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Advancements in Battery Cell Finalization: Insights from an Expert Survey and Prospects for Process Optimization

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Abstract: Battery cell finalization is a crucial process chain in battery manufacturing, contributing to a significant share of CAPEX and OPEX. Thus, there is a high cost-saving potential by improving the process chain. This research paper investigates various crucial facets of the cell finalization process in battery cell production through an expert survey. These include investment cost allocation, potential cost savings in sub-processes, reject generation, early detection of faulty cells, quality measurement techniques, and the utilization of inline data for early quality determination and real-time process control during the formation process. A solution approach for the implementation of electrochemical impedance spectroscopy for inline early quality determination is given. The results yield valuable insights for optimizing the formation process and enhancing product quality.

Keywords: battery production; cell finishing; formation; early quality determination; industrial study; production innovation; electrochemical impedance spectrocopy

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1. Introduction

Anticipating the landscape of battery manufacturing until the end of 2030 reveals a forecasted production capacity of 2.014 GWh in Europe and an ambitious battery demand of 4.700 GWh worldwide [1,2]. This surge underscores the escalating demand for energy storage solutions in the pursuit of surpassing internal combustion engine vehicles.

Absolutely, reducing battery cell production costs is pivotal in achieving this goal, especially given the significant financial commitment of EUR 100 billion earmarked for European battery manufacturing investment by 2030 [3]. Within the operational framework, battery cell manufacturing costs emerge as a huge factor, constituting approximately 14–24% of the total battery cell operational expenditures [4,5]. This fact necessitates careful cost optimization strategies.

The process of battery cell production involves a sequence of intricate stages, each contributing uniquely to the final product's performance and economic viability. From electrode production and cell assembly to the critical phase of cell finishing, the orchestration of these elements underpins the entire battery production ecosystem. An overview of capital expenditures (CAPEX) and operating expenditures (OPEX) is provided on the path to efficient and sustainable production.

The distribution of CAPEX across the different manufacturing stages presents an insightful perspective. Specifically, electrode production commands a significant share, ranging between 35% and 45%, highlighting its complicated and resource-intensive nature. Cell assembly and cell finishing follow suit, with their respective shares falling within the ranges of 25% to 35% and 30% to 35% [6]. A particularly notable investment in cell finishing equipment, amounting to EUR 35 billion in Europe by 2030, underscores the industry's recognition of the huge role of this phase in achieving technological advancements and high-quality products [3].

Operating expenditures (OPEX) play an instrumental role in shaping the overall cost structure of battery manufacturing. At the forefront of this analysis is the battery cell cost, quantified at EUR 91 per kilowatt-hour (EUR/kWh). 12.74 EUR/kWh is attributed to the manufacturing process itself [4]. Delving into the specifics, electrode production, cell assembly, and cell finishing shoulder different OPEX responsibilities, with contributions of 39%, 20%, and 41%, respectively [6]. Therefore, the cell finishing accounts for a total of 5.22 EUR/kWh, taking the highest proportion in OPEX. Figure 1 provides a comprehensive view of the cost distribution, spanning from the overall cell cost down to the specific cost allocation of individual cell finishing processes.

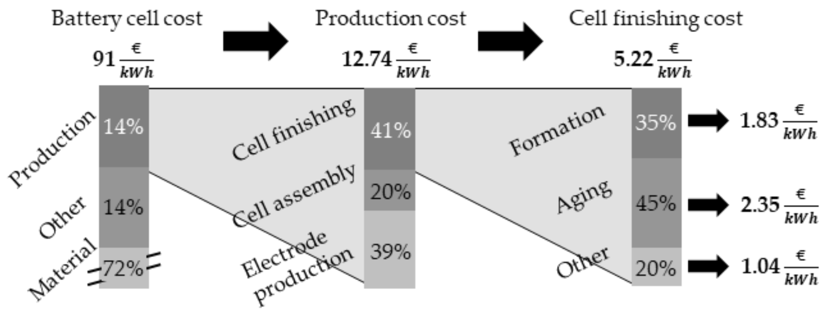

Figure 1. Distribution of OPEX within battery production.

