Lithium-Ion Batteries x Production as a Service

Boosting Battery Cell Production with Production as a Service

FLEXFACTORY
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PEM | RWTH AACHEN UNIVERSITY

“We focus on delivering processes and innovations for a flexible and sustainable battery cell production”

Content

Big, small, round, square – A cross-section of today's battery spectrum

Flexibility and product diversity of lithium-ion batteries

Pioneering the field of consumer electronics, lithium-ion batteries (LIB) are present in an ever-increasing number of applications. With properties such as high energy density, fast charging capability, and extended cycle life, they are outperforming competing electrochemical energy storage systems and have established themselves as the leading battery technology. Current development forecasts show that battery demand and production volumes will witness unprecedented growth rates in the coming years. Europe in particular is rapidly catching up in terms of battery cell production capacities and expects future production volumes to increase tenfold to around 1.5 TWh in 2030.

A cross-section of today's battery cell spectrum shows, that the majority of battery cells can be characterized by one of the following three formats: Cylindrical, Prismatic, or Pouch format. Production of the three formats is spread among major cell manufacturers, most of which have dedicated their production lines to one single format. Only a few offer multiple formats in large quantities by setting up several production facilities for this purpose. A closer look at the market also reveals that no strictly preferred and dominant format has emerged. Each combines advantages and disadvantages that are taken into account for the intended use and purpose. As it turns out, the selection of LIBs as a suitable technology for electrochemical energy storage is only the first of many steps on the way to the final cell specification. Right from the start a multitude of product-specific questions regarding actual design parameters and interfaces for system integration arises. These need to be addressed in the early product development stage. The final battery cell design thus takes many different shapes and forms, influenced by application-specific requirements, constraints imposed by the overall system design and common standards (s. Figure 1). To decide on the best possible configuration, a systemic analysis is required, ranging from the specification of individual cells to module integration and final system assembly. Different requirements such as system voltage, energy content, and maximum power output need to be balanced with mechanical integration, electrical contacting and system cooling to ensure proper function and operational reliability. This multitude of inter-actions and distributed dependencies places the battery cell at the center of attention.

In this course, the question arises as to how such a diversity of variants can be addressed from a production perspective. With the manufacturers' willingness to obtain optimal solutions at minimum cost, effective and efficient ways of offering customized battery cell solutions are becoming increasingly attractive.

The variety of battery products is growing rapidly

Figure 1: *Overview of different battery cell formats and designs available on the market*

Demand for customized battery cells offering optimized solutions

Current battery cell production plants are designed to manufacture predefined battery cells with a high level of automation, at highest quality, and with minimal deviations in end product characteristics. Production lines focused on high production volumes are trimmed for maximum efficiency and yield, thus relying on a (highly) streamlined process flow. Once ramped up, these factories are kept at their optimal operating point with the clear objective on standardizing production runs. Many leading battery cell manufacturers try to maintain the optimum operating window for as long as possible, following the motto "never change a running system". Any subsequent changes in size or shape are demanding due to narrow flexibility corridors and entail high changeover costs and times. The flexible production of customer-specific battery variants in varying and adaptable quantities poses major obstacles for existing factories.

In order to offer economical and leading-edge products, while utilizing raw materials as efficiently and sustainably as possible, battery cell industry is rapidly evolving. This is leading to significant advancements in the product as well as in the manufacturing processes. Along with increased use in a variety of applications, shorter product life cycles, and diverse requirements, battery production systems that are adaptable to these changing needs are emerging as a potential business opportunity.

The need for flexibility and adaptability of production systems in this dynamic environment is increasingly recognized and is already given greater consideration. Moving away from rigid, identically duplicated production lines running in parallel side by side to agile production systems with flexible process management is a promising approach.

The main challenge is to translate the full set of requirements into a functioning system, that is able to offer customized cell variants optimized for different applications. Understanding the product in all its details and capturing the production requirements resulting from the individual elements becomes all the more important. As a result, a modular and flexible production system can be established that is capable of delivering customized battery cells as efficiently as the current Gigafactories.

Moving away from mass production, Production as a Service (PaaS) provides a platform to expand the existing ecosystem by offering customized battery cell solutions. Focusing on small to medium production volumes, the implementation of a PaaS concept represents a promising approach to fully exploit flexibility while strengthening operational resilience. The following study outlines the underlying potential and highlights the key challenges associated with this transformative approach.

and so are the opportunities for new and innovative solutions.

Unprecedented growth shaping the industry – Assessment of battery market potentials

Applications and business opportunities for batteries

	Established markets	*Emerging markets*		
Domains	Consumer Electronics	Stationary Energy Storage Systems	Electric Transport and Aviation	Industrial and Power Tools
Total Battery Demand* Total Market Value* CAGR**	ca. 445 [GWh] 750 bn. [US$] 5% increase	ca. 25 [GWh] 15 bn. [US$] 30% increase	ca. 350 [GWh] 275 bn. [US$] 35% increase	ca. 5 [GWh] 45 bn. [US$] 10% increase
Potential for customized battery cell solutions	low – high	low – high	low – high	low – high
Drivers and barriers	+ High product variety + High innovation level – High target volumes – Small formats only	+ High growth rates – High cost pressure – Long life cycles – Second-life use	+ Highest growth rates + High innovation level + Versatile requirements + Multiple niche markets – High target volumes	+ Special requirements – High cost pressure – High modularity – Long life cycles

* Status of 2022 ** Forecast for 2022–2030

***Figure 2**: Market overview for established and emerging battery markets (PEM market research)*

Today's lithium-ion battery market and its applications are divided into established and emerging markets. The consumer electronics sector is typically considered an established market. Lithium-ion batteries have been used and commercialized in this area for the first time. A further breakdown of this domain reveals several individual segments that are constantly bringing new innovations to the market due to rapid technological development, such as wearables and various smart devices.

Beyond this, a multitude of emerging markets are driving the battery industry. Most prominent domains cover electric transport and aviation, which include various forms of electrified transport on paved roads and in the aerospace. Besides, stationary energy storage systems, as well as industrial and power tools for various types of industrial equipment and applications, represent further key domains. Together, these emerging markets account for a significant share of today's total battery demand, reflected in about 380 GWh of deployed capacity in 2022.

