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Techno-Economic Development Methodology for Mini-Environments in Battery Cell Production

Marius Heller[a]*, Saskia Wessel[a], Thorsten Wilk[a]

[a]*Fraunhofer Research Institution for Battery Cell Production FFB, Bergiusstraße 8, 48165 Muenster, Germany*

* Corresponding author. Tel.: +49-1520-1638594; *E-mail address:* marius.heller@ffb.fraunhofer.de

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Abstract

Due to the rising interest in electric vehicles, the demand for more efficient battery cells is increasing rapidly. To support this transformation, battery cells must become cheaper and environmentally friendly. Energy consumption during production is a major driver of costs and CO_2 emissions. To fulfill societal demand, higher gravimetric and volumetric energy density of lithium-ion battery cells are required. Since these materials are significantly more sensitive to moisture, the production conditions need to be adapted accordingly. Therefore, the preparation of clean and extremely dry atmospheric conditions is crucial for production of high-quality battery cells. The technology approach "Mini-Environment" enables the substitution of conventional clean- and dry-rooms for significant energy and cost savings. However, the diverse product- and process-specific characteristics along the value chain require individual solutions to enable Mini-Environments for highly automated battery cell production. Due to multiple interacting requirements and characteristics, such as operator interventions, logistics interfaces and air handling procedures, there is a very high diversity of variants for the machine equipment design. Moreover, typical methodological procedures for development of quality-oriented and energy efficient production machines remain less applicable to the early stages of technological development. Both issues lead to the research questions, how to identify the independencies between costs, air handling, product and process characteristics and how to reach the most techno-economical machine design. To answer these questions, a systematic techno-economic development procedure was conducted. Following a four-phase analytical approach, based on an extended morphological box, cost analysis, techno-economic utility analysis and sensitivity loop, different Mini-Environment concepts were constructed, analyzed and cross-evaluated. The study also forecasts the CO_2 emission rate reduction and cost savings compared to alternative machine concepts. In summary, a fully interlinked system design was adapted on a cell assembly line with a cost-saving potential of 56% for future battery cell production.

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Keywords: Battery cell production; Technology identification; Energy reduction; Machine design; Mini-Environments

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1. Introduction

The earth and therefore humankind are in a state of change due to global warming. Among others melting of the Arctic Sea ice or permafrost melting are just a few examples which are caused by greenhouse gas emissions (GHG). To address climate change, substantial investments in low-carbon technologies are necessary [1]. In particular, this relates to the energy, transport and industrial sectors, which together accounted for 75% of the overall GHG in Germany in 2021 [2]. Electrochemical energy storages are a promising and scalable solution approach to be key to comply the Paris Agreement goals and support the UN Sustainable development goals [3]. The international demand for energy storage systems and electric vehicles are rising rapidly, and in conclusion battery cells with it. Overall, global demand for LIB was around 470 GWh in 2021 [4]. Most market forecasts assume a global demand of 2 to 3,5 TWh in 2030 [5, 6]. To summarize, a CO_2-neutral battery cell production is to be strived to counteract global warming progress.

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However, to achieve a sustainable battery cell production, the increase in effectiveness and efficiency in production is the key lever in addition to the expansion of renewable energy. Today's production facilities have extremely high operational expenditures (OpEx) due to scrap, labor as well as energy consumption. The construction of a battery cell factory is also characterized by high capital expenditures (CapEx) required for production technologies, technical building services, dry rooms and automation [7]. Nowadays technology approaches are being transferred to the rapidly growing market, which doesn't succeed in reducing GHG [8]. Therefore, a rethink is required and the implementation of innovative technologies are essential as key for competitive and sustainable value creation.

The novelty and the main objective of this work is the derivation of a methodological approach for the analysis and development of individual machine designs in battery cell manufacturing to increase product quality and reduce energy consumption.

2. State of Research

The following sections describe the state of research regarding battery cell manufacturing as well as humidity and cleanliness management in production.

