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Development perspectives for lithium-ion battery cell formats

Index of Abbreviations

3C	consumer, computing and communication
µm	Micrometer
A	Ampere
a	Year
AAM	Anode active material
Ah	Ampere-hour
Al	Aluminum
ASSB	All-solid-state battery
BEV	Battery electric vehicle
BMS	Battery management system
C / C-rate	Current relative to nominal cell capacity
CAGR	Compund annual growth rate
CAM	Cathode active material
CC	Constant current
cEV	Commercial electric vehicle
CharIn	Charging Interface Initiative
CID	Current interrupt device
cm	Centimeter
Co	Cobalt
CO_2	Carbon-dioxide
Cu	Copper
CV	Constant voltage
DIN	German Institute for Standardization
DoD	Depth of discharge
ESS	Energy storage system
EU	European Union
EUCAR	European Council for Automotive R&D
EV	Electric vehicle
Fe	Iron
FMEA	Failure mode and effects analysis
g	Gram
GHG	Greenhouse gas
GWh	Giga-Watt-hour
HEV	Hybrid electric vehicle
HL	Hazard Level
ISO	International Organization for Standardization
kg	Kilogram
km	Kilometer
KPI	Key performance indicator
kW	Kilo-Watt
kWh	Kilo-Watt-hour
L	Liter
LFP	Lithium-iron-phosphate
Li	Lithium
LIB	Lithium-ion battery
LLO	Lithium-rich layered oxide
LMFP	Lithium-mangenese-iron-phosphate
LMR-NMC	Lithium- and manganese-rich NMC
LTO	Lithium-titanate
m^2	Squaremeter
mAh	Milliampere-hour

MCS	Mega-Watt Charging System
Mg	Magnesium
min	Minute
mm	Millimeter
Mn	Manganese
MWh	Mega-Watt-hour
NCA	Lithium-nickel-cobalt-aluminum-oxide
NECP	National Energy and Climate Plan
Ni	Nickel
NiCd	Nickel-cadmium battery
NLL	Nationale Leitstelle Ladeinfrastruktur
NMC	Lithium-nickel-manganese-cobalt-oxide
NMCA	Lithium-nickel-manganese-cobalt-aluminum-oxide
O	Oxygen
OEM	Original equipment manufacturer
P	Phosphorous
PBCM	Process based cost modelling
pEV	Passenger electric vehicle
PHEV	Plug-in hybrid electric vehicle
PTC	Positive thermal coefficient
R&D	Research and development
RoW	Rest of world
RSS	Residential Storage System
s	Second
SE	Solid electrolyte
SEI	Solid electrolyte interface
Si	Silicon
SiMP	Silicon micro-particles
SiNP	Silicon nano-particles
SiO	Silicon-oxide
SoA	State of the art
SoC	State of charge
SSB	Solid-state battery
t	Ton
TR	Thermal runaway
TRL	Technology readiness level
TWh	Tera-Watt-hour
US	United States of America
V	Volt
VDA	German Association of the Automotive Industry
vs.	Versus
VTOL	Vertical take-off and landing device
wt%	Weight percent
xEV	BEV or PHEV or HEV

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Contents

Executive summary

The world is hungry for more clean and renewable energy and battery technology is declared as the crucial element for the cross-industry energy transition to reduce and eventually eliminate greenhouse gas emissions and mitigate anthropogenic climate change.

The increasing electrification of cross-industry applications, from portable electronics to electric vehicles and drones, results in multi-facet and application-specific requirements on battery cells in terms of energy and power needs, packaging space constraints, safety, and other aspects. These battery characteristics primarily follow from the cell to pack level battery design.

As one central result, the market has witnessed a wide variety of manufacturer- and user-specific cell formats in the past. Standard formats for cylindrical cells were established early on, partly because corresponding cell formats were already used in non-lithium battery technologies. However, standards for prismatic formats such as pouch-type and hard-case cells were defined later, especially for electric vehicle batteries. Concurrently, these automotive standards have turned into the go-to format for cross-industry applications beyond electric mobility.

Today, a situation emerges where all three basic cell formats occur in almost all applications. For example, battery cells for electric vehicles vary in format and exact dimension, although usage patterns and general requirements of most electric cars might be very similar. Indeed, the technical fit alone is usually not the primary issue, but about OEMs' strategic and long-term cooperating decisions for suppliers. However, such decisions can naturally only embrace currently available and, at best, expected cell offerings at the closing date. Even beyond mobility applications, non-technical factors such as availability, reliability, or manufacturer compatibility are usually decisive for format selection.

While the automotive industry has launched its hunt for worldwide gigafactories, other industries are likely to follow in the upcoming years while new format decisions are being made simultaneously. In light of the rapidly growing demand in the automotive industry, the available and announced production capacity of individual OEMs exceeds the capacity of any single gigafactory. Thus, OEMs have started to design new factories for customer-specific and partly even vehicle model-specific cell formats. Accordingly, diversification among OEMs continues to advance, accompanied by a further shift from once-defined standard cell formats. Concurrently, OEMs have started defining their platform standards for all subsidiaries in their groups. These new OEM-specific standard cells will be manufactured in-house at dedicated production facilities or in partnership with established suppliers. Battery markets beyond electric vehicles, such as residential or industry energy storages, also show high growth, which is likely to justify soon the economic build-up of GWh-scale production lines for specially designed cells. Thus, an increase in the range of available LIB cells can also be expected for special applications in the coming years.

The whole battery cell design process ranges from material selection, electrode design, and internal cell design to external cell dimensions, including electrical and mechanical contacts and other interfaces to the battery module or pack. This study sheds light on these numerous design criteria. Starting from the status quo, it identifies the most important trends for the next few years and relates them to production process requirements.

Material-wise, new chemistries will be introduced on both the cathode and anode sides, allowing further increases in cell performance or further reductions in cell costs. For cathodes, Nickel-based (Ni) and possibly Cobalt-free (Co) high-capacity oxide materials are firmly anchored on manufacturers' roadmaps. Concurrently, Iron- (Fe) and Manganese-based (Mn) materials are likely to become more widespread, enabling significant cost advantages over the Ni-based systems mentioned above. While Ni-rich cathodes appear set for premium and high-energy applications, Fe-rich systems are likely to dominate the high-power and low-cost market. Complementing, Mn-rich systems are likely to bridge the gap in the volume market. For anodes, Si-based materials are firmly anchored on manufacturers' roadmaps and represent an entirely new class of materials alongside the established graphites and graphite-silicon composites. Furthermore, advances in material design are likely to complement further changes at the electrode level. In particular, this relates to reducing current collector and separator thicknesses for high-energy cells and increasing electrode thicknesses to well above 100 μm (single-sided) in the next 5 to 10 years.

In parallel to new materials and electrode design, new assembly techniques will enable more volume-efficient interior cell structures to increase energy density further. This affects mainly prismatic cells. Manufacturers' roadmaps emphasize stacking techniques up to single sheet stacking. Particularly in large-format cells, this will also impact thermal and electrical interconnection, e.g., through tabless designs or, in general, the integral use of the cell housing for heat dissipation.

Manufacturers' roadmaps, mainly for automotive applications, emphasize the trend towards larger cell formats and, thus, more energy per individual cell. Exemplary, this may involve pouch-type cells of up to 500 mm in length and prismatic cells up to 1000 mm. In contrast, smaller formats with universal compatibility, e.g., prismatic cells with about 300 mm, are likely to remain available as the market might diversify into low-volume versus mass market, low-price versus premium, or standard versus high-priced specialized cells.

Enabled by these technical improvements from material and cell level, peak energy densities of up to 850 Wh/L may become possible by 2025 and up to 950 Wh/L by 2030 using conventional liquid electrolyte-based technologies. Although there will be a further convergence of energy densities of the three principal cell formats, pouch-type cells can be expected to remain at the forefront. This increase in energy density also raises the hazard potential, particularly in large cell formats. However, the distinction between pouch-type, prismatic hard-case, and cylindrical formats plays just a minor role in system safety. Cell chemistry, cell structure (e.g., electrode packaging, gas channels), battery pack integration, and particular hardware- of software-wise safety features are decisive.

While evaluating cell properties at the cell level is standard today, evaluating at the battery pack or even application level will become one key differentiator. In particular, the new allocation of safety and stability functions between cell and pack in so-called cell-to-pack concepts will lead to a re-evaluation of the cell energy density factor, which is still decisive today.

Regarding cell costs, the high share of material costs of 60 to 80% and the corresponding dependence on raw material prices render a forecast difficult. However, several potential technologies will make cell manufacturing more energy, resource, and cost-efficient, e.g., new coating processes, dry coating, and formation methods. If the high growth of battery raw material demand will not incorporate excessively increasing prices, further cost reductions at the cell level can be expected due to the improvements in supply chain management, logistics, and, most notably, manufacturing.

Key learnings for future R&D

While cell manufacturers and their customers have already announced the industrial diffusion of certain materials to cell format innovations, some R&D challenges remain to full-scale usability.

Material-wise, these challenges mainly focus on (electro)chemical stability, processability, and long-term stability of high capacities. In parallel, new approaches are required to enhance sustainability and reduce the greenhouse gas footprint of these active materials downstream from raw material extraction to production. The promising properties of new materials need to be transferred to the electrode and cell level.

- Develop special binder and additive systems for Si-based anodes and thick electrode layers to achieve long-term mechanical stability and high-current capability.
- Develop suitable drying and (micro-)structuring processes for thick electrodes.
- Increase volume utilization in cells and reduce share of passive components.
- Develop cell designs with improved safety architecture.
- Optimize temperature and current density distribution by new contacting methods, e.g., in "tabless" design.

Overall, there is a high demand for optimizing existing and developing new manufacturing processes to implement new material and cell designs while reducing manufacturing costs and the environmental footprint. Plus, larger cell designs require even higher standards for quality and precision in all production steps.

- Produce defect-free electrode production and improve in-line measurement technology
- Reduce solvent content and, thus, reduce drying effort
- Develop highly accurate and automated stacking techniques with the latest positioning and gripper systems
- Accelerate electrolyte filling for large-format cells
- Develop new safety concepts for the formation of large cells

The pack-level integration of battery cells will become more decisive than any cell-level evaluation, since the total pack heavily affects overall system cost and system performance.

- Develop structural batteries with direct pack integration capability and cell-to-X concepts.
- Enable high cell integrity and homogeneous pressure distribution in the battery pack.
- Develop appropriate safety and cooling concepts at module and pack level.

1. Introduction

Without any doubt, there is a large demand for more clean and renewable energy and necessitates electrochemical energy storage systems such as lithium-ion batteries (LIBs) for highly efficient energy conversion and storage. While LIB research dates back to the 1970s, its functional characteristic was elaborated in 1985, and LIBs were first commercialized for consumer electronics in 1991 [1,2].

Since then, battery performance has risen dramatically. While some progress occurred serendipitously, the vast majority happened thanks to the extensive global effort, ingenuity, and innovation [3]. Today, LIBs are already ubiquitous in daily life and almost indispensable. Over the next decade, several governments, including Germany, research institutions, and industries worldwide, declared battery technology as the crucial element for the cross-industry energy transition to reduce and eventually eliminate greenhouse gas emissions and mitigate anthropogenic climate change. While this may involve direct and upstream consumption of fossil fuels and embedded severe environmental pollution first, this ultimately involves nature reserves and increasing resource depletion down the line, too [3]. Given this, LIB research will become increasingly important. Forecasts illustrate and quantify the enormous potential, as visualized in Figure 1; however, these also indicate considerable margins and uncertainty about future demand. Typically, consumer electronics dominated in the early years. While the total LIB demand equaled around 420 GWh in 2021, more than one-half is allocated to the automotive sector. For 2030, projections vary from 2 to 4 TWh [4,5,6,7], corresponding to an annual growth rate (CAGR) of 50% in the coming years and 20% around 2030. Automotive applications are going to account for around 80%. Automotive, stationary storage and industrial applications are future lead markets.

In light of this global growth, battery development is a multi-facet and dynamic industry that necessitates mineral acquisition, complex supply chains, fundamental and applied research & development, and pilot-scale testing to large-scale mass production and quality management. Mastering all these vertically integrated aspects within the battery business is a demanding task. Naturally, battery format and design decisions embed a long-term strategic commitment. Exacerbating this complexity, cross-industry diffusion and increasingly diverse applications, including electric cars, buses, trucks, power tools, smartwatches, medical devices, satellites, or home to industrial energy storage systems, lead to highly optimized LIBs. This involves an increasing divergence of battery designs, chemistries, and sizes to best suit each specific application and its inherent requirements. One natural solution to this dilemma is to admit that no battery technology can be perfect. There are always technical, economic, or ecological trade-offs.

Figure 1: Global LIB demand 2010 to 2030
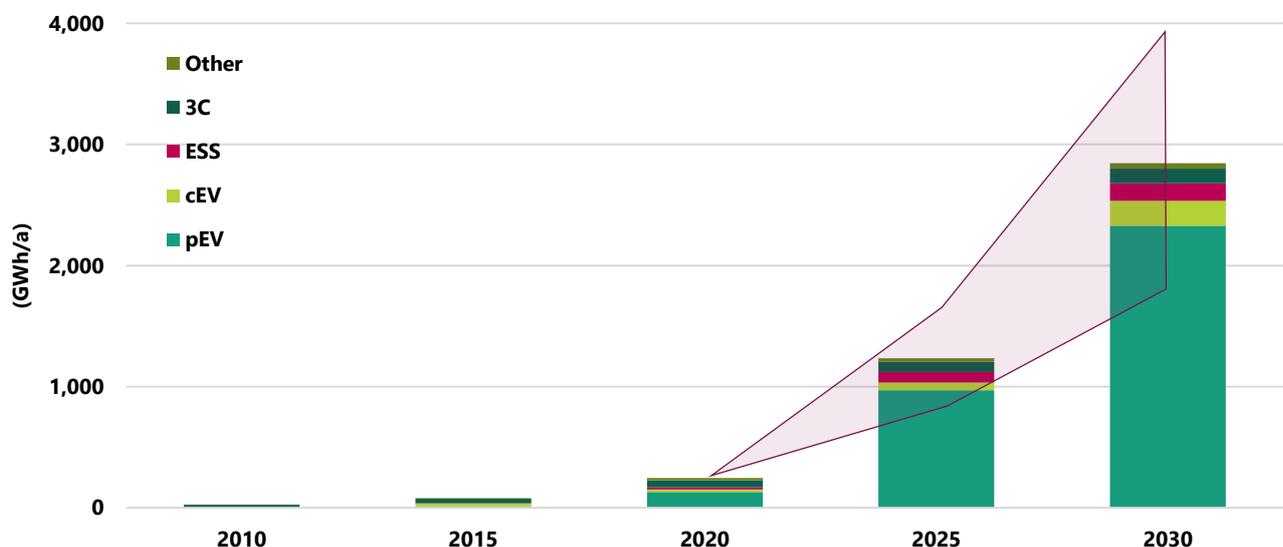
However, any battery technology - from current lithium-ion-based to next-generation battery systems - can be optimized for just a few applications and their specifications step-by-step and by focusing efforts. Hence, it is crucial to understand which products and industries require which energy storage solutions, which overlaps and synergies stand out, which similar requirements arise, which trade-offs must be balanced, and how battery systems can be designed for each of these.

This study aims to evaluate prospects for LIBs regarding technological trends and market requirements.
For this, technological aspects of LIB are discussed from the material to the manufacturing level and matched with application requirements.

- Section 2 starts with methodology, assumptions and premises.
- Section 3 introduces several applications, from mobile to stationary and consumer, and their associated technical requirements.
- Section 4.1 analyses currently available cell formats and production capacities.
- Section 4.2 discusses the complete cell design from material selection, electrode specification to cell formats and presents a forecast for high-energy type LIB.
- Production-related aspects are discussed in Section 4.3. In addition, a short overview of next-generation production technologies is given.
- Section 4.4 translates the technological cell parameters into economic and cost aspects.
- Section 4.5 discusses cell safety.
- Section 4.6 closes with sheding light on solid-state batteries as excursus.
- We close with Section 5 by matching the technological perspective of battery cells and formats to application requirements.

The overview of recent trends in battery cell design, formats, and applications provided in this study can be used as robust guidance and support for suppliers, manufacturers, integrators, end-users, politics, and science.

2. Methodological approach

1. Assumptions and premises

This study reflects certain simplifications and highlights specific trends, cells, and topics according to their timeliness, novelty, and anticipated near-term market relevance. All evaluations are limited to secondary, i.e., rechargeable batteries, and primary batteries are neglected. The following additional premises are defined for cell formats and chemistry:

Cell formats: We only analyze standard LIB formats, i.e., cylindrical and prismatic-shaped cells such as hard-case or pouch bags. Non-common formats (e.g., L-shaped cells) are not considered.

Cell chemistry: We consider current cell chemistries for both cathode and anode. In 2022, this involves NMC, NCA, and LFP for cathodes and graphite-based anodes, partially doped with silicon. Future cell chemistries are assumed based on cell manufacturer announcements and roadmaps up to 2030.

2. Cell monitoring

Our cell format and technology monitoring involve meta-analyses, cell data evaluation, and expert interviews to analyze the status-quo and prospects.
Meta-analyses comprise a literature review (studies, reports, and peer-reviewed papers), publicly available and purchased market studies, and public announcements from major manufacturers or suppliers.
For cell data evaluation, we use datasheet information of commercially available cells that are identified by either the Shmuel de Leon database (n = 13,364 cells) or desk research (n = 156) to detect more recent cells. We filter the database for active and relevant cells that comprises 7,703 pouch cells (58%), 3,304 prismatic cells (25%), and 761 cylindrical cells (6%). Further desk research partially supplements the SDL database with another 156 more recent cells, each with over 3.5 Ah as our chosen threshold capacity. This comprises another 28 cylindrical (18%), 66 pouch bags (42%), and 62 prismatic hard-case cells (40%). Please note that our total sample (n = 11,923) represents a fraction of the total LIB market.

Guided expert interviews (n = 17) validate our findings, confirm or falsify trends, evaluate the feasibility, and finally synthesize key findings. Interview partners include representatives from fundamental research (universities), applied research (Fraunhofer Society), machinery and equipment manufacturers, cell manufacturers, cell integrators, and end customers. The questionnaire comprises common topics (e.g., cell KPI, materials, cell dimensions) and specific questions for each audience.

3. KPI for highlighted LIB cells

The cell-level KPI for highlighted LIB, particularly cell voltage, capacity, and energy density, are estimated based on a self-developed cell design tool that allows for adaptations from the material (active, passive) to the electrode (porosity, thickness, coating area) and to cell assembly parameters (stack/coil assembly, format, housing, contacts, sealing). Potential parameters of future cell concepts are based on expert assumptions or technical parameters published in the literature (e.g., roadmaps of material suppliers and cell manufacturers).

4. Applications and Requirements

We use two different perspectives to evaluate the overall fit of cell formats and geometries for individual applications. This process first comprises technical characteristics and then adds application-specific requirements and battery cell integration. Finally, we combine those technical characteristics with the application requirements.
Technology Push: Our technology perspective summarizes previous findings [8] of general technological properties attributed to generic cylindrical, pouch, and prismatic cells. We validate our findings with further literature information and the expert interviews mentioned above. This evaluation focuses on cell-level perspective rather than pack- or battery-level, and we omit geometry-or chemistry-related differences and any optimized cell designs. In total, we identify six universal properties on the battery technology level that are crucial for any application, namely (1) cost, (2) safety, (3) energy density, (4) flexibility, (5) thermal management, and (6) resilience. These are briefly illustrated below.

(1) Cost-wise, we use relative total production costs between each generalized cell format. (2) Safety-wise, we assess active and passive safety mechanisms and evaluate each format from problematic to unproblematic on a qualitative scale. Safety mechanisms comprise internal gas formation, thermal runaway propagation, cell failures, battery management system (BMS) failure detection, and cell housing.

The three generalized formats were ranked best to worst by forming an average of these properties. (3) Energy-wise, we focus on the volumetric and gravimetric energy density under general format-related differences such as housing, internal cell volume utilization, and the active to inactive mass ratio. (4) Flexibility approximates the adaptability of the cell format for the application and its unique design space. (5) We consider format- and geometry-related differences and the general effectiveness in heat dissipation for each generalized cell format as a proxy for overall thermal management. (6) Resilience integrates safety, energy density, and thermal management and involves application-specific characteristics such as power output tolerance, heat exposure tolerance, load profile irregularities, and mechanical resistance.

Market Pull: The market perspective describes individual applications and defines possible use-cases, including associated usage patterns and battery-related requirements from cell- to pack-level to derive the most specific and crucial battery properties. This process involves matching those use-case-specific requirements to the six aforementioned technical properties. Finally, we evaluate the suitability of these generic formats for each application from suitable to partially suitable to not suitable. We close with recommendations for potential cell geometries, partially following the highlighted LIB.

5. Cell costs

Active material costs are estimated based on market information on resources, precursor and active material costs, and assumptions regarding synthesis processes. Total material costs are calculated assuming average raw material costs in 2021 and overheads for precursor refinement and high-temperature synthesis.

