate benefit, as the influence of the cut edge is lower with conventional systems and very good cut edges can already be achieved.

Professional support

Topic Sponsor:
Johannes Bührle, Industry Manager Automotive - E-Mobility, TRUMPF Laser- und Systemtechnik GmbH

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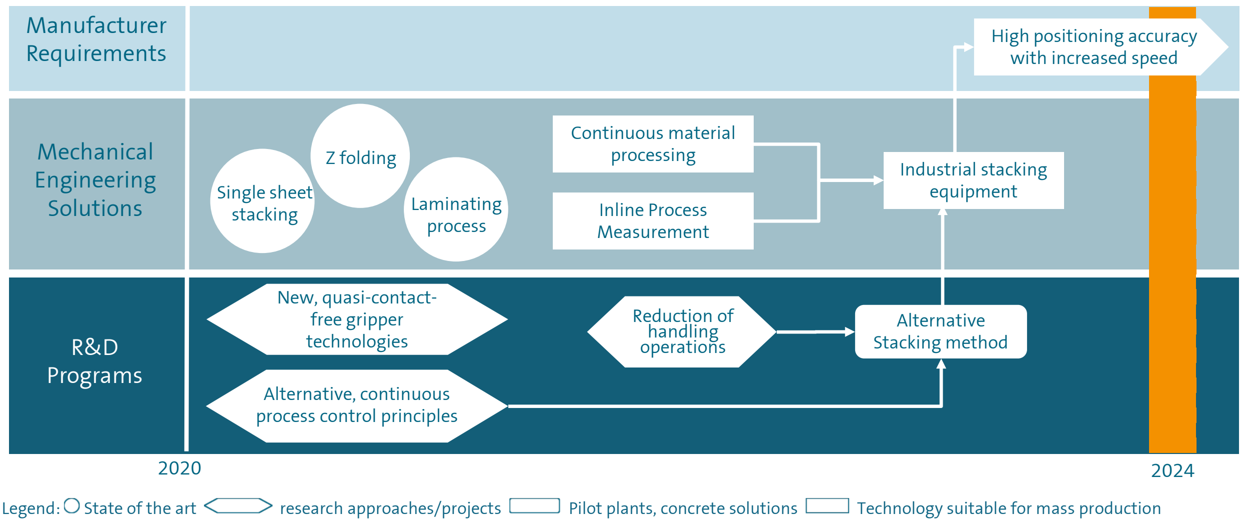
Stacking

No.*	Red Brick Wall	Current status in Comparison to 2018	Relevance**	Timeline***
6.1	High positioning accuracy with simultaneous increase in speed	Moderate progress made	Moderate to high	2024-2025
6.2	Understanding of cell format-specific differences	Progress made	High	(2021-2022)
6.3	Handling of sensitive materials	Little progress made	Medium	2023-2025

RBW 6: Stacking - increasing speed
The stacking process is significantly slower than the winding process and is one of the bottlenecks in cell assembly. Benefits over coiling are the material-appropriate production of electrode-separator assemblies and the better space utilization of the electrode stack. Speed can be increased by combining processes or reducing pick-and-place operations. However, this must not be at the expense of positioning accuracy, cleanliness, or gentle 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 according to Phaal2003b

RBW6: Stacking

Basics

Different assembly processes are used to manufacture lithium-ion cells, depending on the cell format. Pouch cells are generally produced using the stacking process, while cylindrical and prismatic cells are produced using the winding process [Pettinger 2013]. Increasingly, prismatic cells are also stacked in order to increase space utilization in the cell housing and improve electrolyte wetting.

At the cell level, stacking has advantages such as uniform mechanical loading of the electrode, more homogeneous heat distribution, increased power densities, cycle strengths, longevity and safety. However, this is offset by the lower process speed compared to winding.

Single sheet and Z-folding stacking processes are used in an industrial context. In single sheet stacking, the separator, anode, and cathode are placed on top of each other in alternating order [Baumeister 2014, Heimes 2018, Kampker 2014]. In Z-folding, the separator is unwound from a coil and the separated electrodes are inserted alternately between the separator, for example using vacuum grippers [Kampker 2013]. This process is much faster than the single sheet process. This process can be further accelerated by laminating the single sheet electrodes onto the separator before stacking [Kwade 2018b].

In the winding process, on the other hand, separator and electrode strips (anode and cathode) are wound onto a core made into a jelly roll [Heimes 2018, Kampker 2013]. 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 appropriate than winding technologies for next-generation cells such as lithium metal batteries. Another advantage of stacking over winding is better heat control or dissipation when the cell is in operation, which can provide greater safety and cell longevity.

Achievable cycle times for stacking greatly depend on the electrode size and the production technology used. Cycle times of well under 1s per electrode assembly (anode + separator + cathode) can currently be achieved with Z-folding. In winding, speeds of 0.1 s/revolution are possible with continuous process control - [Heimes 2018]. A cell can be wound in this way in a few seconds, whereas the stacking process is at least an order of magnitude slower at slightly less than 1/s per electrode composite for several dozen layers [Heimes 2018]. The stacking method must measure up to the significantly higher winding process speed and compensate for this drawback with better utilization of the available volume and higher cell quality.

Continuous progress in speed and stacking accuracy has been made since 2018. Using Z-folding, the above speeds can be achieved with 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 is still a time-critical process on the cell production line and thus represents a bottleneck [Schröder 2016a]. High positioning accuracy and cleanliness demands must be met despite a required increase in throughput. The quality of the stacking process has a significant influence on the subsequent cell performance [Thielmann 2017]. High positioning accuracy with a simultaneous increase in speed is therefore considered the most important challenge for this production step (RBW 6.1.).

Increasing film or cell size is being discussed in order to achieve cells with higher energy density and to increase throughput [Kurfer 2012]. This approach poses challenges for film handling and requires cell format-specific differences to¬ be addressed (RBW 6.2). Gentle handling of materials due to their size the use of very thin and sensitive materials further complicate this process (RBW 6.3) [Kampker 2014].

Possible solutions

Stacking optimization is focused on developing new gripper technologies [Stühm 2014], achieving continuous process flows, and implementing faster image recognition technology for improved position control [Schröder 2016b]. Virtually contact-free grippers with ultrasonic guidance or even air-guided systems are becoming relevant, but are not yet ready for series production. These developments could make it possible to break through RBW 6.1 in the next four years.

Another approach to increasing process continuity is the use of robust intermediate products made from electrode-separator composites. For example, the electrode sheets could be laminated onto the separator. This intermediate step reduces the number of stacking operations required for each lithium-ion cell and counteracts the wrinkling and buckling of the electrodes and separators. This process is particularly promising for improved handling in the stacking process and even more precise positioning with ever larger cell shapes. Increasingly sensitive - materials may also require stable semi-finished products in production. Therefore, this approach can help solve the challenges of RBW 6.2 and RBW 6.3.

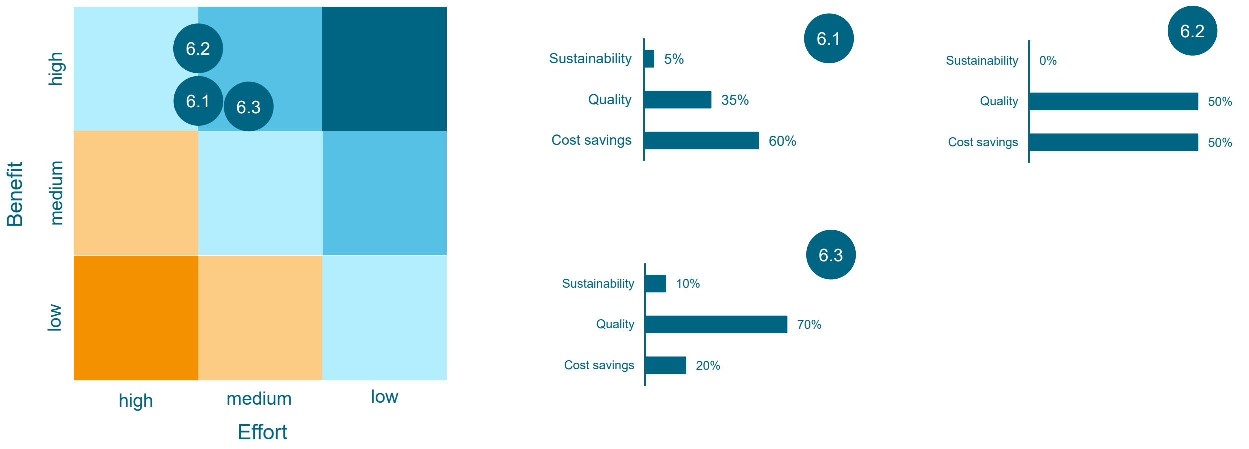
Several innovative stacking technologies, some of which have already been patented, are being tested and subsequently prepared for industrial application in various research facilities throughout Germany [Weinmann 2020, Baumeister 2014, Pelisson-Schecker 2017, Fleischer 2017, KontiBAT 2020]. The differences compared to Z-folding include, for example, guidance of materials in different planes, rotating materials relative to each other ("Helix process", KIT - [IPR 2015]), combination with conveyor belts or more efficient folding mechanisms [Konti-BAT 2020], also known in part as "stack and fold mechanisms." Speeds of well under 0.5s per electrode composite can be achieved in this way, thereby increasing process speed. Together with technologies from the fields of inline process measurement technology, image recognition, and knowledge of continuous material processing that are already available but still need to be optimized, these measures can help to further accelerate the stacking process while also reducing scrap - even during startup.

Effort and benefit evaluation

Since stacking 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 rated as high. Experts rate the associated effort as moderate to high. Handling methods are currently reaching their limits, so alternatives must be developed and made ready for mass production [Thielmann 2017, Michaelis 2018]. The use of stable intermediate products must hold up to conventional production processes. In the future, this could be an alternative for sensitive materials in particular.

Dealing with cell format specific differences (RBW 6.2) is another challenge with moderate to high effort that is of great importance due to ever-increasing cell sizes.

Effort Benefit Diagram and Impact on Sustainability, Quality and Costs



6.1 Increase speed 6.2 Cell format-specific differences 6.3 Dealing with more sensitive materials

The use of increasingly sensitive materials requires ever more demanding film handling. The effort required to achieve the targeted speeds and positional accuracies is also rated as moderate. New materials are used to optimize the battery, so the benefit is correspondingly high.

These challenges all show that the benefits of overcoming them can be considered very high, as increasing the speed can reduce plant investment and footprint, thus lowering battery cost.

Professional support

Topic Sponsors:
Maximilian Wegener, Product Manager Energy Storage, Manz AG;
Oliver Meister, Sales Manager, VITRONIC Dr.-Ing. Stein Bildverarbeitungssysteme GmbH

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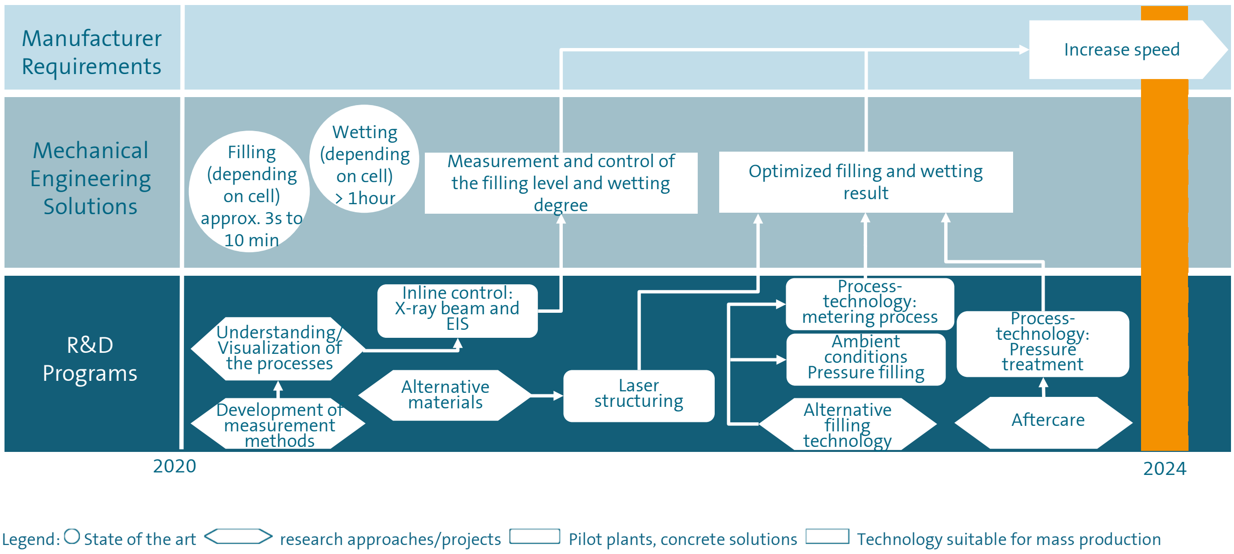
Electrolyte filling

No.*	Red Brick Wall	Current status in Comparison to 2018	Relevance**	Timeline***
7.1	Electrolyte filling & wetting: increase speed through process and material adjustments while wetting the cell stack more homogeneously	Moderate progress made	Moderate to high	2021-2024
7.2	High accuracy during filling (volume, pressure, or vacuum)	Unchanged	Moderate to high	2021-2022
7.3	Reliable monitoring of the filling and wetting process in volume production (e.g., temperature, pressure, etc.)	Unchanged	Moderate	2023-2026

RBW 7: Electrolyte filling - speed and quality
Avoiding foam formation and uniform wetting of the material are critical to quality. Separator, electrolyte, and electrode material properties influence the filling process. The overall goal is to reduce the filling and wetting time while ensuring cell performance, regardless of the cell design, by reliably monitoring the process. This requires close cooperation between mechanical engineering and materials development.



*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

RBW 7: Electrolyte filling

Basics

A distinction is made between two steps of the electrolyte filling process: the filling and the 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. Both production processes are extremely time and quality critical for cell assembly. Due to their porous nature, the electrodes have a large surface area that must be completely wetted by the electrolyte liquid. 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 different currents in the cell, which can lead to dendrite growth.

Currently, the most common method is filling under negative pressure. A vacuum is created in the lithium-ion cell so that the electrolyte can be quickly and efficiently filled into the cell, and the cell interior can no longer have any residual moisture due to the evacuation of the cell. The standard electrolyte used is highly flammable, with a rating of LiPF6, and would form hydrofluoric acid upon contact with water, which attacks the cell components and significantly reduces their service life [Korthauer 2013].

Research has shown that the wetting time for a cell pressurized with negative pressure can be cut in half, and that the amount of electrolyte has a decisive influence on the performance. [Günter 2019]

Pressure is equalized as the filling increases to counteract foam formation. The process is also repeatedly interrupted so that the foam can decompose. Wetting begins at the same time. Capillary forces cause microscopic wetting of the pores in the active materials and separators. Filling and pressure equalization are repeated until the lithium-ion cell is sufficiently wetted.

It has been shown that subsequently treating the filled and sealed pouch cell with pressure (press rolling) can significantly reduce the - wetting time. Battery cell wetting time has already been reduced by 50 in recent years - based on findings about the filling and wetting process.

Challenges

The formation of foam during the filling process and the long wetting phases are largely responsible for the long process times, which can be over an hour depending on the cell type (large prismatic cells with jelly roll). Electrolyte filling is a cell assembly bottleneck. Therefore, increasing the speed through process and material adaptations is a key challenge, - especially due to the trend toward large-format battery cells.

The filling and wetting processes are also influenced by the electrolytes, separators and active materials used, and the contact angle. Insufficient knowledge of the correlations between process parameters and filling quality leads to less-than-optimal filling. The factors influencing the wetting process, which can take up to 48 hours depending on cell chemistry and cell format, have also not been adequately researched. Too little leads to non-wetted areas, too much leads to a longer process time and higher internal resistance. Therefore, another challenge is to increase the accuracy of the process using the parameters to be configured (volume, excess/negative pressure) so that the process can be controlled for specific cell formats and sizes.