2.1. Lithium-ion battery cell manufacturing

Battery cell manufacturing and its diverse value chain consists at least out of 14 individual process steps, which can vary depending on the cell design. Battery cell production is divided into the three main sections electrode manufacturing (mixing, coating, drying, calendering, slitting), cell assembly (post-drying, electrode separating, stacking, contacting, housing, electrolyte filling) and cell finalization (formation, ageing, testing). Furthermore innovative (e.g. dry coating, pre-lithiation, electrode structuring) and alternative (e.g. lamination) process technologies can be integrated in a complementary or disruptive way. Again, this requires the detailed design of the technology chains, considering the interdependencies along the value chain [9].

Another crucial element in battery cell manufacturing is the infrastructure to maintain very clean and dry conditions in the production environment [10]. The product is highly sensitive to changing environmental conditions. Moisture, for example, was found to have the most effect on product quality. Even the smallest amount of moisture leads to the decomposition of the electrolyte and has a significant influence on the lifetime and capacity of the battery [11, 12]. The sensitivity will intensify with future cell materials [13, 14, 15]. Airbone molecular and particulate contamination are another crucial problem in battery cell manufacturing which leads to high reject rates [16, 17]. Therefore, facility-integrated clean and dry rooms (CaD) must be built up and have to be tailored for each production step due to individual material, process and production characteristics [10, 18, 19]. Conventional clean and dry rooms in battery cell manufacturing require 26% to 53% of the overall energy consumption depending on the use case and production conditions [8, 20, 21].

2.2. Humidity and cleanliness management in production

As the requirements are becoming more sophisticated and materials more sensitive to moisture, new machine design concepts are in development to increase product quality and energy efficiency. The FRAUNHOFER RESEARCH INSTITUTION FOR BATTERY CELL PRODUCTION FFB identified various terminologies regarding new airtight housing or so-called encapsulation concepts. Mini-Environments (MiE) and Macro-Environments (MaE) have become established next to the conventional CaD [22]. According to the ASSOCIATION OF GERMAN ENGINEERS, a MiE is a limited, separated product environment to protect the product from contamination [23]. Next to the product, the process and the machine itself can be encapsulated. The interlinking between MiE is crucial for highly automated production systems and its intralogistic processes. Already in semiconductor industry, MiE are fully developed for automatic production and standard mechanical interface formats (SMIF) were integrated [24]. The MiE can be classified into an active (with air supply) and passive (without air supply) system. The active MiE is again divided into adapted and integrated designs. The difference between these two is the interconnection to the production unit itself. Adapted MiE are not permanently connected to it and could therefore offer a good solution for flexible production systems or retrofitting of installed production units. In contrast, integrated MiE are permanently connected to the production system. The MaE represent an intelligent intermediate solution of MiE and clean and dry rooms [22]. Compared to clean and dry rooms, MaE have no less than one atmospheric barrier between the operator, the logistics, the process or product area to maintain at least two independent atmospheric conditions.

The MiE and MaE offer advantages in operator safety, less energy consumption and higher product yields due to controlled atmospheric conditions compared to conventional CaD. On the other hand, the technical integration efforts on machine, production and especially factory level offer high risks and uncertainties regarding technical feasibility and total cost of ownership (TCO) reduction potential. Fig. 1 represents the typological characteristics of the three housing variants to ensure the required sensitive atmospheric conditions.

	Technical integration effort	Product protection & process control	Energy reduction potential
CaD	🟨	🟨	🟥
MaE	🟨	🟩	🟨
MiE	🟥	🟩	🟩

🟥 bad 🟨 middle 🟩 good

Fig. 1. Comparison of the three main housing variants.

3. Techno-economic development methodology for quality-oriented and energy efficient production concepts

To determine the most techno-economic suitable environment design in battery cell manufacturing, a new methodology is evident in both the practical and theoretical deficits. In practice, there is a high number of variants for the design of the holistic production system due to interacting technical requirements and influencing parameters. In addition, the mentioned main encapsulation approaches have different typological characteristics. Based on these two aspects, an individual perspective is needed to implement the most techno-economic design on machine, production and factory level. Furthermore, typical methodical approaches are not applicable in the early stages of technology development due to uncertain data bases. Moreover, the independencies between atmosphere control, high-throughput production, product and economical perspectives have not yet been researched. For these reasons mentioned, a development methodology for the identification of the techno-economically most suitable production environment concept with focus on scalability was elaborated.