Cell manufacturing costs are based on bottom-up cost modeling that features various production processes and cell design variables that may affect final costs. Previous work suggests a process-based cost modeling (PBCM) approach for battery cost calculation [9,10,11]. This PBCM technique features three steps: (1) Process model (development of technical production layout and its technical parameters); (2) Operations model (transfer of operating conditions into resource requirements); (3) Financial model (transfer of resource requirements into financial KPIs). Finally, we validate our results against real-world battery-cell-production planning data and discuss the cost impact of emerging technologies. [10,11]

6. Manufacturing

Both the state of the art and present research and development work about technologies for battery cell production were discussed based on a meta-analysis. Data sources were, on the one hand, databases of scientific publications, in which keyword-based searches were used to identify relevant preliminary work, which was then evaluated in terms of its scope and content. On the other hand, reports and descriptions of (primarily European) publicly funded research projects were reviewed in a targeted manner. In some cases, informal content from interviews with technology developers or experiences of the scientists involved in the preparation of the report were also processed.

7. Safety

Battery safety is summarized based on desk research. Own experiments are limited to prismatic cells only. We test several prismatic cells (length: 148-366 mm, width; 21-46 mm) with unknown chemistry and internal cell structure by nail penetration tests to cause a thermal runaway.

Therefore the cell is thermally isolated in a pressure chamber before being triggered, as described elsewhere [12]. During thermal runaway, the released energy, the temperature (spatially resolved), the gas pressure, and the cell mass (before and after the safety test) are measured. Data evaluation ranks the cells within the EUCAR Hazard Level (i.e., battery requirements for future automotive applications).

3. Battery applications and requirements

Lithium-ion batteries were mainly used in mobility and stationary applications and in consumer electronics in 2020 (see Figure 1). Figure 2 lists various applications within these industries. There may be diverse use patterns, geographic specifics, and further sub-applications for each application, for which an even more specialized battery design may be required. Nevertheless, we try to balance precision, niches, and individual particularities with a generic assessment. Thus, we emphasize that our multi-criteria evaluation reflects certain assumptions and simplifications, so generalized statements shall not be deduced.

We try to assess a broad range of applications to highlight the heterogeneities and diversities. Thus, buses and drones for mobile applications, home storage and buffer for charging stations for stationary applications, and smartphones and power tools for consumer applications will be discussed. Typically, we limit to a German or European standpoint.

Requirements:

The six characteristics from Section 3 were quantified and applied to the market needs to determine the battery requirements for the above applications. As a showcase, Figure 3 visualizes an application where the green area expresses the tolerated and relative properties per characteristic. The outer edge indicates that the application has strict or high requirements, while the inner edge indicates certain insensitivity and low requirements. In conclusion, the green area represents the overall tolerance or flexibility ratio, where characteristics can be weighed against each other and prioritized.

For cell cost, we differentiate between cost-sensitive applications so that most basic and mass-produced cells might be required or cost-insensitive applications so that most advanced and tailored cells might be required. Even though differences within the formats exist, cylindrical cells tend to be the most cost-effective technology, closely

Figure 2: Different LIB applications clustered by mobile, stationary, consumer and industrial applications.

Mobile applications	Stationary	Consumer electronics	Industrial and Services
Passenger Cars	Off-grid Systems	Smartphone and tablet	Power Tools
Commercial Vehicles	Home Storage	Wearables	Medical Devices
Railway	Industrial Storage	Computer & Notebook	Microelectronics
Aviation	Charging buffer		
Maritime Applications	Grid Booster		
Industrial Vehicles	Grid Balancing		
Construction Vehicles			
Light Electric Vehicles			
eBikes			
Defence			
VTOL			
Racing			

followed by pouch cells and prismatic cells trailing behind due to higher production costs (internal cell construction, housing).

Figure 3: Assessment criteria for cell format fit mobile, stationary, consumer and industrial applications.
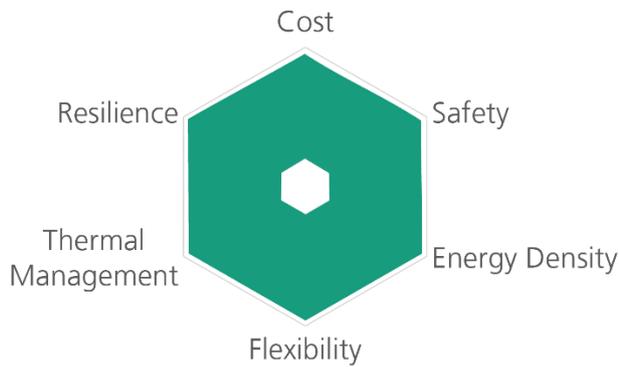
Safety requirements on the outer edge indicate the high need for both cell and system safety, as the application is exposed to, e.g., extreme thermal, mechanical, unforeseen stochastic events, or other conditions that could increase the malfunction probability. Our evaluation criteria imply a tendency for higher ranking for prismatic cells as compared to cylindrical cells.

If applications require high flexibility and a battery design tailored to the limited space, battery modules can be designed in two ways. First, cell size and format may be selected and optimized to the available design space. This flexibility is essential for either large design spaces, i.e., large cells required, or very limited and highly customized spaces, i.e., very small and narrow cells. This cell-level flexibility primarily affects prismatic and pouch cells. Second, many small batteries, such as cylindrical 18650 or 21700 cells, offer high flexibility at the packaging level. If flexibility and design space are no issue, the application has sufficient space so that no prioritization is necessary, and a variety of cells may be considered.

Energy density on the outer edge indicates applications with limited design space or sensitivity towards extra weight, yet a high amount of energy is required to fulfill its functions. Typically, cylindrical cells are ranked best, while prismatic cells are ranked worst.

Thermal management and certain robustness are crucial development goals for applications that might originate from two different circumstances. Either the application is exposed to either extreme ambient temperatures, large fluctuations, or both, or the battery cells are prone to self-

warming induced by high charging / discharging currents. The latter is typical for high-power applications. While the thermal stress can be dissipated or controlled by an active cooling or heating system, the effectiveness is influenced by both cell geometry and format. Generally, for heat dissipation potentials at cell-level, smaller cells are superior to large cells, and prismatic cells are superior to cylindrical cells, which are superior to pouch cells. Applications with a low need for thermal management are either integrated into an environment with an almost constant temperature or operate at moderate charging and discharging currents.

Last, resilience is an aggregated parameter for energy density, safety, and thermal management. This property aims towards stochastic or deterministic operating characteristics. Higher requirements feature unforeseen stochastic events, a broader range of possible operating conditions such as harsh environmental conditions or an inconsistent current flow with high peaks or pulse loads that stress the battery system.

Buses

Buses represent a cost-sensitive transport mode for inner-city, regional and long-haul passenger transport, where use patterns may be classified into regular and occasional services [2]. City buses, equipped with both seating and standing capacity, follow a regular schedule with several inner-city and regional stops yet relatively short individual trip sections. In contrast, opportunities for charging at any bus stop may be given and overnight depot-charging is feasible. Coaches, equipped with seating capacity only, are used for long-haul trips and on rather different routes, with less opportunity for charging. The European bus fleet comprises around 700,000 vehicles [13].

City buses exhibit tremendous market growth [14] as routes are predictable, opportunities for intermediate charging might be built up, overnight depot-charging is feasible, individual trip sections are short and local governments aim to cut local emissions and are encouraged to install zero-emission city centers. In Europe, only 4% of all newly registered buses were electric in 2021 [15]. However, strong growth for electric city buses is expected in the European market, and a sales share of just around 50% is anticipated for 2030. Coaches will probably be electrified much later. With an average battery size between 110 and 350 kWh [16] and annual registrations between 36,000 to 45,000 vehicles, this equals a market volume of at least 4 GWh/a and possibly a double-digit GWh range already in 2030. Given available charging power from 22 to 50 kW for overnight charging and potentially 150 to 350 kW for opportunity charging, charging is typically lower than 1C, whereby peaks (~3C) may be possible. Vehicle motor power ranges from 150 to 300 kW, depending on bus size, so discharging is typically under 1C. Ni-rich chemistries to LFP, partially enhanced with Manganese, are most promising cathode cell materials.

CO_2 emissions from buses are significant and have increased as transport performance increased, which is necessary to cut city motorized private transport. In Europe, buses generate about 8% of the energy-related greenhouse gas emissions from the transport sector [17], accounting for less than 0.2% of the total European vehicle fleet. Exacerbating this, inner-city operation increases particulate exposure for all local residents, while vibrations and noise accompany conventional buses traffic.

Overall, electric city buses are already partly competitive to conventional diesel buses regarding life cycle costs if cheap and durable enough to amortize higher acquisition costs with lower operating costs. For city buses, decision-makers must balance onboard battery storage, rearrange schedules, and establish both opportunity and depot charging infrastructure from a feasibility and total-cost-of-ownership standpoint. Battery cells must either feature high energy density to enable long ranges without opportunity charging or high fast-charging capability for bus stop charging with smaller battery sizes. Nevertheless, any additional energy or power requirements such as passenger cabin temperature control must be fulfilled. Plus, compliance with all applicable safety standards [18] must be ensured.

Drones (VTOL)

VTOL is an acronym for Vertical Take-Off and Landing, which refers to the ability to take off and land vertically without a runway, and typically includes drones or - primarily seen for passenger transport in urban air mobility - helicopters and air cabs. We limit our review to non-military, private or commercial drones.

Drones should be distinguished between consumer and commercial drones, whereas the latter is being specifically equipped and specified for their industrial application [19]. Applications range from (1) search and rescue missions as drones can reach isolated or impassable areas faster and more securely than humans or vehicles without and cover larger areas per time; (2) first-aid missions to deliver life-saving medical supplies, (3) agricultural missions such as pest control, seeding or soil analysis, (4) indoor or outdoor parcel delivery and cargo missions, (5) military missions such as surveillance or attack, (6) facilities and power plants inspection, to (7) sports and entertainment missions such as drone racing or aerial photography. Accordingly, drones can be equipped with communication systems, GPS, cameras, different sensors (light, gas, or temperature), solar panels for in-use recharging, or high-performance motors [20,21].

As specialized as the application and equipment are, as different are battery requirements and energy capacity. However, high power requirements during takeoff and landing (15 to 100C) are common with high (gravimetric) energy density for low curb weight, high flight time, and sufficient supply of any auxiliaries. Typical service life is between 1 and 5 years. The flight time ranges from a few minutes to just around 30 minutes. An hour may be seen as a potential threshold [21]. Operating distance ranges from a few hundred meters to around 45 km. Given this operating profile, drones are frequently charged - often with high charging power - so many charging cycles must be completed [22].

In 2019, consumer and commercial drones reached 4.9 million units (92% consumer). Although consumer drones are likely to account for the largest number of units, batteries are relatively small, i.e., 0.25 to 1.5 Ah for (ultra-)lightweight drones and 2 to 8 Ah for larger drones [22]. Commercial drones are instead placed in the range from 2 to 30 Ah, depending on the intended use case. Thus, the total market volume is expected to rise from just around 3 GWh in 2020 to 17 GWh in 2030, with around 60%

market share for commercial drones and about 35% market share for larger consumer drones. Here, the period from 2017 to 2025 marks the most extensive expansion phase, with a CAGR of over 30%. As of 2022, and according to [22], cell format is dominated by pouch cells and, to minor proportions, cylindrical cells [22]. Ni-rich chemistries are the most promising cathode cell materials.

Quantifying any social and environmental potential is complex and depends on the intended use. However, the elimination of vehicles previously used for on-road delivery reduces total traffic, which bears the potential to cut emissions and particulate exposure and ultimately influence long-term urban planning to improve life quality further. Second, remote control reduces human exposure during operations and may save lives.

Residential storage systems (RSS)

Grid storages are pivotal technologies to increase the renewable share (volatility, grid fluctuation, optimization) and therefore contribute to energy sector decarbonization. RSS are primarily used to increase solar (or wind) self-consumption and, thus, self-sufficiency from the low-voltage grid and increasing overall system efficiency. These decentralized battery systems are typically equipped with up to 30 kWh total energy capacity. In contrast, an average power of 4 kW, an average usable energy capacity of 8 kWh, and 48 to 500 V nominal system voltage are typical [23,24]. Naturally, this varies with home size and connected systems such as electric vehicles or heat pumps [23].

Renewable energies such as solar and wind typically exhibit inherent volatility, meaning that there is high regional, daytime or seasonal dependence. Thus, energy generation regularly exceeds the household load so that excess energy is either fed into the grid or - if available - temporarily stored in the RSS. The grid feed-in is capped to prevent grid damage so that excess energy is not used without a dedicated storage facility. Thus, local RSS can minimize energy loss for peak shaving (generation) and interim storage until the household consumption exceeds its generation (typically for PV systems in the evening or at night). Hence, system response for self-consumption ranges from seconds (charging) to hours (discharge). Both forecast-based (stochastic) and deterministic operating strategies are possible.

Operating conditions for RSS are controlled, without significant volatility of external conditions. Since installation space is usually not limited, integrating a suitable battery (thermal) management system for monitoring and control is possible. Furthermore, requirements for energy density are relatively moderate. RSS should be designed for around 20 years (80% nominal capacity), with standard warranty periods being around 10 years. Measurements imply around

0.3 to 0.8 equivalent full cycles per operating day. A specific system efficiency (90-95%) is required for RSS to ensure that the avoided emissions by load shift exceed grid-fed [25]. LFP chemistries are one promising cathode cell material.

Batteries account for most of the overall RSS system costs (60 to 90%), so battery prices are crucial for market diffusion. Thus, and facilitated by sharply decreasing battery costs, residential storage systems showed strong market grow. By 2020, a total number of 285,000 systems was installed with a capacity of about 1.2 GW and an installed storage capacity of 2.3 GWh in Germany [24,26]. Market outlooks for 2030 deviate from 175 to 420 GWh in [27] or around 300 GWh in [103] for the global market. While Avicienne assumes between 100 and 150 GWh for ESS in 2025 [28], a boost is generally expected from 2025 onwards. Overall, RSS might occupy up to 50% of the market [27].

Given the significant energy capacity and home application, RSS are subject to special quality requirements, fire protection in case of thermal runaway, and other safety concepts. Some standards and guidelines are provided in [29,30,31,32].

Buffer for EV charging stations

Sufficient (fast-) charging infrastructure is a prerequisite for rapid market diffusion of electric vehicles and thus decarbonizing road transport emissions. However, this might necessitate huge energy outputs and several hundred kW of remaining transformer power. To avoid local peaks and prevent power grid collapse, especially at the distribution level and for areas with weak grid connection, decentralized battery-based storages are one concept to support or even bypass the grid connection. Furthermore, facility costs, network enhancement costs, or high grid tariffs can be avoided [33,34,35,36,37]. However, batteries must be cheap to facilitate low charging prices.

Today, power ranges from 44 to 400 kW are common for individual passenger car fast-charging points [38], whereas 270 kW charging peak power (20 to 80% SoC) is typical for current models. The CharIN initiative develops a one MW standard (MCS) that is expected to enable charging capacities of up to 4.5 MW and, thus, meet higher charging requirements from commercial vehicles. Most electric cars have a system voltage of 400 V, while premium models with higher charging power have 800 to reduce losses. The MCS standard is developed for system voltages up to 1250-1500 V [39].

Higher discharge rates (>> 1C) may characterize typical operating profiles to increase the vehicle charging rate. In contrast, charging may occur if a lower grid load or excess

energy is available. Thus, charging may be featured at constant and low to moderate rates (<< 1C). Energy capacity and power strongly depend on charging power, the number of charging stations, the amount of recharged energy, and dwell times. More precise data on station utilization - including temporal information - are currently unknown. Overall, use patterns tend to be highly irregular, including some base-load and volatile peaks due to high seasonal function, daytime differences, and regional differences within Germany or Europe.

In December 2021, around 51,000 public-accessible charging points were registered [40], which equals around 1.5 GW of installed power. By 2030, the NLL predicts demand for 440,000 to 840,000 charging points [41], whereas the NECP mandates one million public-accessible charging points for passenger cars [42]. Plus, further charging points for trucks and buses will be required.

Today, the low market penetration of xEVs does not cause high stress on power grids, yet their increasing share might strengthen fast-charging points with buffers from 2025 onwards [104]. First commercial systems are equipped with 184 [43] to 240 kWh [44]. Similar to RSS, the service life of buffer storages could be up to 20 years. An appropriate BMS for system monitoring control is necessary to ensure security [45]. Given the significant energy capacity, special quality requirements and fire protection concepts apply to prevent any human damage and spread of fire to any surrounding or toxic vapors.

Apart from decarbonizing road transport, first studies propose this application as second-life use for traction batteries from xEVs with about 70 to 80% residual capacity at the end-of-life that would boost resource efficiency and circular economy.

Smartphones

Smartphones stopped being optimized for doing phone calls years ago. Instead, these devices are multifunctional and designed for connectivity, customization, and supporting various features in the smallest possible space. Smartphones have a relatively short lifecycle, between 2 and 3 years [46]. As for all consumer electronics, safety is a crucial element for such battery cells (e.g., when dropped).

Making smartphones smaller, thinner, lighter, and even more powerful is the biggest multi-facet challenge for the electronics industry. The technology and the battery must be housed in a case with a certain thickness and edge-to-edge display across the entire panel. The battery is crucial as it accounts for a large proportion of the weight and has a space-filling function. Thus, the cell housing geometry and characteristics are diverse, and formats range from prismatic, L-shaped, to C-shaped cells. Even several

decentralized batteries within one smartphone are possible. Typically, total capacity ranges from 3 to 6 Ah, with operating voltage trending towards 4.5 V instead of around 4.2 V due to higher cathode capacity.

On the one hand, smartphone users are power-hungry, with an average total runtime of up to 6.4 hours [46]. Typically, a discharge raring of 0.1C to 0.4C is recommended by many manufacturers. However, peaks between 0.6c to 1C may occur [47]. On the other side, users have vital need for charging convenience, especially when the battery is low.

According to [48], smartphones typically use CC-CV charging, whereas fast charging today uses higher voltage (4.35±0.05 V than 4.2±0.05 V) and constant current than slow charging. Typically, smartphones make use of around 18-25 W of charging power. Some manufacturers may use pulse charging too. For CC-CV charging, the median C-rate is around 0.2 to 0.4C and peaks at 0.7-1.1C [48]. These charging rates are in line with an average charging time of 2.6 h today and indicate the desired one of around 1.3 h as possible [46]. Operating system, functionality, and price are crucial apart from runtime and charging time. The battery life of smartphones depends on display brightness, network traffic, connections to other devices, and computing power. Surrounding conditions are widespread, and battery cells must operate at high and low temperatures, and, as expected, there is a likelihood that they will often be discharged too deeply.

Smartphones have become an integral part of our daily life. Accordingly, an established market with significant size and moderate growth already exists. The world's largest manufacturers (Apple, Samsung, Xiaomi, Huawei, Vivo) are based in the USA and Asia, so Germany and Europe have no decisive role for the R&D of new smartphone batteries. According to Avicienne [46], the CAGR from 2019 to 2030 is around 4%, increasing from around 10 GWh to 15 GWh.

Power tools

Power tools are versatile and may accomplish various functions, but they are normally designed and engineered for precisely one purpose (except for multi-function tools) and application (i.e., private or professional). Such tools are used in industry, construction, gardening, and housework. Typically, one may distinguish between low-end private applications (typically 6 V and 10 Wh) to high-end applications to professional use (typically 36 V and 50 Wh), with which both requirements and use patterns as well as purchase costs vary [49,50]. 18 V power tools dominate the market to date, while an expansion to >21 V is anticipated as higher voltages drive higher capacities and motor torque [51]. Apart from this application-based distinction, such tools are either stationary or hand-held devices. While the latter has its advantage in portability and flexibility,

stationary power tools score higher on power, precision, and speed.

Enabled by substantial battery improvements, the prevailing trend for power tools is designing cordless hand-held devices to increase flexibility and convenience. At the same time, major drawbacks or limitations during actual operation shall be avoided or at least minimized. While both electronic components and the battery must be packaged within the housing, the battery accounts for a large proportion of the weight - crucial for usability and ergonomics - and takes on a space-filling function so that battery cell geometry and housing are essential. Power tools' main success factors are high operating time, powerful motors, compact design, low weight, reliability and robustness, safety (e.g., when dropped), and reasonable prices. Thus, battery requirements are versatile and include operating temperature (-30 to 50 °C, typically passive cooling to air cooling), energy density, charging or discharging rates, self-discharge (especially for private application), service life (1 to over 5 years, typically up to 3-year warranty), cycle stability (> 500 cycles), and compact and lightweight geometry. Given the uncertainty for operating temperatures, long service life for private devices (> 5 years), and high likelihood for deep discharge, controlling cell aging is essential [51,52]. As diverse as the function (fastening, drilling, cutting, grinding, milling, polishing, painting, cleaning, heating, etc.) and differences in private and professional use, the battery specifications are different. According to Weydanz [52], peak currents for cordless power drills may range from 20 to 25 A (> 10C, >250 W) and the mean operation current is around 8 A (4-5C, 50-100 W), while charge currents may range from 4 to 6 A (2–3C).

Today, the global market is dominated by electric power tools, yet others exist (e.g., pneumatic). The market is already fragmented regarding power tool manufacturers, global alliances, associated battery manufacturers, and the split between Li-ion and NiCd batteries, with the former expected to occupy the entire market in the long term. Due to rising infrastructural developments, growing urbanization, and do-it-yourself trends, the global market is expected to grow. According to Avicienne [51], the CAGR from 2020 to 2030 is around 8%. This equals an increase from around 6.3 GWh to over 14 GWh by 2030.