Consumer Electronics. Battery cells have been used in the electronic entertainment industry for several decades. Over the years, this market has built up a total market value of around $750 bn. with an average annual growth rate of about 5% until 2030. Key applications within this domain include smartphones, tablets and laptops, multimedia, as well as smart devices and wearables. These devices therefore often rely on small-format and tailored battery solutions with compact form factors. Smartphones are a vivid example, as they are getting even thinner, although higher performance and longer usage times are required. As a result, battery cells are increasingly adapted to the available packaging space, leading to non-rectangular shapes to maximize energy content.

Besides shorter product life cycles, the growth of a tech-savvy population, and thus the rising awareness of available technologies is driving further market demand in this segment. New products, e.g. fitness tracker, smartwatches and other health devices keep entering the market.

Stationary Energy Storage Systems. The energy market is currently transforming to align the increasing demand for energy with a growing emphasis on renewable energy sources. As a result, stationary energy storage systems are being developed to provide buffer capacities and increase the residential and commercial use of clean, renewable sources of energy. This refers primarily to grid storage and home storage systems, as well as auxiliary power supplies. The lithium-ion battery is suitable for both, small and medium sized applications with high power and energy storage requirements. However, standardized formats are generally preferred as they require less capital per kWh. In addition, second-life or refurbished EV batteries will play a critical role in residential and grid storage systems.

Electric Transport and Aviation. The combined overview of the market situation shows that demand for additional battery capacity is driven primarily by electric transport and aviation. Besides electric vehicles, the e-mobility segment also covers truck and bus solutions, as well as electrified scooters, boards and bicycles.
For electric vehicles, most OEMs are focusing on securing overall battery demand to support their mass market electrification strategy. Therefore, they are aiming for a standardized battery cell produced in-house, serving up to 80% of the planned EV roll-outs in the mass market. For the remaining premium and high-performance segments as well as other niche applications, customized solutions will still be needed. The focus here shifts to novel cell chemistries for high-performance and fast charging battery cells as well as adjusted battery designs suited for innovative battery systems (e.g., cell-to-pack).
Besides the automotive market, also the segment of electric air travel attracts significant attention due to high growth rates. Incumbent companies as well as multiple start-ups are currently pursuing their goals to revolutionize air travel as currently known, developing all-electric solutions for private and commercial use.

Alongside the demand for customized battery cells in small quantities, a flexible and adaptive production setup can support all market participants in their research and development activities by applying new cell chemistries, differentiating themselves from the market through innovative solutions and piloting application-optimized cell designs.

Industrial and Power Tools. Power tools can be characterized as cordless electric handicrafts, powered by rechargeable batteries. Industrial applications typically include forklifts and other material handling equipment as well as sensors and IoT applications.
For power tools, however, easy and efficient operation, advantages of portability, and greater degrees of freedom are key factors driving the growing demand. Customized battery cells here offer the opportunity to stand out with high-performance product lines.
In logistics applications and in material handling equipment such as forklifts and AGVs, a high pressure to minimize capital costs can be observed. As pure utility investments, systems are expected to be standardized, robust and reliable. In contrast, storage systems for IoT devices and sensors are designed for high performance and often miniaturization. For battery cell applications with dimensions of less than a few millimeters, production is more and more challenging due to the need for complex thin-film technologies.

In Summary, the 2020s are expected to mark the decade in which lithium-ion battery energy storage will become an integral part of everyday life, finding application in vehicles, consumer goods, power tools, and many more segments. Especially for emerging markets, demands are expected to grow in double digit rates over the next years, driving today's and future need for battery cells.

EXPERT STATEMENT: PROF. DR. ACHIM KAMPKER, RWTH AACHEN UNIVERSITY
"The dynamic development of battery technology continues to drive the electrification of our modern world society. Supporting new application areas with optimal and tailored solutions on demand becomes a crucial part of this transformation."

Not all battery cells are built the same – Overview of flexibility areas and design features

Product diversity explained by common flexibility areas

1st Gate — 2nd Gate — 3rd Gate — 4th Gate

Degree of specification

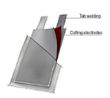
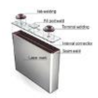
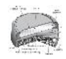
Chemistry	Format	Shape and Size	Tabs & Terminals	Final product
Cathode: NMC, NCA, LMO, LFP, Other	Pouch	Most pouch cell sizes are within a ratio corridor (width and length) of 1:1 and 1:2 with the trend towards a ratio of 1:4.	One-sided tabs Counter-sided tabs Custom tabs	
Anode: Graphite, Silicon, LTO, Other	Cylindric	Cell dimensions span across a wide spectrum, serving various applications with a trend towards growing diameters (e.g. 4680).	Standard lid Custom lid	
Other: Binder, Carbon Black, Solvent, Electrolyte	Prismatic	Trend towards increasing energy densities gears developments towards larger formats while vehicle restrictions impose an limit on max. cell heights.	Standard lid Custom lid	
	Other	Custom	Custom	

Figure 3: *Approach for battery cell specification and development of product variants*

As previously outlined, the rapid development and optimization of battery cell technology is accompanied by a large number of product variants. These can differ considerably in terms of format, chemistry, and other product features. This observation already indicates that there is no such thing as the perfect battery or standard cell that offers a "one-fits-all" solution for the multitude of possible applications. Moreover, since this is a comparatively young technology, its potential is far from exhausted. New materials, improved cell concepts and innovative processes with disruptive technologies are appearing on the industry's horizon.
Investigating today's variety, battery cells show a number of components, and elements that are subject of recurring change and customization.

The variety of observable battery cell variants on the market can be captured by four main flexibility areas. Different materials and designs will lead to a variety of different configurations and product features, allowing for recurring change and customization.