Fig.2 defines the scope and application area of the developed methodology in this paper. While the interfaces to technology management, production systems development as well as engineering methods and tools are crucial, the combination of existing methods is indispensable [25, 26, 27]. The overall objective of the methodology applied is to accelerate the implementation and integration of the most technically and economically feasible production systems for future battery cell manufacturing.

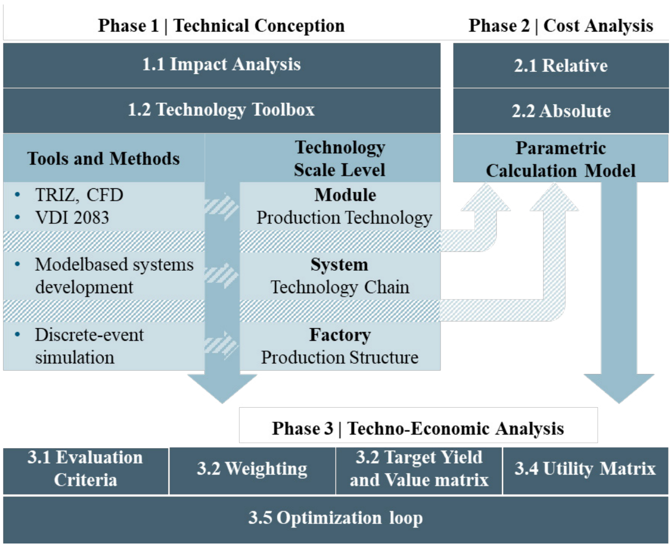


Fig. 2. Techno-economic development methodology for individual production concepts in battery cell manufacturing.

The goal of the first phase is to define and couple several design concepts through a development-supported toolbox, which contains the essential technology elements. In the second phase, these alternatives are then evaluated qualitatively or quantitatively in economic terms. The results of the first two phases are directly connected for the holistic techno-economic analysis. Here, various alternatives are cross-compared to determine the most promising solution regarding the respective conditions and use-case. In the final phase, the solutions are analyzed in terms of their opportunities and risks to optimize or combine the advantages of the alternatives.

3.1. Technical conception

The beginning of the first phase is the execution of an influence analysis based on expert teams. Here, all influencing variables are collected regarding the target system. In general, a classification can be made between general variables and system limits, technical as well as economic input parameters. In order to consider all elements taking influence on the techno-economic execution of local environments in battery cell manufacturing, stakeholder analysis is conducted. In a further sub-step, necessary exclusion criteria are derived from the structured parameters to ensure the safety of the personnel, the process stability, product quality and technical feasibility. For example, toxic materials are not allowed to come into direct contact with the operator and therefore require MiE approaches to separate the operator from the process.

In the next step, an extended morphological box of the general as well as technical influencing variables is set up based on the influence analysis carried out. The general attributes have an increasing influence on the economic evaluation and mainly represent the cell manufacturing conditions, while the technical attributes represent both the engineering and manufacturing functionalities. The level of detail of the attributes for the present methodology is quite high and leads in a complex matrix. For example, the individual attributes include different air-drying technologies or possible logistics concepts. Hence, the morphological box must be extended in two dimensions, conflict analysis as well as cost influence allocation. Table 1 shows a comprehensive overview of the extended morphological box set up, which represents the central module of the overall technology toolbox. The column “Attributes” represents the parameters derived from the influence analysis in 1.1 and should be structured in different sub-categories for a better mapping of the single attributes *n*. Each configuration listed must be evaluated in terms of technical adaptability on modular, production and factory level. To counteract the complexity of all the defined attributes and its specific variations, the “Cross-Impact to” column highlights the interacting properties. At least, the column “Cost influence on” ensures the link to the phase 2 *Cost analysis*.

Table 1. Structure of extended morphological development box

No.	Attributes	Config-uration	Cross-Impact to	Cost influence on
1	General			
1.n	Location, Energy, Factory, Building, Manufacturing concept, Cell design, Process	1 to n	2.n	CapEx, OpEx
2	Technical			
1.n	Scope of housing, Machine design, Air handling, Intralogistics, Degree of automation	1 to n	1.n, 2.n	CapEx, OpEx

Considering the modular (production machine), system (interlinked production machines) as well as factory attributes and its interdependencies in one morphological box enable a holistic techno-economic design for the target system. Nevertheless, the application of the technology toolbox should be followed bottom-up (modular-factory) to identify synergies in the overall system. The definition of solution alternatives according to the required application scenario is the last step and is supported by the methods of the technology toolbox. As in Fig. 1 shown, the main differentiation is by the attribute *scope of housing*. Using engineering methods and tools lead to the necessary level of detail within the technology toolbox (e.g. atmosphere recovery times determined by computer fluid dynamics (CFD) and validated by physical demonstrations (see Fig. 2)).