4. Cell format analysis

4.1 Status Quo and announcements

Formats and suppliers

While solid growth for the global battery cell market is expected to continue, the market is expected to become more fragmented. As of 2021, Top10 EV battery manufacturers are headquartered in Asia and localized in China, Japan, and South Korea, while three companies already comprise 70% of the total market volume (CATL, LG Energy Solutions, and Panasonic). Typically, no format substitution is foreseeable, so all three formats will continue to exist, forcing leading cell manufacturers into either multi-format strategies or high-level specialization. An overview of cell manufacturers and their available cell formats - as far as publicly known - is visualized in Table 1 [53,54,55].

Available formats and production capacity per country

Proportions per cell format as well as the corresponding total quantity per country is visualized in Figure 4. Chinese cells account for roughly 78%, with prismatic cells representing the predominant format and similar shares for others. Europe and the US trail well behind, yet with peak shares for pouch cells (EU) and cylindrical cells (US). Korea and Japan are tied at around 4%. However, this is a snapshot for 2021, and as global announcements roll out, proportions per format and between countries will shift.

Table 1: Cell formats by company.

Cell manufacterer	Country	Pouch	Hard-Case	Cylindrical
CATL	China	Not available	Focus technology	Not available
LG Energy Solutions	Korea	Focus technology	Not available	Focus technology
Panasonic	Japan	Not available	On offer	Focus technology
BYD	China	On offer	Focus technology	Not available
Samsung SDI	Korea	On offer	Focus technology	Focus technology
SK Innovation	Korea	Focus technology	Not available	Not available
CALB	China	Not available	Focus technology	Not available
AESC	Japan	Focus technology	Not available	Not available
GuoXuan (Gotion)	China	Focus technology	Focus technology	On offer
EVE / PEVE	Japan	Focus technology	Not available	Focus technology
Lishen	China	Not available	Focus technology	Focus technology
Murata	Japan	Not available	On offer	Focus technology
Northvolt	Sweden	Not available	On offer	Focus technology
SVOLT	China	Not available	Focus technology	Not available
Varta	Germany	Not available	Not available	Focus technology
SAFT	France	Not available	Focus technology	Focus technology

Focus technology | *On offer* | *Not available*

Figure 4: Production capacity 2021 - Left: share per format [%]. Right: Total volume [GWh].
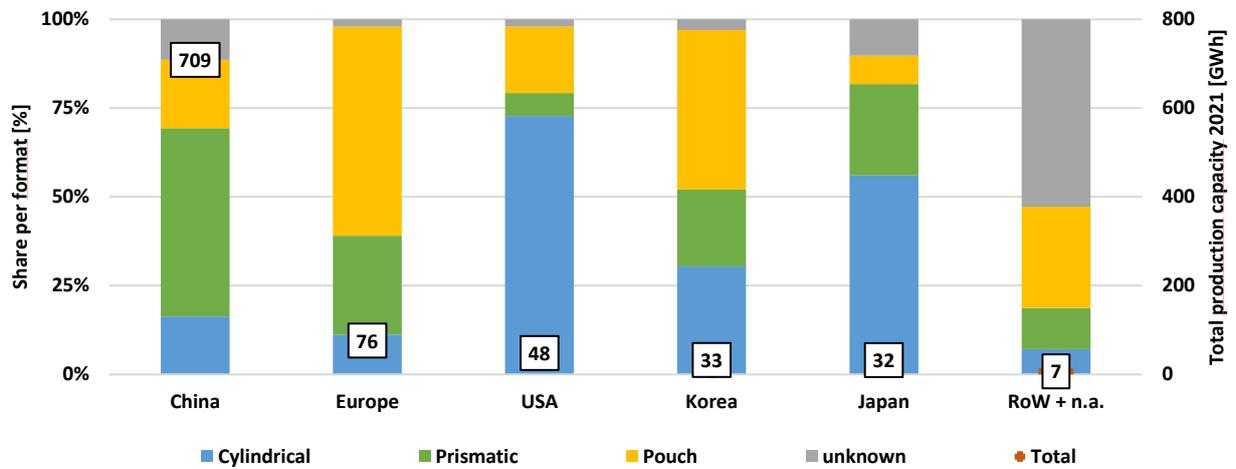
Announced production capacity per format in Europe

Europe is on the rise, and new announcements for cell production capacity are pouring in. While the global battery production split allocates less than 10% in Europe for 2021, up to 1.4 TWh of production capacity is announced until 2030, equivalent to an 18-fold increase. This boom is balanced across all three formats. About 380 GWh production capacity of prismatic cells, 240 GWh of pouch cells, and 100 GWh of cylindrical cells are announced by 2030. Around 300 GWh cannot yet be specified (see Figure 5). This massive expansion for all three formats suggests high demand for market entrants and technological innovation.

Next, we look at the current cell offers and the latest industry announcements to capture all facets of these three formats. Indeed, there is no standardized cell and already a widespread in outer dimensions to fit the respective applications best. Forecasts even assume that further specialization and differentiation of cells will occur in line with the electrification of new applications. While the following section focuses on outer cell dimensions, interior cell design will be discussed later.

Figure 5: Announced European production capacities per cell format up to 2030
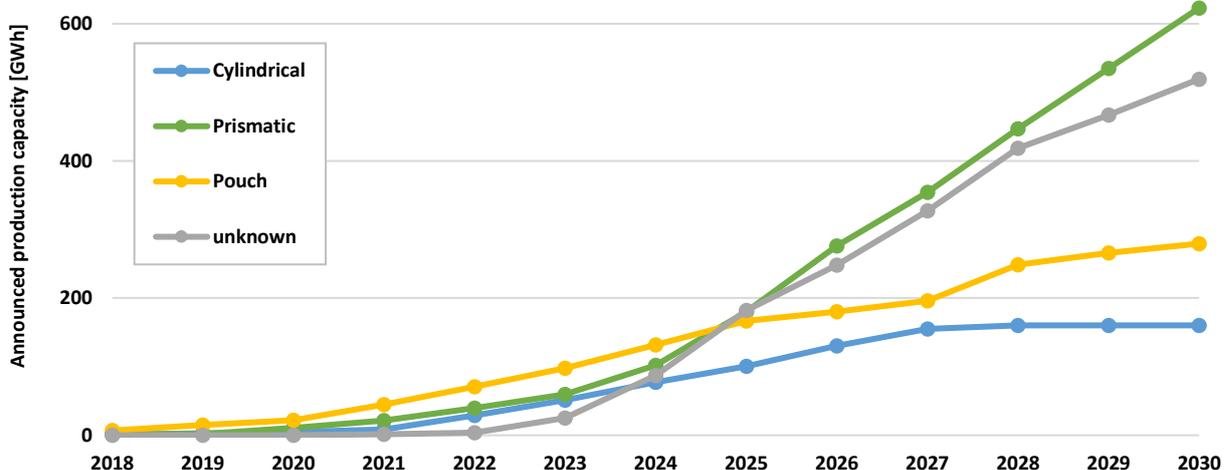
Prismatic cells: Evaluation of available and announced cell dimensions

For prismatic cells, we find that the ratio (longest versus shortest side) spreads between 1:1 and 4:1, with up to 900 mm possible for the longest. Typically, we find that most cells are well below 300 mm for the longest side and well below 200 mm for the shortest. For automotive applications, the installation in the vehicle underbody limits the cell height to roughly 120 mm when installed vertically. Current automotive standard formats range from 120 (HEV 1) to 225 mm (BEV 4) for the longest side, whereas the ratio is closer to 2:1. The latest automotive announcements reveal rather long and narrow cells (e.g., BYD Blade). The graphical evaluation can be found in Figure 6.

As for length and width (longest and shortest side), there is also a considerable variation in cell thickness depending on the available design space. Cell thickness ranges from 5 to just over 70 mm. Typically, cells for consumer applications range from 4 to 14 mm. Mobile applications range from 12 to 60 mm, and 10 to 72 mm for stationary applications. Automotive standard formats range from 12 to 45 mm.

Pouch-type cells: Evaluation of available and announced cell dimensions

For pouch-type cells, we find that the ratio is similar to prismatic cells and spreads between 1:1 and 4:1, yet the distribution is less scattered. However, cells are smaller, mainly because of lower mechanical stability and stiffness as there is no hard case. Typically, cells are up to 400 mm long. Current automotive standard formats range from 160 (HEV 2) to 330 mm (BEV) for the longest side.

The latest automotive announcements reveal larger cells between 500 and 600 mm for the longest side (e.g., AESC 590, VW MEB). Compared to narrow and elongated prismatic cells, the ratio is smaller. The graphical evaluation can be found in Figure 7.

Thickness for pouch cells ranges from 2 to around 15 mm, where the maximum thickness is generally limited by the manufacturability of thermoformed foils and cell stability. Generally, while pouch cells for consumer applications like smartphones or wearables typically range from 2 to 6 mm, pouch cells for mobile applications range from 5 to 15 mm and 7 to 15 mm for stationary applications.

Figure 6: Prismatic hard-case cell evolution. Upper: Ratio longest versus shortest side. Including corridor for current dimensions (gray), VDA / Din standard sizes (orange) and currently announced automotive cells (purple). Lower: Thickness range.
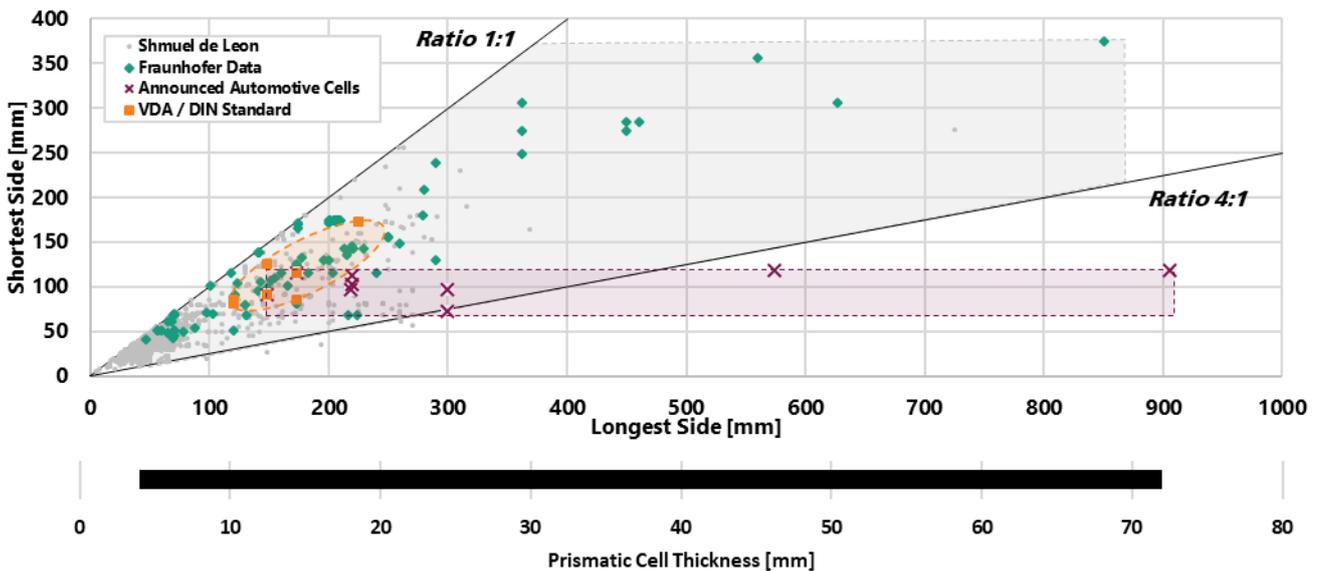
Figure 7: Pouch-type cell evolution. Upper: Ratio longest versus shortest side. Including corridor for current dimensions (gray), VDA / Din standard sizes (orange) and currently announced automotive cells (purple). Lower: Thickness range.
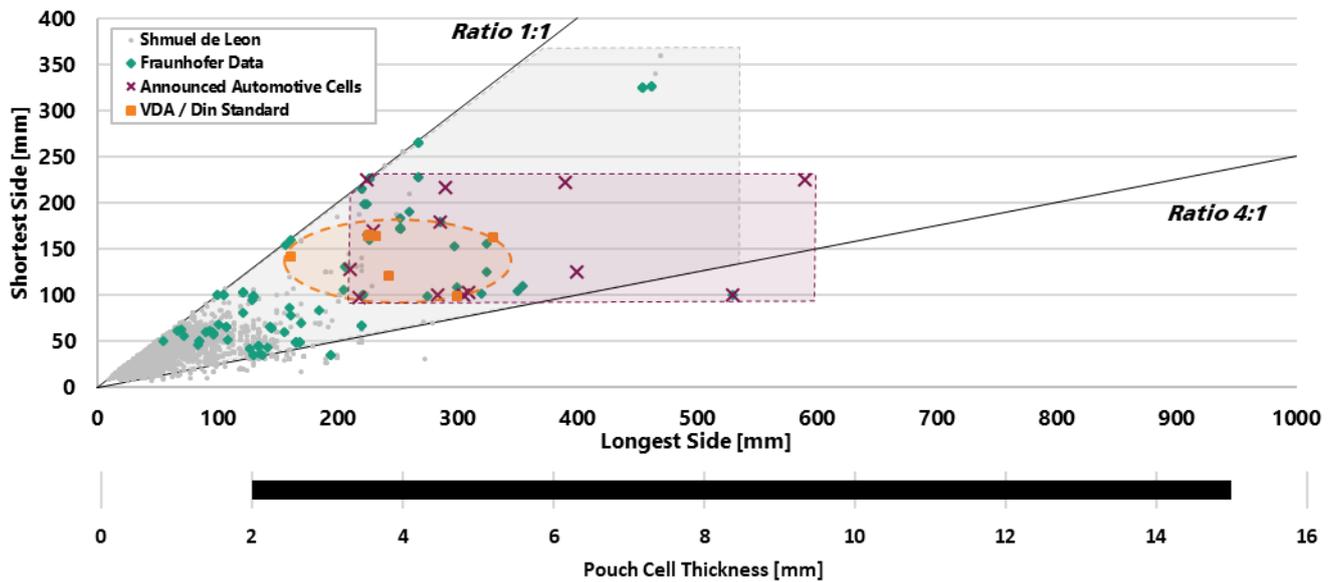
Cylindrical cells: Evaluation of available and announced cell dimensions

As for the rectangular cells, considerable variability exists for the cylindrical ones, even if a few formats are best known from consumer and household electronics (e.g., AAA cells) or automotive applications (e.g., 18650 or 21700). Specifically, 18650 and 21700 cells are now an established cross-application standard format for large cylindrical cells. Current announcements from Tesla or Samsung also indicate even larger cells, i.e., 4080 or 4680 format, as promising for future automotive applications. The graphical evaluation can be found in Figure 8.

Figure 8: Cylindrical cell evolution. Ratio diameter versus cell height.
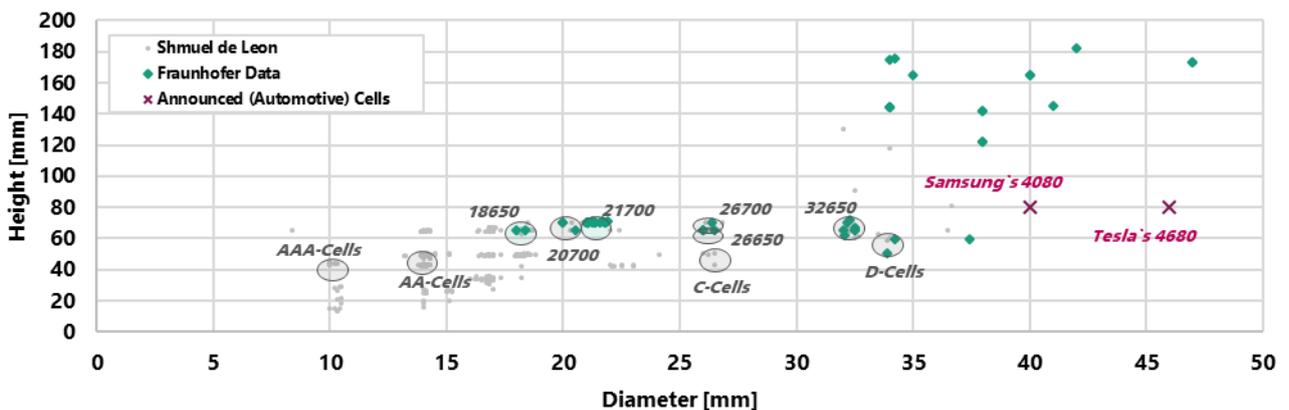
4.2 Active materials and electrode design

Graphite and silicon-based anode materials

Graphite or graphite composites with small parts of silicon compounds remain state-of-the-art for anode active materials in LIB [56]. Typical high-energy anodes in 2021 featured around 5 wt% of silicon oxide (SiOx) or silicon nanoparticles [57]. With a theoretical capacity of >3500 mAh/g for silicon and >2200 mAh/g for SiO, the practical specific capacity of respective graphite mixtures can be enhanced to values of more than 400 mAh/g, significantly exceeding the practical capacity of stand-alone graphite of around 340 mAh/g. However, the volume change of the silicon compounds during lithiation is roughly 300%, which puts a high burden on the mechanical stability of the electrode composite, binder structure, particle structure, and solid-electrolyte interface (SEI). The chemical stability of silicon towards typical electrolytes is also relatively low, which causes a high loss of lithium in the irreversible SEI build-up reactions.

There are several approaches to overcome the described challenges and utilize silicon, either as a stand-alone anode active material or in a composite with graphite. Using a graphitic matrix embedding the Si-particles is often described to be a way to stabilize the electrode both mechanically and chemically. The graphite matrix can host lithium-ions and hence contribute to the anode capacity and provide a relatively rigid and porous structure in which the Si-particles can undergo a large volume change without putting too much stress on the macroscopic electrode structure. At the same time, if graphitic or other carbon-based particles can cover the Si-particle surfaces, the SEI might not directly be formed on the Si-surface and hence would not have to withstand the volume expansion. For this concept, Si-nanoparticles (SiNP) are used [58]. Since the lithiation potential of silicon (approx. 0.3 V) is slightly higher than graphite, the Si-particles have to undergo full lithiation and hence volume change before the intercalation potential of graphite is reached. For this kind of "deep cycling" of silicon in silicon/graphite composites, the nano-size of particles provides the best overall mechanical stability and long-term cycling stability. The manufacturing cost of nanoparticles is, however, relatively high.

There are several approaches to utilize silicon with a particle size in the micrometer range (SiMP) [59-61] and hence to enable more cost-efficient anodes. By limitation of the anode potential and hence of the charge cut-off voltage at cell-level, the degree of lithium-silicon-alloying can be

limited, e.g., at an effective capacity of 1000 to 2000 mAh/g ("limited cycling") and respective smaller volume change [62]. While these concepts may still require specialized binders and surface coatings to provide the necessary mechanical and chemical stability, these are already placed on OEM roadmaps due to their potentially lower cost as compared to SiNP-based or even graphite-based anode materials [63].

High energy NMCs

Further developments of NMC layered oxides (NMC, NCA, ~3.8 V vs. Li/Li$^+$) have lead to the commercialization of high nickel cathode materials in state-of-the-art LIB cells. NMC622 (LiNi$_{0.6}$Mn$_{0.2}$Co$_{0.2}$O$_2$) achieves about 170 to 180 mAh/g in conventional LIB, NMC811 (LiNi$_{0.8}$Mn$_{0.1}$Co$_{0.1}$O$_2$) even more than 190 mAh/g. An essential prerequisite for such high capacities is to improve the intrinsic stability of the delithiated crystal structure of the materials and the electrode-electrolyte stability. The stability of the delithiated crystal structure can be improved, for example, by doping with other elements, such as aluminum - which is exploited in the case of NCA (Li(Ni,Co,Al)O$_2$, >190 mAh/g) cathode materials [64].

Several cell producers and automotive OEMs have announced their plans to develop and commercialize NMC-like materials beyond 811. It is likely that a couple of cathode materials will be commercialized in the upcoming years, which feature comparable chemical compositions, but will differ in doping levels, coatings, the gradient of chemical composition (e.g., core-shell), and other properties. Due to their high share of Ni and low share of Co, a distinction between the highest-Ni NMC-type and NCA-type may not be applicable anymore. Hence these materials are often considered a convergence of NMC and NCA to „NMCA" (LiNi$_{1-x-y-z}$Co$_x$Mn$_y$D$_z$O$_2$ with x < 0.05, (1-x-y-z) > 0.9 and D being a dopant such as Al or Mg) [65-67].

High performance and high stability cathode materials

While not featuring the highest energy densities, several established materials are still of high interest for LIB due to their overall performance and stability, particularly in " high-duty " applications. For example, the spinel-type oxide LMO ($LiMn_2O_4$, ~120 mAh/g @4.1 V vs. Li/Li^+) is used today as an additive in NMC or NCA-based cathodes to improve their performance and stability. The substitution of Mn with Ni in LMNO ($Li(Mn,Ni)_2O_4$, >120 mAh/g @4.6 V vs. Li/Li^+) leads to a significant increase in cell voltage. The material could be used in high-voltage cells in the future, but most likely away from automotive mass markets. NMC111 and NMC622 are established LIB materials. They offer a good thermal and cycling stability combined with reasonably high energy density. Recent material developments [64] aim to improve the properties of these materials further. For example, single-crystalline NMC622 particles seem to open further possibilities to extend the stability window, so that related materials offer increased capacity and electrochemical stability.