They represent clear distinguishing features in form of the active materials, the cell core (known as the electrode-separator-composite, ESC), and the interfaces for electrical contacting. However, there are some components where only minor changes occur or which are part of a standard product portfolio, such as current collector foils or center pins. After the final product specification, the distinguishing features essentially determine the properties and performance of the battery cell. In general, these design spaces, accounting for a variety of specifications can be summarized and classified as cell chemistry, cell format, cell shape and size, and cell connections, with latter referring to tabs and terminals that provide the electrical contacting at the module level. These four aspects are responsible for the majority of variants and are considered flexibility areas in the scope of this study.
An illustrative example is given by the area of cell chemistry, where a variety of different active materials (e.g., NMC, NCA, Graphite) can be used in the cathode or anode structure. Depending on the selection of active material combinations, different cell properties result.

Among the established cell formats (pouch, prismatic, and cylindrical), there is also a high variance in terms of actual shapes and sizes. While the demand for further maximization of energy content and density generally pushes towards ever larger dimensions, still a wide range of dimensional ratios shows up on the market.

The design of the tabs and terminals offers yet another degree of flexibility. Alongside those modifications driven by technical aspects, e.g. to minimize contact resistances and to directly integrate additional safety features, the positioning and internal interconnection of the tabs and terminals vary considerably.

Market segments showing preferences for certain cell types

Combining the product diversity at cell level with the individual segments of the established and emerging markets, some evident correlations and trends can be observed.
E-Mobility stands out as the main field of action, where all common cell formats are used in various configurations. However, prismatic and pouch formats are more widespread across the different vehicle classes. The aviation market is moving in a similar direction, although only tentative statements can be made due to the early stage of development. In both areas, the premium segment in particular places special demands on the battery cells. These can only be fulfilled to a certain extent by solutions currently available on the market, thus driving demand for customized solutions.
From a performance perspective, the key challenge is summarized in delivering high specific power densities for short performance peaks while at the same time providing high specific energy densities for long transport distances. This observation is also in line with publicly stated statements by major OEMs.

While emphasizing the advantages of unified and standardized cells, in the same course it's pointed out that these will only be able to serve about 70 - 80% of the total vehicle fleet. This results in a considerable demand for customer- and application-specific solutions, produced in small to medium production volumes.
Taking a closer look at segments such as consumer electronics, smartwatches, and power electronics, it becomes clear that decreasing product sizes and complex geometries are driving the use of small and flexible pouch formats. Depending on the specific application, e.g., in the case of health and hearing aids, small coin cells might also be a suitable solution.

Overall, the observed product diversity at cell level is closely related to the multitude of battery-powered applications that can be seen across the industrial landscape. These do not only benefit but often rely on specialized and customized battery solutions.

Format	Chemistry	Shape & Size	Terminals & Tabs
Pouch	NMC & Graphite	Standard	One-sided tabs
	LMO & Graphite	Small	One-sided tabs
	NMC & Silicon	Large	Counter-sided tabs
	NMC & Graphite	Custom	Custom tab position
Cylindric	NMC & Graphite	Standard	Standard lid & terminal
	NMC & Silicon	Standard	Custom lid & terminal
	LFP & Graphite	Large	Custom lid & terminal
Prismatic	NMC & Graphite	Standard	Standard lid & terminal
	LFP & Graphite	Standard	Custom lid & terminal
	NMC & Silicon	Large	Custom lid & terminal

Aviation · Smartphones · E-Mobility · Wearables · Micro mobility · Power tools

Figure 4: Battery cell variants offering solutions for different market segments and requirements

How Product and Process go hand-in-hand – Product variants and flexible production systems

Cell formats determining the underlying process chain

The generic process chain for Lithium-Ion batteries is subdivided in the three main sections of electrode manufacturing, cell assembly and cell finishing, each valid for all of the established cell formats. However, a closer look quickly reveals that production lines differ significantly in their actual implementation, resulting in cell-specific processes (e.g., stacking vs. winding), further supplementary or omitted process steps, and substantially different manufacturing technologies (laser cutting vs. punching).
The differences in the required process chain are particularly noticeable in cell assembly and find their origin in the different structures of the cell formats. Whereas for prismatic and round cells, a hard-case housing is used, pouch cells are characterized by a flexible housing and free standing tabs. These components are manufactured differently and require fundamentally different processes to hermetically seal and secure the electrolyte of the cell. Many other differences in the process chain can be traced back to the various components that are assembled to form the final cell. The main distinguishing feature becomes the electrode-separator composite (ESC). In the pouch cell, the ESC features a stack of electrode sheets (anode and cathode) separated by intermediate layers of separator foil. For the other formats, it is characterized by its rolled shape – the jelly roll.
In direct comparison, electrode production is less specific to each cell format, as they all rely on a current collector film coated with active material. Anode and cathode production is therefore mostly uniform, apart from in-process differences in coating patterns, widths, and thicknesses. However, if taken into account during equipment engineering these can be usually set and adjusted by inline process parameters.
Cell finalization remains largely similar across all cell formats. Whereas the pouch cell deviates more due to the need for active degassing and subsequent resealing. For the electrochemical activation of the battery cell – a pivotal process step within this process section – the equipment used is currently precisely matched to the format of the battery cell. The same applies to the aging process, during which the cells are stored and their properties are monitored. Once mechanical processing is complete, all battery cell variants undergo a final quality inspection concluded by grading and sorting processes. The evaluation criteria and inspection methods thereby are not prescribed and differ depending on cell type, manufacturer standards, as well as negotiated and binding quality standards.