3.2. Cost analysis

For an economic comparison of different production system alternatives, the cost analysis of the concepts is essential. Depending on whether specific data, cost estimations or no information are available, a relative or absolute cost analysis is performed. The basis for both is the corresponding cost structure. The cost categories are divided in CapEx and OpEx. Further elements of the cost categories are defined for a detailed structure. For the simplified assignment of cost categories and cost variables, the link to the extended morphological box was realized. Due to insufficient data in the pre-development phase of these innovative machine designs, the methodology in this paper focuses on relative cost analysis. Table 2 shows the cost elements identified and their weighting for the relative cost comparison, based on the average assessment of five production technology experts. Relative cost analysis is performed using the pairwise comparison method. The pairwise comparison includes a seven-point scale in order to obtain detailed significance. In addition, the cost elements, depending on the associated cost category, are clustered to create a resulting matrix per cost category (Table 2).

Table 2. Individual weighting of cost elements for cross-comparison (results for an industrial round cell assembly line in Germany described in chapter 4)

No.	Cost position	Single weighting	Overall weighting
1	**Capital Expenditures**	**0.33**	
1.1	Development	0.17	0.05
1.2	Planning	0.12	0.04
1.3	Production and purchase	0.18	0.06
1.4	Transaction	0.1	0.03
1.5	Installation and commissioning	0.14	0.05
1.6	Employee	0.12	0.04
1.7	Area	0.18	0.06
2	**Operational Expenditures (Operation)**	**0.43**	
2.1	Energy consumption	0.34	0.14
2.2	Emissions	0.24	0.10
2.3	Setup	0.20	0.09
2.4	Scrap	0.23	0.10
3	**Operational Expenditures (Maintenance)**	**0.25**	
3.1	Cleaning	0.15	0.04
3.2	Process equipment	0.24	0.06
3.3	Air handling unit	0.21	0.05
3.4	Production downtime	0.39	0.10

For each identified cost element, another pairwise matrix is created in which the designed solution alternatives from phase 1 are compared economically. Multiplying the individual weights by the evaluated matrices results in a total sum for the corresponding cost category in CapEx and OpEx. The dimensionless ratio provides information on the costs incurred within the evaluated alternatives. Furthermore, a total cost comparison is created analogous to the determination of the matrices of the single cost categories. Moreover, the degree of fulfillment of an ideal solution is calculated based on the ratio of the single and total costs. Here, it is assumed that the ideal solution receives the full number of points compared to other alternatives. By the ratio of the final sum of the alternative and the ideal score the degree of fulfillment per cost category and the total cost is calculated. These are decisive for the following phase of the techno-economic analysis.

3.3. Techno-economic analysis

In the third phase a decision-making tool is implemented. The defined solution alternatives are evaluated based on the results of the first two phases. For this purpose, concrete evaluation criteria are defined within a target system, weighted and the target yields of the alternatives are normalized. To ensure a holistic evaluation of the alternatives, the PESTEL analysis is used during the development of the methodology to identify the most techno-economic system. The established target system for encapsulated production environments consists of two levels with five superordinate targets, which again are divided into ten sub-targets, as shown in Fig. 3.

Fig. 3 shows exemplarily the cross-evaluation between three different main machine designs based on an interlinked assembly line and its dimensionless indictors of a CaD, MiE and MaE approach. The higher the utility value (N) achieved, the better the individual attribute or the overall system. The pairwise compared and weighted PESTEL criteria (w_x) are used to calculate the subsystem. The subsystem utility values, in turn, result from multiplying the scaling matrix by the individual weighting.