There is also a lack of reliable inline monitoring technologies for controlling and optimizing the electrolyte filling and wetting process already in the production process.

Possible solutions

There are several methods for optimizing this process. The most important factors for increasing the speed are preventing the formation of foam, faster wetting, and optimizing filling parameters. To speed up the process, it is essential to understand the influence of electrolyte properties and the interactions between the active material, separator, and electrolyte on the filling and wetting process. Important influencing factors include the penetration coefficient (COP), solid state permeability (SPC), and electrolyte salt concentration. The filling and ambient pressures are also critical factors in the quality of the filling process. The volume and post-treatment - with pressure have a particular influence on the quality of the cell during wetting. [Davoodabadi 2019]

The process time could also be reduced by using alternative process controls, such as setting different pressure gradients or implementing pre-filling or filling at several points in the lithium-ion cell which are oriented to the fill level. Filling at several points is feasible for pouch cells, but would be significantly more difficult to implement for hardcase cells.

An additional research approach is the development of alternative separator materials and surface structures. In particular, the use of laser structuring in electrode production and its influence on the filling result has been investigated in recent years. In laser structuring, the trade-off between higher pore volume for faster wetting of the cell and the drop in performance due to excessive removal of active material must be taken into account. These changes have a major influence on foam formation and wetting time. However, their characteristics must be determined by the product and the technology as well as the process.

Above all, new separators, electrodes, and electrolytes must meet increasing cell safety demands or technical requirements for achieving high-voltage cells with 5 volts.

Pre-treating the separator with a plasma is another promising approach for improving - separator materials. By modifying the separator surface (increasing the hydrophilicity), the degree of wetting and adhesion between the electrode and separator is improved, which increases the ionic conductivity of the separator. The electrodes could also conceivably be pre-treated with plasma. Here, too, a more hydrophilic surface could lead to better and faster wetting.

Additives could also be used in the electrolyte to reduce foaming and/or improve wetting. Developments in this area will primarily contribute to breaking through RBW 7.1 in the next four years. The process time and reliability of the filling and wetting process can be improved significantly by 2024.

The development and use of solid-state electrolytes would make the electrolyte filling step completely obsolete. However, production-ready cells with solid-state technology are not expected to be established on the market for at least the next 5-10 years at the earliest. [Habedank 2019]

In addition to process and material adaptation, the development and integration of new measurement methods is necessary to enable industrialized, detailed process monitoring. Analysis contributes to a better understanding of the processes and interactions and is necessary for optimizing cell production throughput and lithium-ion cell quality. A distinction is made between macroscopic and microscopic wetting control. In macroscopic wetting control, it is important to develop methods that measure the filling level and the degree of macroscopic wetting during the process. X-rays and neutron radiography are currently being researched for this purpose. These methods both offer the benefit 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. Developments in electrochemical impedance spectroscopy (EIS) show great potential for checking the microscopic degree of wetting, especially for large-format cells [Günther 2019]. Other important process parameters are the cell temperature, the filling pressure, the mass flow rate, and the weight and density of the lithium-ion cell. This solution will contribute to breaking through RBW 7.3 and the knowledge gained related to parameter-quality relationships will also lead to breaking through RBW 7.2 [Knoche 2016, Weydanz 2018].

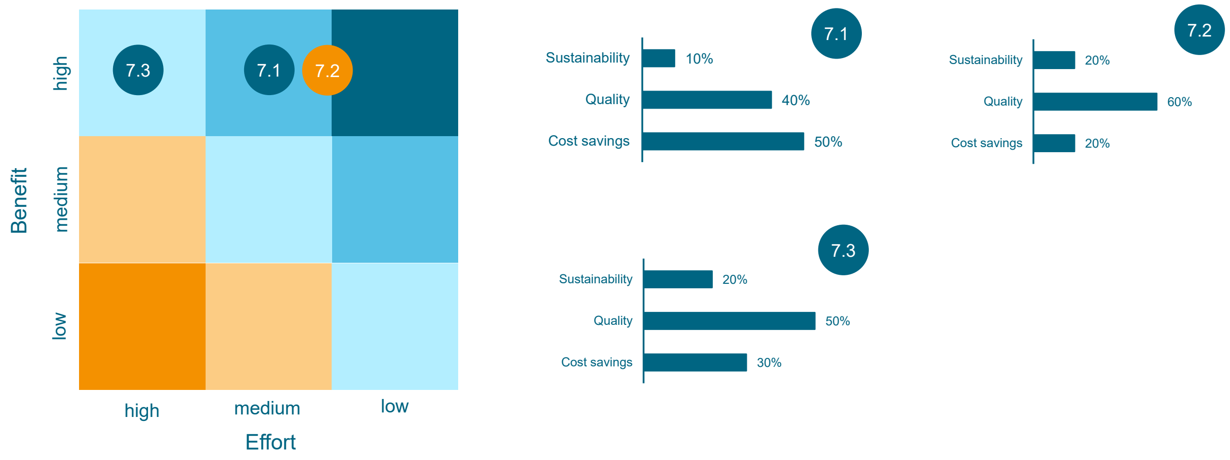
Effort and benefit assessment

The benefits of all RBWs in the area of electrolyte filling are rated as high. Costs can be greatly reduced by reducing process times, especially wetting. Homogeneous wetting also leads to an increase in quality. Experts rate the effort required to achieve this as moderate, as improvements have already been made in this area by adapting materials. Sustainability is only slightly improved by breaking through this RBW.

The improvement in filling accuracy in RBW 7.2 has a particular effect on performance, and thus on the quality of the battery cell. Defined filling quantities can also reduce process time and allow electrolytes to be used in a more targeted manner. This has a positive effect on costs. This RBW also has only a minor effect on sustainability. The effort required to break through the RBW is estimated to be low, since the research findings can be transferred into industry relatively easily, especially as it pertains to adjusting the filling quantity, filling angle, and wetting time.

The development of an inline quality control for achieving RBW 7.3 also shows a high benefit. With better understanding of the filling process, it can be better controlled and adapted to - different formats and sizes. This significantly influences the quality of the cell. Improved knowledge of the filling and wetting process can reduce electrolyte scrap. This would have a positive effect on the cost and sustainability. However, achieving this RBW is associated with increased effort, as integrating inline measurement methods for detecting the fill level and wetting degree is more difficult in a closed cell, and the approaches used to date cannot easily be integrated into a production - line.

Effort Benefit Diagram and Impact on Sustainability, Quality and Costs



7.1 Increase in speed with simultaneous homogeneous wetting

7.2 High accuracy during filling

7.3 Reliable monitoring

Professional support

Topic sponsor:
Ulrike Polnick, Project Manager /Quality Management Officer, Industrie Partner GmbH Radebeul-Coswig

With additional support from:
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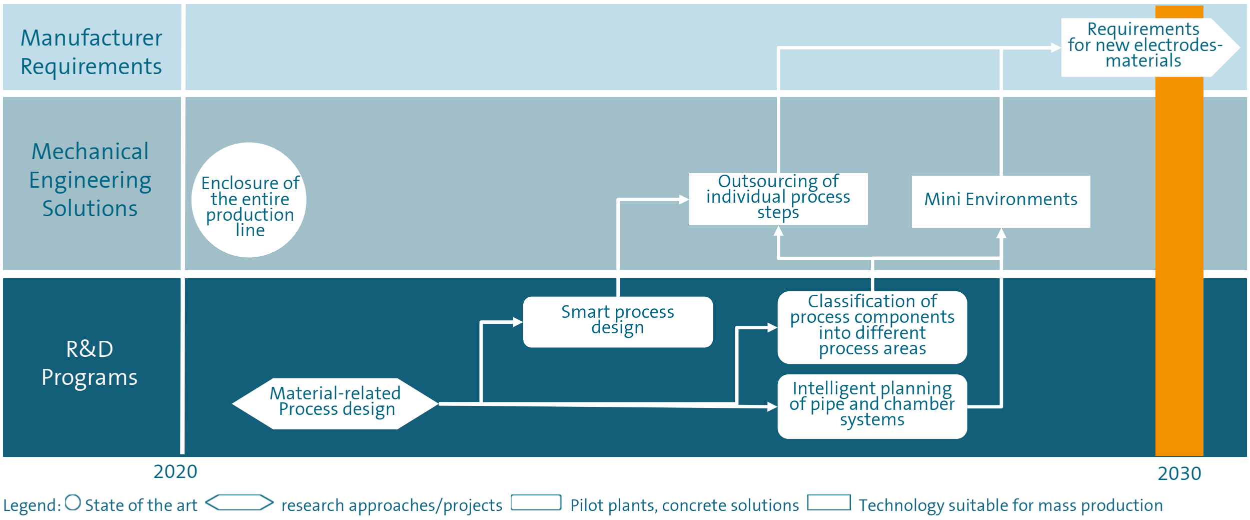
Clean and dry rooms

No.*	Red Brick Wall	Current status in Comparison to 2018	Relevance**	Timeline***
8.1	Cost and benefit optimization of clean and dry room design for current and future cell generations	Unchanged	High	2030
8.2	Improve dry and clean room energy efficiency	Progress made	Moderate	2020-2024

RBW 8.1: Clean and Dry Rooms – Cost and benefit optimization of clean and dry room design for current and future cell generations

Reducing cell manufacturing costs is a major challenge to increasing the competitiveness of batteries compared to other technologies. Producing the required manufacturing conditions through dry and clean rooms is a major cost issue. In particular, the design of clean and dry rooms for current and future electrode materials (for example, cathode materials with high nickel content) is a key challenge.



*RBW priority decreases from top to bottom.

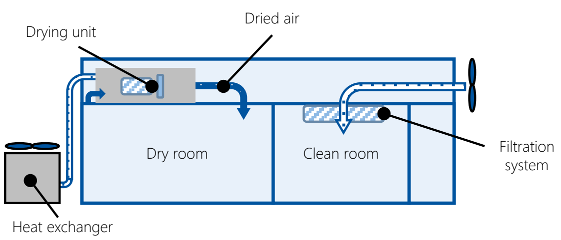
**Relevance from the point of view of a battery manufacturer

***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

RBW 8: Clean and dry rooms

Basics
The production environment plays a key role in the manufacture of lithium-ion cells. In particular, humidity and possible contamination by foreign particles during the production process have a significant influence on the quality and safety of the manufactured battery cell. Only after the cell has been sealed are less stringent conditions imposed on the environment. Appropriate consideration must be given to the different production environment requirements for individual process steps in the design and planning of the production line (see Table 93). Significant parts of the production process are currently performed in clean and dry rooms to meet these high requirements.



	Clean room class	Dry room (dew point)	Temperature	Annotations
Mixing	ISO 8	/	22 ± 2 °C	The electrode manufacturing takes place under clean room conditions, since foreign particles in the coating cannot be removed in the later process by cleaning methods (e.g. suction).
Coating	ISO 7	semi-dry (5°C to -5°C)		
Drying				
Calendering	ISO 7 - ISO 8			
Slitting				
Vacuum drying		Dry (0°C to -30°C)		
Separation	min. ISO 7	Dry (-25°C to -35°C)	22 ± 2 °C	The cell assembly must be carried out under dry conditions, as water inside the cell leads to strong quality losses (service life) and to a safety risk (formation of hydrofluoric acid).
Stacking / Winding		Dry (-40°C to -50°C)		
Packaging				
EL filling		Extra dry (-50°C to -70°C)		
Formation	/	/	22 ± 3 °C	Cell finishing takes place in a normal environment. Since the cell is already sealed and degassing takes place in a vacuum chamber, there are fewer requirements for the particle environment and humidity.
Degassing				
HT aging			30 °C to 50 °C	
NT aging			22 ± 3 °C	
EOL testing				

Overview of manufacturing environment requirements for different process, Source: PEM

The discussion about dry and clean rooms focuses on the high investment costs, high running costs, and high CO_2 emissions generated during operation of the infrastructure. Up to 20 percent of the investment costs and 40 percent of battery cell production line costs are incurred from setup and operation of the dry and clean room atmosphere. Therefore, there is a great need for cost and CO_2 savings to be achieved through technical innovations in this area [Nelson 2019, Yuan 2017].

Challenges
Moisture is removed from the ambient air in the dry room atmosphere to prevent possible reactions of water-sensitive materials (cathode, electrolyte). Dry rooms are categorized by their dew points; dry room requirements depend on the material to be processed and its characteristics. For electrolyte filling, in particular, dew points of -50 to -70°C must be maintained, as the electrolyte forms hydrofluoric acid even at very low humidity levels.

Additional purity requirements are placed on the dry room environment in the production of lithium-ion cells to prevent contamination with particles from the environment. Clean rooms must also prevent cross-contamination between individual steps of the production process. Cell assembly typically requires clean rooms of ISO class 6-7. Electrode production typically requires clean rooms with an ISO classification of 7-8, especially in the mixing, calendering, and slitting steps. Even small deviations from dry and clean room environmental requirements have a negative impact on the quality and lifetime of the cell. [Heimes 2018]

The exact requirements depend on the battery materials used, especially the electrodes. The relationship between material and process parameters and clean and dry room requirements has not been sufficiently investigated. The development and use of new cathode materials, especially with a high nickel content, can increase the cost of maintaining - production conditions. The high investment cost of clean and dry room designs to meet the requirements of current and future cell generations is a key challenge (RBW 8.1).

A large part of the energy demand of cell production is due to the size and continuous maintenance of the dry and clean room atmosphere. If consistent product quality can be ensured, innovations that increase energy efficiency in this area could have a direct impact on reducing operating costs, and thus on the profitability and sustainability of the production line (RBW 8.2).

Finally, continuous monitoring of the dry and clean room parameters as well as limitation of the number of personnel must be implemented to comply with requirements and prohibit - moisture in the room. Another challenge is the limited time personnel can spend in the room due to health concerns [Scientific Climate Systems 2020].

Possible solutions

The development of an improved process understanding with regard to the interrelationships between operating parameters, design, and energy consumption is fundamental for the optimization and process stability of dry and clean rooms. Knowledge of possible cross-contamination between process steps and potential contamination at individual process-steps is important for optimum process design and stability. Intelligent and economical process design and control can be achieved based on interrelationships, especially for future electrode materials. By exploring the requirements of future electrode materials in - conjunction with intelligent process design and control, it is expected that RBW 8.1 can be broken through in the next 10 years. [Ahmed 2016].

There are several approaches for reducing energy requirements. Generally speaking, the energy demand of dry and clean rooms depends on the air volume. Smaller rooms have a much lower energy requirement and can be controlled and monitored in a much more targeted manner. Concepts based on this approach in which only the plant itself is enclosed are being tested. The air volume can be significantly reduced by using small, encapsulated clean and dry rooms, so-called glove boxes or mini-environments. For example, high-purity nitrogen or argon can be used to achieve a pure gas atmosphere in the box and comply with requirements for residual concentration of impurities. Furthermore, the risk of contamination by personnel can also be reduced, as they only access the process area via rubber gloves. However, interfaces between the individual process steps as well as flexibility and accessibility of these enclosed clean and dry rooms during the process and maintenance work still pose challenges. Limiting intervention with the ongoing production process to indirect access only makes things more difficult. To be - used in volume production, this solution requires stable, robust processes that require virtually no external intervention. Additional energy savings potential can be achieved by using more energy-efficient components, such as pumps, and utilizing waste heat within the entire process.