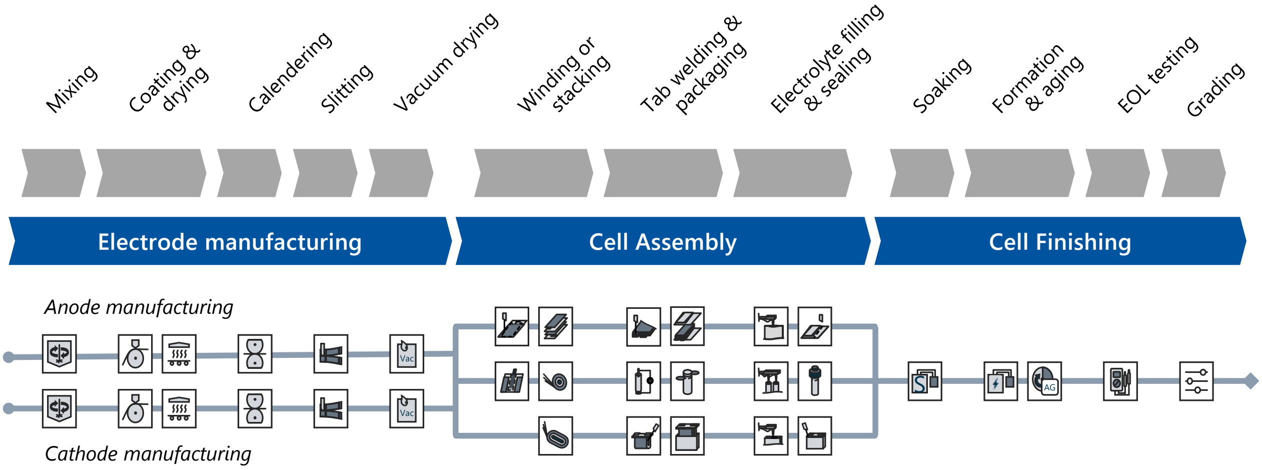


Figure 5: Comprehensive and flexible process integration for LIB x Production as a Service

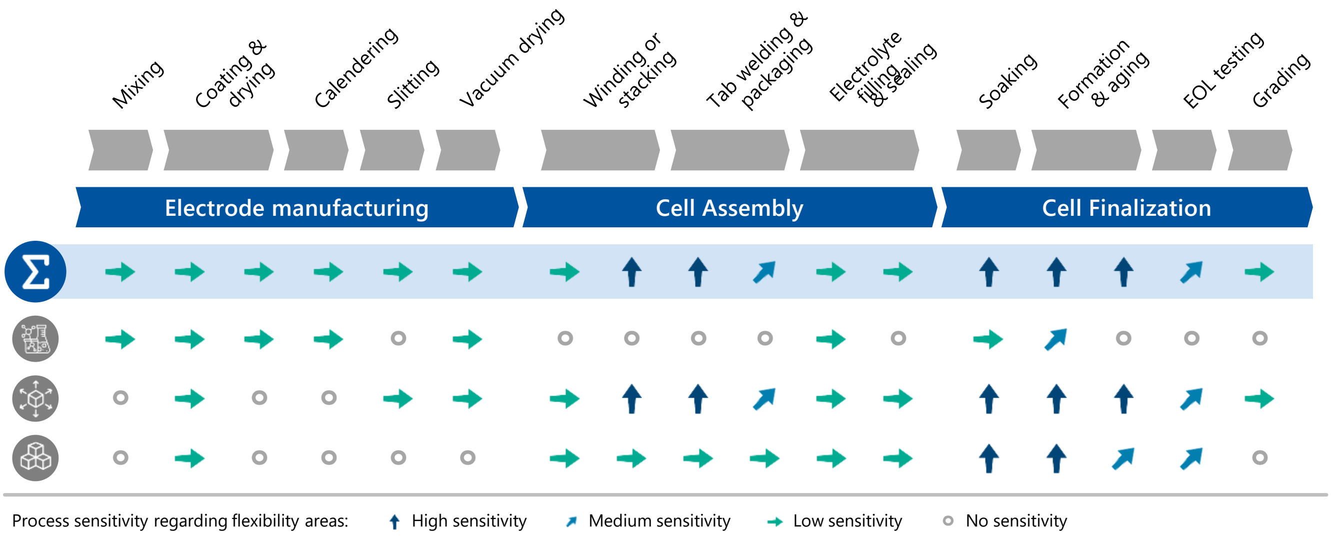


Figure 6: Process sensitivity of current production equipment with regard to product flexibility areas (Top-to-down: Σ Overall, Material, Size & Shape, Tabs & Terminals)

Understanding flexibility areas and their impact on process design

Battery cell production offers many opportunities to address different flexibility areas in terms of different cell chemistries, formats, shapes and sizes, as well as individual tabs and terminals.

Electrode Manufacturing. Examining the process chain more closely, the electrode production is least sensitive to changes in one of the four flexibility areas. Different cell chemistries such as NMC, LFP or NCA can be processed with great flexibility. The effort required to adapt to new product variants is relatively low, as it mostly involves adjustments to the process parameters (e.g., mixing times and speeds) without the need for further changes to the equipment. However, a changeover may be necessary in case of the slot die, being a high-precision tool specially designed for high-quality coatings.

Cell assembly. Product changes have a much greater influence on overall cell assembly. While some minor variations in cell design can be accommodated by the flexibility of current off-the-shelf equipment, limits are quickly reached due to tools, technologies and supporting automation designed for a specific product. All three cell formats are based on different assembly and production steps, which also require different handling processes. In addition, the large number of individual cell components assembled induces propagation effects, so that small changes in one of the flexibility areas have an impact on several downstream process steps. For instance, the packaging and sealing process of the pouch cell is highly dependent on the positioning of the tabs. However, with adaptable processes an intelligent equipment design it is possible to use existing technologies to provide format and size flexibility throughout cell assembly.

Cell finalization. High sensitivity towards product variations and design changes can be seen in particular in the cell finishing. This is mainly due to the current need to precisely match and fit the process equipment to the final product design (e.g., precise tab and terminal connections for a reliable and defined charging process). Combined with innovative contacting solutions a modular setup of formation and aging chambers is able to provide necessary flexibility potentials.

Expert Statement: Sarah Michaelis, VDMA

"In Europe, and especially in Germany, there are numerous specialists in machinery and equipment manufacturing who bring the necessary competence and know-how for the implementation of flexible battery production. Innovative and customer-specific solutions in this area can and should be driven systematically."