Low-cost cathode materials

Several international automotive OEMs have recently expressed interest in using LFP-based ($LiFePO_4$, 160 mAh/g @3.3 V vs. Li/Li^+) batteries for future low-range and low-cost EVs. Although the overall volumetric energy density on pack level does not meet NMC- or NCA-based batteries, the concept could be feasible for smaller EVs with limited cruising range [68,69]. The energy density of the material could be increased by substitution of Fe with Mn (LMFP, $Li(Mn,Fe)PO_4$), which features a higher cell voltage (e.g., 3.7 V vs. Li/Li^+ for $LiMn_{0.5}Fe_{0.5}PO_4$) as compared to LFP. An alternative route to lower cost is Mn-rich NMC oxides, e.g., NMC370 or NMC820. Compared to their Ni-rich counterparts, they feature a distinctly lower capacity, but the demand for expensive Co and Ni is drastically reduced. Other approaches utilize Li-rich layered oxides (LLO) [70,71]. Like Mn-based materials, these are focused due to their high theoretical capacity and potential low costs. While the crystallographic structure of these materials deviates from NMC, they are often termed high-energy NMC or LMR-NMC ($Li_{1+x}Mn_aNi_bO_{2+y}$, e.g. a=0.7, b=0.3, >220 mAh/g @3.45 V vs. Li/Li^+).

Assumptions for the future use of high energy active materials

To assess the cell KPI of future LIB, we assume the availability of high-energy cathode and anode active materials in 2025 and 2030. In particular, for 2025 NMCA-type materials with specific capacities of around 220 mAh/g and for 2030 high-capacity materials (e.g., LMR-NMC) with specific capacities of around 250 mAh/g, however, with a lower voltage as compared to the state-of-the-art. LFP or further developments like LMFP may play an ongoing role for lower-cost LIB.

Based on silicon as the active material, we assume the availability of anode composites of silicon, graphite, and other carbons with a specific capacity of around 900 mAh/g in 2025, e.g., as Si/C-composite with limited utilization of the silicon capacity, and around 1800 mAh/g in 2030, e.g., as Si/C composite with close to theoretical utilization of the silicon capacity.

As the ratio of passive to active materials is already minimized for the cathode, we do not expect big changes here. However, increased fast charging capabilities or higher electrode thicknesses might require more specialized conductive additives like carbon nanotubes or increased shares of conductive additives. With the transition from graphite to graphite/silicon or stand-alone silicon concepts, a change in the binder system and an increase in binder volume fraction in the anodes can be expected.

Table 2: Design parameters for HE or HP lithium-ion cells.

Component	High-Energy Cell (HE)	High-Power Cell (HP)
Electrodes	• Thick electrodes (high coating weight) • Low porosity • Little conductive carbon additive • Medium/ large particle size	• Thin electrodes (low coating weight) • High porosity • High conductive carbon additive • Small/ medium particle sizes
Current collector	• Thin • Coated to increase adhesion	• Thick • Coated to reduce contact resistance
Separator	Thin	
Electrolyte	High safety	High safety and high conductivity

Electrode design

The design and development of new commercial lithium-ion cells are characterized and limited by an engineering trade-off between either high-energy or high-power density [72] specified by the intended application. This trade-off implies different objectives at both cell design and electrode design levels. For high-energy applications, maximizing electrode volume to battery cell volume and active material to electrode volume are key. In contrast, electrode resistance must be minimized for high-power applications (i.e., electronic, ionic, and thermal) [64]. Alongside this binary high-energy or high-power design approach, multi-objective optimization is possible, i.e., maximizing the product of energy density and power density [73]. Electrode design parameters cover (1) electrode layer thicknesses, (2) properties of the porous materials (porosity, tortuosity, particle size, and permeability), (3) current collectors, (4) separator, (5) electrolyte, and (6) connection tags. The individual component characteristics are chosen to fulfill best the cell safety and performance requirements [72].

Here, it is essential to include all mutual interdependences between the components and among themselves. Three examples shall illustrate this. (A) Electrode porosity influences not only energy density and power density but also mechanical stability and particle cohesion [74]. (B) Electrode thickness influences the specific capacity [mAh/cm²] and the ratio of active to passive material and thus energy density but also the internal resistance and thus high-power capability. (C) Thinner current collectors increase thermal and ohmic resistance and, thus, reduce high-power capability but increase energy density as the ratio of active material to electrochemically passive current collectors increases. Typically, conductive additives and binders, suitable for the electrode material, further optimize the electrode properties [72]. Table 2, adopted from [72], summarizes the engineering trade-off and classifies the design direction.

Figure 9: Basic structure of the electrochemical unit cell of state-of-the-art LIB (left) and Si-based concepts (right). [105]
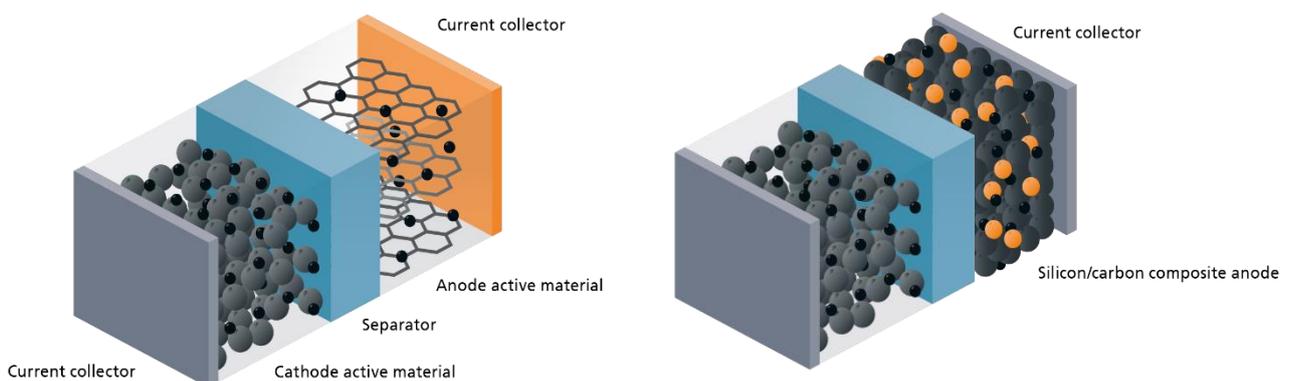
Focus: Silicon anodes

Due to the high volume change of silicon during cycling, silicon-based anodes have high mechanical structure and stability requirements. There are two different concepts for designing such anodes: (1) A porous host structure, e.g., a carbon-based structure, provides electronic conductivity and a hollow framework in which silicon particles can breathe without impacting the electrode's macrostructure. Silicon volume expansion happens within the pores and drives out a certain amount of electrolyte from the anode. The weight share of this porous host structure in the anode can be well above 25%. (2) Silicon composites, where carbon additives function as electronic conductors in the anode, allow for higher density, while the silicon volume change may cause certain cell breathing on the cell-level. In this concept, displacements on the micro and macro scale necessitate specialized and highly flexible binders, ensuring mechanical stability and electronic coupling even after repeated cycling. For both anode concepts, decreasing anode thickness can be expected. Due to the high capacity of silicon, the ratio of anode to cathode thickness might become more asymmetric in a balanced cell.

Assumptions on electrode design

In particular, for high energy concepts, we assume an increase of cathode thickness to 90-100 µm until 2025 and to 100-120 µm in 2030. These values may not apply to high-power cells. Based on the cathode active materials discussed in the previous sections, reversible area capacities of 6.2 (NMCA-type) and 7.7 mAh/cm^2 (LMR-NMC-type) can be reached vs. the specified silicon anodes. On the anode side, this translates to a thickness of approximately 75 to 80 µm for silicon anodes assuming a highly porous discharged anode of 50% (Si/C 900 mAh/g) to 65% (Si/C 1800 mAh/g) porosity which can accommodate the total volume change of silicon particles during cycling (concept 1, see above).

Due to the SEI formation on the silicon particle surface, which can be more pronounced than graphite, a certain loss of lithium can be expected during cell formation. Here, we assume that the lithium needs to be introduced by the cathode active material, and no lithiation agents are used. The actual delithiation capacity of the cathodes in the first cycle hence is higher as compared to the values stated above.

Regarding current collector foils, we assume an ongoing trend towards thinner Al- und Cu-foils. Cu-foils with a thickness of approximately 10 µm and Al-foils with approximately 15 µm are state-of-the-art. Some producers have already announced using Cu-foils with a thickness of less than 10 µm in their next-generation cells.

Table 3: Properties of state-of-the-art and future electrode designs.

Concept	Material system	Loading (mg/cm²)	Coating (µm)	Capacity (mAh/cm²)	Porosity (%)
SoA LFP	LFP	20	75	3.1	25
SoA NMC811	NMC811, 185 mAh/g, 96 wt%	24	70	4.2	23
SoA Graphite/SiO (balanced to SoA NMC811)	Graphite 97%, SiO 3%, 350 mAh/g, 92 wt%	14	90	4.6	25
NMCA 2025	NMCA 220 mAh/g, 96 wt%	32	95	6.2	23
Si/C 900 (balanced to NMCA 2025)	silicon 67%, carbons 33%, 900 mAh/g, 89 wt%	8.5	80	6.8	50
LMR-NMC 2030	LMR-NMC 260 mAh/g, 96 wt%	34	110	7.7	23
Si/C 1800 (balanced to LMR-NMC 2030)	silicon 77%, graphite/carbons 23%, 1800 mAh/g, 89 wt%	5.2	75	8.4	65

4.3 Cell design and cell formats

Apart from the form factor and the application-specific suitability to design space restrictions, all three principal cell formats (cylindrical, prismatic hard-case, and pouch-type) also differ in other properties.

Cylindrical cells feature high energy densities based on a good volume utilization of wound electrodes, high cell robustness, and low costs due to established manufacturing processes. Due to their comparably small volume and low energy content per cell, high integration effort for high-capacity battery packs formed by many individual cells is required. The dynamic winding radius of the electrode leads to inhomogeneous mechanical forces in the cell.

Pouch-type cells can also provide high energy densities due to the low weight of the cell housing, high flexibility in manufacturing, and possibly easy recycling after the end-of-life (EOL). However, the low mechanical stability of the pouch foil sets high constructional demands in module design.

Due to their high mechanical robustness, prismatic cells feature good integrability in modules and packs leading up to direct integration (cell-to-pack). At present, the cells have a lower energy density than cylindrical and pouch-type cells, which results from volume utilization in the cell and the weight of the cell housing.

In automotive and other applications, there is an ongoing trend towards larger cell formats. The establishment of 4680 cylindrical cells (more than double the diameter of 21700) will particularly be interesting for larger battery packs >1 kWh. The cell format will not play a role for mobile or electronic applications currently served by 18650 and 21700 cells. Developments for prismatic and pouch-type cells are strongly driven by requirements resulting from passenger car geometries. Several cell producers have introduced large-format cells covering the whole width or integer fractions of a passenger car's underbody. This integration has led to the development of thin prismatic cells (e.g., 20 mm) with a length of up to 1000 mm or pouch-type cells with 500 to 600 mm. The extreme aspect ratio of these cells results in little cross-compatibility to other battery applications.

Electrode and cell assembly

Two basic techniques are available for cell assembly: (1) Winding of continuous electrodes (see Figure 10 b and c) and (2) stacking of pre-cut electrodes [75,76]. In practice, several combinations of both techniques exist, such as Z-folding (see Figure 10 a) or stack-winding. Electrode winding is applied for both prismatic as well as cylindrical cells.

All these techniques feature specific safety properties and production footprints, often expressed in terms of cells per minute, expressing their respective significance for different battery applications. However, the final electrode geometry and cell housing geometry can lead to dead volumes inside the cell, directly affecting achievable energy densities. Intuitively, wound electrodes in cylindrical cells do not create any intrinsic dead volume, which consequently only results

Figure 10: Basic techniques of electrode assembly: (a) with pre-cut electrodes in a stacking process, (b) cylindrical coil of continuous electrode on a winding mandrel, (c) flat coil of continuous electrode. Combinations of the techniques are possible, e.g. multiple flat coils stacked onto each other or pre-cut electrodes laminated to a continuous separator which is then wound to a flat coil. The coating thickness is exaggerated for better visibility.

(a) Stack

Z-folded separator
Cathode
Al-current collector
Anode
Cu-current collector

(b) Cylindrical coil

Winding mandrel
Anode
Separator
Cu-current collector
Cathode
Al-current collector

(c) Flat coil

Cathode
Cu-current collector
Separator
Anode
Cu-current collector
Separator
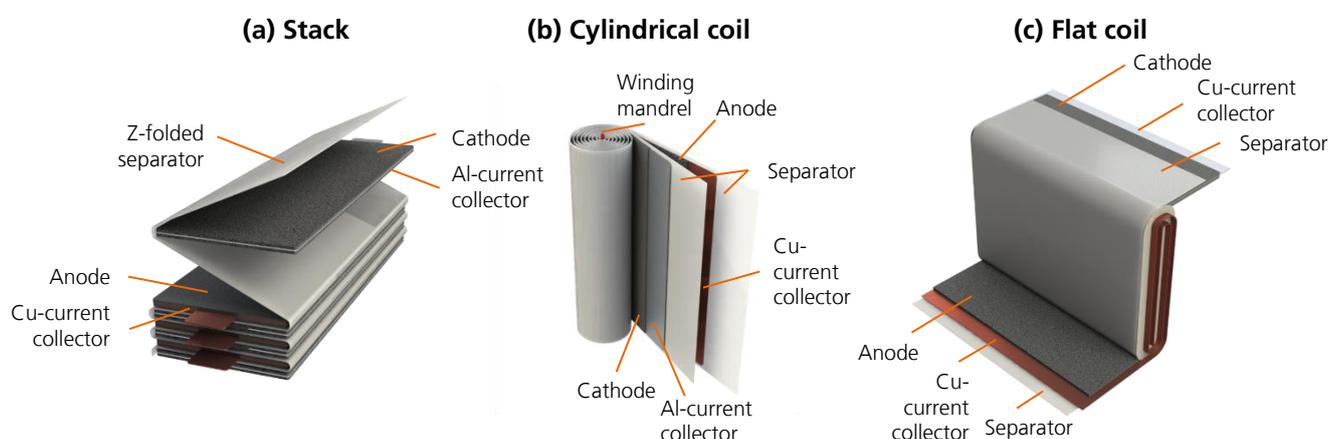
from the space required for contacting and the cap and sealing components. Hence, this type of cell natively features high energy densities. In contrast, an elongated electrode role in a prismatic/rectangular cell housing will create a large dead volume due to the coil radius, which can be several mm in prismatic cells, even for multi-coil electrodes.

Therefore, an important trend is the transition from a single flat-coil (large radius) or multi-coil (smaller radii) to stacked electrodes in prismatic cells. Compared to coils, electrode sheets' positioning accuracy during stacking is a major issue for the quality of stacks. The technique of Z-folding is one way to ensure good safety properties of cells, even if electrode sheets might have some misalignment since the continuous separator band effectively prevents any shortcuts between electrode sheets.

Tab and tabless design

There are seveal possible tab designs for all cell formats and electrode stacks. For cylindrical cells, the established method is to weld strip-like tabs on the current collector foils. This technique requires uncoated current collector areas, which may slow down the coating process due to intermittent operation, and reduces the total coated area and, thus, energy density. For next-generation cylindrical cells, tabless designs have been proposed which make use of the direct connection of continuously uncoated segments of the current collector foils with the cell contacts. By this technique, the contact area between the current collector and cell contacts can be drastically increased and thermal and electrical conductivity improved. A tabless design can also be applied for pouch-type and prismatic cells.

Assumptions on future cell formats

For next-generation LIB-cells, we assume more and more stacked electrode designs for prismatic and pouch-type cells. For cylindrical cells, tabless designs will appear particularly in high-power cells. A reduction of dead volumes in the cell can be expected for all cell formats through optimized electrode contacting, sealing, and safety devices.

Table 4 shows exemplary cell formats that might play a big role, particularly in electric vehicles in the future. Specifically, we assume a transition from 2170 to 4680 cells in passenger cars, from 300 mm pouch-type to 500+ mm formats, and from established and standardized PHEV or BEV formats to flat prismatic cells, e.g., 200+ mm or 900+ mm.

Table 4: Exemplary cell formats and characteristics. The table includes the energy content of state-of-the art cells as well as estimations for 2030.

Type	Dimensions (mm³)	Assembly	Energy 2022 (Wh)	Energy 2030 (Wh)	Characteristics
Cyl. 21700		Jelly role	18	20	
Cyl. 4680		Jelly role	<90	110	Tabless
Pouch 300	300x105x(9-12)	Stacked / Z-folded	230	330	Contacts on opposite sides
Pouch 550	530x100x(9-11)	Stacked / Z-folded	285	460	Contacts on opposite sides
Prism. 220 "MEB"	220x100x(20-25)	Multi-coil / stacked	295	410 / 290 (LMFP)	
Prism. 220 large	220x110x60	Multi-coil / stacked	600 (LFP)	880 (LMFP)	Cell-to-pack
Prism. 900	905x120x15	Multi-coil / stacked	650 (LFP)	880 (LMFP)	Cell-to-pack, contacts on the sides

4.4 Cell energy density

The analysis and evaluation of different cells cover seven cell formats, divided into three cell geometries. For cylindrical cells, we analyze the common 21700 format and the latest 4680 cell format, for which BAK, LGES, Panasonic, Samsung SDI, and Tesla have announced production capacities build-up. The prismatic cells include the slim 220 mm format currently utilized in VW's MEB battery packs, the full vehicle body format introduced as "Blade battery" by BYD, and a large-format prismatic cell used for the LFP chemistry by CATL. Pouch cells represented by the 300 mm format produced, e.g., by AESC, CATL, LGES, and SKI, and the slim 550 mm format, again utilized in VW's MEB battery pack, are also included in the analysis. The individual cell formats intend to reflect the current status quo and the transition to 2030 based on common dimensions and cell structure (for 2022) of popular electric vehicle models. The underlying assumptions are listed in Table 3 and Table 4.

As a general assumption for all cell formats, a transition to higher energy materials and electrode geometries was assumed. As discussed, this means the utilization of silicon as anode material and NMCA-type (2025) and LMR-NMC (2030) as cathode materials in the smaller volume cells

(V < 0.5 l) and LFP (2025) and LMFP (2030) in the large volume cells (V < 1.5 l). Especially the transition to silicon and LMR-NMC means a large increase in cell capacity. However, this increase in capacity does not fully translate into cell energy since the higher delithiation potential of silicon compared to graphite (approx. +0.3 V) and the lower lithiation potential of Mn-rich LMR-NMC compared to Ni-rich NMCA (approx. -0.3 V) leads to a lower total cell voltage. The cell voltage of the proposed LMR-NMR / silicon system is only 3.0 - 3.1 V (3.3 - 3.4 V for the NMCA / silicon system). For LFP/LMFP cell line, the assumed transition from LFP to LMFP increases the average cell voltage by more than 0.3 V to 3.2 - 3.3 V due to the Fe/Mn-substitution (2.9 V for the LFP / silicon system).

Cylindrical cells

The energy density calculations for 21700 and 4680 cells are based on commercialized cell designs and data published by several cell producers on their proposed first generation of tabless cylindrical cells. The 4680 design published by Tesla features an energy density comparable to existing 21700-type cells. Given the 4680 format, optimizing material and cell design for the highest energies may increase energy density to 790 Wh/L (260 Wh/kg) in 2025 and 870 Wh/L (295 Wh/kg) in 2030. Due to a lower volume utilization, the energy density for 21700-type cells will be smaller in the same configuration.

Figure 11: Development of volumetric energy density over time and industry roadmaps. Calculated values for exemplary future cell concepts are highlighted.
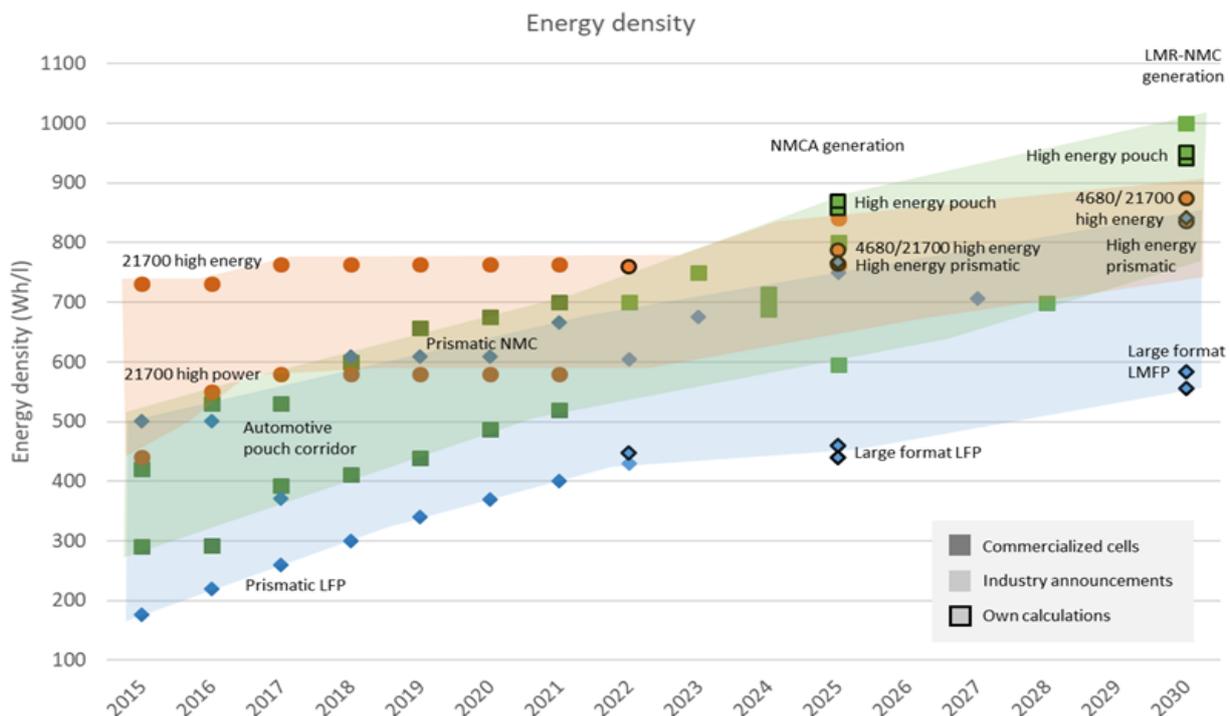
Prismatic hard-case cells

New material systems and a stacked electrode assembly can lead to a strong increase in energy density for prismatic hard-case cells. Until 2025, an energy density of 770 Wh/L (280 Wh/kg) can be reached with high energy/medium volume cells. Until 2030, 840 Wh/L (315 Wh/kg) are possible.