The cell finishing process not only is an expensive process chain but comes with high potential for cost savings. One promising approach is inline quality control and intelligent parameter settings based on it, which make use of the data collected inline. Leveraging big data analytics for smart inline quality control during cell finishing can substantially trim cell production costs by up to 15%, resulting in a battery cell cost reduction of 2.87% or 2.61 EUR/kWh [6].

This study places a strong emphasis on the substantial potential for cost reduction within the cell finishing process. It specifically focuses on describing challenges in optimizing the cell finishing process with a focus on smart inline quality control. Moreover, it seeks to identify viable solution approaches for integrating this technology seamlessly into the cell finishing process chain.

2. State-of-the-Art Battery Cell Finalization and Quality Determination

In Figure 2, the cell finishing process chain is divided into three main categories: pre-treatment, formation procedure, and quality testing. Pre-treatment focuses on the creation of optimal conditions for the formation itself and can be divided into thermal, mechanical, and electrical sections [7]. During thermal pre-treatment, the cells are stored at elevated temperatures from 40 °C to 60 °C to reduce the contact angle of the liquid electrolyte and to improve the access of the electrolyte to the electrode mesopores [8]. This wetting/soaking process can last for 12 to 24 h depending on the cell design and size [9]. For this process the cells are stored in racks in a temperature-controlled room or chamber.

The main task of the formation procedure is the development of the passivation layers at both boundary layers of the electrodes to the electrolyte [7,10]. The formation procedure (according to Figure 2) starts with a pre-formation up to 20–30% SOC. Most of the gas evolution takes place in this phase so that a degassing step takes place after pre-formation. In addition to degassing, an optional second electrolyte filling can occur to compensate for electrolyte losses during the pre-formation in large cells. High-temperature (HT) aging is then carried out to give the electrolyte time to wet after the second filling. This is followed by the first formation, in which the battery cell is fully charged and discharged [11]. Finally an HT aging is applied to stabilize the SEI Layer [12].

The last stage, quality testing, in Figure 2, begins with a capacity test and is followed by room-temperature (RT) aging. During RT aging, the self-discharge rate is determined and allows us to check for micro short-circuits. Afterwards, a direct-current inner-resistance (DCIR) test is conducted. Finally, the cells undergo an EoL test with visual inspection [7].

The process chain composition varies for each cell format, especially because prismatic and pouch cells are often much larger than cylindrical cells [13].

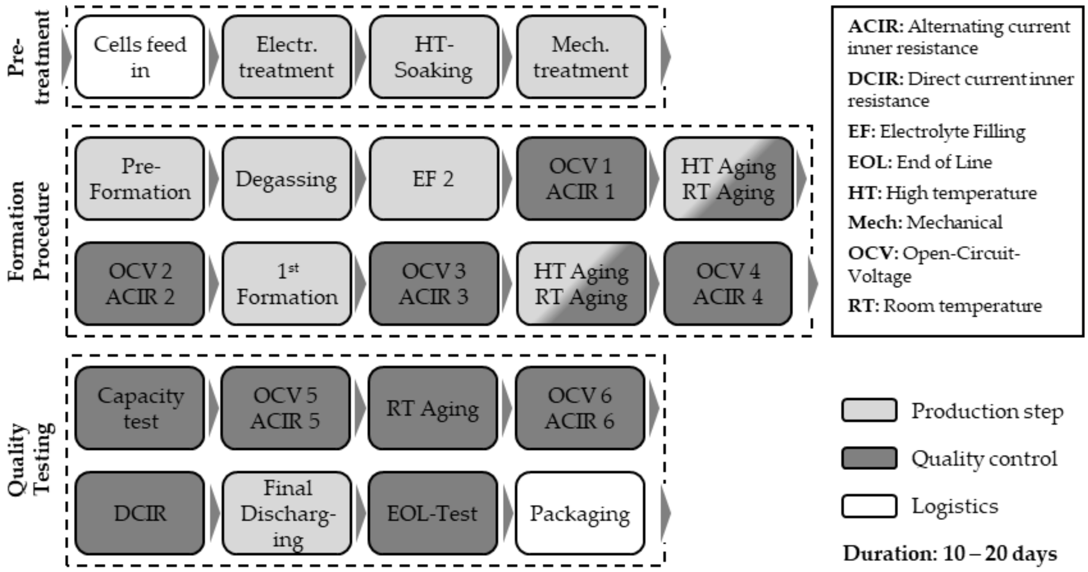

Figure 2. Example cell finishing process route [7].