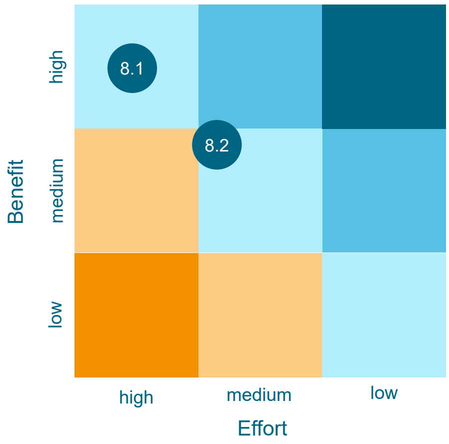
Outsourcing entire process steps from the dry and clean room only makes sense if high costs and quality and time losses (e.g., due to additional infeed and discharge of the cells) can be avoided.

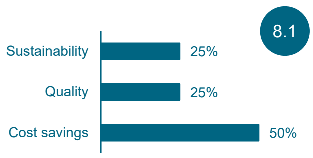
Another approach is to use closable metering valves, which allow work to be performed under normal conditions as soon as the cell has been placed in the pouch housing and the corresponding sealing step has been completed. Electrolyte filling and all subsequent process steps can thus take place outside the drying chamber. Electrolytes do not need to be inserted or removed after the sealing step. Using all of these approaches, it is expected that we can break through RBW 8.2 in the next four years.

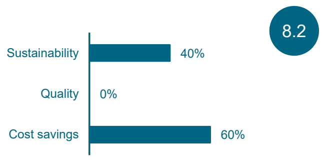
Effort and benefit assessment
The benefits of designing dry and clean rooms to meet future material requirements are estimated as high. This is primarily due to the high potential for reducing clean and dry room operating costs with intelligent process design. Adapted process control and the associated reduced CO_2 emissions can also improve quality and sustainability. However, the high benefit comes with a high cost attributed to the complex planning phase and process design.

Experts estimate that moderate to high effort is required to improve energy efficiency; e.g., through the use of mini-environments, more energy-efficient components, and the outsourcing of process steps. The process chain must be revised as a result of these changes, and additional production work may be required. The benefits of RBW 8.2 are rated as moderate to high. Changes can reduce energy costs and CO_2 emissions, which has a positive effect on both costs and sustainability.

Effort Benefit Diagram and Impact on Sustainability, Quality and Costs







8.1 Optimize cost and benefits of clean and dry room design for new electrode materials

8.2 Improve energy efficiency

Professional support

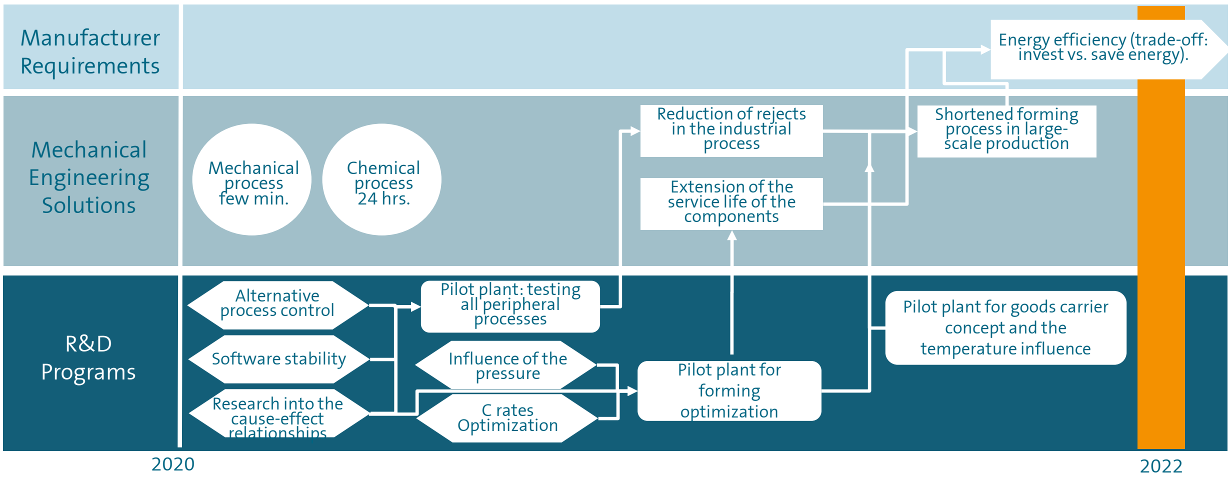
Topic Sponsors:
Christian Voigt, Managing Director;
Dirk Möder, Project sales technical cleanliness and cleanroom
mkf GmbH

With additional support from:
BST GmbH
Colandis GmbH
Festo Vertrieb GmbH & Co KG
Gebr. Becker GmbH
Grob-Werke GmbH & Co. KG
Industrie Partner GmbH
Leybold GmbH

Formation and maturation

No.*	Red Brick Wall	Current status in Comparison to 2018	Relevance**	Timeline***
9.1	Energy efficient formation (trade-off: investment vs. energy savings)	Unchanged	High	2022
9.2	Process control to reduce process durations	Unchanged	High	2030 (update every 2 years)

RBW 9.1: Energy efficiency of formation (trade-off: investment vs. energy savings)
Forming is one of the most energy-intensive process steps in battery cell production. There are various concepts for counteracting energy costs, including using optimized process control to shorten the process time and researching cause-and-effect relationships during formation. The challenge is that the costs saved through increased energy efficiency must be higher than the investment costs for implementing the new concepts.



Legend: ◯ State of the art ⬭ research approaches/projects ▭ Pilot plants, concrete 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

RBW 9: Formation and maturation

Basics

During formation, battery cells are charged and discharged for the first time, using cycles with increasing currents, and the so-called Solid Electrolyte Interface (SEI) is formed. This is probably the most important quality parameter of the lithium-ion cells, and has a significant influence on safety and lifetime. [Li 2017]

Several lithium-ion cells are always formed simultaneously within a product carrier during the forming process. There are essentially two concepts pursued by machine and plant manufacturers. In the rack concept, the battery cells are contacted and stored in racks. In the chamber concept, on the other hand, the battery cells are contacted on a module carrier and pushed into a chamber together for forming.

Contact is made using contacting pins, which ensure a secure connection and low contact resistance. The individual contact connections are called channels. The forming process parameters are recorded in flow charts. Forming can take up to 24 hours, depending on the cell chemistry, and significantly determines the service life and safety of the lithium-ion cell. The long formation times are due to the fact that the initial capacity loss and the contact resistance are greater at higher C rates than at low C rates.

Furthermore, there is an increased risk of lithium-ion cell channel failure and thermal runaway during formation. These can occur due to contacting problems, cell defects, or unstable software. This can lead to an entire batch being damaged, resulting in considerable losses. There is a risk of thermal runaway due to the high heat generation or accumulation, especially at the contact points. Appropriate safety concepts must be observed during formation to account for the increased risk of fire due to the large number of cells charging simultaneously within a confined space.

The subsequent self-discharge test, formerly referred to as "maturation," is for quality assurance purposes only, and is therefore assigned to the "end-of-line test" process step. In this step, the lithium-ion cells are stored for - several weeks, during which regular cell voltage measurements are taken. Predictions can be made about the service life of the lithium-ion cell based on the self-discharge rate. Significant capital is tied up due to these long resting periods, the need for storage space and goods carriers, and the lithium-ion cells themselves.

Recuperation is a major opportunity for reducing energy consumption during formation. In this process, the energy released during the discharge of one lithium-ion cell is used to charge another. The Coulombic efficiency of lithium-ion is about 67 percent for the first charge/discharge cycle [Pham 2016]. This has a positive impact on energy consumption during formation. Few other mass market improvements have been achieved since 2018.

The processes of formation, maturation, and EOL testing of a lithium-ion cell account for about one third of the cell costs, and usually take one and a half to three weeks. Therefore, this remains highly relevant for battery manufacturers [An 2016].

Challenges

The biggest challenge in forming is to improve energy efficiency (RBW 9.1), as forming equipment has high power consumption in continuous operation. Plant operation is one of the largest cost factors in battery cell - production. For this reason, it is necessary to reduce energy loss during the forming process, or to use new approaches to reduce the forming time in combination with low energy use. The costs savings from changes to the forming process must be greater than the investment - costs for integrating the new concepts.

The long process time during formation and maturation is another challenge (RBW 9.2). More targeted battery formation should be made possible by investigating the influences on these process steps and researching the relationships between chemical process parameters and the formation of the SEI. This could reduce the long process time and save capital costs in addition to increasing quality.

Possible solutions
The relationships that influence the formation of the SEI are currently being researched in order to increase the energy efficiency of the forming process. The aim is to form an SEI layer that is homogeneous and as thin as possible using the least amount of energy in the shortest possible forming time. The measurement of process and product parameters and their collection, analysis, and utilization during the forming process and upstream process steps is becoming increasingly relevant for understanding these relationships. New forming strategies and protocols will be developed based on these findings, for example with a lower number of forming cycles and optimized stress levels to reduce energy loss during forming. However, the entire production line must be digitized and a large data and analysis model must be developed using AI applications to derive these correlations (see RBW interactions). One project that addresses this approach is the Effiform project, which aims to accelerate the forming process and establish an intelligent testing method. This would make it possible to approve the cells more quickly and save resources [Effiform].

Another approach for reducing the forming time involves using additives, modification of the electrode material, and substitution of the binder, so that chemical reactions can be used to reduce the forming time and energy use. Due to the risk of breakdown, the electrolyte composition must also be precisely matched to the graphite anode to form a high-quality SEI [Buqa2006].

Laminating the individual electrode-separator composites in the lithium-ion cell also has a positive influence on the duration of the formation process. Not only does this reduce the initial capacity loss due to the formation of the SEI layer, it also improves fast-charging capabilities and increases the energy efficiency due to lower losses during the formation process [Frankenberger 2019].

However, the challenge with these approaches to increasing energy efficiency is to find a trade-off between higher investment costs for integrating the new concepts into battery cell production and the resulting lower operating and energy costs in order to break through RBW 9.1.

In recent years, a number of concepts have been explored for reducing the duration of the forming and curing process and the associated capital expenditures. One promising approach is the influence of temperature and the application of mechanical pressure during forming. Increasing the temperature to approximately 50°C affects the conductivity of the electrolyte through the separator, the solid diffusibility in the active material particles, and the charge transfer resistance at the electrode-electrolyte interface [Leng 2017]. These factors lead to an increased reaction rate and a reduced total internal resistance of the LIB cell. High temperature forming leads to faster, more uniform SEI formation, which increases the capacity of the graphite electrode when the cell is subsequently cycled at room temperature

[Bhattacharya 2014]. However, the temperature window must be precisely maintained, as even small temperature deviations above 50°C can lead to undesired side reactions and cell degradation.

By applying pressure, the physical distance between the electrodes can be reduced due to the elasticity of the separator and the diffusion of the electrolyte can be increased [Weber 2014]. This leads to a reduction of the internal resistance in the cell, and thus to a reduction of the forming time. However, forming under a defined mechanical pressure not only reduces the forming time, but also the risk of thermal runaway of the cell during the process. There are approaches for product carrier concepts in forming lines to achieve these pressure and temperature requirements during forming. In addition to ensuring the forming parameters, these approaches can also improve the handling and process time of the Li-ion cells using alternative process control. A pre-installed connection to a contacting unit also avoids the risk of cable wear [Heimes 2020].

In addition to forming, the temperature also has a positive effect on the maturation of the cell. Resting storage at higher temperatures can accelerate processes within the cell and thus detect quality defects more quickly and/or reliably. Cycling at higher temperatures leads to a decrease in cell performance because continued growth of the SEI increases cell resistance [He2008]. Furthermore, integrating the end-of-line test into the forming procedure should reduce the process time and make it possible to detect the quality of the cell at an early stage.

External forming outside the cell housing [patent 1] before final sealing could significantly improve the efficiency of the forming process. The cell stacks would be formed in an electrolyte bath, allowing gases to be discharged more quickly and side reactions to be more effectively avoided. Another process for pouch cells eliminates the degassing step, which enables forming with simultaneous degassing using port technology [patent 2]. The gas produced in the forming process is discharged directly through ports, similar to valve connections.

Digitalization of the ripening process can also be helpful for reducing its duration. It should be possible to obtain a better understanding of the quality of the cell and cell aging by collecting data during ripening using a product carrier concept with a BMS system, which could be used to individually adapt the ripening period.

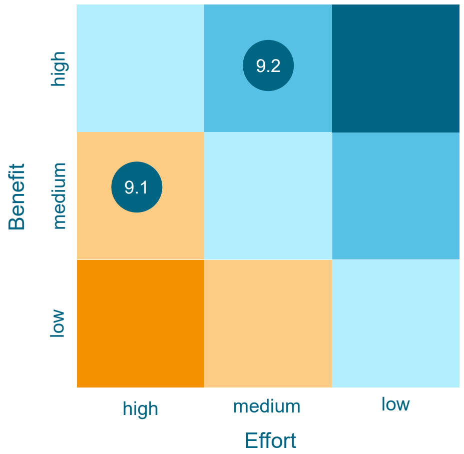
With the multitude of approaches to shortening process time, it is expected that we will be able to break through RBW 9.2 in the next few years.

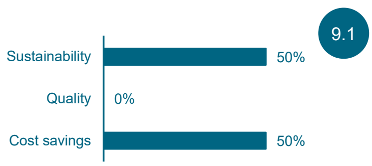
Cost and benefit assessment

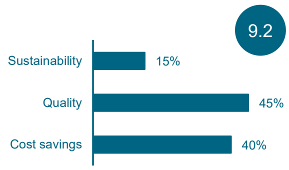
The benefits of improved energy efficiency are rated as moderate, as there are high initial investment costs for manufacturers. Breaking through the RBW would lead to increased sustainability and cost savings. The effort required to convert plants to these new concepts is rated as high.

The benefit of reducing the process time for forming and maturing Li-ion cells is high, as significant capital is invested in both process steps. The effort is seen as moderate for machine and equipment manufacturers as adding additives, for example, does not require the forming process and the equipment to be changed. Therefore, breaking through this RBW primarily affects the cost of a battery cell. Adding additives should also help to increase the quality of the cell. However, the sustainability is only slightly improved by this increase in quality.

Effort Benefit Diagram and Impact on Sustainability, Quality and Costs







9.1 Energy efficiency 9.2 Reduction of process durations

Professional support

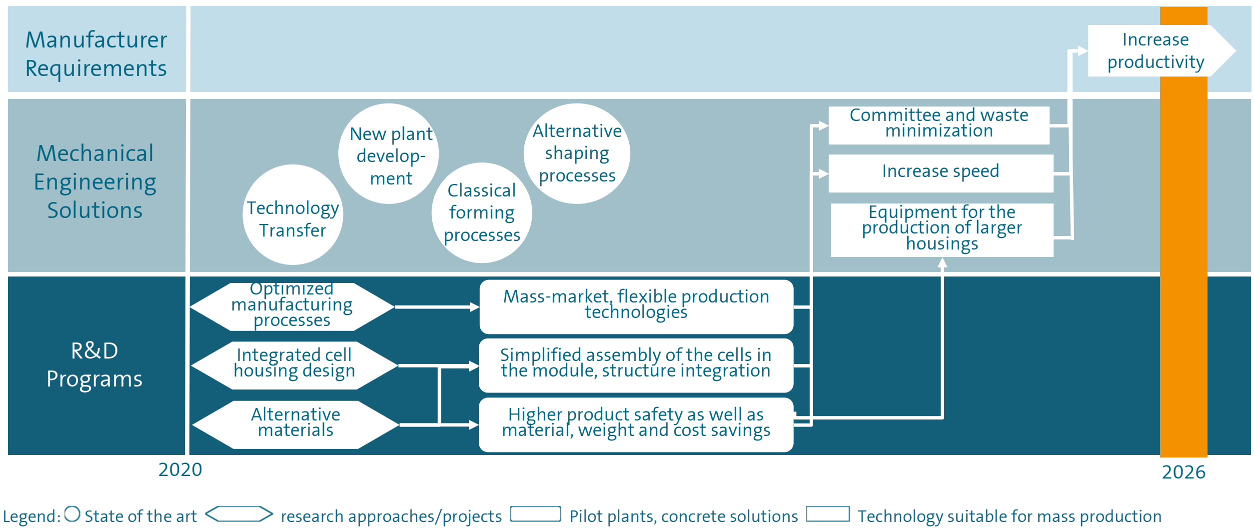
Topic Sponsors:
Tobias Grobe, Account Manager Battery Solutions;
Toni Wolfgang, Account Manager Formation, thyssenkrupp System Engineering GmbH

With additional support from:
Festo Vertrieb GmbH & Co KG
Industrie Partner GmbH
Maschinenbau Kitz GmbH

Housing production (cell)

No. *	Red Brick Wall	Current status in Comparison to 2018	Relevance**	Timeline***
10.A.1	Efficient production: minimize scrap and punching grid waste	Progress made	Moderate to high	2023-2026
10.A.2	Processing of innovative materials in the cell: lightweight construction, steels, aluminium alloys	Little progress made	Moderate to high	2023-2025

RBW 10.A.1: Housing production (cell) - increasing productivity
The diversity of cell dimension variants continues to increase due to the wide range of applications for lithium-ion cells. Lithium-ion cells are also becoming larger, regardless of the cell type. This also poses challenges in cell housing production, which must be met with optimized production processes and equipment as well as alternative material combinations. Furthermore, the potential for reducing scrap and waste must be leveraged and innovative cell housing concepts implemented to ensure long-term competitiveness.