The energy density of large-volume LFP-based cells will likely stay below 500 Wh/L until 2025. Based on higher voltage LMFP, an energy density of up to 580 Wh/L (230 Wh/kg) is possible until 2030. The elongated and flat "Blade"-type battery produced by BYD is not as favorable in energy density at cell-level compared to cell designs with a more balanced aspect ratio. However, it may still reach an energy density of >550 Wh/L (200 Wh/kg) in 2030.

Pouch-type cells

Newest generations of pouch-type cells can compete with cylindrical cells in terms of energy density as of today. Due to their high volume utilization, energy densities of up to 870 Wh/L (310 Wh/kg) may become possible in 2025 and up to 950 Wh/L (350 Wh/kg) in 2030.

The calculations of potential energy densities represent automotive-type high-energy cells. They are at the upper boundary of industry announcements, which, besides high-energy, often also refer to high-power or high-cycle-life cells. In total, industry announcements seem feasible based on the material systems and choice of cell design discussed in this study.

Several features of these new generations of high-energy cells may be disadvantageous for their power densities and fast charging capabilities, e.g., low current collector thicknesses, high electrode loadings, and large cell volumes. Larger cell formats and volumes have a reduced surface area to energy content and a smaller number of contacts per energy content. Both surface area and cell contacts are used for cooling purposes in battery packs. The approach of using tabless designs may, however, allow for new cooling concepts. A conclusive assessment of internal resistance and thermal properties must involve a consideration of material, electrode, and cell properties and will be highly individual for each cell format.

4.5 Cell integration

The path towards higher useable energy densities remains the overarching goal for cell integration. Apart from the cell-level perspective, decisions and technology trends can also be tracked at the module and pack level. From 2020 onwards, we observe a trend towards elongated cells, i.e., an increase in length/width ratio, yet without a significant volume increase. Especially for prismatic cells, it is assumed that this development results from further integration efforts for a Cell-2-Pack design (CATL, BYD,...) primarily into the passenger car's underbody. This means omitting the intermediate level of modules and directly integrating individual cells into a complete pack to save inactive material at the pack level. In contrast, this trend entails limitations in undesirable electrical and thermal conditions at the cell level. Thus, further research focuses on the demand-oriented design of current collectors, internal cell structure, and high-performance thermal management.

Regarding the influence of tab orientation and size on temperature distribution and depth of discharge (DoD), studies have shown that changing tab size produces a less significant DoD imbalance in the cell than the current collector thickness. When the tabs are aligned on opposite sides of the cell, a more uniform temperature and DoD distribution are observed than when the tabs are aligned on the same side [77]. Larger cells than the 21700 (e.g., the

26650, or 4680) struggle with heat build-up due to larger cell diameters and thus longer distance to the current collector. Choosing the right tab design (single-, multitab, or tabless) is important for improving rate capability, charging efficiency, thermal safety, and resistance to Li plating [78].

Regarding the influence of cell geometry on the thermal behavior of a cell, the current challenges in thermal management lie primarily in external cooling. The upscaling of cell size/thickness is limited, as too large temperature gradients within the cell can lead to a shortened lifetime. Studies address cell thermal behavior over various ambient temperatures and C-rates during charging and discharging. Temperature gradients are discovered to explain current density distributions and local charge state differences, leading to undesirable electrical inhomogeneities [79,80]. In further studies, the specific heat capacity is found to have the largest effect on the maximum temperature rise. In contrast, the in-plane thermal conductivity most affects the maximum temperature distribution [81]. Further research shows the limited cooling capability of any cell format and size, which seems to be defined by the ratio of cooled surface area to electrode area and the thermal resistance of the particular cell geometry. Only thin cells with a large cooling surface to electrode area can be physically maintained within a non-critical operating temperature window and SoC when a low impedance is applied externally [82]. Other work examines the influence of cell formats in thermal management during cell integration. The investigation of minimum cell spacing and the subsequent determination of the sensitivity of module temperatures to cell spacing are addressed [83].

Figure 12: Schematic representation of the system integration of battery cells and modules.
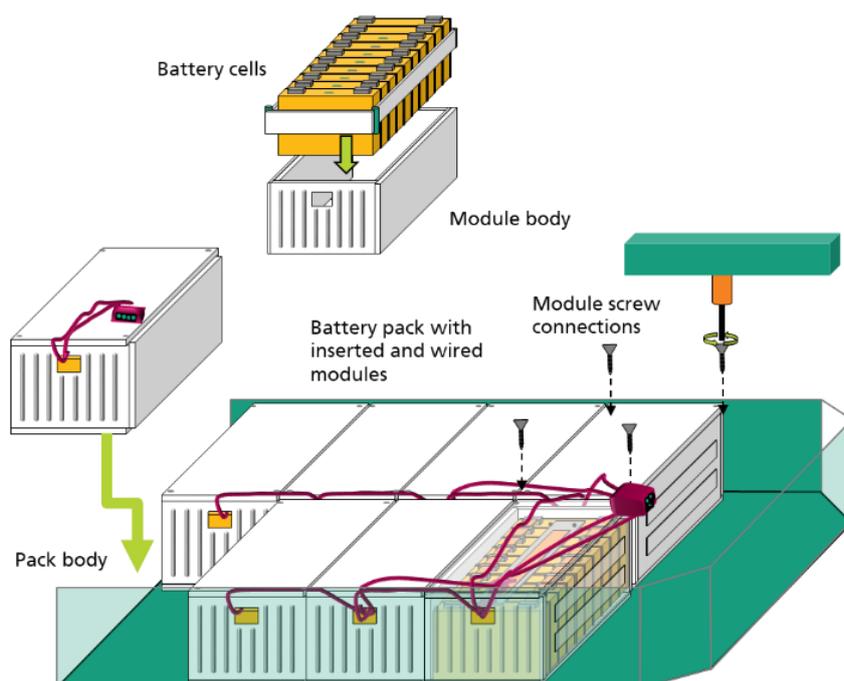
4.6 Cell production

While changes in the material selection, internal cell design, and cell dimensions affect the individual cells and the application-specific integration into the final product, the production processes are also affected. Thus, we start by introducing the current status of the battery cell production process in the following. These processes can be grouped into three manufacturing steps: Electrode fabrication, cell assembly, and formation/aging.

Electrode manufacturing requires active material powders for cathode and anode, passive material powders like binders or conductive materials, and aluminum and copper foils. First, electrode slurries for anode and cathode are mixed before processing in several roll-to-roll processes. The slurry is coated on the corresponding metal foil. This coating is typically on both sides and can be continuous or intermediate. Afterward, binders are evaporated in a continuous furnace. Electrode foils are calendered, slit into the required width, and wound to coils. Finally, coils are dried in vacuum ovens for several hours before being moved over to the cell assembly. Typically, cell format changes entail adaptations to the coating width by adjusting the slitting processes. The maximum cell dimensions are limited by the coating width ability of the coater. However,

increasing the coating width complicates attaining the required homogeneity of the coating thickness.

Cell assembly heavily depends on the cell type (cylindrical, prismatic hard-case, or pouch-type) as it requires specialized equipment and machinery. The assembly starts with the processing of the electrode coils. The anode and cathode materials are stacked, winded, folded, and joined with the separator. Several contacting and handling steps follow, the electrolyte is filled in, and the assembly ends with a sealing process (foil, can, or hard-case). The different processes of pouch, prismatic and cylindrical cells are compared in Figure 13 below. All processes up to the final sealing should be executed in a dry and clean environment. Typical requirements are a dew point below -30 °C and a cleanroom class 8 according to ISO 14644-1. In order to reduce energy requirements, innovative process designs address the realization of dry room atmosphere by using mini-environments (process-specific enclosures).

Assembly equipment is generally adapted to one specific cell size. As there are many handling processes, all grippers and tools are specific for each cell dimension. Especially the required space inside the machine is adapted to the cell size. A change in cell format is interrelated with a change of tools or often even equipment. Changing the cell size especially affects electrode and separator processing and electrolyte filling. Any electrode sheet processing gets more complex for larger formats, as precise handling and positioning steps are required. Further details are described

Figure 13: Comparison of the assembly of pouch, prismatic and cylindrical cells.
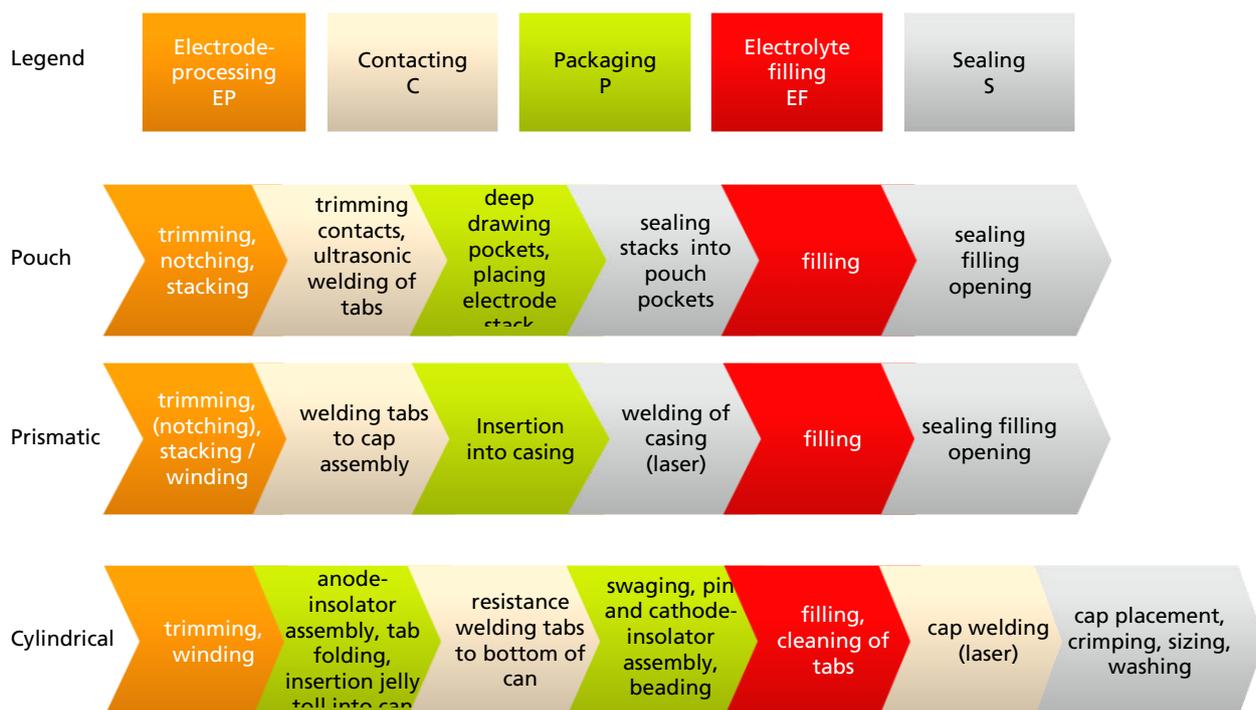
in the section on stacking/winding below. During the electrolyte filling, the electrolyte must infiltrate a greater surface and potentially more layers, which takes more time and makes any homogenous electrolyte distribution inside the cell stack/roll more vulnerable.

During formation and aging, the cells are charged for the first time and the SEI creation takes place. This involves several charging and discharging cycles during which an aging process happens. These steps can last several hours or even days. Enlarging the format requires higher current or even more time, but further obstacles, besides the general high safety precautions for larger cells, are not expected.

Due to the challenges described above in the production process as a whole and in particular with regard to certain cell formats, continuous improvements and innovations are indispensable. Some of the most relevant approaches and process steps are discussed in more detail below.

Tabless design

As described in the previous sections, larger cell formats must entail cell design changes to retain certain power efficiency (i.e., low internal cell resistance and good heat dissipation). This correlation spawned the so-called tabless design for cylindrical cells, e.g., presented by Tesla in September 2020. The internal layout of a conventional cylindrical cell a) and a tabless design b) is depicted in Figure 14. Several process steps need to be changed for manufacturing such a tabless cell design. First, electrode foil notching with a laser is required before the coil winding, while the winding machine need to handle shifted electrode foils with structured sides. The protruded metal strips must be folded while winding to ensure a planar tab. Also, the

electrical contacting processes must be adapted. Tesla has announced a frictional connection, but two-dimensional welding processes to decrease the internal resistance might be interesting too.

Cell production process steps

The connection of electrode and separator foils prior to folding/stacking simplifies the handling of foils (especially separator). The objective is to reinforce individual sheets to simplify the handling and avoid wrinkles and kinks. This can lead to higher process accuracy and minimized scrap, allowing for higher processing speeds. Furthermore, this connection might entail higher safety and stability since the cathode is secured against displacement. Since the stacking/winding process is the speed limiting process in cell assembly for both pouch-type and prismatic hard-case cells, this **lamination/gluing** technique has the potential to speed up the overall manufacturing process. In contrast, a further production step becomes necessary. Plus, the use of adhesives might also increase the proportion of inactive materials, reducing overall energy density. Limitations must be considered during material selection, as not all separators can be laminated.

Figure 14: Electrode and jelly-roll design of a) a conventional cell and b) a tabless cell design.
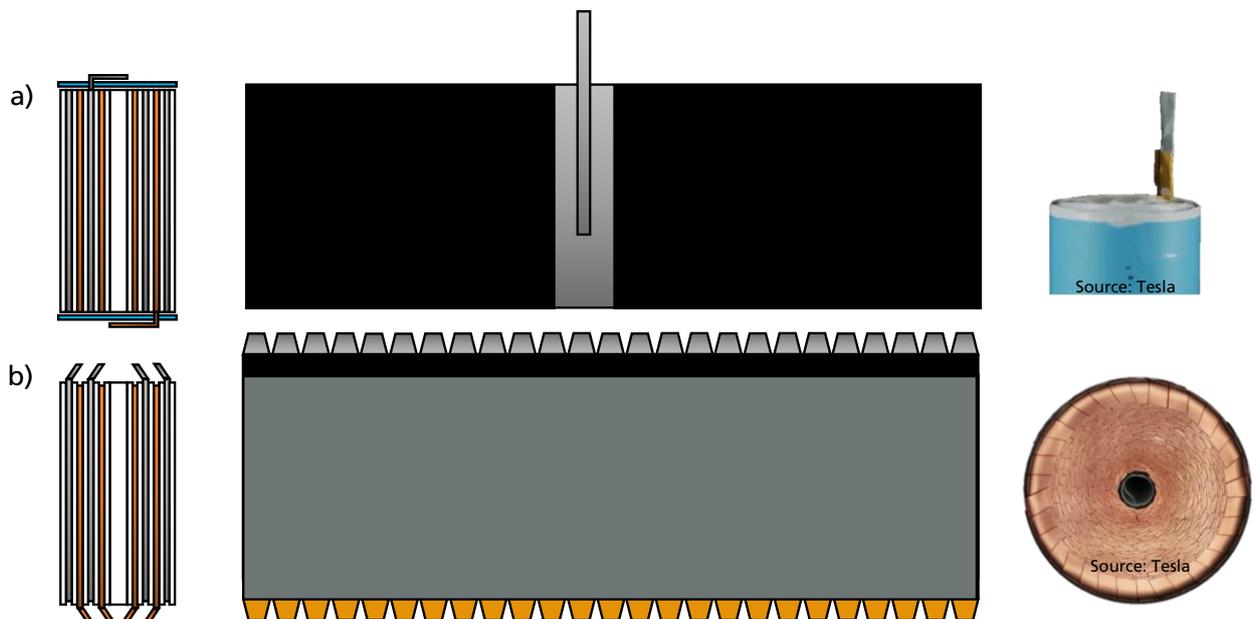
Given higher process speeds and larger cell dimensions, major challenges are currently still seen in the stacking process regarding positioning accuracy (short circuit, sealing) and separator handling (wrinkling and shrinking). As described above, the current technological status distinguishes between single sheet **stacking and flat winding / Z-folding** (used for pouch-type and prismatic hard-case cells) and **round winding** (cylindrical cells).

Single sheet stacking promises the highest energy density, high quality, and lower mechanical stress on the separator, while research focuses on higher process speeds and high positioning accuracy. In general, high positioning accuracies can be achieved by pick-and-place motion compared to Z-folding (High positioning accuracy (±0.01 mm), very low throughput speed < 1 sheet/s). Z-folding is well established. Current research aims to an even higher process speed with a simultaneous increase in positioning accuracy (approx. 0.1 - 0.5 mm; 18 cells per minute). Winding has already reached industrial maturity due to its simple process design and high speed, while higher mechanical stress on the electrodes is accepted.

In the light of ever-larger cells such as the BYD blades (900 mm), some experts consider large-scale series production unrealistic due to handling difficulties (susceptible mechanical stability and transport difficulties/gripper type) and positioning inaccuracy. Others see fully automated manufacturing as the solution to the handling challenges of large cells. In any case, continuous measurement and quality control loops should be considered. The investigation of air- or ultrasound-guided gripper systems for handling the individual sheets is also a research focus. Large cells place increased demands on manufacturing quality (minimizing the error rate). Thus, we synthesize that the perfect trade-off between production output, cell size, and scrappage must be evaluated individually. While this was likely around 20 Ah, considering the standard formats and many available automotive cells, this remains unclear today.

The influence of cell formats on the **joining technology** to electronically connect the cells on a module/pack level leads to a discussion on the suitability of technological alternatives. While ultrasonic welding is particularly suitable for joining pouch cells and wire bonding is suitable for large modules of small cylindrical cells, there are application-specific other technologies to be considered.

Laser welding is advantageous through flexible process control and low wear. Thus, it is suitable for cylindrical cells but may be less suitable in joining large cells with geometrically large connectors since it requires complete melting of the connector. Resistance spot welding and its process variants is another flexible technology that can be used for all battery cell types since the welding is local to the contact surfaces [84].

Depending on the cell size to be processed and, in particular, the current collector size, the technology selection should be based on a trade-off between necessary flexibility, wear, and technical feasibility.

In the next process step, the partially assembled cells are filled with electrolyte solution. **Electrolyte filling** is still one of the processes that have a significant influence on the process time in cell production. When producing larger cell formats, the amount of electrolyte to be filled increases. Depending on the cell design, this has a negative effect on the filling time, since longer wetting times must be expected. A distinction must first be made between rolled and stacked cells. Cell coils, such as those used in round cells, have two wetting directions, whereas cell stacks of pouch or prismatic cells have four wetting directions.

For rolled cells, the influence of the wetting time can be significantly reduced by increasing the diameter while maintaining the length of the cell coil. However, this negatively affects the required space for battery pack assembly. For cell stacks, wetting time can be reduced by increasing the number of layers in the cell stack rather than using larger outer dimensions of the electrode sheets. Wetting time can also be minimized by optimizing the outer dimensions of the electrode sheets. If wetting in two directions is applied, very long and thin cell sheets have an advantage in terms of wetting time. When all four wetting directions are utilized, a squared outer contour results as the optimum for shortening the wetting time.

With larger cell formats, mechanical processes for accelerating the wetting time are becoming increasingly important. Examples are the stimulation of wetting using alternating pressure cycles. Examples of novel processes for accelerating the wetting process are the roll pressing of

pouch cells, a wetting or tempering step for cylindrical and prismatic cells, and surface coatings/structuring. Particularly for large prismatic hard-case cells, longer process times until cell sealing and an increased electrolyte surface area lead to higher evaporation rates of the volatile solvents. This increases the extraction and filter technology demands in the electrolyte filling area.

Innovations in the field of cell finishing deal with an optimized design of the cyclic charge/discharge program for the **SEI-formation** to reduce the energy requirement. Second, the focus is on reducing the processing time during cell aging through innovative measurement methodologies for capacity degradation. Larger cell dimensions can impact the subsequent formation. General discussions on the process corridor for forming very large cells indicated that the output power per channel must be correspondingly high to cycle these cells even at higher C-rates. However, the total current required in the formation should barely change, as there are fewer cells for the same production output.

Excursus: Baseline energy consumption and GHG emissions

With an increasing societal focus on environmental issues, the topic of "green" manufacturing is gaining importance. In Germany, for example, CO_2 emission certificates will cost

55 EUR/t-CO_2-eq in 2025 [85]. As battery cell production is energy-intensive, this will be a significant cost driver. To assess the emissions by different process step, we consider an exemplary battery cell production line. Electricity is used as the energy source for virtually all processes. Natural gas is used only for dry room operation, accounting for roughly one-half of the total required energy. Together with vacuum drying, these three processes already account for up to 80% (depending on the factory's equipment) of total energy consumption [86]. The remaining energy is required as electricity, mainly for battery cell formation.