It is to be noticed that, especially for testing the quality, the processes and parameters are cell-format independent. For quality assurance, usually the self-discharge rate, cell capacity, direct current inner resistance (DCIR), alternating current inner resistance (ACIR) at 1 kHz, and optical criteria are evaluated. If each criterion stays in its defined limits, the battery cell will be considered OK.

However, the named quality assurance processes have major disadvantages when integrating them into the production steps. During the measurement of the self-discharge rate and the ACIR, the battery cell requires staying at open-circuit voltage (OCV), allowing no current flowing and, therefore, no formation process. Optical criteria cannot be observed, since the battery cells are stored in trays covering their surface. Separate DC protocols must be used for capacity testing and DCIR, which are also incompatible with the formation process. In total, an uninterrupted formation process with integrated quality control cannot be implemented with today’s quality control processes due to the necessary test conditions (quiescent state or defined DC protocols). Hence, it is imperative to explore alternative processes that assess battery quality using different parameters, with the aim of optimizing the cell finishing process chain.

There are multiple solution approaches to integrate quality testing in the production process. One promising approach is to evaluate the DC data during formation. However, this technique is quite inaccurate and gains accuracy with more cycles provided to the models [14]. Other approaches rely on EIS measurements to determine the resistance of the SEI Layer [15–17]. To conduct the EIS measurement, the battery cells are charged to a defined voltage. After reaching the measurement voltage, the formation is interrupted and paused until the battery cell reaches OCV. Then, the EIS measurement is conducted [16,18,19]. Another approach by Heins et al. [15] charges to defined voltages and operates the EIS measurement at OCV but also takes measurements at different temperatures for each voltage [15].

The mentioned methods for using EIS during the formation process all rely on a process interruption. This can lead to lower battery quality in comparison to an uninterrupted process. Additionally, the formation time is significantly higher than in uninterrupted processes. As a result, the measurement methods cannot be used in series production and there is a need for action to integrate EIS technology into an uninterrupted formation process in order to save time and not negatively affect battery cell quality.

3. Materials and Methods

For this study, the following hypothesis was formulated based on the state-of-the-art review in Section 2: "The battery cell finishing process chain has a high optimization potential regarding quality determination processes. The currently conducted quality testing after production processes is inefficient and an early quality determination can increase the cell finishings efficiency significantly".

To confirm the hypothesis, questions were formulated that could either confirm or refute the hypothesis. For this purpose, different question categories were created, which, on the one hand, address the aspect of optimization potential in cell finalization and, on the other hand, address the relevance of early quality determination.

Based on the question categories, specific questions were developed to cover the particular section of the survey. This results in a question catalog of 15 questions in 5 categories.

After the development of the questionnaire, experts were selected and contacted based on the knowledge requirements regarding the different sub-areas. The experts were selected to be representative of the required area of the company. Based on these requirements, 19 experts from 19 different companies active in cell finishing were contacted. Of the 19 experts or companies contacted, 8 agreed to participate in the survey. The companies represent the different industries as follows: two cell finishing equipment manufacturers, two research institutes, one measurement equipment manufacturer, two battery cell manufacturers, and one tier-one supplier for battery production. The selection of companies was limited to European companies.

The experts consulted were process specialists (37.5%), cell finalization executives (37.5%), and C-level managers (25%). This diversification results in a broad picture of optimization potential across all hierarchical levels of the companies.

The survey was conducted as online face-to-face interviews. During the interview, the questions were asked to the experts and the experts were asked to reflect their answers in the form of a rating on a Likert scale or as free text depending on the question.

4. Results

The findings of the survey will be summarized, and the key results will be presented in the results section. The detailed expert answers are presented in Figures A1–A12 in Appendix A.