*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

RBW 10.A Housing production (cell)

Basics

With the increasing spread of electromobility and the associated strong growth in demand for batteries, the production of cell housings is also becoming increasingly relevant. Production is based on different process technologies, depending on the type of housing. For example, the production strategies for prismatic and cylindrical cell housings are based on deep drawing or impact extrusion [Pettinger 2013]. For pouch cells, an aluminum-plastic composite film can be formed into a half-shell shape by deep drawing [Singer 2020]. These processes have been further optimized in recent years. - Existing cell housing production technologies can be described as industrialized, as progress has been made in production speed and process accuracy. However, cost reduction targets of up to 50 percent are still required for this type of production.

A leak detection test is useful to increase safety and safeguard cell housing production by means of a leakage test, although this also incurs significant costs. However, sufficiently secure processes are required to prevent leakage during technical production.

Challenges

Current production and quality assurance processes used in the manufacturing of housings must be made more efficient to respond to predicted cost pressure in the coming years (RBW 10.A.1). New geometries will need to be produced and the production process must be made more efficient by minimizing punching grid waste and scrap. The use of alternative processes such as impact extrusion for hard case cells (prismatic and cylindrical) is also becoming increasingly relevant [Singer 2020].

These requirements are reinforced by the trend towards larger cell formats, which make process control in housing production more complex. The main challenges for pouch cells are the workability of the aluminum composite foil in the thermoforming process and the sealing for cell closure represent the main challenges [Michaelis 2018]. Increasingly better process design can allow greater deep drawing depths. For prismatic and cylindrical cells, achieving housings with increasingly thinner wall thicknesses and therefore less weight while maintaining the same strength is a challenge [Thielmann 2017]. In general, large cells require larger sealing surfaces and more sophisticated bonding techniques. Leakage of the harmful electrolyte from a leaking housing would render a battery cell unusable and pose a significant safety risk.

Another challenge is the research and use of innovative materials, for example that contribute to reducing the weight and increasing the stability of the housings [Foreman 2017, Hong 2019, Zhang 2019]. Producing cell housings from new material combinations would also open up potential for structural integration as well as improvement of the inherent safety of the subsequent battery pack. Facilities will need to be designed for these new materials (RBW 10.A.2).

Possible solutions
First, transferring manufacturing technology from similar industries, such as high-speed pressing, can be beneficial for cost-effective mass production. Further development of production processes can be accelerated by integrating these new technology approaches. The challenges of RBW 10.A.1 should be - addressed in the next six years at the latest to reduce costs. The standardization of cell sizes could be another important approach.

Parameter studies and the development of an in-depth process understanding can be beneficial for the deep drawing process of Al half-shells for pouch shells [Fleischer 2017]. Tearing or thinning of the film must be avoided when increasing the thermoforming depth.

As a response to the trend toward thick, large-format cells, research is being conducted into pouch films with a higher thickness that can be deep-drawn to a greater depth. Other developments are aimed at further optimizing the production technology to increase the current thermoforming depth of 0.5 cm.

Solid aluminum alloys could potentially be used to achieve smaller wall thicknesses for weight savings [Thielmann 2018].

In general, equipment must be developed for the production of larger cell housings, production speed must be increased, and restrictions of established processes must be reduced.

In addition to the optimization of existing approaches, there is currently great potential for research and development in the areas of alternative housing concepts and geometries, which feature new material combinations and functional integration [Forman 2017, Hong 2019, Zhang 2019]. For example, cooling channels or sensors could be integrated into the cell to improve functionality and safety.

Effort and benefit assessment
Compared with other red brick walls in battery production, housing production at the cell level can be considered as industrialized and the materials are improving incrementally (10.A.1).

As the number of units market competition increase, the benefits of optimizing scrap in cell housing production are likely to increase overall in the coming years. However, the cost of these changes is estimated to be high (RBW 10.A.2).

In contrast, new housing concepts and materials that are not yet mature could be used to achieve lighter or more sustainable products, possibly with integrated sensors.

Effort Benefit Diagram and Impact on Sustainability, Quality and Costs

10.A.1 Innovative materials 10.A.2 Scrap minimization

Professional support

Theme sponsor:
Volker Seefeldt, Managing Director
H&T Marsberg GmbH & Co. KG

With additional support from:
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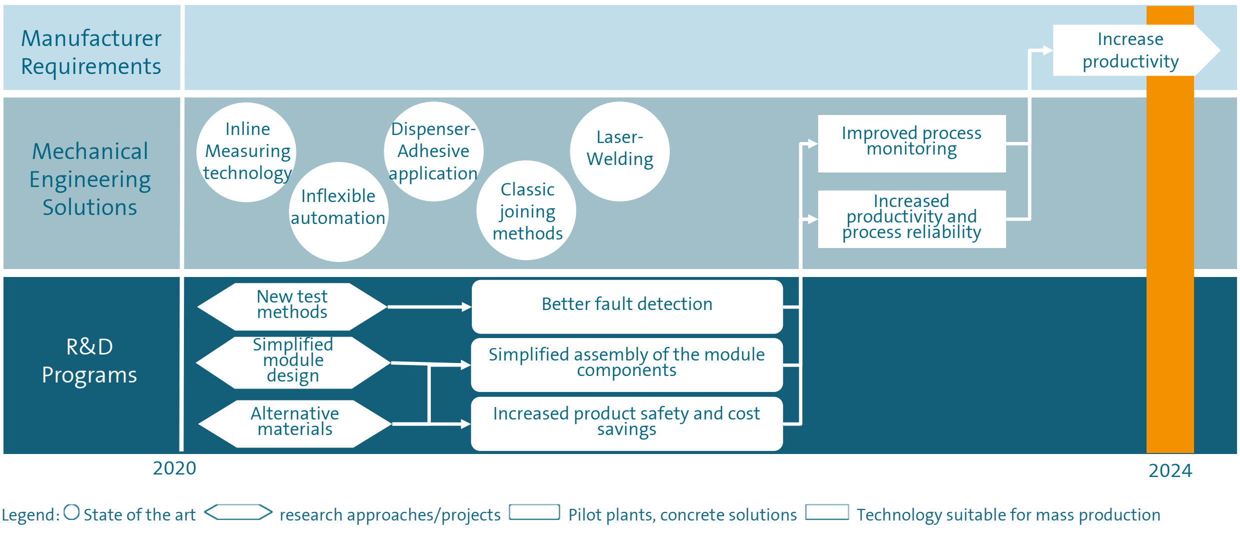
Housing production (module)

No. *	Red Brick Wall	Current status in Comparison to 2018	Relevance**	Timeline***
10.B.1	Increase productivity and master complexity	Little progress made	High	2021-2024
10.B.2	Processing of innovative materials in the module: Lightweight construction, plastic housings, composite materials, steels, aluminum alloys.	Little progress made	Moderate to high	2023-2025
10.B.3	Flexible design systems	Little progress made	Moderate	2023

RBW 10.B.1: Enclosure Manufacturing (Module) - Increase productivity and master complexity

Efficient production plays an increasingly important role in module production due to high cost pressure. Costs must be reduced and processes improved to enable mass production. Module production requires many different joining processes, which increases process complexity and requires increased quality assurance efforts.



*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

RBW 10.B Housing production (module)

Basics
Module production and assembly requires a particularly large number of precise handling and joining processes with a low level of automation, especially in smaller series. These - include safe handling of the cells along with joining technologies in the housing such as gluing, screwing, and welding, all in the immediate vicinity or on the cell itself, with corresponding safety concepts [Larsson 2019, Kampker 2014, Das 2018, Schmidt 2015].

Challenges
Current module manufacturing production and quality assurance processes must be made more efficient to respond to the cost pressures of mass production in the automotive industry. The focus is on increasing productivity (RBW 10.B. 1) and raising the level of automation. In special applications, the challenge of a high diversity of variants must also be dealt with.

Another significant challenge in module manufacturing is researching and using innovative materials (RBW 10.B. 2), for example, to reduce the weight and increase the stability of the housings [Foreman 2017, Hong 2019, Zhang 2019]. Examples may include modules with integrated cooling channels, special combinations of thermal insulation and conductivity, wireless sensor communication, - and the use of composite materials in the module.

The variety of different joining methods makes the processes complex and increases the susceptibility to errors. Typical methods include bonding using adhesive bead application, laser or ultrasonic welding of the individual cells, and screwing of other electrical components to the module [Heimes 2018, Das 2018]. Module housing production must be able offer flexible manufacturing in terms of size, especially with smaller quantities and high flexibility requirements outside of automotive applications (RBW 10.B.3).

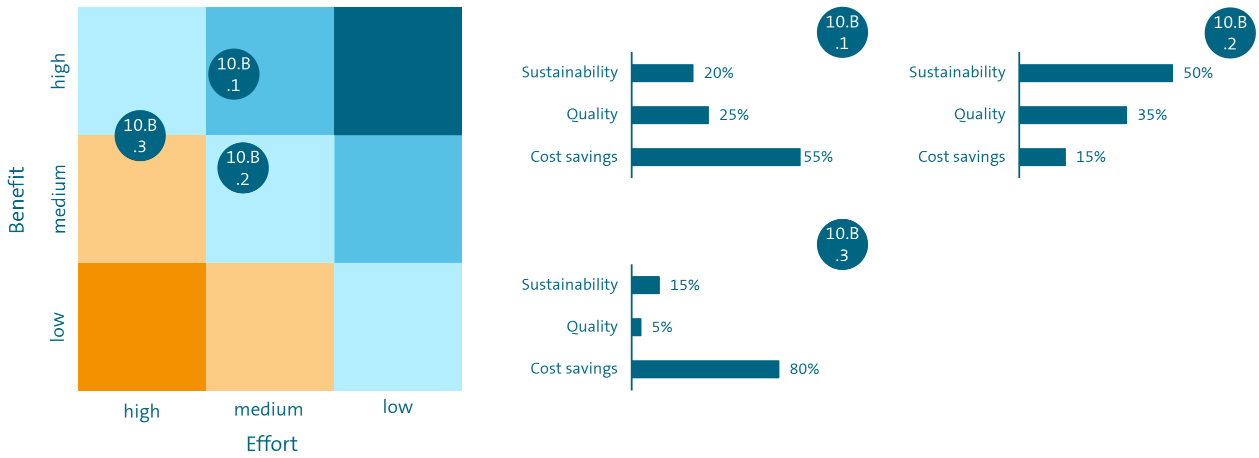
A fundamental challenge is that knowledge of process technology capabilities often does not align with system developers' designs.

Possible solutions
At the module level, product design is primarily tasked with developing solutions that allow the use of consistent joining processes. However, new testing methods can also increasingly be used to improve quality in module production, such as optical coherence technology for checking the successful application of adhesive beads. Automatically guided handling systems with in-situ measurement technology are one possible solution to make module production even more efficient (RBW 10.B.1).

New materials, such as fiber composites, must undergo extensive process development. These approaches also require the creation of product development approaches as well as lightweight and integrated designs. Fiber composites also impose high demands on leak testing. The thin-walled materials change their shape when subjected to pressure (both negative and positive), leading to apparent leakage and similar measurement errors. This in turn results in extended commissioning times and additional expenses. (RBW 10.B.2.)

Design flexibility can be achieved with modular product design, such as adjustable clamping elements. In general, equipment manufacturers, manufacturing technology experts, and battery module developers should interact more often to improve synergies (RBW 10.B.3).

Effort Benefit Diagram and Impact on Sustainability, Quality and Costs



10.B.1 Increase in productivity 10.B.2 Processing of innovative materials

Effort and benefit assessment
Module production is already highly industrialized compared to other red brick walls in battery production, because standard manufacturing processes are used. Increased efficiency should be an achievable task. The effort required to increase the efficiency of module production is considered to be moderate, but the benefits for module production are high (RBW 10.B. 1).

These measures primarily contribute to a reduction in costs, but also increase sustainability and quality. Experts classify the processing of innovative materials as a moderate effort with moderate benefit (RBW 10.B.2). Experts rate the effort required to develop flexible-design products and suitable production facilities for moderate module and system production volumes as medium and mainly aimed at reducing costs (RBW 10.3).

Professional support

Theme sponsor:
Volker Seefeldt, Managing Director H&T Marsberg GmbH & Co. KG

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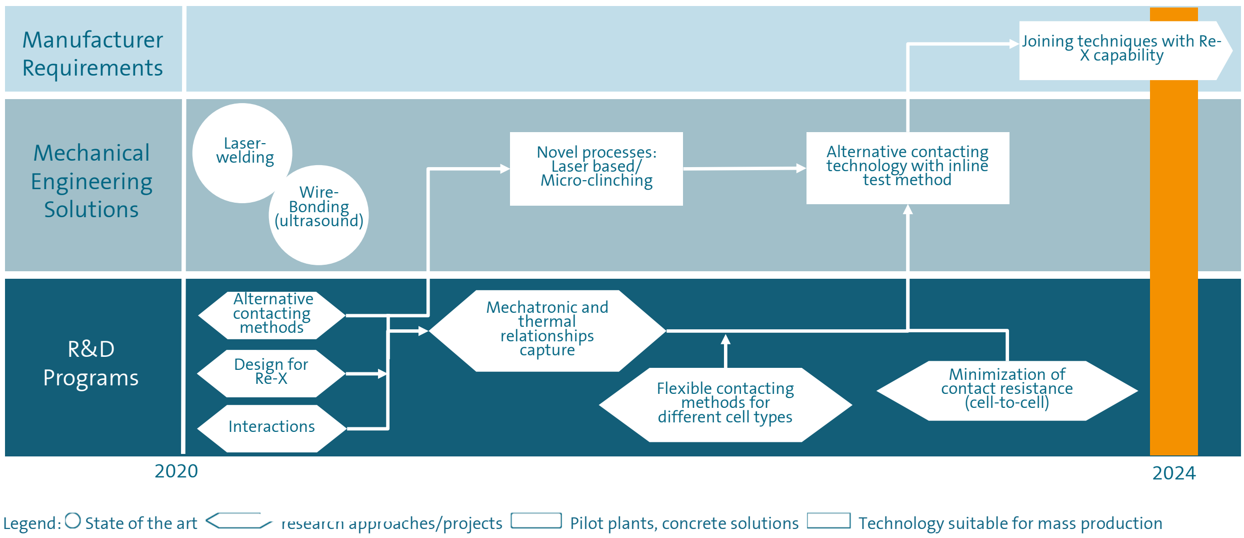
Contacting

No. *	Red Brick Wall	Current status in Comparison to 2018	Relevance**	Timeline***
11.1	Connection technologies designed for remanufacturing/recycling/rapid contact interruption	Unchanged	Moderate	2020-2024
11.2	Contact surfaces for larger currents and larger cells	Progress made	High	2020-2024

RBW 11.1: Connection techniques with Re-X capability

To handle large currents safely, arresters inevitably become larger, making contacting more complex. Furthermore, the dynamic loads in the vehicle place additional stress on the cell connectors. At the same time, the increase in pack-side voltages poses enormous challenges for contacting technology. In order to implement the Re-X capability of lithium-ion batteries, finding a fast contacting solution that is as gentle on the material as possible is becoming increasingly relevant. Optimized connection technology can reduce material defect costs.