Given this energy consumption split, we assess the greenhouse gas emissions (GHG) caused directly or via the electricity mix. This is visualized in Figure 16. The highest share of GHG emissions is attributed to cell formation, with around 30% of total GHG emissions. The drying rooms, coating, and drying each account for about 20% of total GHG emissions. Overall, these three processes thus have a combined share of 70% of the GHG emissions.

Caption: Overview of CO_2 emissions per process step
Technological innovations to reduce energy consumption and emission rates in battery cell production should focus on these steps accordingly. The remaining production steps have shares of <6% each. Changes in cell geometry primarily affect the cell assembly processes and therefore have little influence on overall energy consumption. However, suppose the dry-room atmosphere is operated through mini-environments to increase overall energy efficiency. In that case, a format change to larger cells could potentially lead to an enclosure of the assembly steps with increased dimensions.

Figure 15: CO_2-footprint of selected cell manufacturing process steps.
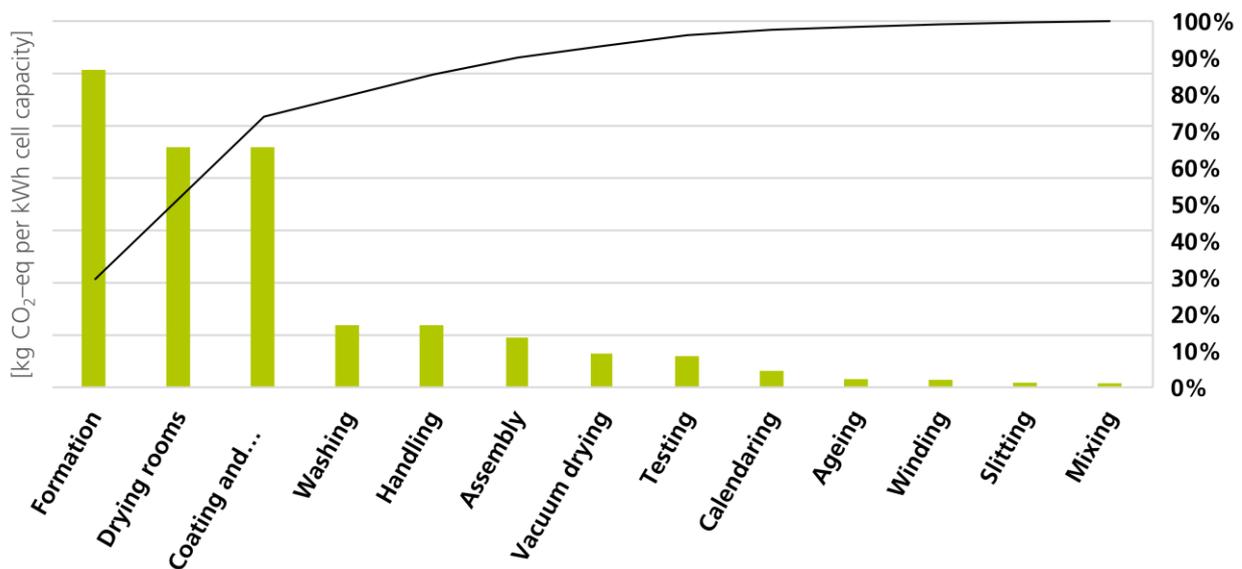
4.7 Cell costs

The cost of LIB cells consists of several components starting from resource cost, material and component manufacturing cost, cell production costs, and finally, profit margins and other overheads. All cost items can differ significantly depending on the application.

Cathode active material cost

Resource and raw material costs are the most decisive cost factors for cathode active materials. Typical battery resources like lithium, nickel, and cobalt have shown high price volatility during the last years. Since their major application is in batteries, lithium and cobalt prices are directly coupled to the demand generated by battery markets. Nickel is also utilized in many other steel sorts and materials and hence less prone to demand fluctuations in the battery market. Since 2018, cobalt prices have fluctuated up to 300% (max./min.) and lithium of up to 700%. While resource costs are the baseline for the cost of cathode active materials, there are additional costs for precursor refinement and material synthesis. The battery-grade purity requirements for the precursors require complex and multi-step production processes.

Cathode active material synthesis happens at high temperatures (600 to 800 °C) and is energy-intensive. Final cathode material prices can be double the resource cost for Ni-, Mn-, Co-based materials, depending on the specific composition (also dopings), particle morphology, coatings, synthesis technique, and facility locations (e.g., labor and energy costs).

Figure 17 shows final material costs for typical active materials. The numbers are based on average resource and precursor costs in 2021 and a cost model considering the synthesis procedure and exploitation rates. Orange diamonds indicate ranges from market studies. Note that in 2022, raw materials costs have significantly increased, particularly for lithium. The values shown in Figure 17 are hence not representative for 2022.

Anode active material cost

The impact of raw material costs on the cost of typical anode active materials is less pronounced than cathode active materials. On the one hand, this results from relatively low raw material costs for natural graphites, tars, and metallurgical silicon. On the other hand, the demanding production process may involve purification, milling, and coating for natural graphites, synthesis at extremely high temperature (~3000 °C) for synthetic graphites and purification, and high-energy milling and stabilization for silicon nanoparticles. Although metallurgical grade silicon can be obtained for a few EUR/kg, the cost of nanoparticles is often 40 to 80 EUR/kg and hence strongly decoupled from the cost of raw materials. This example demonstrates again the high potential for cost reductions that optimized material concepts and production techniques can leverage.

Other materials

The costs of other LIB cell materials like the electrolyte, separator, current collector, or housing components strongly depend on their function and scale of production. Over the last years, the price of typical automotive-grade separators and electrolytes has significantly decreased and is now around 1 EUR/m² and 5-10 EUR/kg, respectively. Electrolyte cost is mainly driven by the high purity requirements of the components and the Li-salt.

Figure 17: Material cost estimation of several active materials (cathode and anode) based on average resource costs and metal values in 2021. Estimations taken from external market studies are shown for some materials.
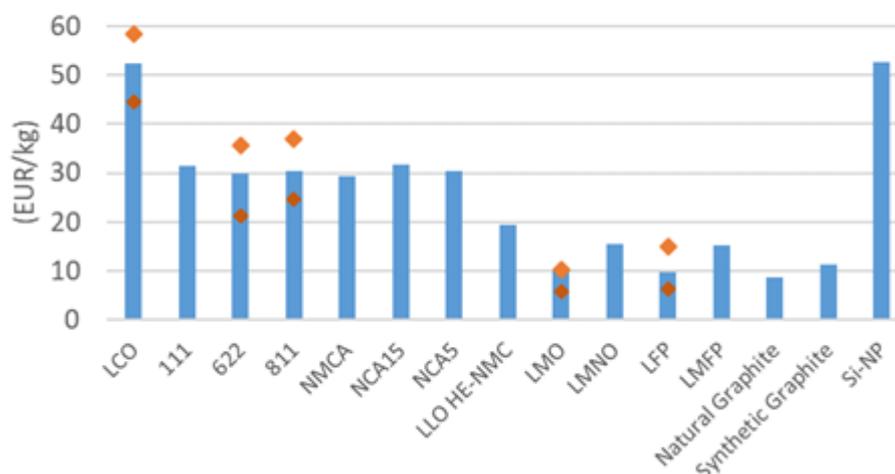
Electrolytes for niche applications (e.g., high- or low-temperature LIB cells) can have a significantly higher price than automotive or consumer applications.

The cost of cell housing is small compared to other cell components. Steel cans and other housing components for cylindrical cells are relatively cheap for the standardized formats (e.g., 21700) since these are typical bought-in parts from mass-market production. This standardization is different for many prismatic hard case housings with a high degree of customization and, thus, often smaller production quantities. The cost of pouch foils is relatively cheap. However, it cannot be directly compared to hard-case cells because the actual process of housing production (cutting, deep drawing) is part of the cell production and hence not included in the foil cost.

Manufacturing costs

In addition to the mere material costs, further costs are incurred in battery production. Actual costs are familiar, and modeling the impact of cost-reducing measures is possible using analytical and parametric methods. For example, process-based bottom-up calculations based on real data provide a solid foundation for structuring and validation. In the following, the distribution of different cost components in manufacturing (machinery, energy, labor, footprint, building, dry room, and overhead) is discussed based on the case of 21700-cell manufacturing in Germany. Subsequently, cost reduction potentials are illustrated by optimizing the individual cost positions. Finally, future technologies and their influence on manufacturing costs are outlined.

Figure 18 shows the cost structure of an exemplary battery cell production process. C_{total} reflects the total production costs aggregated from several cost positions mentioned (machinery, energy, labor) in the following. It is estimated that for this production plant, the production of 1 kWh

battery capacity costs between 25 and 30 EUR. Furthermore, the effect of individual cost-reducing measures (M1 production output homogenization, M2 reducing investment costs of machinery, M3 location with lower electricity costs, M4 location with lower labor costs) is shown in Figure 18.

The main cost drivers are costs for machine depreciation, followed by labor and energy costs. The costs for the footprint and building are negligibly small. These general parameters are largely independent of the cell format. Studies describe a slightly higher capital investment for pouch cells' manufacturing equipment than for prismatic and cylindrical cells. For an annual production of 4 GWh of storage capacity, an investment of 58.5 million EUR for pouch cells and 55 million EUR for prismatic/cylindrical cells is exemplarily mentioned [87].

Besides cost-reducing measures such as negotiations and site selection, the use of future technologies might also positively affect the cost structure of battery cell production. Potential cost reductions are noted for the following technological innovations: F1 using NMC811 / silicon-containing cell chemistry, F2 processing tabless electrode & continuous coating, F3 applying dry-coating technologies.

Referring to the announced introduction of larger cell dimensions required by the application in the automotive industry, handling technology and measuring methods, and quality controls must be further developed to reduce scrap. Due to the necessary higher demand for automation in the process technology of assembly, higher investment costs are expected, but with lower scrap rates and higher machine availability.

Figure 18: Overview of manufacturing costs for an exemplary 21700 cell production with cost reduction potentials.

Total LIB cell costs

Various studies address the ratio of material to manufacturing costs for battery cell production. Leaving aside any additional overheads, their statements assess the share of manufacturing and materials between 20-35% for manufacturing costs and 65-80% for material costs to the total costs per cell [3,6,7,9,63,65,66,67,68]. The outlined example of manufacturing costs with a cost range of 25-30 EUR/kWh (see above) indicates an average total cost of 100 EUR/kWh at cell-level. As noted before, these values might not be representative for 2022, since raw material and energy cost have significantly increased.

When comparing the costs of cells in different cell formats, consideration must be given to production volumes, process automation, the inclusion of inactive components (such as housings and electrical connectors), production country, and the intended application. In many cases, the following order of cell formats is found, ranked by cost: cylindrical < prismatic < pouch. However, estimates assume that, especially for the application fields xEV and ESS, this order might change to "prismatic < pouch < cylindrical", as much optimization potential is still seen in the design and processing of these formats.

Both material and manufacturing costs entail a high potential for cost savings and an overall decrease in LIB cell costs. However, this assumes decreasing or at least stable raw materials and energy costs, which was not the case in

the last years. Hence, any price forecasts for LIB cells need to be taken with caution and a quantitative forecast of material costs is not possible in light of fluctuating raw material costs. Figure 20 shows the analysis of several price forecasts taken from market studies. By implementing the economic measures on the manufacturing level, which were described above, new manufacturing technologies could contribute to a cost reduction of about 15 EUR/kWh.

Figure 20: Meta-analysis of several market studies (colored dots) on the future development of LIB-cell costs [6,88,89,90,91,92,93,94,95,96]. Lowest costs could be possible with LFP or Mn-based materials.
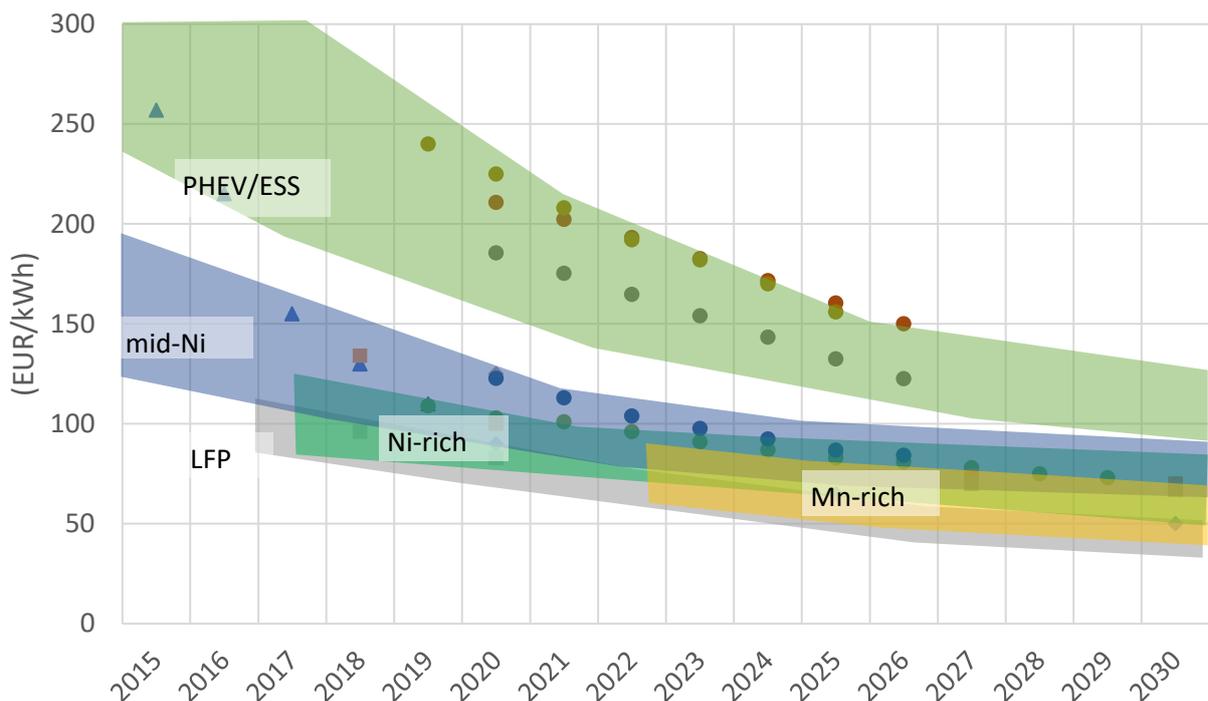
4.8 Cell safety properties

Battery safety is one crucial factor in choosing the best battery cell for the specific application and its requirements. Thus, we aim to provide a rough assessment of cell safety and focus on differences in safety behavior between different formats with a given module concept. Since a detailed safety analysis in the sense of an FMEA (Failure Mode and Effects Analysis) would exceed the scope and focus of this study, we limit to a qualitative cell format assessment based on the event of a thermal runaway (TR) triggered by nail penetration. Note that the assessment focuses on the current state-of-the-art (period 2019 - 2020), as it is difficult to estimate the design of future cells and modules regarding safety-relevant elements. Setup and measurement are schematically shown in Figure 21. Measurements involve the released energy, spatially resolved temperature distributions, gas pressure curve, and cell mass determination before and after the test.

Figure 21: Scheme of the experimental setup for heat determination [12].
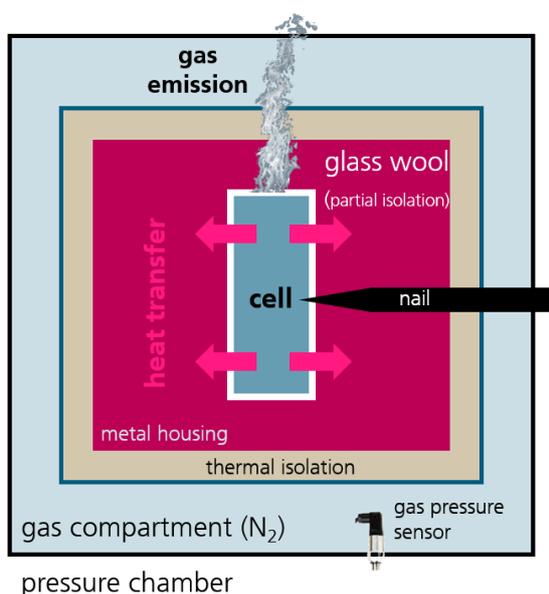
Only prismatic Li-ion cells with different cell formats (length: 148 mm to 366 mm, width: 21 mm to 46 mm) were tested and considered here.

As passive safety devices, all cells tested had a bursting plate (also safety vent) to degas the cell as directionally as possible in the event of internal gassing (triggered by the TR). This is to prevent rupture of the cell housing at high internal pressure. The housings were made of aluminum for all cells.

The cell chemistry and internal cell structure were largely unknown. The safety of the cells was evaluated based on the 7 EUCAR Hazard Levels (HL) (cf. Table 5).

Table 5: EUCAR classification [18]

Hazard Level	Descript.	Classification Criteria & Effect
0	no effect	No effect. No loss of functionality.
1	passive protection activated	No defect; no leakage; no venting, fire, or flame; no rupture; no explosion; no exothermic reaction or thermal runaway. Cell reversibly damaged. Repair of protection device needed.
2	defect/ damage	No leakage; no venting, fire, or flame; no rupture; no explosion; no exothermic reaction or thermal runaway. Cell irreversibly damaged. Repair needed.
3	leakage (Δmass < 50%)	No venting, fire, or flame; no rupture; no explosion. Weight loss < 50% of electrolyte weight (electrolyte = solvent + salt).
4	Venting (Δmass $\geq$ 50%)	No fire, or flame; no rupture; no explosion. Weight loss $\geq$ 50% of electrolyte weight (electrolyte = solvent + salt).
5	fire or flame	No rupture; no explosion (i.e. no flying parts).
6	rupture	No explosion, but flying parts of active mass.
7	explosion	explosion (i.e. disintegration of the cell).

The average energy density of the cells has been increasing for years (gravimetric energy density > 250 Wh/kg on average from 2019), which also increases their hazard potential. Accordingly, all tested cells reached at least Hazard Level 6. This happens due to "sideruptures", i.e., ruptures on the cell housing and observed ejected particles consisting of active material. In addition, cells were categorized as Hazard Level 7 once the cell lid was blown off and the cell interior (electrode stack or electrode coil) was pushed out of the cell housing by the TR of the cell. This process features increased mass loss (> 60%) and decreased energy dissipated through the cell case to the environment. The experiments showed that not packing the electrodes too tightly in the cell is critical for high cell safety

(whether stacked/wound). Gas channels must be present, or the cell will explode during TR (HL 7). The size of the safety pressure release valves and design of the burst plate (i.e., opening at defined pressure) is also critical to safety. Melting of the aluminum housing is the most serious safety problem since the vent gas should be discharged via the safety vent and not in an uncontrolled manner. Here, the cell format probably plays only a minor role in single-cell safety compared to cell chemistry, structure, and bursting plate design.

Cell safety plays a crucial role in prismatic cells (as described above) and for all formats. In general, the hazard potential indeed increases with increasing energy density for all cell formats. Besides typical effects for all cells such as loss of cell voltage, self-heating of the cell, production of gas, cell rupture, and particle ejection during thermal runaway, cylindrical and prismatic cells can withstand internal pressure better than pouch cells due to their hard-case housing compared with a more flexible and thinner pouch foil housing [97]. However, increasing energy density risks building higher internal pressure and slightly reduces safety. Venting rates are also format-dependent and differ between hard-case housings and pouch cells. In cylindrical and prismatic hard-case cells, the venting gas escapes through a small hole in the housing (i.e., bursting plates) with higher stream velocity than in pouch-type cells. Pouch-type cells rupture along welding seams for bigger openings (special breaking points and safety vents cannot be installed). Cylindrical cells are equipped with two protective devices: a CID (current interrupt device) that opens to stop the inner current circuit when pressure rises in the cell and a temperature-dependent disc (PTC, positive thermal coefficient), which reduces the current when the internal cell temperature rises. Once the CID opens, the cell can no longer be discharged or charged. To increase safety in prismatic cells, a CID is also installed in addition to the bursting plate. Pressure relief takes place at about ≤ 0.5 bar. At the level of cell chemistry, the cell formats play a minor role in cell safety. In addition to suitable electrodes (e.g., the temperature released during TR with LFP cathodes is lower than with NMC or NCA materials), overcharge protection additives or flame retardant additives may be added to the electrolyte. Shut-down separators and ceramic coatings significantly increase safety. Shut-down separators are mainly used in small-format cells; in large-format cells, their shrinkage can be challenging so that a short circuit can occur at the edges of the cell.

The thermal management is another important factor that could reduce safety risks. In cylindrical cells the heat generation mainly starts next to the core while it is initially observed close to the tabs in prismatic and pouch cells. Proper heat dissipation and cooling (depending on current densities) are necessary and part of a suitable cell design (e.g., tab configurations, tab materials, structures, and

welding). Enclosing cylindrical cells with heat-absorbing materials, for example, can prevent propagation because the heat is dissipated quickly and efficiently. However, enclosing the cell with thermally and mechanically stable materials (e.g., steel) increases its safety but lowers the energy density and increases the cell costs.

In summary, a qualitative comparison of the safety of the different cell formats is complex, as the cells differ greatly (e.g., cell design, high-energy vs. high-power). General trends can be observed: a) the safety risk increases with increasing energy density for all formats, b) prismatic and cylindrical cells have better resistance to higher internal cell pressure, and c) harmful heat generation occurs first in cylindrical cells near the core, in pouch-type and prismatic hard-case cells at the tabs. In all formats, safety features on different cell levels (cell chemistry, electrolytes, separators, protective devices (CID, PTC), housing, sensors, battery management) do not always prevent a thermal runaway or a propagation. However, they significantly reduce the risks of safety-related incidents.