Re-thinking traditional LIB production – Potential of Production as a Service (PaaS)

A transformative approach for new operational resilience

The ongoing and ever-increasing integration of battery cells into a wide range of applications and industries is currently posing a number of challenges for battery cell production:

+ **Product volumes.** Leading OEMs as well as battery cell manufactures are responding to increasing product volumes by relying on high-volume production lines designed for specific cell formats, and variants to achieve the high performance at minimal cost.
+ **Disruptive innovations.** The battery cell market clearly shows that both product features and manufacturing processes, are continuously evolving. Therefore, production lines must react adaptively to new innovations and breakthroughs all at once.

To succeed in this dynamic and rapidly evolving environment, the impact of new active materials, production methods, and cell variants must be considered early in the production planning process. This allows to increase and improve responsiveness to changing customer demands while strengthening operational resilience. At the process and equipment level, flexibility should focus on quick and easy changeovers to reduce machine downtime and quickly adjust production volumes. This requires in-depth product and process understanding, as well as knowledge of customer needs and market insights.

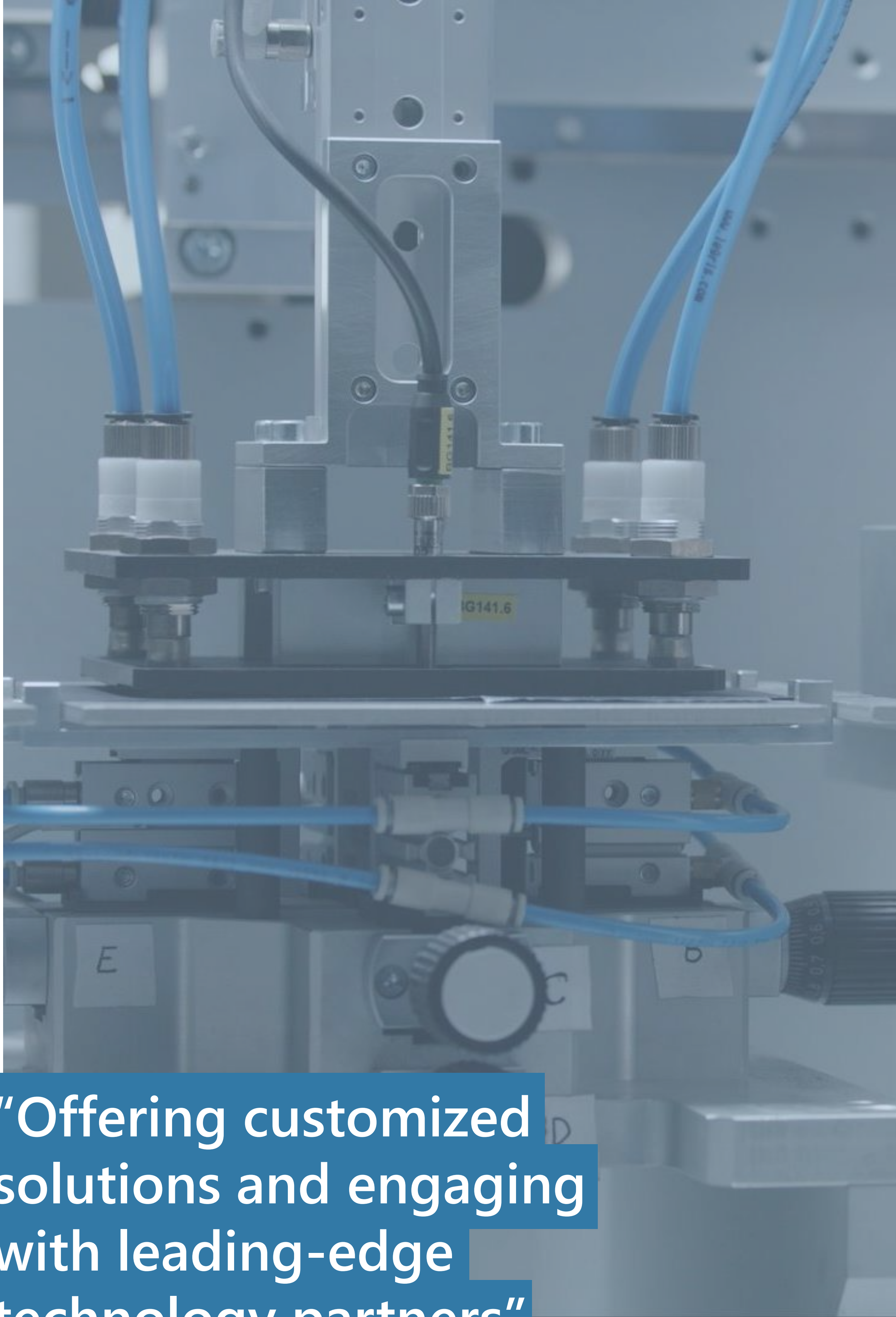
Understanding and thoroughly considering the LIB flexibility areas within the production system is essential. A look at currently used equipment for battery cell production shows different levels of flexibility and adaptability:

+ **Cell chemistry.** Most cell production plants nowadays are able to process different active materials without major modifications. Main limitations arise only due to electrochemical aspects, solvent recovery, or gassing behavior.
+ **Cell format.** Given the different product structures, the assembly of the cell formats currently requires the use of specific and closely interlinked equipment technologies. Intelligent process routing can increase flexibility through systematic automation.
+ **Cell dimension and design.** The equipment is currently designed for very specific cell shapes and sizes, allowing only a small design margin for deviations in product dimensions.

The trade-off between modifying systems for more configurability and adaptability versus adding new, dedicated systems represents the main challenge. In an ideal arrangement, the available flexibility corridors are utilized as much as possible before new systems are added to the infrastructure. Mastering these challenges will enable companies to offer customized battery solutions while ensuring economic viability.