*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

RBW 11: Contacting

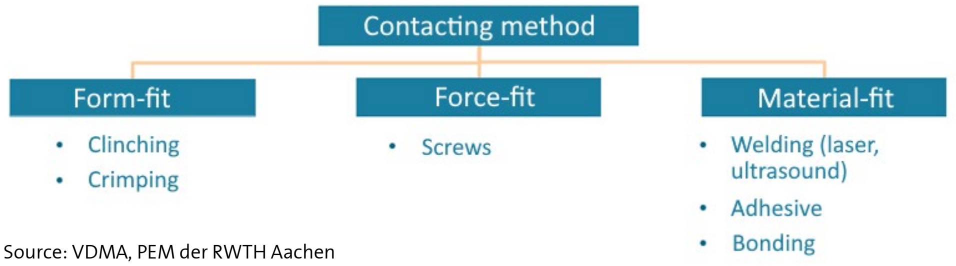
Basics

The goals of increasing energy and power density along with faster charging cycles require an increase in system voltages in the battery system. The contacting quality has a significant influence on achieving these goals. A distinction is made between three types of contacting in connection and contacting technology: form-fit, force-fit, and material-fit connections [Haberhauer 1996]. Central contacting systems, or busbars, are the current industry standard. Modules are typically contacted uisng laser welding, laser bonding, and ultrasonic welding. Alternatively, the connections can be made with a force-fit connection; e.g., screw connections. - An overview of the different contacting methods and their advantages and disadvantages is shown in "Assembly processes of a battery module and pack" [Heimes 2018]. The selection of the contacting method also depends on the material of the busbars and the cell format [Das 2018].

Challenges

A major challenge is the development of a process which ensures good contacting of - components while also permitting a fast - solution for contacting, which must be as gentle on the material as possible to enable and guarantee the ability to Re-X batteries (RBW 11.1). The term Re-X covers all processes for optimizing the service life of a battery and the battery components. This includes the processes of reuse, remanufacturing, and recycling. For example, it may be easy to use welding as a key method of contacting, but this has two to three times the contact resistance of contacting using lasers [Schmidt 2015].

Another challenge is the contacting of the individual components of the module with higher currents and large-format cells (RBW 11.2). Due to higher currents flowing in the battery module, the arresters must be enlarged to reduce the contact resistance. Thus, more surface area is available for the contact. The dynamic stress in mobile applications also places a high mechanical load on the contacts. Optimized contacting technology can reduce material defect costs.



Source: VDMA, PEM der RWTH Aachen

Suitable techniques must be used to prevent high heat input and ensure good, permanent contacting of the components. It is essential to prevent brittleness and corrosion of the contacts, even under demanding climatic operating conditions.

The surface of the contact should have a low isotropic electrical resistance. Depending on the battery design, a mix of materials can be reliably connected. Incorrect contacting can cause short circuits in lithium-ion cells and thus damage the battery system. For this reason, wear on the contacts must be minimized. Closed-circuit methods offer the advantage of allowing a vibration-resistant connection with low contact resistances between the different materials. However, non-destructive separation of the connections is not possible without considerable effort. Force-fit connections, such as bolts, can usually be easily undone. However, these are not often used in the automotive sector because they have a high contact resistance.

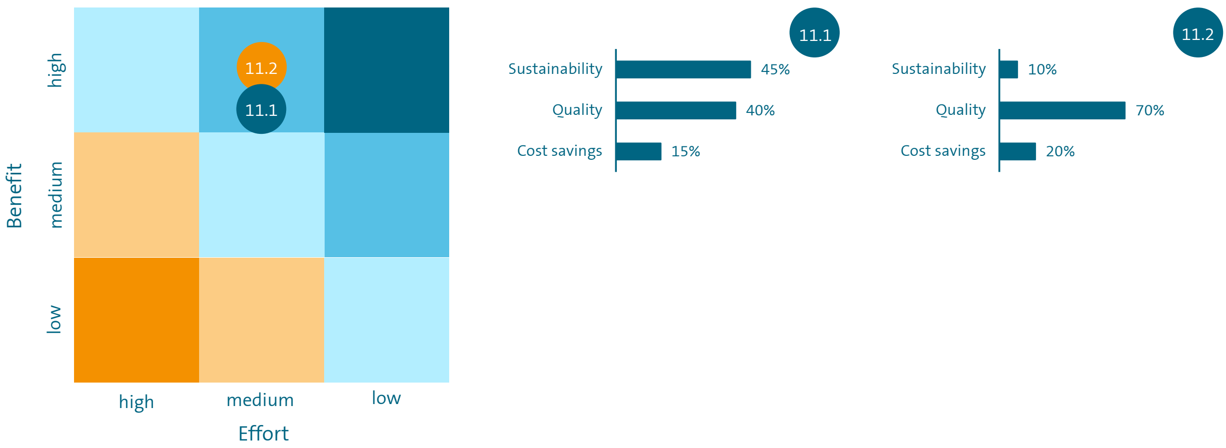
Possible solutions
with regard to a 2nd-life use of automotive cells as stationary storage or renewed mobile applications. This is particularly applicable when the contacts are welded and a non-detachable connection is used (form-fit or material-fit - connections).

The minimum requirements of both - applications must be met, otherwise the cells cannot be exchanged. Laser bonding and - module-level mechanical connections address - this challenge. The relatively thin electrical connectors used in laser bonding with wire-shaped bonding material, or so-called ribbons with rectangular cross-sections, can be removed with limited effort and facilitate reuse or replacement of defective cells.

For the contacting of high-voltage connectors in the system to be suitable for mass production, existing processes will have to be improved or new processes will need to be developed, and electrical connection will have to be integrated early in cell designs . Laser bonding and micro-clinching are promising approaches in this regard. [Das 2018]

By developing alternative contacting methods, knowledge of thermal relationships can also be gained and evaluated inline to allow direct assessment of the quality of the connection. Quality controls after contacting could be replaced by integrated inline measurement technology. For example, thermographic analysis and optical 3D inspection could be used for non-destructive inline quality checks of connection points. The development of flexible contacting processes for the requirements of - different cell formats is very relevant for variant-flexible production of battery modules and battery packs. This could eliminate changeover times and production standstills [Ebert 2014, Just 2018].

Effort Benefit Diagram and Impact on Sustainability, Quality and Costs



11.1 Re-X capability 11.2 Larger currents

Even if only one cell format is produced, it may make sense to adapt the contacting tool if it could lead to a reduction in process times or an increase in quality. Further improvements and - the development of new contacting processes should contribute to the breakthrough of RBWs 11.1 and 11.2. Based on progress to date, this is expected by 2024. These findings are a decisive factor for the service life of the battery system.

Effort and benefit evaluation
The design of contacting for larger currents and cell formats and the remanufacturability of the battery system will play an increasingly important role in the future, so the benefit of breaking through the Red Brick Walls is classified as high. Experts describe RBW 11.1 as more important in the long term, as - improvements in this area can increase the added value of the battery, modules, and cells. On the other hand, RBW 11.2 is more urgent, as contacting for higher currents and larger cell formats increases the performance of batteries compared to conventional technologies, making it more competitive and forming the basis for further developments.

Remanufacturing capability greatly increases the sustainability and quality of battery systems. The service life of the battery can be extended through detachable connections, and quality can improved by further development of the processes. However, battery system remanufacturability only results in minor cost savings.

The design of contacting for higher currents only has a minor influence on the sustainability and cost of the battery system. However, since a good material connection with different materials and components and low resistance become more relevant at higher currents, it is expected that contacting quality can be significantly improved by breaking through this RBW.

The effort to refine existing contacting methods and explore new alternatives is considered as moderate, as significant development effort has already been invested in the solution of these RBWs in recent years, and some very promising approaches are already in an advanced stage of development, such as laser bonding.

Professional support

Topic Sponsor:
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With additional support from:
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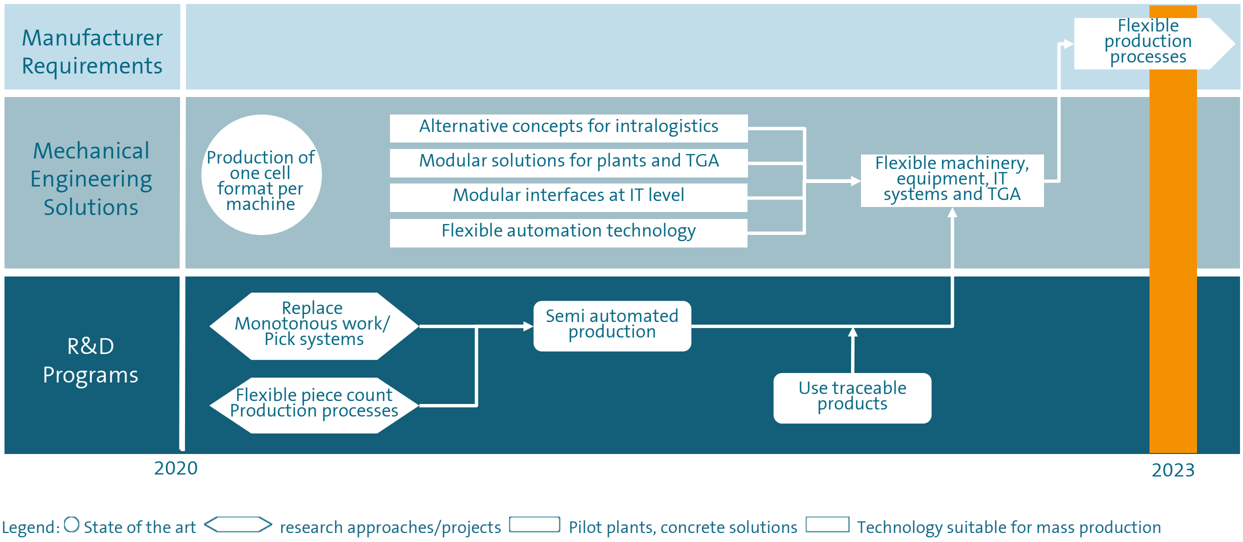
Flexible production

No. *	Red Brick Wall	Current status in Comparison to 2018	Relevance**	Timeline***
12.1	Designing flexible production processes: Ramp-Up and Piece Count Flexibility	Progress achieved	Medium to High	2023
12.2	Dealing with "similar" cells on a plant / convertibility	Progress achieved	Medium to High	2022

RBW 12: Flexible production - Modular and flexible piece count
The number of different cell formats and chemistries continues to grow. This results in different manufacturing processes, especially for module and pack production, which must be responded to with flexible and modular concepts for machines and technical building equipment (TGA). Flexibility includes variant, process and unit number flexibility as well as scalability (scale-up or modification of the production equipment).

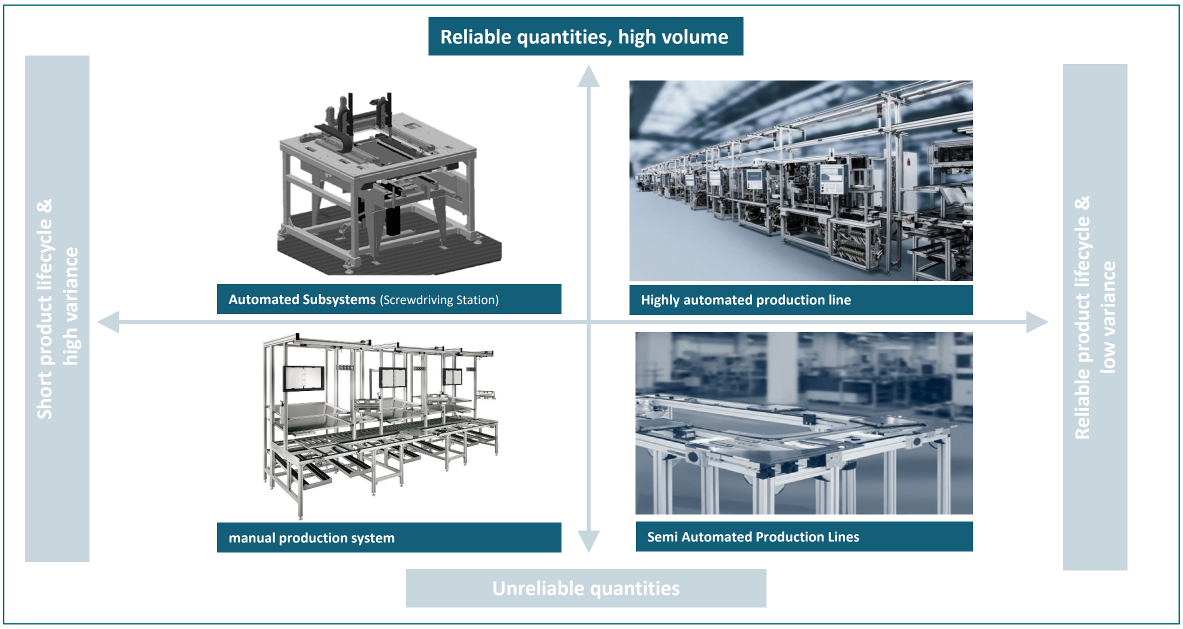


*RBW priority decreases from top to bottom.

**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

RBW 13: Flexible production

Basics

Flexible cell production, producing different cell formats and dimensions on one line, is not considered sensible from an expenditure point of view. Speed is reduced considerably, and high reject rates at the start of production have a direct effect on profitability. The following will discuss challenges and solutions for module and pack production.

Prismatic, cylindrical, and pouch cells are currently used in battery modules and systems. These cell types differ fundamentally in their geometries and properties [Kampker 2014a,b]. As the number of battery applications increases, so does the number of battery module and system variants on the market.

Increased automation in module and system production is becoming increasingly economical, especially for the vehicle industry, due to exponentially increasing sales figures of electric vehicles and the associated higher production volumes. The importance of flexibility has declined slightly declined for the sector in recent years as a result of the higher overall unit volumes [Sonnenberg 2018]. A high degree of automation and correspondingly high investment are also accompanied by particularly high quality requirements.

Automation is not as prevalent in other applications, such as commercial vehicles, two-wheelers, industrial trucks, and non-automotive applications such as ships and power tools. With a significantly lower production volume, the - number of variants is many times greater than for electric vehicles [Sonnenberg 2018]. -

Production that is both highly cost effective and as flexible as possible with regard to the number of variants and units produced is becoming increasingly important, especially for module and system assembly. In addition to plant and automation planning, the design of a flexible production concept also includes aspects of logistics, technical building equipment, and IT-supported organizational processes within production [Edström 2020]. Production design options, depending on flexibility and the number of units, are summarized in Figure at the beginning of this chapter.

Challenges
There are a large number and wide variety of challenges facing flexible module and pack production. One important issue is the design of flexible production processes themselves, so that they can respond to changes in production volumes, such as a scale-up. This also applies to measurement technology. In addition to -individual processes, the ability of the system to respond to changes and to produce a wide range of module formats and packaging variants in a single system is of great importance. Cell generations also develop faster than production systems are replaced. The systems must therefore be compatible with different but "similar" cells [Bognar 2018 , Küpper 2018]. This flexibility must be taken into account in module and system design.