4.9 Excursus: Solid-state batteries

Due to their market maturity, the currently market-dominating cell chemistries may reach technical limits in 5 to 10 years. Given this, alternative battery technologies are currently under investigation, which may surpass the performance of the current generation of batteries. One of the most promising and currently researched alternative cell technology is the solid-state battery (SSB). Advantages might be an increased energy density through alternative anode materials, especially Li-metal anode, and safety advantages due to the elimination of flammable electrolytes in the cell concept. First applications (mainly busses) are already available in small series with SSB batteries. [105]

The structure of SSB compared to state-of-the-art LIB is slightly different (Figure 21). The first difference compared to LIB is the solid electrolyte (SE) which replaces the separator and the liquid electrolyte. The porous electrode active materials for the cathode (and anode, if porous material are used) are mixed with the SE for contacting all components. This mixture is then called catholyte or anolyte. For cathodes, the same active materials can be applied as in conventional LIBs. Due to technical challenges (e.g., conductivity or processability), gel electrolytes might be used instead of SE. Thus, conventional electrolytes can be considered an intermediate step to all-solid-state batteries (ASSB). Another difference compared to state-of-the-art LIB is the possible use of Li-metal anodes instead of porous material (e.g., graphite, graphite-silicon composite, LTO). Given this, SEs are required because of chemical stability towards Li-metal and mechanical stability against Li-dendrite growth.

Three different electrolyte classes seem most promising: polymers, oxide- and sulfide-based solid electrolytes. Oxide and sulfide materials are inorganic, whereas polymers are often declared organic components (even if the conducting salt is inorganic). All three classes have different properties. Polymers are the most established and have advantages in material availability and production technologies.

Challenges are poor ionic conductivity at room temperature and low compatibility with high-voltage cathode active materials (CAM) or metallic lithium. Oxides are brittle yet have a high mechanical and chemical stability and therefore entail the lowest process environment requirements. However, oxides require high production temperatures. Sulfides tend to have the highest ionic conductivities and are mechanically softer, enabling easier processing. However, the precursor availability and the stability against Li-metal and high-voltage CAM are low. In addition, they need high process environment requirements.

The different material properties of the SE also entail differences in the production of the individual electrolyte classes. In initial approaches, oxide and sulfide materials are produced in wet processing. The starting materials are mixed and subsequently coated on the cathode or fabricated as free-standing SE. Sulfides have to be calendared or cold-pressed in a dry atmosphere afterward. For the production of oxide SE separators, a sintering processing step is necessary to enable contact, low porosity, and high ionic conductivity. This requires high temperatures above 1000 °C and causes a high energy input and thus high cost. The processing of inorganic SE materials is not established yet. Polymer SE can be produced in a solvent-free approach with a dry extrusion process, which is already established.

Figure 21: Structural design of liquid electrolyte LIB (left) and SSB electrode stacks (right). [105]
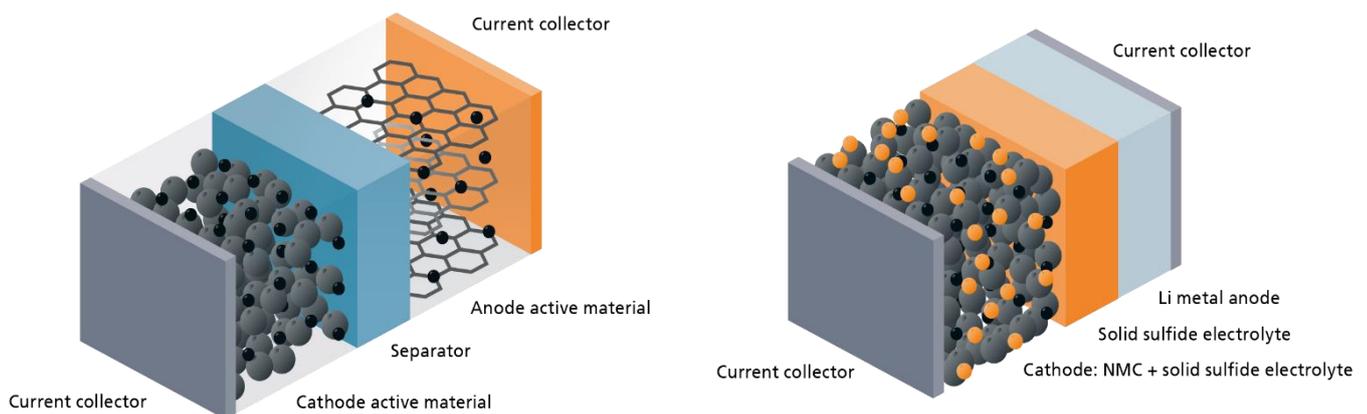
In the future, aerosol deposition processes may be used. For oxides, this may dispense the sintering step. Cathode composites are processed according to the processing steps of SE separators with additional CAM. For oxides, a low-temperature sintering step is necessary. An extrusion process realizes the processing of Li-metal anodes to produce a thin-film active material. In the future, anode-free "in-situ" cell concepts may be implemented.

The components must be cut in the first step to assemble the cells, e.g., by laser cutting. Thereby, the cell components (anode, SE separator, and cathode) can be stacked in a single-sheet stacking process that still poses challenges (see the previous section). Afterward, the cell stack is pressed together. Formation and aging are shorter than those of LIBs. Bipolar stacked SSB electrodes (current collector functions as a collector of two adjacent cells) are often mentioned as a future possibility to increase energy density at the module level. Furthermore, SSB batteries do not require cooling units at the pack level, as operation at higher temperatures is possible due to SE separator properties. However, some SSB systems (e.g., polymers) require heating units to reach cell temperatures that enable proper ionic conductivity.

Compared to state-of-the-art LIBs in different cell formats, pouch-type cells are most convenient for SSBs because bending or winding is problematic for SE materials. Up to now, external high pressure is used to ensure good contact between the layers. An additional casing to the pouch foil during the cell-to-stack assembling is required, reducing energy density. This technical implementation is more difficult for round cells and prismatic cells. The cyclic volume change amplifies additional problems for the contacting of winded SE in round cells.

Even though SSB cells are at a very early stage of development, there are already available cells or prototypes. The current market share of SSB is well below 1% (mainly based on polymer electrolyte SSB) and will probably only slightly increase in the coming decade. Today, SE separator thicknesses of 20-30 μm have been demonstrated [98,99,100]. The production of uniform and defect-free layers in large-scale production is still challenging. Target thicknesses are 5-10 μm, which is comparable to separators in conventional LIBs (10-20 μm) [101]. Li-metal anodes of actual cell concepts have layer thicknesses >30 μm. Processing of thinner layers is still challenging. In the future, the layer thickness may be less than 20 μm.

For the cathode, a similar trend in terms of coating thickness may be followed as described for liquid electrolyte LIB in Section 4.2. A pre-condition for high cathode thicknesses is required to ensure proper ionic conductivity, which is today not given for all SE classes. Prototype cells of inorganic electrolyte SSB have dimensions between 70 x 85 mm and 90 x 200 mm and 4 to 22 layers. Those cells feature a capacity of 100 mAh to 20 Ah [98,102]. So far, there are challenges concerning processing or material compatibility for all-solid-state material and cell systems. However, new process routes and coatings chemically separating the components may solve these problems in the future. A further challenge is the scale-up of individual SSB manufacturing processes.

5. Cell formats and applications

We now close our study by comparing previous findings for six widespread applications and their requirements (see Section 3) versus technical characteristics given available as well as announced cell formats (Section 4.1) and their cell design parameters (Section 4.2-4.5). To do so, the evaluation method, introduced in Section 2, comprises cost, safety, energy density, flexibility, thermal management, and resilience. The evaluation focuses on qualitative assessment rather than precise quantification to define inner and outer limits for importance or achievement level respectively. Thus, we emphasized that our multi-criteria evaluation reflects certain assumptions and simplifications so that generalized statements cannot be made.

Figure 22 shows the final result per application that involves a spider diagram to visualize the techno-economic fit, a description and dimensioning per format, and the suitability per format. This evaluation demonstrates that classic development goals, cost-optimized or energy density-optimized, are important. However, real-world applications require even more heterogeneity and goals beyond to reach the perfect fit. While requirements for buses are moderate and no format is inherently unsuitable, VTOL requires small-scaled and lightweight cells with high energy and power density, making prismatic hard case cells unsuitable. For stationary storages, higher safety due to the cell housing of the prismatic cells does not result in any effective advantage. Thus, cheap cells, i.e., currently most cost-effective cylindrical cells closely followed by pouch cells, benefit. While this stability and best heat dissipation would be advantageous for power tools, both design space, lightweight, and flexibility make cylindrical cells primed for this application rather than prismatic ones. Last, minimal weight, best design space utilization, and high cost-effectiveness make pouch cells primed for smartphones.

Eventually, we reflect our previous findings against the standard formats from the old study [8] where two cylindrical formats, i.e., 18650 and 21700, the two prismatic formats, i.e., PHEV2 and BEV2, as well as one pouch format were analyzed for automotive application. This study finds the pouch cell format as consistently most advantageous over time and with different optimization criteria, followed by 21700 cells. Indeed, we do not find these results outdated or falsified by today. However, in addition to these few formats, many other formats have developed in contrast to the presumed penetration for

higher economies of scale. This is precisely in line with highly individual requirements per electrified application, cross-effects between different applications and highly individual manufacturers' and suppliers' philosophies.

Charging Stations		Size not critical 21700 or 18650 because of cost efficiency Aspect ratio and volume not critical Cost efficient format should be implemented Cell format would work Cell cost may be too high
Smartphones		No fitting format for application Adaptable size for best volume usage No fitting format for application
Power Tools		18650 or 21700 preferred formats with optimized energy and power density Could be fitted in battery pack Mechanical stress should be considered No fitting format for application

6. Summary and conclusions

The increasing electrification of cross-industry applications entails multi-facet and application-specific requirements on battery cells. The battery characteristics are significantly influenced by the cell chemistry, material composition, and cell format. The latter directly affects the volumetric and gravimetric energy density, the production processes, the cell costs, the thermal management, and the safety properties. To date, four principal formats have emerged: prismatic hard-case, cylindrical, pouch-type, and small coin-type cell. While each of these cell formats has its intrinsic advantages and disadvantages, design decisions are often been based on single characteristics (i.e., cost-optimized, high-energy, or high-power), availability, and established supplier relationships rather than on a holistic technical-fit assessment. Therefore, this study investigates these different cell formats and their relation to cell chemistries, production, costs, safety, and suitability for several applications. Starting from the status quo, we identify the most important trends for the next few years.

In order to assess cell formats and geometries regarding their fit to a specific application, two different perspectives should be considered: technology push and market pull. The technology push covers main properties such as (1) cost, (2) safety, (3) energy density, (4) flexibility, (5) thermal management, and (6) resilience. Typically, pouch-type cells have the best flexibility since small geometrical changes, especially the cell thickness, can be easiest implemented in the cell manufacturing process compared to the other cell formats. While the thermal management depends on the cell geometry type and the resulting heat dissipation, general assumptions of the three formats are still feasible. Prismatic hard case cells showed the best heat dissipation potentials, and pouch-type cells with a polymer foil on the outside showed the worst.

Status Quo and announcements

A shift towards larger cells and correspondingly higher capacities per cell can be identified across all formats in recent years. Given the identified cell dimension trends for pouch-type and prismatic hard-case cells, a corridor of around 0.4 to 1 L cell volume emerges. A local concentration between 0.5 and 0.75 L is noticeable. Exemplary for pouch cells, this volume corridor correlates to between 250 and 600 mm for cell length, 70 to 120 mm for cell width, and 7 to 12.5 mm for cell thickness. Typical automotive examples to enable high vehicle underbody

utilization are the full-body-width Blade battery or the 500+ mm pouch-type MBE cells.

Regarding handling, manufacturability, cell stability, safety, and failure costs, cells are likely to not become any larger than already available cells or the latest announcements. Thus, ultra-large cells may rather represent an exception. Note that even these cells like the BYD blade cell or the AESC Gen5 have only around 1.4 L cell volume. For cylindrical cells, the 18650 (0.017 L) may co-exist as a high-power format in parallel to 21700 (0.024 L) as volume format and even larger formats like the 4680 (0.133 L) as potentially premium format as well as other common formats - especially for consumer applications - and other non-common formats.

Cell designs and materials

Concerning cell concepts and especially materials, we conclude that a wide range of new or optimized high-energy materials is available for future use in LIB. For example, it is foreseeable that Si-based anode concepts will be introduced on a larger scale in LIB in the next 5 to 10 years. This can be seen as the most important lever at the material level for increasing the energy density of the cells. However, there will also be important advances on the cathode side. Increased cell energy can be expected from advanced NMCA-type materials or the new class of Mn- and Li-rich layered oxides. In parallel, the trend towards lower-cost materials like LFP will become more pronounced, even though this means less increase in energy density. These new material concepts require changes also on the electrode level. This concerns, for instance, new binder systems and electrode designs that can withstand the high volume change of Si-particles during cycling. For high-energy cells, an increase in cathode thickness to more than 100 µm can be expected by 2030.

For pouch-type and prismatic hard-case cells, electrode stacks will replace flat electrode coils because these assembly techniques enable a higher volume utilization. Enabled by these material and cell design improvements, energy densities may reach around 850 Wh/L for pouch-type and 750 to 800 Wh/L for prismatic hard-case and cylindrical cells by 2025. By 2030, these values could increase to about 950 Wh/L for pouch-type and 850 to 900 Wh/L for prismatic hard-case and cylindrical cells.

In addition to the concrete cell-level improvements, the effects and integration measures at the module and package level are decisive for achieving the best possible fit, for example, high energy density or low costs. Especially for prismatic hard-case cells, these further integration efforts are assumed to result in a "Cell-2-Pack" design. Respective adaptations to thermal management at cell and module/pack level are crucial for integration and are evident in work on requirements-based cooling concepts.

Cell production

The decision for a specific cell format has a tangible impact on the production and may involve considerable adjustments. In the case of electrode production, for example, a change of format requires an adjustment of the coating width, as the equipment of an assembly line is generally adapted to specific cell sizes. Thus, only limited variations are allowed. Since there are many handling processes, all grippers and tools are specifically adapted for each cell size, possibly leading to a change of tools or often even equipment. The increase in size also implies higher power consumption or even more time for production. Furthermore, larger formats also require more time for electrolyte filling due to a longer wetting time. The precise handling of such large electrode sheets is challenging.

As the issue of energy consumption and CO_2 footprint, in particular, is becoming increasingly important, there is also intensive research into innovations to reduce these. Such innovative approaches concern, for example, the creation of a dry room atmosphere using mini-environments (process-specific enclosures).

Costs

Considering the actual cost share at the material and cell level reveals that the costs for active cathode materials show high volatility due to fluctuations in raw material and resource costs. This effect can be partially counteracted with improved production techniques and further integration along the supply chain. This is particularly important for special silicon materials, which are now much more expensive than their precursors. Another current approach aimed at further reducing costs is using lower-cost active cathode materials based on Fe or Mn. Although these materials are coupled with energy density drawbacks compared to Ni- and Co-based materials, they prove suitable for cells in applications with corresponding requirements.

Production costs account for about 20-35% of the total battery cell costs (currently around 100 EUR/kWh). The main cost drivers are the cost of machine depreciation, followed by labor and energy costs. In addition to cost-reducing measures such as supplier selection and production location, innovative production approaches can also positively impact the cost structure of battery cell production. When comparing the costs of cells in different cell formats, consideration must be given to production volumes, process automation, the inclusion of inactive components (such as housings and electrical connectors), production country, and the intended application. In many cases, the following order of cell formats is found, ranked by cost: cylindrical < prismatic < pouch. However, estimates assume that, especially for the application fields xEV and ESS, this order might change, as much optimization potential is still seen in the design and processing.

Safety

Cell safety is decisive for all formats. However, a quantitative comparison of the safety of the different cell formats is complex, as the cells differ greatly from each other (e.g., cell design, high-energy vs. high-power) and moreover, are used for a wide range of applications (e.g., 3C, e-mobility, stationary, medical devices, aviation). It is not the cell format but the cell design, cell chemistry, cell structure, and safety features (e.g., protective devices (safety vent, CID, PTC), separators, housing, thermal management, sensors) that determine the cell safety of individual cells. Nevertheless, general trends can be observed: a) the safety risk increases with increasing energy density for all formats, b) prismatic and cylindrical cells have better resistance to higher internal cell pressure, and c) harmful heat generation occurs first in cylindrical cells near the core, in pouch-type and prismatic hard-case cells at the tabs. Within the scope of the study, prismatic Li-ion cells with different cell designs were tested with regard to their hazard potential. The cells were then classified within the EUCAR hazard level.

Battery applications and requirements

The market pull perspective combines the characteristics mentioned above of the cell formats with the specific requirements of six exemplary applications from the field of mobile, stationary, and consumer applications: Buses, drones (VTOL - Vertical Take-Off and Landing), residential storage systems, buffers for charging stations, smartphones, and power tools. The cylindrical cells thereby seem to be suitable for most of the applications considered here. This is particularly due to the high system voltage in limited space and the low costs. Their use in smartphones is rather disadvantageous due to the unfavorable round format. The prismatic format seems to be predominantly suitable for mobile applications such as buses. For the other applications, it is considered unsuitable because the comparatively higher costs play a more important role. The pouch format shows medium to good suitability for all the applications considered. The flexibility and cost-efficiency, in particular, are an advantage.

References

[1] Dorrmann, L.; Sann-Ferro, K.; Heininger P.; Mähliß, J. (2021): VDE: Kompendium Li-Ionen-Batterien. Grundlagen, Merkmale, Gesetze und Normen. Frankfurt am Main: VDE Verband der Elektrotechnik Elektronik Informationstechnik e.V.

[2] Allekotte M.; Bergk F.; Biemann K.; Deregowski C.; Knörr W.; Althaus H.; Sutter D.; Bergmann T.; Umweltbundesamt, „Ökologische Bewertung von Verkehrsarten," 2020.

[3] Grey, Clare P.; Hall, David S. (2020): Prospects for lithium-ion batteries and beyond-a 2030 vision. Nature communications 11 (1), S. 6279. DOI: 10.1038/s41467-020-19991-4

[4] B3 Corporation (2021): B3 Report 21-22 Chapter 8 "LIB-equipped Vehicle Market Bulletin"

[5] Pillot C. (2020): The Worldwide rechargeable Battery Market 2019 – 2030, 28th Edition

[6] Roskill (2020): Li-ion batteries: Outlook to 2029. Update 4

[7] Yano Research Institute (2020): 2019-2020 Current Status and Future Prospects of LiB Material Market: Major Four Materials

[8] Hettesheimer T.; Thielmann A.; Neef C.; Möller K.; Wolter M.; Lorentz V.; Gepp M.; Wenger M.; Prill T.; Zausch J.; Kitzler P.; Montnacher J.; Miller M.; Hagen M.; Fanz P. (2017): Entwicklungsperspektiven für Zellformate von Lithium-Ionen-Batterien in der Elektromobilität. Pfinztal: Fraunhofer-Allianz Batterien

[9] Duffner, F.; Mauler, L.; Wentker, M.; Leker, J.; Winter, M. (2021): Large-scale automotive battery cell manufacturing: Analyzing strategic and operational effects on manufacturing costs. In: International Journal of Production Economics, 232, S. 107982.

[10] Field, F.; Kirchain, R.; Roth, R. (2007): Process cost modeling: Strategic engineering and economic evaluation of materials technologies. In: JOM, 59 (10), S. 21–32.

[11] Tornberg, Katja; Jämsen, Miikka; Paranko, Jari (2002): Activity-based costing and process modeling for cost-conscious product design: A case study in a manufacturing company. In: International Journal of Production Economics 79 (1), S. 75–82. DOI: 10.1016/S0925-5273(00)00179-1.

[12] Hoelle, S.; Scharner, S.; Asanin, S.; Hinrichsen, O. (2021): Analysis on Thermal Runaway Behavior of Prismatic Lithium-Ion Batteries with Autoclave Calorimetry. In: Journal of The Electrochemical Society, 168 (12), S. 120515.

[13] Acea Fact Sheet [Online]. Available: https://www.acea.auto/files/buses_fact_sheet_ACEA.pdf (accessed on 18. March 2022)

[14] Heid, B.; Kässer, M.; Müller, T.; Pautmeier, S. (2018): Fast transit: Why urban e-buses lead electric-vehicle growth. McKinsey, 2. Oct. 2018, https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/fast-transit-why-urban-e-buses-lead-electric-vehicle-growth (accessed on 12. May 2022)

[15] IEA (2021): Global EV Outlook 2021 [Online]. Available: https://www.iea.org/reports/global-ev-outlook-2021 (accessed on 12. March 2022)

[16] Bloomberg, https://assets.bbhub.io/professional/sites/24/2018/04/graph.jpg (accessed on 12. March 2022)

[17] Generaldirektion Mobilität und Verkehr (Eurpoäische Komission) (2021): EU transport in figures [Online]. Available: https://op.europa.eu/de/publication-detail/-/publication/14d7e768-1b50-11ec-b4fe-01aa75ed71a1 (accessed on 14. April 2022)

[18] EUCAR (2019): Battery requirements for future automotive applications [Online]. Available: https://eucar.be/wp-content/uploads/2019/08/20190710-EG-BEV-FCEV-Battery-requirements-FINAL.pdf (accessed on 4. May 2022)

[19]   Business Insider (2019): Drone technology uses and applications for commercial, industrial and military drones in 2021 and the future. Business Insider, 12. Jan. 2019, https://www.businessinsider.com/drone-technology-uses-applications (accessed on 14. April 2022)

[20]   Nawaz, H.; Ali, H. M.; Massan, S.-R. (2019): Applications of unmanned aerial vehicles: a review. In: 3C Tecnología_Glosas de innovación aplicadas a la pyme, S. 85–105.