R&D pilot cell production	*Industrial high-volume battery cell production*	*Production as a service for flexible cell production*
Pilot-scale production lines primarily **serve R&D activities for materials testing and validation** as well as process integration and **scale-up of new technologies and innovations.**	**High-volume production** lines are typically designed for **dedicated cell formats and variants** in order to **achieve the matching output at minimum cost.**	**PaaS facilities have a flexible production setup** designed to handle **multiple customer orders** and **reduce projects specific investment costs.**
+ Beneficial research environment + Environmental controllability – Low process reproducibility – Fluctuating product quality	+ Streamlined for maximum efficiency + Process stability and reproducibility – Low format and product flexibility – Sensitive to production changes	+ Efficient and stable batch production + Flexibility and product variety – Higher initial investments – Need for customized equipment

Figure 7: *Differentiation of the PaaS concept and its role within the context of battery cell production*



“Offering customized solutions and engaging with leading-edge technology partners”

Flexibility manifests in many ways – Implications for transformed production systems

Implementation concepts for increased flexibility

The spectrum of flexibility opportunities between a streamlined, ramped-up production line for a specific cell format and a fully flexible battery cell production, offering highly customized solutions as a service, is vast. Already in early stages of factory and process planning, as well as conceptualization of logistics and warehouses, this becomes very apparent. In each case different degrees of flexibility can be considered and realized accordingly.
However, ensuring flexibility has its price that needs be taken into consideration. The general question arises as to how flexibility can be addressed so that initial efforts and investments ultimately pay off. The transformation of currently known LIB factories in a way that offered end-of-line products are able to incorporate customer-specific requirements and serve several markets becomes the key challenge. To set up a production system in this intersection of process optimization, flexible production, and financial transformation, several approaches are feasible.

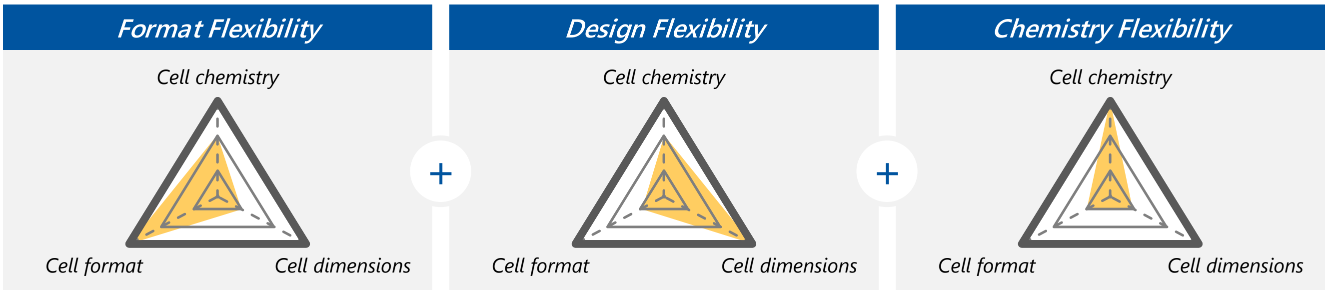
Opportunities to establish the PaaS within LIB-Production are manifold, providing interested users with the vital freedom to accommodate their existing core competencies in the best possible way.

Driven by the market demand and the expertise of technology partners, different flexibility areas can be addressed selectively or in a joint manner (s. Figure 8). Independent of the final business case, following questions have to be answered:

Which format? A crucial decision for production planning with major implications is whether to produce all three or only one specific cell format. By focusing on one cell format, the overall process complexity (especially within the cell assembly) can be significantly reduced.

Which design? The demand for various cell designs is driven by the market and its diversity of applications. Focusing on cell designs with specific shapes and sizes as well as connections (tabs, respectively terminals), distinct market segments can be deliberately selected and prioritized. A production system then can be dedicated to the flexible production of such variants.

Which chemistry? Depending on the intended use of the battery different cell chemistries are preferred and processed in separate production runs. Setting up dedicated equipment enables flexible coordination of multiple customer orders, while ensuring optimal plant utilization.



Format Flexibility
+ Diversification in cell formats to expand customer base in multiple markets
– High equipment investment required, especially in downstream processes

Design Flexibility
+ Focused production of customized format variants and designs possible
– High efforts in adaptation and change-over for shared production lines

Chemistry Flexibility
+ Low implementation effort due to minimal equipment changeovers
– Already applicable in most of current running cell production lines

Figure 8: Overview of PaaS-oriented production systems with different flexibility focus (⊕ combinations possible)

Product diversity in one single factory

However, simultaneously integrating all of the ambitious flexibility areas (s. Figure 3) is only possible if included and prioritized during the process and production planning. A factory designed according to these flexibility areas differs from conventional configurations in several aspects, most notably in an even greater equipment complexity. The desired flexibility thus becomes the challenge of optimal coordination of individual equipment units within the production system, from process to logistics and personnel to the underlying supply chains.
With sufficient knowledge of the specifics of each cell format and applicable flexibility corridors in production, it is possible to set up a flexible production system that is capable of serving the needs of multiple customers. Once embedded in the overall system, a range of benefits can be achieved through Production as a Service. The challenges of supplying specific variants and changing market requirements can be overcome by adaptive electrode production and by expanding the equipment infrastructure within cell assembly and finalization as required. This enables on-demand production of different cell variants within one factory, with parallel processing of individual production orders. In contrast to currently running and planned gigafactories, the focus with this implementation of PaaS shifts from conventional mass production towards meeting customer-specific demands by leveraging economies of scale within small to medium production volumes.

The implementation of PaaS is able to close the gap between economic mass production and customer-specific built-to-order production. In contrast to existing production concepts, PaaS complements the existing battery landscape by providing significant added value for distinct market niches and a growing customer base.