Track and trace applications, which have already been implemented to a large extent in cell production for automotive applications, must also be implemented in systems that are flexible with regard to the number of variants and units produced to ensure the greatest possible adaptability (13.2).

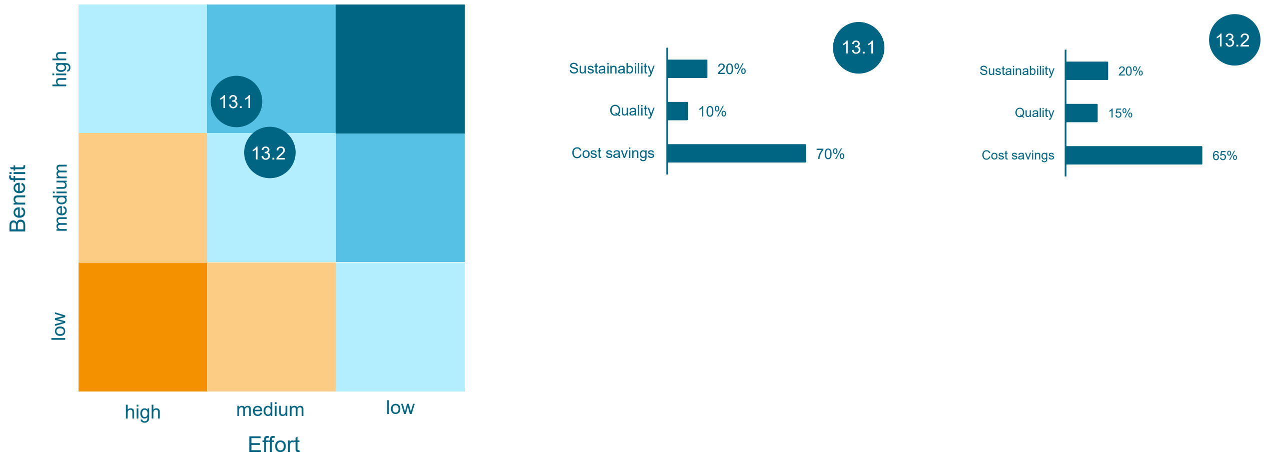
Possible solutions
The most common solution approaches are aimed at designing flexible plants, processes, and production systems [Fuchslocher 2019, Heidelberger 2020]. Due to further increases in production volumes in the coming years, a degree of automation that grows along with production would be advantageous. It is also desirable to be able to produce a flexible number of units on one line.

Even in smaller productions, semi-automated processes and human-robot collaboration can be used to reproduce monotonous and complex assembly work in a single station, or augmented reality can be used to improve operator guidance in assembly and make variant diversity more manageable.

System assembly is particularly suitable for the use of human-robot collaboration [Küpper 2018]. Human skills (such as experience, improvisation, or the combination of human senses) are combined with the strengths of the robots (such as accuracy, power, and -retrievability); e.g., for intricate cable assembly. The resulting high-quality product execution and simultaneously increased productivity have a positive effect on the competitiveness of battery production. Based on the knowledge and experience in the field of process automation, it is expected that RBW 13.1 can be broken through in the next 2-3 years.

Flexible module production equipment, especially for similar battery cells, requires a good process understanding of tolerances, joining and gripping technology, as well as system interlinking that allows process parameters to be flexibly adjusted in response to changing input products. Implementing cell standardization could reduce these flexibility requirements.

Effort Benefit Diagram and Impact on Sustainability, Quality and Costs



12.1 Design of flexible production processes   12.2 Dealing with "similar" cells

Standardization of battery modules aims to allow variant diversity to only occur during system assembly at the end of the production process. These approaches reduce the need for flexibility. To solve RBW 13.2, the challenge must therefore be considered from both the product and process sides. ¬With this approach, breaking through this RBW is expected in the next two years.

Effort and benefit assessment
The effort required to introduce semi-automated processes, human-machine collaboration, standardized data structures, digital twins and also track & trace systems in battery module and system production can be - estimated as medium. The existing technologies already being used successfully in related industries. High added value results from higher-quality products. In addition, the variant flexibility and higher productivity lead to reduced costs, especially for medium quantities Sonnenberg2018] (RBW 13.1).

The efficient handling of "similar" cells in module production can be assigned to a - medium level of effort and benefit overall; effective changeover capability can reduce - changeover efforts and thus costs and supplier dependencies. (RBW 13.2).

Professional support

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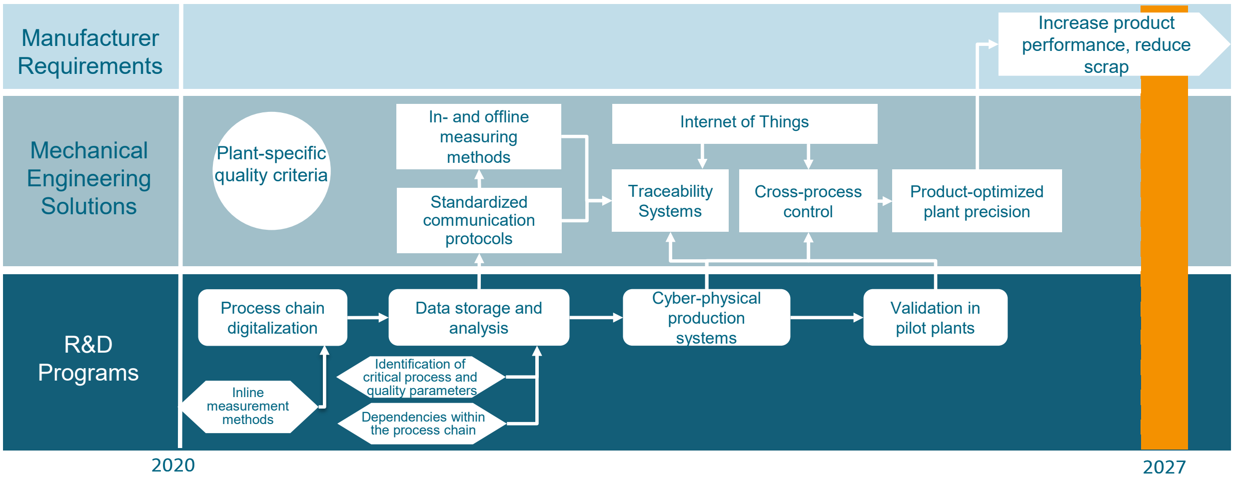
Interrelationships

No. *	Red Brick Wall	Current status in Comparison to 2018	Relevance**	Timeline***
13.1	Identification of the main interdependencies along the process chain	Progress made	High	2027
13.2	Communication between heterogeneous production warehouses + cross-process control /regulation	Progress made	High	2027
13.3	Traceability of the battery cell and its product characteristics over the entire life cycle	Progress made	Moderate	2030

RBW 13.1: Identification of the interdependencies along the process chain
Recording critical plant process parameters, intermediate product quality parameters, and battery cell electrochemical properties are used to identify the complex interactions within battery cell production. This knowledge can be used with AI-based control systems, for example to eliminate the influence of the environment or fluctuating material parameters on production. Communication between the heterogeneous production systems via uniform standards can enable cross-process impact toward fully automated production, so that product quality is increased and waste is reduced.



Legend: ◯ State of the art ⬭ research approaches/projects ▭ Pilot plants, concrete 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

RBW 13: Interdependencies - use of digitalization, Industry 4.0, efficient production

Fundamentals

Battery cells and their manufacturing process are characterized by complex interactions - between the processes, the structure of the individual intermediate products, and the - properties of the final cell. These interactions - require a high level of understanding in the fields of electrochemistry, electronics, mechanics, process engineering, and manufacturing technology. The lack of comprehensive knowledge of the interactions along the process chain, especially in battery cell production, is currently reflected in the high reject rates (low double-digit percentage range) and very long start-up phases up to robust series production.

This results in current untapped potential for both process and production efficiency. These must be achieved using Industry 4.0 approaches, which refers to digitalization, networking, and - intelligent control of processes and production.

Effiency of each process step	Process chain efficiency (for 25 processes)
99,5	88,2
99	77,8
97	46,7
95	27,7

Effect of different process efficiencies on the efficiency of the overall process chain with 25 process steps.
Source: BLB of TU Braunschweig

For example, suitable database analysis methods can be used to make transparent conclusions about possible causes of errors and then automatically correct them. The use of - Industry 4.0 solutions, such as cyber-physical production systems, data management in cloud computing, or artificial intelligence, promises a significant reduction in the previous reject rates and an increase in flexibility.

Challenges

A deep understanding of the interdependencies is required to unlock potential in the process and process chain (RBW 13.1). Each process step has individual process parameters that directly influence the quality of the intermediate products and the final battery cells. Even low reject rates per process step can quickly increase to significant reject rates along the process chain.

For example, a process efficiency or yield of 99.5 percent results in an overall efficiency of around 88 percent for a process chain with 25 process steps (see Table 121). For this reason, identifying critical quality parameters and their effects along the process chain is one of the main challenges of efficient process design.

Heterogenous production systems from different manufacturers also results in a wide range of different parameters and communication interfaces (RBW 13.2). Suitable standards and the associated algorithms must be implemented for communication between these systems, particularly against the backdrop of intelligent control and regulation based on artificial intelligence (AI), which is expected to increase in the future.

Similarly, standards must be defined for transferring the content from the individual assets (e.g. asset parameters, key performance indicators [KPI]).

For the successful implementation of electromobility, the impact on battery cell performance in the utilization phase as well as the production data must be taken into account in a lifecycle-oriented evaluation and analysis of the battery cells (RBW 13.3). This poses a variety of challenges in terms of suitable KPIs for monitoring, storing, and protecting the generated data.

The heterogeneity of the data generated over the battery cell lifecycle due to the multitude of battery cell types, manufacturers, OEMs, and application capabilities also requires non-competitive standardization for integrating different systems across domains and hierarchies.

Possible solutions

The digitalization of production and the use of Industry 4.0 approaches can make a valuable contribution to controlling the many interdependencies along the entire process chain and the resulting complexity (RBW 13.1), for example by providing transparency into - various interdependencies or identifying sensitive setting parameters.

Digitalization enables continuous recording of relevant process and quality parameters, which can later be used to support decisions, control, or regulation of the plants using Industry 4.0. The essential process and quality parameters should be identified in a pilot line before being implemented in series production. The aim of this pilot line is to monitor all measured variables so they can be selected and reduced to a necessary minimum during subsequent scaling to series production. Inline measurement methods should also be increasingly used to characterize the intermediate products to support the development of efficient production. The data can be stored on internal servers or in a cloud platform.

The actual value of these considerations lies not in the collection of the data itself and its continuous monitoring during series production, but in its evaluation and the associated knowledge gained. This approach of systematically processing large amounts of data is also known as data mining.

Typical approaches always include the individual areas of data classification, segmentation, forecasting, dependency, and deviation analysis. Specially developed methods can also be used to process and evaluate large data sets to identify the underlying process interconnections and their interdependencies. Measured data or mechanistic models can also be used to determine production tolerances, making it possible to reduce production costs or increase quality by avoiding costs associated with unnecessarily precise tolerances.

Manufacturer-independent standards are needed for system interfaces for linking sequential production plants, e.g., OPC UA (RBW 13.2). Plants can be linked together for automated control of successive process steps without human intervention. In the future, controls will be developed using artificial intelligence approaches (primarily machine learning) to reduce the influence of the environment and stochastically fluctuating product specifications as much as possible. Additionally, the experience of the plant operators can and should be incorporated into the development of the control algorithms.

Cyber-physical production systems can also be used to create a digital image of the actual production/product, which continuously records important production parameters and uses suitable models and simulations (e.g. artificial neural networks, process chain simulations) to assist in making production decisions.

The final quality control of the battery cells is the monitoring of cell performance in the utilization phase. Significant conclusions can be drawn about key quality production parameters by linking the data from the production and utilization phases (RBW 13.3). As in production, only parameters that enable a high level of information about the quality of the battery cell should be measured in the utilization phase. However, this requires a binding legal framework regarding access, ownership, usage of the data, and more. The entirety of the data generated over the life cycle can be bundled into a battery pass (see CEID Traction Batteries report).

Effort and benefit evaluation

Determination of the interrelationships within production (RBW 13.1) forms the basis for potential assessments that are relevant for process integration in future production lines as well as the required process adaptations and monitoring methods. Consideration of the identified process and disturbance parameters and their influence on the quality of the intermediate and end products makes it possible to limit process monitoring to essential measurement variables to reduce digitalization (measurement infrastructure, including maintenance and operation) and data storage (local servers, cloud) costs as much as possible. This type of demand-oriented system design can help to increase the return on a system investment.

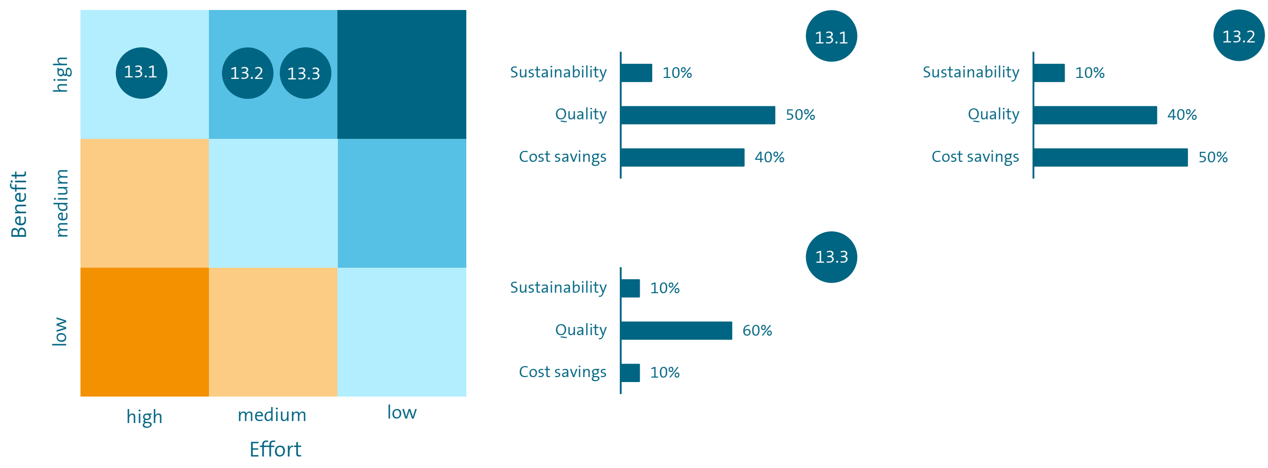
Similarly, in-depth knowledge of the interrelationships along the process chain can make a significant contribution to reducing the currently high reject rates. As a result, the benefits of a deep understanding of the process are offset by a relatively moderate additional cost for digitalization and analysis of large volumes of data.

Creating fully-automated production based on communication between systems (RBW 13.2) also offers a high benefit at a moderate cost to the battery manufacturer. Support from AI-based control systems can be expected to increase process stability, which will have a positive impact on battery cell quality and reduce production waste.

This has a positive effect on the sustainability of battery production. Intelligent control systems can also be used to identify reasonable tolerances for intermediate product characteristics in the individual processes with regard to final battery cell performance. The aim is to avoid unnecessarily high process accuracies, which increase investment and operating costs (e.g. for more precise systems) but do not have a decisively positive influence on battery performance.

Similarly, implementing fully automated process control and regulation requires moderate effort for the developing standards for machine-to-machine communication, supplying data to the AI system and, above all, the AI-based control algorithms.

Effort Benefit Diagram and Impact on Sustainability, Quality and Costs



13.1 Identification of cause-effect relationships

13.2 Communication and control/regulation heterogeneous production plants

13.3 Traceability over life cycle

Linking the data from the production and use phases provides significant added value (RBW 13.3). Product characteristics of battery cells or individual battery cell types which are particularly useful for different applications can be inferred from analysis of the collected data.