4.1. Investment Costs and Cost Saving Potential of the Cell Finishing Process Chain

Due to the time-intensive nature of the formation and aging processes, there is a high demand for space and a significant number of machines. Consequently, the cell finishing process chain constitutes a substantial portion of the capital expenditures (CAPEX) in battery production. On average, experts estimate the CAPEX share of cell finalization to be 35.62% (Figure A1). However, it is worth noting that this estimate exhibits a wide range, varying from 20% to 60% in CAPEX share. Nevertheless, the 35.62% figure aligns with current industry assessments of similar estimates [3,6,7].

Both the cost drivers and the potential for cost reduction are most pronounced in the formation and aging processes, as compared to the wetting and end-of-file (EoL) processes (Figure A2).

According to expert insights, doubling the capacity of a single channel within the formation department, thereby halving the formation time and equipment requirements, does not yield any cost reduction in the formation department. This is due to the disproportionate increase in costs associated with more powerful formation equipment despite the time savings. Consequently, cost efficiencies in the formation process can only be achieved through process shortening, such as adopting a single formation cycle or implementing a lower charging cut-off voltage. Existing research results support the viability of both approaches in reducing the formation process duration [20–22].

However, further assessments regarding the parametrization of the formation process must be conducted specifically for the battery cell under consideration.

4.2. Scrap during the Formation Process

The expert responses regarding scrap rates during the formation process range from 0.01% to 10% with a median of 5.5%. This variance underscores the disparities in battery quality achieved by different manufacturers. Figure 3a illustrates the spectrum of expert responses. In the literature, scrap rates of 0.1–1% up to 5% can be found [23].

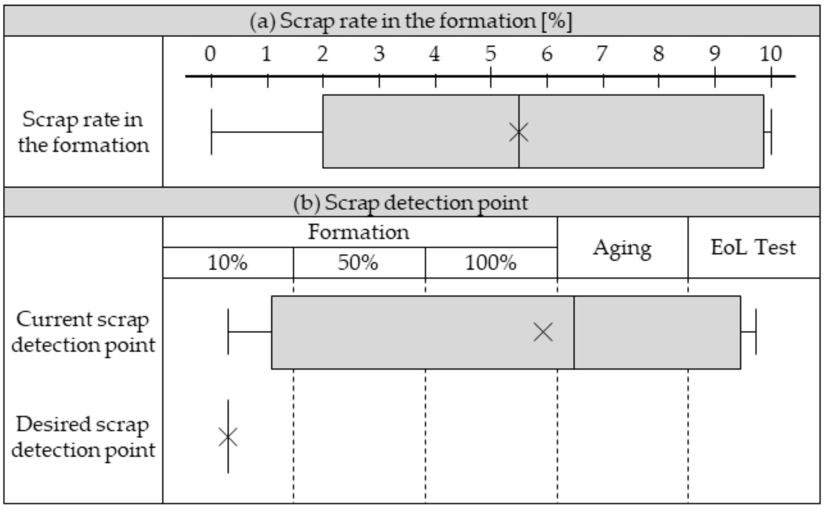

Figure 3. Evaluation of scrap rate (**a**) and scrap detection points (**b**) in the formation.

Figure 3b shows the expert responses for scrap detection points in the cell finishing process chain. On average, a faulty cell is typically identified immediately after the formation process. However, this timing hinges significantly on the specific defect exhibited by the cell. In cases of major short-circuits, a battery cell would be incapable of undergoing the formation process and would therefore be identified before initiation. In contrast, cells with minor defects, such as low capacity or higher internal resistance, may only be identified after completing formation, aging, or even after undergoing end-of-line testing.

It is worth noting that none of the experts mentioned the rejection of scrap cells during the formation process. Consequently, quality assessment will only be performed at the beginning and end of the formation process.

The experts unanimously emphasized the importance of early detection of defective or low-quality cells right at the outset of the formation process. This is crucial for both safety and optimizing production efficiency.