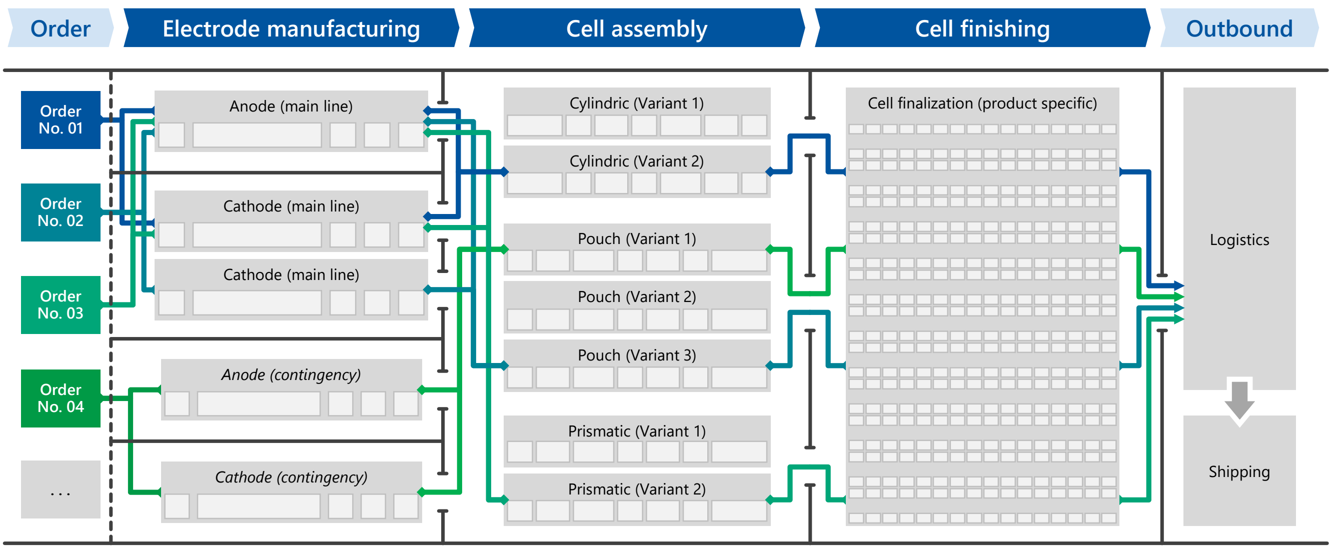
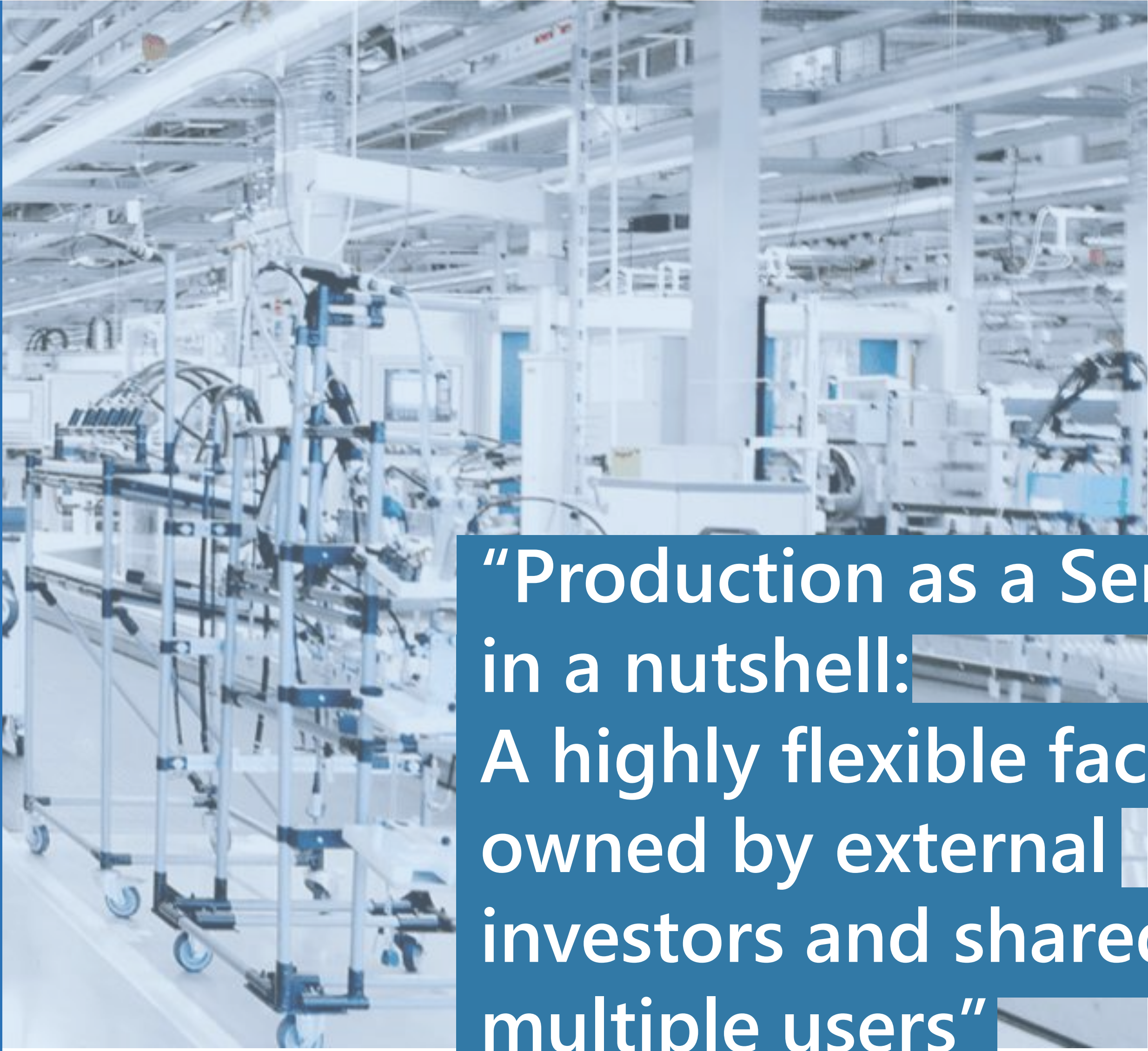


Figure 9: *Schematic of a fully flexible plant layout for comprehensive production of different cell chemistries, formats and designs*

Expert Statement: Dr. Florian Degen, Fraunhofer FFB

"The flexibility and adaptability of the production systems and the factory is essential for the implementation of Production as a Service in a scaled and industrially oriented battery cell production. The planning of technical building equipment, the factory layout, the logistics and storage concept, the definition of production process, and the specification of process technologies must enable a reconfiguration with minimal effort."