These findings can be integrated into the product design and the production process in order to increase the quality of the battery cell in the utilization phase. Adapting the batteries to the subsequent usage profile can enable, for example, suitable dimensioning or selection of a sufficiently high-performing battery cell to meet the applicable quality requirements, which also has a positive impact on sustainability.

The medium-term effort required for implementation is relevant for the development of uniform standards for establishing monitoring as well as the creation of comprehensive legislation regulating the ownership and handling of data generated during the utilization phase.

Professional support

Topic Sponsor:
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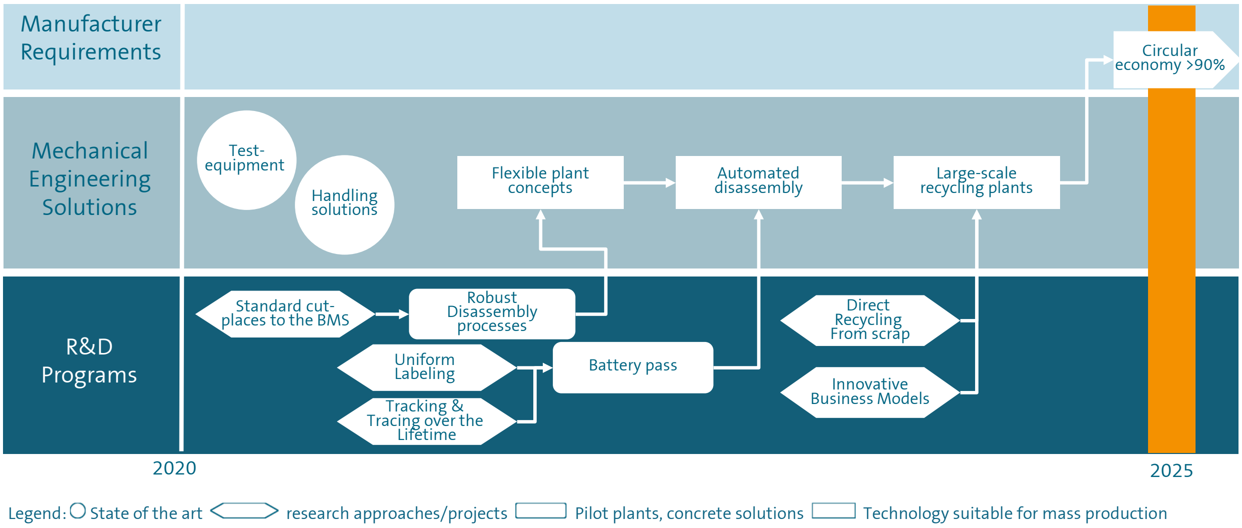
Circular economy

No. *	Red Brick Wall	Current status in Comparison to 2018	Relevance**	Timeline***
14.1	Automation of disassembly with large packing variety	Progress made	High	2025
14.2	Direct recycling of rejects in production	Progress made	Moderate	2022
14.3	Implementing re-manufacturability in the production process	Unchanged	Moderate to high	2022
14.4	Innovative business models to support 2nd life and recycling	Unchanged	Moderate	2025

RBW 14.1: Automation of disassembly with large packing variety:
Large-scale systems 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 percent for true closed-loop recycling to be possible. Due to the increasing quantities of returned battery systems, the flexibility and automation of battery system dismantling is gaining in importance. Remanufacturing of discarded battery systems and second life concepts support the goal of the circular economy.



*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

RBW 14: Circular economy

Basics

The recycling of battery materials is of crucial importance for the sustainability of the overall battery system, as the reuse of cell materials can reduce their environmental impact. A central prerequisite for this guiding principle is a high quality of secondary battery materials.

In order to secure the important raw materials of a battery cell, the goal is to establish a functioning recycling economy by 2025 in which more than 90 percent of the materials remain in the cycle, in contrast to current material recovery rates of between 50 and 80 percent. At the very least, the resource-critical and environmentally harmful materials should be recycled. The basic technical prerequisites for achieving this goal are already largely in place. Currently, pyrometallurgical recycling processes are predominantly used at the material or cell level. Mechanical and hydrometallurgical recycling processes are also being further developed [Ciez2019], [CEID2020].

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 pushed by the European Green Deal, among other things. In this context, EU Directive 2006/66/EC is being reviewed and updated which currently stipulates that at least 50 percent of battery waste must be recycled. It can be assumed that high recovery rates will be specified for resource-critical substances [CEID2020].

Challenges

A number of obstacles must be overcome to enable a true circular battery economy.

The focus is on the economic efficiency of the recycling process, which is dependent on the costs of the recycling process and the prices of secondary material output and spent battery input. This relationship also determines which secondary materials are recovered, and at what rate. For example, the rate of recovered cobalt in the pyrometallurgical process is already very high at over 95 percent due to the expensive material prices, but this is at the expense of other materials such as lithium.

Due to the large variety of battery cells, modules, and systems used, the disassembly process is currently performed by cost-intensive manual labor. Flexible automation solutions for battery disassembly must be implemented. The number of returned Li-Ion battery systems from electric vehicles alone is increasing and will exceed 1 million worldwide by 2028. The degree of dismantling required depends on the quality of the battery, usually specified as SoH (State of Health), as well as the dismantling process and the subsequent material-oriented recycling processes.

Furthermore, the variant diversity means that mixed fractions of active and inactive materials must be robustly processed in the recycling processes, which has a major impact on process reliability and product quality [Diekmann 2017]. This poses the challenge of finding a robust and adaptable process technology that enables recycling processes to react to different material fractions [CEID 2020].

In addition to the recycling strategy, the avoidance of rejects is a second central challenge that lies within the sphere of influence of battery manufacturers. In - production, this strategy refers to the direct recycling of rejects in the production process through intelligent process design as well as a battery design that reduces rejects.

Possible solutions

During dismantling, the battery modules and systems are first discharged so that the peripheral components can then be dismantled and reconditioned. Mechanical engineering already offers very good solutions for testing and discharging. Flexible handling and system technology is also being developed to automate these process steps. A uniform or even standardized BMS interface can support robust process control at this point. Important information about the usage profile and possible faults of the battery, but especially about the SoH, could be determined via the interface and used as information for the rest of the process to control the subsequent discharge process and be able to react to safety risks in the process. Safe, non-destructive, and cost-effective analysis methods must be established for this purpose [CEID 2020].

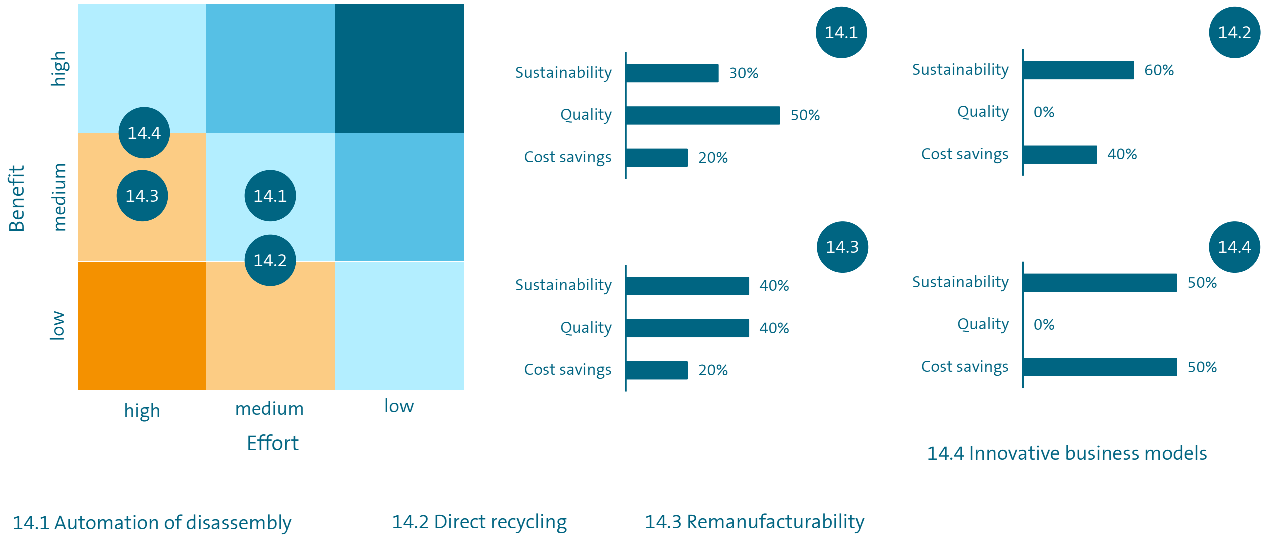
The automation process can also be supported by uniform labeling of battery systems. This solution approach is particularly effective in - combination with a transparent database that serves as a battery pass which supplements a labeling and BMS interface, and can "track" and "trace" the installed materials and connections as well as the states in the life cycle of the battery system. This can create flexible system concepts that can respond to the current battery system. However, business models for implementation must first be developed. Knowledge of the SoH for Second Life applications is valuable in determining the most appropriate secondary application.

Subsequent recycling of the lithium-ion cells aims to recover the valuable metals such as cobalt, nickel, and copper. In addition to the established pyrometallurgical processes, - mechanical and chemical process routes are increasingly being developed. In addition to recovering the individual substances with the necessary purity, approaches are also being pursued to recondition the active materials and reuse them in cells. The "Recycling/Green Battery" BMBF-competence cluster launched in 2020 is researching innovative recycling processes to increase the achievable recycling to more than 80 percent of the battery [Kwade 2018a].

Two possible solution approaches for the circular economy can be identified in battery production. The focus is on reducing rejects within production, as these have an enormous influence on the cost of a battery cell. Here, in-line quality measurements must be made possible at the right points in the processes in order to detect and reduce rejects at an early stage. Bad cells are often only detected after forming. Early defect detection and process feedback could make a valuable contribution to decreasing costs.

In addition to the reduction of rejects, solutions must be implemented for the reprocessing of rejects without loss of quality, which enables them to be fed back into the production process. Processes for this are largely available in the European industry portfolio, one example being mechanical separation processes.

Effort Benefit Diagram and Impact on Sustainability, Quality and Costs



Electrohydraulic comminution, which uses sound waves for material-selective comminution, is particularly suitable for cells with poor quality after the end-of-line test. In this case, functional materials (synthesized compounds) can be processed directly instead of being metallurgically separated into individual elements [NEW-BAT 2016].

"Design for recyclability" product design can significantly facilitate the dismantling and recycling process, and is therefore a key research topic. However, many design options associated with this are contrary to current developments, such as those relating to modularization, substitution of adhesives, or reduction of battery module voltage. At this point, cooperation between OEMs and machine and plant manufacturers is required to drive forward the development of a recycling concept and new 2nd-life business models

Effort and benefit assessment
The benefits resulting from RBWs depend heavily on the business models with which battery manufacturers operate. The benefits for all RBWs which are rated in the moderate range are therefore subject to a certain degree of uncertainty.

An economical recycling system is a prerequisite for the circular economy. Since promising technological approaches already exist, this potential can be realized at moderate to high cost.

A circular economy with a recycling rate of >90 percent of battery materials enables sustainable and responsible use of the raw materials that are irreplaceable for battery production. It also offers the potential to reduce the costs and environmental impact of the battery cell, and to become more independent in the supply of raw materials. The degree to which the recovery of electrolyte, binder, and carbon black is really useful is still under discussion[2].

This means that the implementation of the circular economy has a particular impact on ecological sustainability. Since recycling companies as well as battery manufacturers can benefit from the exploitation of this potential, it is still unclear at present what responsibility the circular economy will bear in the future. The decisive factor in this question will be the design of economic concepts and business models which are primarily determined by costs.

In addition to its influence on cost and sustainability, the automation of dismantling has a significant impact on the grade purity of - the input streams into the recycling process, and thus on the quality of the material from recycling.

Professional support

Topic Sponsor:
Rainer Forster, Head of Technology Competence Centre, Maschinenbau Kitz GmbH

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[2] There is currently an intense ongoing debate about the degree to which an overall recovery rate is really meaningful, and whether it would not be better to define a material-related recovery rate. For example, it is currently questionable whether the recovery of electrolyte, binder, and conductivity additives as a whole makes ecological and economic sense [CEID2020].

Project	Brief description	Research Institutes	Runtime	RBW
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	BatterySystem 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-size 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
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
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
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
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	Increasing 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
Fab4LiB	Research into measures to increase material and process efficiency in LIB production across the	PEM RWTH Aaachen, MEET Batterieforschungszentrum der Uni Münster	2018-2019	5, 6

Project	Brief description	Research Institutes	Runtime	RBW
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
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 the formation and end-of-line test 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
HEBEL	High energy battery with improved electrolyte separator composite (HEBEL)" 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
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
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
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

Project	Brief description	Research Institutes	Runtime	RBW
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
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
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
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
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

Project	Brief description	Research Institutes	Runtime	RBW
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	Digitalization 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
Sim2Pro	Multi-level simulation of product-process interactions	Technische Universität Carolo-Wilhelmina zu Braunschweig - Institut für Werkzeugmaschinen und Fertigungstechnik	2016-2019	13
Sim4Pro (ProZell 2)	Sim4Pro Digitaliization 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
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 are we headed?

Central developments in energy storage - technologies beyond Li-ion batteries have been considered since the first roadmap on battery production equipment [Maiser 2014], after the technology chapters. Since this updated roadmap also focuses on optimized Li-ion batteries, the main analysis of high-energy lithium-ion batteries here is followed by a brief - discussion of emerging or possible battery technologies of the future (see also [Thielmann-2017]).

Lithium-ion technologies

High energy lithium ion batteries

For the further technology development of high-energy LIB, there will be a successive change of the cell components. Based on the lithium-ion batteries already established on the market, the future use of high-energy active materials (e.g. Si/C composites) and ultimately Li-metal anodes might be possible using solid-state electrolytes. An evolutionary further development and the coexistence of lithium-based battery technologies is expected.

The current state of the art for cathode materials is NMC811, which is being used in the first electric vehicles, and 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 pack level. These and related materials are up against high-voltage cathodes, which could permit average cell voltages above 4 V. However, such cells require suitable electrolytes that are not currently available on a large industrial scale. In addition, the higher cell voltage would require a redesign of the BMS. On the other hand, 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 still considered as possible candidates for cost-efficient LIB.

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. Today, Si/graphite composites with 2 to maximum 5 percent silicon oxide are already being 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. As of today, these are not yet in the qualification stage. Depending on how the energy density of the cathode develops, the attractiveness of higher silicon contents will increase. For their utilization, there is a - particular need to develop suitable electrolytes and techniques that can curb 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 stem from the use of liquid, flammable or explosive electrolytes. Solid-state batteries do not use - liquid organic components, which reduces the safety risks. Hopes for solid-state electrolytes also lie in enabling Li-metal anodes, which would allow high energy densities at the cell level. Announcements by various players point to energy densities in excess 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 electrochemical reactions, are also linked to the properties of the currently used organic solvents and Li-salts. The use of solid-state electrolytes and thus the realization of solid state batteries can break through the before mentioned limitations.

Research is currently being conducted on several groups of solid-state 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 LIB. However, the power densities achieved by such batteries do not yet permit their use in electric vehicles without additional heating. In contrast, ceramic electrolyte systems are available, e.g. based on oxide, phosphate or sulfide materials.

In some cases, high energy and power densities have already been achieved with these materials. However, often the materials with the best kinetic properties have the worst 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 classic particle coating process for the anode. This could be replaced either by the production of functionalized metal foils (initial Li-free anode) or by the thin Li-coating of carrier foils in electrochemical or sputtering processes (initial Li-coated anode). Adjustments may also be necessary on the cathode side, especially if ceramic electrolytes are used. 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 area of cell assembly, the fracture behavior of the ceramic layers could require a transition from winding to stacking electrodes. The classical electrolyte filling is no longer necessary.