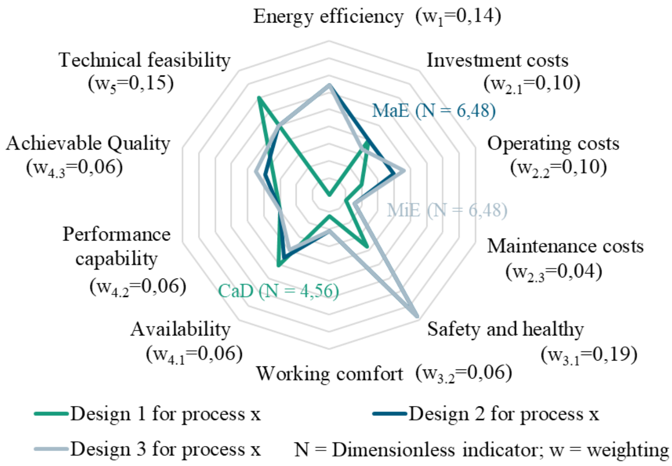


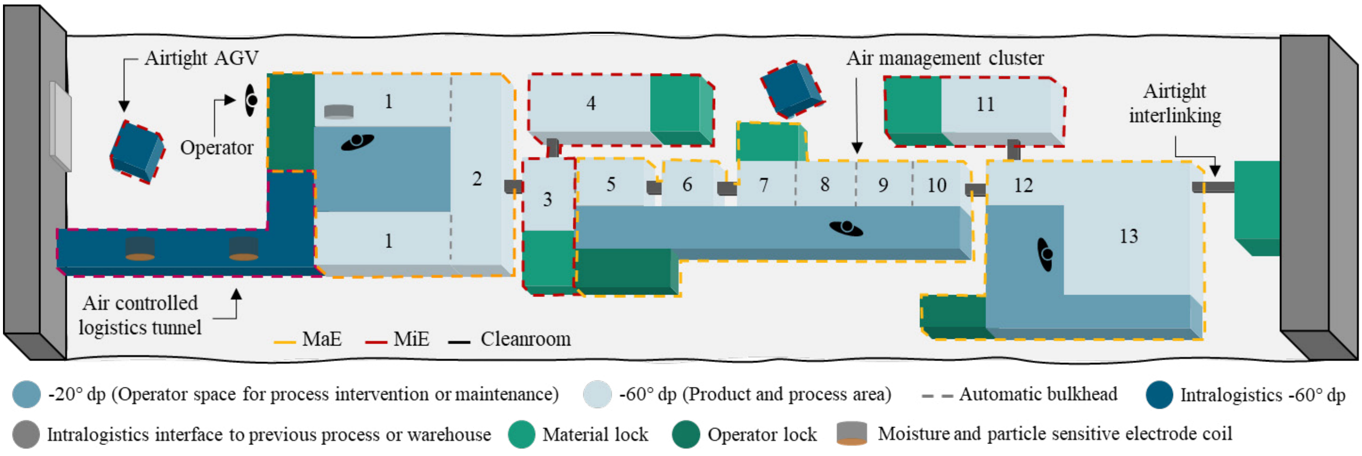
Fig. 3. Spider chart for evaluation of different environment characteristics (results of three alternatives for the use-case described in chapter 4)

The goal "Reduction of CO_2 emissions" is set as a political factor as well as an ecological factor. The economic factor includes the goal of "reducing costs" and the socio-cultural as well as the legal factor includes the goal of "increasing employee acceptance". The technical factor is considered by the criteria "increase of OEE" and "increase of technical feasibility". The overall evaluation again is weighted regarding the impact-factor for battery cell manufacturing. The different target values for the designed alternatives are transferred in a target yield matrix. Finally, by normalization using a scaling matrix, the respective partial values and the total utility value of the alternatives are calculated. The result is a final overall ranking of the alternatives, in which the highest key indicator represents the most techno-economically suitable concept. In the last step, both the relative strengths and weaknesses are identified and ranked using difference matrices to compare the alternatives. Through the revealed optimization potential, the solution alternatives are adjusted at the appropriate points in general, technical and economical terms. The aim of changing the parameters and variables is to optimize the alternative at the identified weak points. Subsequently, a new techno-economic analysis is performed with the modified parameters. The comparison of both techno-economic analyses shows whether the improvements were successful and in which degree of sensitivity the normalized values changed.