"Production as a Service in a nutshell: A highly flexible factory, owned by external investors and shared by multiple users"

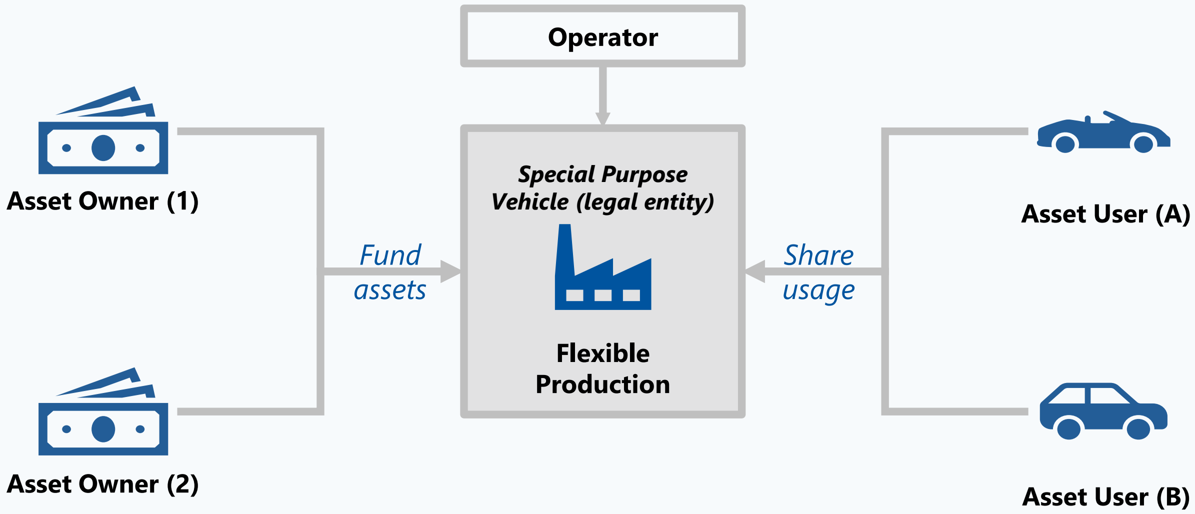


Figure 10: Main elements of Production as a Service (PaaS)

PaaS in a nutshell – A flexible factory owned by external investors and shared by multiple users

Key enablers and benefits of flexible production

Within the battery cell production, key challenges and manufacturing requirements are influenced by a fast-changing market environment that requires producers to improve their value proposition (cost, quality, time). Additionally, the COVID-19 pandemic and the war in Ukraine have exposed the inherent risks of global supply chains. Material supplies and prices have exhibited extreme volatility while geopolitical conflicts and sanctions have shaken up the global economy. Even before the recent major disruptions, producers had to cope with growing protectionism in many regions. To address these challenges, companies are regionalizing production in order to manufacture goods closer to their core markets, strengthening their resilience. The key enablers of a flexible production archetype include:

+ **Flexible Production:** Factory produces multiple products efficiently and can adapt to volume changes quickly.

+ **Financial transformation:** Smart structuring enables third parties to share operational risk and provide funding.

+ **Sharing:** Multiple users share infrastructure on pay-per-use basis, variabilization of fixed costs.

In the PaaS approach, multiple stakeholders join together and complement their assets to build a shared production system. By merging different competencies, equipment technology and skilled personnel, production is enabled to meet the growing pressure from customers to produce sustainably and to adapt production planning towards adaptive and redesigned operations. Synchronizing highly automated equipment and the right production software results in a flexible and scalable production concept. These production assets are then owned by third-party investors.

From a user's perspective, the Production as a Service concept yields multiple advantages. First, the user gains additional financial flexibility, as upfront investment for the production assets is transformed to pay-per-part (CapEx to OpEx). Second, shared production results in synergy effects due to economies of scale as well as a mitigation of utilization risks due to the ability to employ unused production capacity for other products. Third, Production as a Service enables efficient and economical regional production, promoting supply chain resilience, market responsiveness, and sustainability.
From an investor's perspective, Production as a Service setups enable investments into a broader market rather than a single product. Instead of making a bet on the success of a specific cell variant, an investor can invest into the fast-growing battery cell market as a whole. This is enabled through a flexible production which can produce different kinds of cells. As a result, market and product life cycle risks are lowered for the investor. Furthermore, risks of ownership can be mitigated by volume guarantees from users and technical performance guarantees from asset producers or insurers.
Based on risk adjusted financials and a highly automated layout, Production as a Service thereby transforms the factory into an investable asset.

A flexible production plays out its advantages when demand is fluctuating, given its ability to compensate by shifting unused volumes to products with higher demand. As a result, PaaS lays the operational and economic foundation for flexible cell factories with the ability to produce small series at scale.

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The chair PEM of RWTH Aachen University was founded in 2014 Professor Achim Kampker and has been active in the field of battery production of lithium-ion battery technology for many years. In our research groups, the team is dedicated to all aspects of the development, production and recycling of battery cells and systems and their individual components. PEM's activities cover both automotive and stationary applications. Due to a multitude of national and international industrial projects with companies of all stages of the value chain as well as central positions in renowned research projects, PEM offers extensive expertise. PEM focusses on sustainability and cost reduction with the goal of a comprehensive innovation chain from fundamental research to large-scale production.

WWW.PEM.RWTH-AACHEN.DE

FlexFactory is a joint venture of MHP, Munich Re, and Porsche that offers multiple services by bundling expertise in digital value chain, flexible production, and financial transformation. The company serves as a business enabler and incubator to set up a highly flexible factory owned by third-party investors and shared by multiple users. This is what we call Production as a Service (PaaS). When implementing PaaS, different stages of sharing are possible, as the solution is fully customized. PaaS comes with its own complexity and challenges. FlexFactory thereby acts as an orchestrator and trusted advisor that connects the necessary stakeholders and designs a business model which is valuable for all parties. Based on highly flexible production layout and viable business model, our offering further transforms a new factory into an investable asset.

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