So far, there is no clear picture in terms of costs compared with conventional LIBs. At the material level, research is being conducted into compounds whose high metal prices make commercial use unlikely.

However, solid-state electrolytes are also being tested, which 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. Solid-state batteries with initial Li-free anodes in particular 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 startups as well as established companies and OEMs around the world are working on the development of solid-state batteries. In addition to developing the technology, the challenge lies in setting up supply structures from the material to the production plant. Despite the high level of interest from the industry, solid-state systems in xEV applications are not likely to become established until after 2030 and will then diffuse into the market. Before then, niche applications are conceivable.

Beyond lithium-ion technology

Alternative battery technologies with higher energy density?

The performance parameters (usually gravimetric and volumetric energy density and cycle stability) of alternative batteries show that, even for technologies with theoretically high achievable energy densities, the energy throughput (the product of energy density and achievable number of cycles) is not better than that of LIB or the future optimized high-energy Li-based or Li-solid-state batteries.

Measured against the current requirements of electric mobility applications, most alternative - battery technologies must be classified as unsuitable at their current stage of development.

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, for example, could be used in flight applications.

Batteries with conversion materials

Conversion materials (e.g. metal oxide anodes or fluoride cathodes) is used as an umbrella term for many different materials with very high specific capacities, often unsuitable for potential use as anode/cathode in Li-based batteries. Theoretically, material combinations with high energy densities are conceivable. Current research topics concern the material de sign and the nanoscaling of the materials. Challenges are posed by volume changes in the particles, which lead to a low lifetime and cycle stability. In terms of production technology, no processes have yet been established, and other components require adaptation (electrolyte, cell design).

Sodium-ion batteries

Sodium is present in the earth's crust at 2.6 percent and Na_2CO_3 costs less than one-tenth of Li_2CO_3 (Li carbonate). Sodium ion batteries (SIB) would provide a cost-effective alternative to LIB. The patent landscape is less densely populated. This could facilitate entry into material and battery production. Similar host materials exist for SIBs as for LIBs (layer oxides, phosphates). However, graphite cannot be used as the anode in SIBS because of the ion size of sodium. Hard - carbons must be used. However, at 250-300 mAh/g, these have a lower gravimetric capacity than graphite. The choice of material for the anode is therefore a challenge. In comparison with LIB, parallel development is seen, which takes place with a time lag and is associated with reductions in the performance parameters of 20 to 30 percent in each case. 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 very interesting 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 reduction 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 poly-sulfides in many organic solvents, which serve as the basis for electrolytes. This leads to decomposition of the cathode during 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.

Me air/O2 batteries

Metal-air/oxygen batteries are the subject of basic research. The prevailing opinion is that rapid commercialization will not be possible. Various steps in 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 in terms of increasing the lifetime 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 in price and energy density are to be expected. The advantage of PbC batteries is, on the one hand, the increase in power density compared to lead-acid batteries. On the other hand, the electrode structure allows them to be used and stored in a partially charged state. This is essential for buffer applications (e.g. solar or domestic storage). Compared with LIBs, a price advantage can also be expected in the long term. There is very good compatibility with existing lead-acid-based applications (drop-in). The design of the negative electrode and the manufacturing technology are the main challenges.

Organic batteries

Organic batteries, or organic cathode materials, are an example of another storage technology No transition metals are needed for their realization 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 cycle stability is not given. Overall, the lack of suitable electrolytes is very often a barrier to the utilization of alternative battery technologies and materials. The challenges are manifold and concern, for example, chemical/electrochemical stability, corrosivity and solvent properties.

Conclusions and recommended actions

Conclusions

This update confirms the trend of previous versions. Market penetration of electromobility continues to grow, bringing with it rising demand for lithium-ion batteries (LIB). Global demand for LIB cells was estimated at 200 GWh for 2019.

The rapid expansion of cell production capacity, especially in China, underscores the dynamic worldwide situation in impressive fashion. Should electromobility develop in line with optimistic estimates, the terawatt/hour (TWh) boundary for LIB cell demand for electric vehicles overall could be broken as early as 2023 to 2024. While globally relevant cell manufacturers still come almost exclusively from Asia, production facilities are increasingly being placed where demand arises. Europe in particular benefits as the location of the headquarters of the largest vehicle OEMs. With Northvolt as a pioneer, European cell manufacturers have also taken up the challenge of establishing themselves as suppliers in the automotive market.

As a result, there is great business potential for the globally active European mechanical and plant engineering industry in the dynamic markets of electromobility and LIB production. The innovative strength of the mechanical and plant engineering sector can contribute to enabling the transition to alternative technologies such as electromobility. This has already been impressively demonstrated in related industries.

Roadmapping process

Differences in requirements on the user side, the varying stages of development of the technologies for electrical energy storage, and the wide variety of process technologies involved demand clearly defined procedure parameters for generating roadmaps. These parameters were formulated back in 2014 and maintained for this 2020 update.

We have taken the roadmapping process widely used in the semiconductor industry and applied this to battery production. The requirements of battery manufacturers define immovable target corridors for which mechanical engineering companies will attempt to develop and offer solutions. In cases where, from the present point of view, these do not exist, this method will cause technological barriers, the so-called “Red Brick Walls,” to emerge. These can be used to derive very specific requirements for research and development during the study period.

Focus LIB technology

The most promising battery technology from today’s point of view remains LIB technology. The roadmap centers around large-scale cells for high-energy applications, although high-power cells for 48 V batteries will also increasingly become a focus. Production research requires technologies which are ready for series production. Optimized LIBs up to generation 3 will, from the present-day point of view, represent the central technology for the next 10 to 20 years. It is for the production of these optimized LIB cells that global capacity will be built up in the coming decade. Production technology here is upwards compatible in the area of LIB generations 1 to 3.

Focus on production engineering

In the roadmap, the focus is on production technology based on a fundamental revision of the technological state of the art and a study of the complete process chain, from material preparation to pack assembly. It is important to assess all production solutions with regard to their relevance for large-series production.

Period under review through 2030

As in the previous versions, the period under consideration is set to 2030. Due to the high market dynamics, process solutions will primarily become relevant in the next few years. Therefore, a breakthrough should be aimed for as early as 2022 for many of the formulated RBWs, and for almost all of them by 2025. Very few address solving the challenges for the following years. Looking beyond 2030 would be speculative or could at best done in scenarios.

Involvement of key players

The results of the present roadmap are based on discussions held in the workshops and the evaluation of questionnaires and expert interviews. As with the last updates of the roadmap, VDMA Battery Production member companies have contributed to the technology chapters.

The member companies have become even more involved in the process through mentorships and technical support for each technology chapter. The roadmap is publicly accessible and attracts worldwide attention. Many of the ideas and suggestions received can be taken up and implemented. We have intensified targeted dialog between battery producers, production research, and the mechanical and plant engineering industry, also drawing on experience gained with international experts.

Starting point for mechanical and plant engineering

Intelligent production technologies are a key tool that can help achieve the urgently necessary reduction of the costs of batteries for electromobility and stationary energy storage. The German mechanical engineering industry stands out here with its strong specialization and contributes its experience with other industries and with digitalization (Industry 4.0). Asian players continue to profit from the exchange of information gained in many years of supplying equipment for factories for consumer batteries. The requirements for the production of large-sized batteries for use in electromobility or in the field of stationary applications are, however, also high for them. The obstacles described in the roadmap apply to all market participants.

Recommended actions

Targeting research needs

All actors along the value chain of battery production as well as potential private and public investors must be made aware of the identified need for targeted and sustainable research. Close cooperation between industry - partners and research institutes is essential. - BMBF funding measures such as Battery 2020 or the ProZell cluster already address important topics [ProZell2016]. Other measures, such as the InZePro cluster, intend to move more strongly toward implementation. Economic stimulus package 35c also offers the opportunity to realize research with a strong industrial focus and broad applicability in the field of battery production resources. Projects that go beyond pilot plants can help industry realize new approaches in volume production and minimize investment risk. They should also continue to be supported by funding policy. Clear emphasis is also being set by the EU: in addition to the IPCEI alliances with the aim of setting up gigafactories in Europe, there are further activities within ETIP Batteries Europe and the European Battery Partnership.

Joint industrial research enables smaller companies in the mechanical engineering sector in particular to build up basic knowledge in the pre-competitive area, thus creating the conditions for new ideas. The successful X-MOTIVE network in the VDMA is an ideal platform for this.

Production research creates the basis for establishing competitive cell production; and is the key to process innovation and the development of unique selling points. References and unique selling propositions - create the conditions for European battery mechanical engineering to position itself in this future field sustainably and in the long term, and also to become more attractive as a worldwide solution partner.

Concrete research needs to improve production technology for machinery and plant engineering arise from the following contexts, in particular:

Creating **learning effects:** Planning the factory capacities of the future requires careful study of many aspects, including the requirements regarding 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 at the same time master the interplay between supply, demand, capacity utilization, cost and price development etc. in terms of planning. Optimized production technologies should therefore be used to generate learning effects quickly.

Scale-up of processes: As cell factories grow in size, this is a keyway to reduce costs. It is an alternative to numbering up, in which the number of lines is simply increased. To achieve this, however, the process technology must be appropriately optimized. Process stability and quality must be ensured even with a high throughput and the understanding of processes must be continuously expanded

Alternative system topologies: The primary aim of alternative system topologies at module-pack level is to maximize the battery pack fill level and thus to increase the energy content. This is principally possible through reducing the proportion of housing components, function integration, and standardized modular systems.

Avoiding **overengineering:** Building up process expertise in a targeted way can allow interrelationships to be tapped. This requires comprehensive process monitoring and collection and analysis of an extensive set of data. This approach of systematic processing of large quantities of data is also known as data mining. Each step in production has individual process parameters.

In order to define useful tolerance limits, it is important to understand the extent to which the respective process influences the quality of the intermediates and the final battery cells. The most sensible solution from both a technical and an economic point of view must be reached.

Early involvement of mechanical engineering

For new materials and processes, manufacturability and readiness for series production are crucial for success: mechanical and plant engineering must be involved in the development of new products at an early stage, above all in new technologies and cell design decisions.

As things stand today, optimized LIBs will be the central technology for at least the next 10 years. Despite this, it is important for the mechanical and plant engineering sector to already start to deal with the process issues and challenges in the production of advanced LIBs and generally advanced battery technologies.

Strengthen international competitiveness

Delivering competitive solutions internationally demands references and USPs, which requires research into production. The innovative strength and efficiency in total cost of ownership studies and sustainability of European machinery and plants is impressive. In order to offer cost-effective services, understanding of the cost of individual process steps and the product life cycle as a whole must be improved.

In international cell production competition 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 situation also demonstrates the importance of local suppliers and acts as an accelerator for European cell production and supply chains..

Creating access to large-scale production

Direct participation in large projects is the only way for manufacturers of production equipment to gain experience in volume production. It is particularly important to work directly with manufacturers. The expansion of global cell factories in the next 10 years will be carried out almost exclusively by Asian players from Japan, South Korea, and China. Production locations will, however, be shifted to all world regions (Asia, America, and Europe). Export business enables the mechanical and plant engineering industry to gain an insight into production operations overseas and thus to recognize important technological requirements and develop appropriate solutions. As the market grows, a strong and sustainable bond between the small number of Asian cell manufacturers and the German mechanical and plant engineering industry will become ever more important and make the difference between success and failure.

Innovation and new approaches

In rapidly growing markets, the focus is on meeting demand. This means that there is a risk that there will not be time to pursue innovation and new approaches. It is precisely now that it is important to recognize opportunities and develop corresponding strategies. It is not just a matter of optimizing existing processes, but of "thinking outside the box!"

Sustainable battery production

Batteries play a key role in reducing the negative environmental impacts of alternative mobility technologies and the energy transition. Li-ion batteries represent the core technologies for **decarbonization.** Only with appropriate storage options can renewable energies such as solar and wind power be used when the need arises.

The primary aim of electromobility is to reduce the **CO_2 footprint**. The production of battery cells, including the necessary raw materials, is responsible for the majority of these environmental impacts. Therefore, increasing the material and energy efficiency of production is essential. R**ecycling processes and technologies must also be** developed. Recycling offers opportunities to generate sole source materials. Production solutions that contribute to re-x capability will gain in importance as a competitive advantage, as will the resynthesis and reconditioning of battery materials integrated into cell factories.

Stimulate courage and risk taking

Production research is the key to innovations, which are absolutely necessary to succeed in battery machine manufacturing. At the same time, it requires a certain willingness to take risks to implement new approaches in series production, or to establish oneself on the market as a provider of turnkey solutions or as a general contractor. This is increasingly demanded by customers.

Instruments that minimize investment risks are important for this. This requires establishing the following framework conditions:

- Introduction of tax support for research
- General degressive depreciation to allow amortization of significant depreciation in plant value due to economic and technical developments in the first few years
- Pre-competitive, broad-based industrial joint research
- Collaborative research with transfer services to promote a broad culture of innovation
- Cooperation along the entire value chain in funded projects, as is already partly implemented in so-called "Important Projects of Common European - Interests"(IPCEI)

Perpetuate the roadmapping process

Roadmapping is a dynamic and iterative process. VDMA Battery Production has stabilized the dialog with this new edition and will continue to actively drive forward the implementation of the roadmapping process begun with the first roadmap in 2014.

List of abbreviations

Abbreviation	Meaning
3C	Consumer, Computer, Communication or Portable Devices
Al	Aluminum
ASP	Average Sales Price
BEV	Battery electric vehicle
BMBF	Federal Ministry of Education and Research
BMS	Battery management system
COP	Penetration coefficient
C-Rate	Charge (or discharge) current of a battery in relation to its capacity.
Cu foil	Copper foil
DCM	Dichloromethane
EIS	Electrochemical impedance spectroscopy
EOL test	End of line test
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
IGF	Industrial collaborative research
IPCEI	Important Project of Common European Interest
IR dryer	Infrared dryer
KPI	Key Performance Indicators
LCO	Lithium Cobalt Oxide
LCOE	Levelized Cost of Electricity
LFP	Lithium iron phosphate
Li	Lithium
LiB	Lithium-ion battery
Li-S	Lithium sulfur
LiTFSI	Lithium bis(trifluoromethanesulfonyl)imide
Me	Metal
Me-S	Metal Sulfur
Na-IB	Sodium-ion batteries
NCA	Lithium nickel cobalt aluminum oxide
NDA	Non-disclosure agreement
Ni content	Nickel content
NMC	Lithium nickel manganese cobalt oxide
NMP	N-methyl-2-pyrrolidone solvent
NPE	National Platform for Electromobility
OEM	Original Equipment Manufacturer
OPC UA	Open Platform Communications Unified Architecture
Pb batteries	Lead-acid batteries
PbC	Lead Carbon
PE	Polyethylene

PET Flow Fabric	Polyethylene terephthalate-
PHEV	Plug-in hybrids
PP	Polypropylene
PV	Photovoltaics
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
SEE	Solid Electrolyte Interface
SG&A	Selling, general and administrative expenses
Si/C composites	Silicon/carbon composites
SoH	State of Health, quality of the battery
SPC	Solid state permeability
V2G, G2V	Vehicle to Grid, Grid to Vehicle
VCSEl laser	Vertical-cavity surface-emitting laser
WEZ	Heat-affected zone
xEV	BEV, PHEV and HEV

Appendix

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VDMA Battery Production is your contact for all questions to machine and plant engineering relating to battery production. The member companies of the department supply machines, systems, 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 battery system production. The current focus of VDMA Battery Production is on Li-Ion technology.

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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 group Battery Production of Professor Kampker's chair deals with the manufacturing processes of the lithium-ion cell as well as with the assembly processes of the battery module and pack. The focus is on integrated product and process development approaches to optimize cost and quality drivers in manufacturing and assembly processes. Through a large number of national and international industrial projects as well as central positions in well-known research projects, the PEM of RWTH Aachen offers extensive expertise in the fields of battery cells and battery modules and packs.

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