4.3. Inline Early Quality Determination during the Formation Process

Figure 4 shows the expert answers for the technology potential for early quality determination (EQD) during the formation process of the respective measurement technology on the y-axis and the probability for a current use in series battery productions on the x-axis. The diagram is divided into four quadrants, clustering the technologies. Technologies in quadrant 1 (Q I) are already in use in series production and have a high potential for EQD purposes. Quadrant 2 (Q II) contains technologies with a high EQD potential but that are not commonly used in series production. In Quadrant 3 (Q III), the technologies with low EQD potential and low use in series production are clustered. Quadrant 4 (Q IV) contains the technologies with low EQD potential but that are, however, integrated in series production.

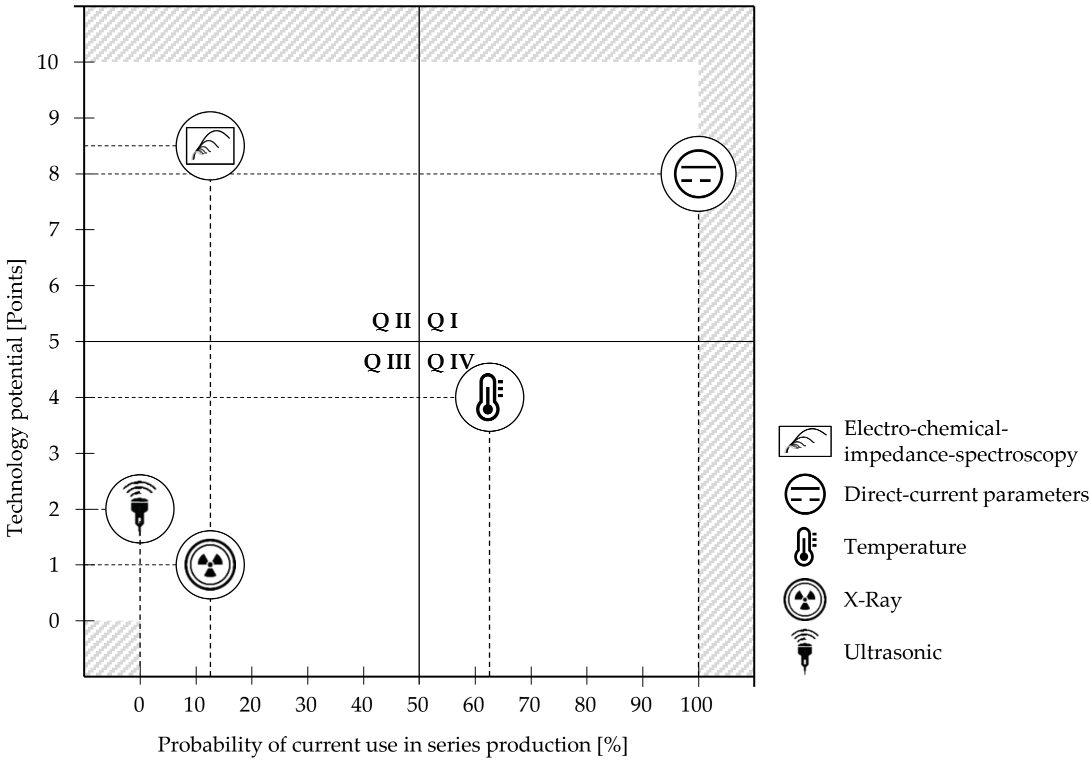

Figure 4. Technology potential for early quality determination in comparision to the current implementation in series productions.

Electrochemical impedance spectroscopy, located in Q II, reaches the highest technological potential (8.5 points) for the purpose of early quality determination during the formation process. However, this technology is barely used in series production. The main reason for no use in series production is the high cost for integrating this technology. However, according to the experts, the lack of knowledge and the estimation of the necessity, whether added value is given or not, are other frequently mentioned reasons resulting in a too low TRL for series implementation. Finally, the generated EIS data have a high computational effort for data evaluation.