4. Application of the methodology on a fully interlinked automatic battery cell assembly line

The »FFB Fab« is a battery cell manufacturing factory of the FRAUNHOFER RESEARCH INSTITUTION FOR BATTERY CELL PRODUCTION FFB (FFB) in Germany with Start of Production in 2027. The presented work was carried out as part of the 21700 round cell assembly line planning. The goal and therefore novelty of this fully interlinked production line will be the integration of MiE and MaE. The cell design is based on NMC 622 cathode, graphite anode and LiPF6 electrolyte as the key components. The overall throughput of 30 ppm must be achieved with a technical availability of ≥92% while the product is continuously exposed to an atmosphere of -60°C dp. Within the scope of the activities and the plant specification, the functional requirements and initial solution approaches were identified within the engineering, production and factory team of the FFB. The three identified main housing approaches (Fig. 1) have been considered and evaluated in this work.

The conceptual design based on the current maturity of the model and the holistic analysis shows from a techno-economic point of view that the individual combination of MiE, MaE as well as CaD is the most suitable solution for the FFB use-case (Fig.4). For example, the required operator interventions due to higher maintenance intervals in case of short tool service life or low process stability results in the application of MaE, because of the ergonomic accessibility for the operator which has to be provided. The implementation of space and ergonomic optimized rooms have the advantage of lower contamination gradients for operator interventions. Through CFD simulations, time-critical parameters for recovery times could be determined and implemented in the technology toolbox. Therefore, the target dew points -20°C and -60°C were integrated in the MaE modules. Further technology elements, such as dry air knives, can be integrated at the modular level for further contamination gradient minimizing. In sum, 3 MaE are implemented within the production line, while MiE are provided for all logistics and handling processes. Individual technology elements were conceptualized and implemented within the toolbox for system and factory scale-up. Among others atmosphere-controlled logistics tunnels have been implemented to realize the interface of a central warehouse or as a production balancing system. Furthermore, automated guided vehicles (AGV) as MiE were provided for direct coupling to the upstream electrode manufacturing. However, the encapsulated machine housings are integrated in clean rooms to avoid particle contamination. The operator on the shopfloor still has an enormous risk potential to the product quality rate. Another advantage of the identified production concept that should be emphasized is the coupling of similar process characteristics. Thus, so called air management clusters can be set up to implement standardized air handling units on system and especially factory level in a technical, ecological and economic way. Based on a rough subsequent absolute cost assessment including CapEx and energy costs (OpEx), a cost reduction of 56% and CO2 saving potential of



AGV (Automated guided vehicle), dp=dew point, 1=Winding, 2=Jelly-Roll (JR) loading, 3=Insulator supply and insertion , 4=Can supply, 5=JR insertion, 6=Anode tab welding, 7=Swaging, Insulator supply and insertion, 8=Beading, 9=Hi-Pot check, 10=X-Ray, 11=Cap loading, 12=Cathode welding, 13=Electrolyte filling and crimping

Fig. 4. Most techno-economic conceptional design for the machine encapsulation of the 21700 round cell assembly line of the Fraunhofer FFB

33t over seven years could be achieved compared to nowadays integrated and used CaD. Due to the uncertain data basis in the early technology conception, the selected relative cost analysis presented a 36% higher cost utility value and thus equally lower total costs. It must be considered that there is no quantitative causality to the absolute cost analysis.

5. Conclusion and Outlook

In this paper, a techno-economic development methodology for quality-oriented and energy efficient production systems in battery cell manufacturing has been presented. It could be shown that the methodology and especially the implemented technology toolbox contribute to a scalable and systematic development approach. The focus of the methodology is the customized development of processes and equipment to produce battery cells at different scaling levels with the emphasis on an assembly line. Further research activities should aim at the stepwise physical evaluation of the technology elements according to the TRL-path shown. The extension, adaptation and establishment of detailed parameterization approaches in the technology toolbox are focus of further research. Furthermore, standardization approaches for intralogistics systems and air handling units must be identified for an efficient production. In addition to the virtual and simulation-based development of MiE and MaE at module and system level, it includes the integration of elements for scaling up to factory level as well as the extension to the entire value chain, in particular electrode manufacturing.

The overall future goal is the rollout of this cutting-edge technology approach in battery cell manufacturing for supporting improvements in quality, production yield, efficiency and costs.

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