[21]   Cohn P.; Green A.; Langstaff M.; Roller M. (2017): Commercial drones are here: The future of unmanned aerial systems. In: McKinsey & Company

[22]   Avicienne Energy (2020): Drone battery market 2019 to 2030

[23]   Figgener J. et al., "The development of stationary battery storage systems in Germany – A market review," Journal of Energy Storage, vol. 29, p. 101153, 2020, DOI: 10.1016/j.est.2019.101153.

[24]   Figgener J. et al., "The development of stationary battery storage systems in Germany – status 2020," Journal of Energy Storage, vol. 33, p. 101982, 2021, DOI: 10.1016/j.est.2020.101982.

[25]   Figgener J.; Haberschusz D.; Kairies K.; Wessels O.; Tepe B.; Sauer D. (2018): "Wissenschaftliches Mess- und Evaluierungsprogramm Solarstromspeicher 2.0 - Jahresbericht 2018," Institut für Stromrichtertechnik und Elektrische Antriebe der RWTH Aachen, Aachen, Deutschland, 2018. [Online]. Available: https://www.bves.de/wp-content/uploads/2018/07/Speichermonitoring_Jahresbericht_2018_ISEA_RWTH_Aachen.pdf (accessed on 14. April 2022)

[26]   Bundesverband Energiespeicher e.V., "BVES Branchenanalyse 2021: Entwicklung und Perspektiven der Energiespeicherbranche in Deutschland," Pressekonferenz BVES, Berlin, Deutschland, 2021. [Online]. Available: https://www.bves.de/wp-content/uploads/2021/03/2021_BVES_Branchenanalyse.pdf (accessed 7. June 2021)

[27]   Ralon P.; Taylor M.; Diaz-Bone H.; Kairies K.-P. (2017): "Electricity Storage and Renewables: Costs and Markets to 2030," [Online]. Available: https://www.irena.org/publications/2017/oct/electricity-storage-and-renewables-costs-and-markets (accessed on 14.March 2022)

[28]   Avicienne Energy (2020): The rechargeable battery market 2019-2030: Energy storage systems and industrial applications

[29]   Karlsruher Institut für Technologie (2014): "Kurz-Checkliste für Li-Ionen-Heimspeicher," Karlsruhe, Deutschland [Online]. Available: https://www.kit.edu/downloads/KIT_Li-Ionen_Checkliste.pdf (accessed on 14. March 2022)

[30]   BVES, BSW, DGS, ZVEH, and StoREgio (2014): "Sicherheitsleitfaden Li.Ionen-Hausspeicher" [Online]. Available: https://www.bves.de/wp-content/uploads/2017/02/Sicherheitsleitfaden-Li-Ionen-Hausspeicher.pdf (accessed on 14. April 2022)

[31]   DE (2017): "VDE-AR-E 2510-50 Anwendungsregel:2017-05 Stationäre Energiespeichersysteme mit Lithium-Batterien" [Online]. Available: https://www.vde-verlag.de/normen/0500098/vde-ar-e-2510-50-anwendungsregel-2017-05.html (accessed on 14. April 2022)

[32]   DFV and AGBF (2018): "Risikoeinschätzung Lithium-Ionen Speichermedien: Empfehlungen der Arbeitsgemeinschaft der Leiter der Berufsfeuerwehren und des Deutschen Feuerwehrverbandes," [Online]. Available: https://www.feuerwehrverband.de/app/uploads/2020/05/2018-01_Fachempfehlung_Risikoeinschaetzung-Lithium-Ionen-Speichermedien.pdf (accessed on 14. April 2022)

[33]   Trocker F.; Teichert O.; Gallet M.; Ongel A.; Lienkamp M. (2020): City-Scale Assessment of Stationary Energy Storage Supporting End-Station Fast Charging for Different Bus-Fleet electrification Levels, Journal of Energy Storage, 32, 101794.

[34]   Smatric (2020): HPC-Das Laden der Zukunft [Online]. Available: https://smatrics.com/fuer-unternehmen/news/hpc-das-laden-der-zukunft?utm_campaign=Konjunkturpaket% (accessed on 14. April 2022)

[35]   Mayr F. (2020): Buffered charging- how batteries can close the widening "charging gap". Berlin: Apricum [Online]. Available: https://smatrics.com/fuer-unternehmen/news/hpc-das-laden-der-zukunft?utm_campaign=Konjunkturpaket% (accessed on 14. April 2022)

[36]   https://www.daimler.com/nachhaltigkeit/lebenszyklus-batterie/nutzung-charging/ionity-reportage.html (accessed on 14. March 2021)

[37]   Ionity GmbH Available [Online]. Available: https://ionity2025.eu/de/weareonit (accessed on 14. April 2022)

[38] DKE; BDEW; ZVEH; ZVEI; VDE FNN (2020) "Der Technische Leitfaden Ladeinfrastruktur Elektromobilität," Version 3 [Online]. Available: https://www.vde.com/resource/blob/988408/ca81c83d2549a5e89a4f63bbd29e80c6/technischer-leitfaden-ladeinfrastruktur-elektromobilitaet---version-3-1-data.pdf (accessed on 14. April 2022)

[39] Tetik S. (o.J): Megawatt charging System (MCS), o.O.: Charin [Online]. Available: https://www.charin.global/technology/mcs/ (accessed on 14. April 2022)

[40] Schaal S. (2021): Bundesnetzagentur meldet 50.901 öffentliche Ladepunkte [Online]. Available: https://www.electrive.net/2021/12/23/bundesnetzagentur-meldet-50-901-oeffentliche-ladepunkte (accessed on 14. April 2022)

[41] Windt A.; Arnhold O. (2020): Ladeinfrastruktur nach 2025/2030: Szenarien für den Markthochlauf [Online]. Available: https://www.now-gmbh.de/wp-content/uploads/2020/11/Studie_Ladeinfrastruktur-nach-2025-2.pdf, Berlin: Nationale Leitstelle Ladeinfrastruktur (accessed on 14. April 2022)

[42] Bundesregierung (2019): Mehr Ladestationen für Elektroautos [Online]. Available: https://www.bundesregierung.de/breg-de/themen/klimaschutz/ladeinfrakstruktur-1692644 (accessed on 14. April 2022)

[43] Kreisel Electric GmbH & Co KG: Chimero 360 [Online]. Available: https://www.kreiselelectric.com/wp-content/uploads/2021/03/Kreisel-Electric-CHIMERO-HPCEES-Flyer2102-360-EN.pdf (accessed on 14. April 2022)

[44] ads-tec Energy GmbH (o.J): ChargeBox Dispenser [Online]. Available: https://go.ads-tec.de/de/hpc/dispenser (accessed on 14. April 2022)

[45] Fischhaber S.; Schuster S. F.; Regett A.; Hesse H. (2016): Second-LifeKonzepte für Lithium-Ionen-Batterien aus Elektrofahrzeugen, Schaufenster Elektromobilität-Eine Initiative der Bundesregierung.

[46] Avicienne Energy (2020): Battery market for cellular phones 2019 to 2030

[47] Ali H.; Khan H. A.; Pecht M. (2020): Evaluation ofLi-Based Battery Current, Voltage, and Temperature Profiles for In-Service Mobile Phones [Online]. Available: https://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=9072141(accessed on 14. April 2022)

[48] Hoque M. A.; Tarkoma S. (2016): Characterizing Smartphone Power Management in the Wild [Online]. Available: https://arxiv.org/pdf/1607.06402.pdf (accessed on 14. April 2022)

[49] Trumpf (2021): Electric- and cordless power tools [Online]. Available: https://www.trumpf.com/filestorage/TRUMPF_Master/Products/Power_Tools/Brochures/TRUMPF-Power-tools-catalog-EN.pdf (accessed on 14. April 2022)

[50] Bosch (2021): 2021 Produktprogramm. Stuttgart: Robert Bosch Power Tools GmbH

[51] Avicienne Energy (2020): Battery market for Power Tools 2019 to 2030

[52] Weydanz (2009): Power Tools Batteries. Erlangen: Siemens AG

[53] Gutiérrez M.; Careaga I. (2022): Which format do major batterie cell manufacturers bet on? Prismatic, cylindrical or pouch? [Online]. Available: https://cicenergigune.com/en/blog/format-battery-cell-manufacturers-prismatic-cylindrical-pouch Álava: CIC eneriGune (accessed on 14.04.2022)

[54] Ulrich L. (2021): The top 10 EV-battery makers [Online]. Available: https://spectrum.ieee.org/the-top-10-ev-battery-makers (accessed on 14. April 2022)

[55] Venditti B. (2021): The top 10 EV-battery manufacturers [Online]. Available: https://elements.visualcapitalist.com/ranked-top-10-ev-battery-makers/ (accessed on 14. April 2022)

[56] Mao, C.; Wood, M.; David, L.; An, S. J.; Sheng, Y.; Du, Z.; Meyer, H. M.; Ruther, R. E.; Wood, D. L. (2018): Selecting the Best Graphite for Long-Life, High-Energy Li-Ion Batteries. In: Journal of The Electrochemical Society, 165 (9), A1837-A1845.

[57] He, S.; Huang, S.; Wang, S.; Mizota, I.; Liu, X.; Hou, X. (2021): Considering Critical Factors of Silicon/Graphite Anode Materials for Practical High-Energy Lithium-Ion Battery Applications. In: Energy & Fuels, 35 (2), S. 944–964.

[58] Li, P.; Kim, H.; Myung, S.-T.; Sun, Y.-K. (2021): Diverting Exploration of Silicon Anode into Practical Way: A Review Focused on Silicon-Graphite Composite for Lithium Ion Batteries. In: Energy Storage Materials, 35, S. 550–576.

[59] Choi, S.; Kwon, T.-W.; Coskun, A.; Choi, J. W. (2017): Highly elastic binders integrating polyrotaxanes for silicon microparticle anodes in lithium ion batteries. In: Science (New York, N.Y.), 357 (6348), pp. 279–283.

[60] Lopez, J.; Chen, Z.; Wang, C.; Andrews, S. C.; Cui, Y.; Bao, Z. (2016): The Effects of Cross-Linking in a Supramolecular Binder on Cycle Life in Silicon Microparticle Anodes. In: ACS applied materials & interfaces, 8 (3), pp. 2318–2324.

[61] Xu, Z.; Yang, J.; Zhang, T.; Nuli, Y.; Wang, J.; Hirano, S. (2018): Silicon Microparticle Anodes with Self-Healing Multiple Network Binder. In: Joule, 2 (5), pp. 950–961.

[62] Obrovac, M. N.; Krause, L. J. (2007): Reversible Cycling of Crystalline Silicon Powder. In: Journal of The Electrochemical Society, 154 (2), A103.

[63] Tesla (2020): Tesla Battery Day Presentation Deck. Available: https://tesla-share.thron.com/content/?id=96ea71cf-8fda-4648-a62c-753af436c3b6&pkey=S1dbei4 (accessed 16. December 2021)

[64] Ding, Y.; Cano, Z. P.; Yu, A.; Lu, J.; Chen, Z. (2019): Automotive Li-Ion Batteries: Current Status and Future Perspectives. In: Electrochemical Energy Reviews, 2 (1), pp. 1–28.

[65] Li, W.; Lee, S.; Manthiram, A. (2020): High-Nickel NMA: A Cobalt-Free Alternative to NMC and NCA Cathodes for Lithium-Ion Batteries. In: Advanced materials (Deerfield Beach, Fla.), 32 (33), e2002718.

[66] Schaal S. (2020): SK Innovation kündigt schnellladefähige Zellen für 2021 an [Online]. Available: https://www.electrive.net/2020/10/26/sk-innovation-kuendigt-neue-schnellladefaehigen-zellen-fuer-2021-an/ (accessed on 14. April 2022)

[67] Hill J. S. (2020): China's Svolt says cobalt-free car batteries coming in 2021 [Online]. Available: https://thedriven.io/2020/05/22/chinas-svolt-says-cobalt-free-car-batteries-coming-in-2021/ (accessed on 14. April 2022)

[68] Lima P. (2020): BYD prismatic battery cell specs and possibilities (update) [Online]. Available: https://pushevs.com/2020/05/26/byd-blade-prismatic-battery-cell-specs-possibilities/ (Updated on 25. March 2022)

[69] Meng X.; Zheng E. Y. (2020): The Next-Generation Battery Pack Design: from the BYD blade cell to Module-free Battery Pack [Online]. Available: https://medium.com/batterybits/the-next-generation-battery-pack-design-from-the-byd-blade-cell-to-module-free-battery-pack-2b507d4746d1 (accessed on 14. April 2022)

[70] Song, J.; Li, B.; Chen, Y.; Zuo, Y.; Ning, F.; Shang, H.; Feng, G.; Liu, N.; Shen, C.; Ai, X.; Xia, D. (2020): A High-Performance Li-Mn-O Li-rich Cathode Material with Rhombohedral Symmetry via Intralayer Li/Mn Disordering. In: Advanced materials (Deerfield Beach, Fla.), 32 (16), e2000190.

[71] Zheng, J.; Myeong, S.; Cho, W.; Yan, P.; Xiao, J.; Wang, C.; Cho, J.; Zhang, J.-G. (2017): Li- and Mn-Rich Cathode Materials: Challenges to Commercialization. In: Advanced Energy Materials, 7 (6), p. 1601284.

[72] Lain; Brandon; Kendrick (2019): Design Strategies for High Power vs. High Energy Lithium Ion Cells. In: Batteries, 5 (4), p. 64.

[73] Mei, W.; Chen, H.; Sun, J.; Wang, Q. (2019): The effect of electrode design parameters on battery performance and optimization of electrode thickness based on the electrochemical–thermal coupling model. In: Sustainable Energy & Fuels, 3 (1), pp. 148–165.

[74] Sabrina Rauscher (2014): Dissertation: Einfluss von Material- und Beschichtungsparametern

auf die Elektrodenmorphologie und die Leistungsparameter von Lithiumionen-Zellen. UNIVERSITÄT ULM

[75] Kwade, A.; Haselrieder, W.; Leithoff, R.; Modlinger, A.; Dietrich, F.; Droeder, K. (2018): Current status and challenges for automotive battery production technologies. In: Nature Energy, 3 (4), pp. 290–300.

[76] Schröder, R.; Glodde, A.; Aydemir, M.; Bach, G. (2015): Process to Increase the Output of Z-Folded Separators for the Manufacturing of Lithium-Ion Batteries. In: Applied Mechanics and Materials, 794, pp. 19–26.

[77] Kosch, S.; Rheinfeld, A.; Erhard, S. V.; Jossen, A. (2017): An extended polarization model to study the influence of current collector geometry of large-format lithium-ion pouch cells. In: Journal of Power Sources, 342, pp. 666–676.

[78] Sturm, J.; Frank, A.; Rheinfeld, A.; Erhard, S. V.; Jossen, A. (2020): Impact of Electrode and Cell Design on Fast Charging Capabilities of Cylindrical Lithium-Ion Batteries. In: Journal of The Electrochemical Society, 167 (13), p. 130505.

[79] Grandjean, T.; Barai, A.; Hosseinzadeh, E.; Guo, Y.; McGordon, A.; Marco, J. (2017): Large format lithium ion pouch cell full thermal characterisation for improved electric vehicle thermal management. In: Journal of Power Sources, 359, pp. 215–225.

[80]   Klein, M.; Tong, S.; Park, J. W. (2016): In-plane nonuniform temperature effects on the performance of a large-format lithium-ion pouch cell. In: Applied Energy, 165, pp. 639–647.

[81]   Wu, B.; Li, Z.; Zhang, J. (2015): Thermal Design for the Pouch-Type Large-Format Lithium-Ion Batteries. In: Journal of The Electrochemical Society, 162 (1), A181-A191.

[82]   Rheinfeld, A.; Sturm, J.; Frank, A.; Kosch, S.; Erhard, S. V.; Jossen, A. (2020): Impact of Cell Size and Format on External Short Circuit Behavior of Lithium-Ion Cells at Varying Cooling Conditions: Modeling and Simulation. In: Journal of The Electrochemical Society, 167 (1), p. 13511.

[83]   Coleman, B.; Ostanek, J.; Heinzel, J. (2016): Reducing cell-to-cell spacing for large-format lithium ion battery modules with aluminum or PCM heat sinks under failure conditions. In: Applied Energy, 180, pp. 14–26.

[84]   Zwicker, M.; Moghadam, M.; Zhang, W.; Nielsen, C. V. (2020): Automotive battery pack manufacturing – a review of battery to tab joining. In: Journal of Advanced Joining Processes, 1, p. 100017.

[85]   The Federal Government Germany, Foundations in place for CO2 pricing: Cabinet takes decision on

national emissions trading. [Online]. Available: https://www.bundesregierung.de/breg-en/issues/nationaleremissionshandel-1685054 (accessed: 21. January 2022)

[86]   Agora (2021): Batteriestandort auf Klimakurs. [Online] Available: https://www.agora-verkehrswende.de/veroeffentlichungen/batteriestandort-auf-klimakurs/ (accessed on 14. April 2022)

[87]   Mauler L.; Duffner F.; Zeier W.G.; Leker J. (2021): Battery cost forecasting: a review of methods and results with an outlook to 2050, Energy and Environmental Science 9, https://doi.org/10.1039/D1EE01530C

[88]   FEV Group Malli Veeramurthy; Madhura Medikeri (2020): Development and production challenges for the success of automotive battery systems to be Announced, AABC US 2020

[89]   Hummel P.; Bush T.; Gong P.; Yasui K.; Lee T.; Radlinger J.; Langan C.; Lesne D.; Takahashi K.; Jung E.; Shaw L.; Haire G. (2018): UBS Q-Series Tearing down the heart of an electric car: Can batteries provide an edge, and who wins?. UBS Limited

[90]   UBS Limited (2020): Tearing down the heart of an electric car: Can batteries provide an edge, and who wins.

[91]   Yole Development (2019): Li-ion Battery Pack for Automotive and Stationary Storage Applications, 2020; Status of Rechargeable Li-ion Battery Industry

[92]   B3 Corporation (2021): Report 20-21: LIB Materials Market Bulletin (21Q1)

[93]   B3 Corporation (2020): Report 20-21: LIB Materials Market Bulletin (20Q4)

[94]   B3 Corporation (2020): Report 19-20: LIB Materials Market Bulletin (20Q1)

[95]   B3 Corporation (2019): Report 18-29: LIB Materials Market Bulletin (19Q1)

[96]   Henze V. (2020): Battery pack prices cited below $100/kWh for the first time in 2020, while market average sits at $137/kWh. [Online] Available: https://about.bnef.com/blog/battery-pack-prices-cited-below-100-kwh-for-the-first-time-in-2020-while-market-average-sits-at-137-kwh/ (accessed on 14. April 2022)

[97]   Essl, C.; Golubkov, A. W.; Fuchs, A. (2020): Comparing Different Thermal Runaway Triggers for Two Automotive Lithium-Ion Battery Cell Types. In: J. Electrochem. Soc. 167 (13), S. 130542. DOI: 10.1149/1945-7111/abbe5a.

[98]   SolidPower (2021): A New Breed of Battery: Investor Presentation June 2021 https://s28.q4cdn.com/717221730/files/doc_presentations/Solid-Power-Investor-Presentation-June-2021-Final.pdf (accessed 21. December 2021)

[99]   Yi E.; Wang W.; Kieffer J.; Laine R. M. (2017): Key parameters governing the densification of cubic-Li7La3Zr2O12Li+ conductors Journal of Power Sources 352 156–64

[100] Nam Y. J.; Oh D. Y.; Jung S. H.; Jung Y. S. (2018): Toward practical all-solid-state lithium-ion batteries with high energy density and safety: Comparative study for electrodes fabricated by dry- and slurry-mixing processes Journal of Power Sources 375 93–101

[101] Yang X.; Adair K. R.; Gao X.; Sun X. (2021): Recent advances and perspectives on thin electrolytes for high-energy-density solid-state lithium batteries Energy Environ. Sci. 14 643–71

[102] Quantum Scape (2021): Investor Presentation 2021 [Online]. Available: https://s26.q4cdn.com/263384136/files/doc_presentation/2021/08/Investor-Presentation_Sep_2021.pdf (accessed 21. December 2021)

[103] BloombergNEF (2021): Global Storage Market to Double Six Times by 2030. Available: https://about.bnef.com/blog/global-storage-market-double-six-times-2030 (accessed 21. December 2021).

[104] Apricum-group (2021): https://apricum-group.com/buffered-charging-how-batteries-can-close-the-widening-charging-gap%E2%80%8B/ (accessed 21. December 2021).

[105] Schmaltz, T., Wicke, T., Weymann, L., Voß, P., Neef, C., Thielmann, A., Solid-State Battery Roadmap 2035+, Fraunhofer Institute for Systems and Innovation Research ISI, 2022, https://www.isi.fraunhofer.de/content/dam/isi/dokumente/cct/2022/SSB_Roadmap.pdf

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Imprint

Notes