The potential for direct-current parameters and voltage/current curves during formation have slightly lower EQD potential (8.0 points) but are already observed during the formation process. However, the data evaluation is similarly complicated as the evaluation of EIS data and makes use of machine-learning algorithms needing high computational performance. The data are therefore taken during the formation but barely used for EQD. Whether these data will be sufficient for a reliable EQD is highly dependent on the battery models operating.

Temperature monitoring is conducted during the formation process. Typically, there are not individual temperature sensors for each cell; rather, a few sensors are allocated to a cell carrier. These sensors primarily serve to ensure safety throughout the process. When the temperature of each cell is monitored, it allows for insights into the inner resistance and, consequently, offers a means to partially assess the quality of the battery cell in real-time.

Ultrasonic and X-ray technologies exhibit limited potential for inline measurements. This is primarily due to the challenge of accessing the cells for performing these measurements, as battery cells are typically housed in carriers that restrict access to the sides of the battery.

A well-implemented EQD system can lead to significant improvements in both the speed of the formation process and the overall quality of battery cells. This implementation also results in a modest increase in process knowledge while having a minimal impact on safety considerations (Figure A6). When evaluating these aspects in terms of their importance, safety consistently emerges as the paramount concern. The following are battery quality and process speed in order of significance (Figure A7).

In current factory settings, only significant production defects, such as a ripped separator or the presence of metal chips, can be identified during the formation process (Figure A8). Nevertheless, there is a pressing need to detect all potential production errors, particularly for the purpose of effectively troubleshooting the upstream processes. A malfunctioning battery cell necessitates different safety measures. A cell with no apparent safety concerns will be deactivated, yet it will remain within the formation chamber until the remaining cells inside the carrier complete the formation process. Subsequently, the faulty cell will be designated for disposal. However, in the case of cells presenting safety issues, immediate ejection is warranted. This requires the entire carrier of cells to be discarded, as all cells must be removed from the process.

4.4. Live Control of the Formation Process

In a live-controlled formation process, the process parameters are continuously fine-tuned throughout the formation. This involves evaluating battery cell parameters such as voltage and current curves, EIS, and temperature data to derive an optimized formation protocol for each cell [7]. The primary advantage of live-controlled formation lies in enhanced process speed and battery quality, as each battery cell undergoes a tailored and optimized process (Figure A10).

However, for this approach to be viable, the formation equipment must be capable of making inline adjustments. Additionally, there is a requirement for substantial computational resources to calculate battery models for each cell in the process. As a result, live-controlled formation processes have not yet been implemented in the series production of batteries (Figure A9).

4.5. Overall Optimization Needs of the Cell Finishing Process Chain

The paramount optimization needs in the cell finishing process chain, as identified by experts, revolve around cost reduction and early quality determination. Given the persistently high scrap rate during formation, production error detection and subsequent reduction also emerge as critical areas for improvement. Conversely, process know-how and safety aspects are deemed less urgent, as they are already deemed sufficient in series production (Figure A12).

Electrochemical impedance spectroscopy stands out as having the highest potential, particularly in the realm of early quality determination. It also demonstrates promise in providing reliable information on various error patterns for production error detection. However, when it comes to the potential for live control of formation processes, EIS is not as favored. In this context, DC data prove to be sufficient (Figure A11).

4.6. Result Summary

The result summary will compromise the findings in the previous result sections. Table 1 gives an overview of all questions asked to the experts. For each question, a simplified answer is given to condense all experts' opinions to a short answer. The question ID corresponds to Figures A1–A12 shared in Appendix A.

Table 1. Summary of asked questions and key results.

ID	Question	Key Result
1	**Investment costs and cost savings potential of the cell finishing process chain**	
1.1	How high do you estimate the investment cost share (CAPEX) of cell finalization for battery cell production to be?	On average, the CAPEX share of the cell finalization is 35.62%. Respective max. and min. answers were 20% and 60%.

Table 1. *Cont.*

ID	Question	Key Result
1.2	How high do you estimate the cost saving potential (CAPEX) of the sub-processes in cell finalization to be?	The CAPEX-lowering potential is the highest for the formation and the aging processes.
2	**Rejects during the formation process**	
2.1	How many rejects do you estimate are generated in the formation process?	The reject share during the formation process varies from 0.01% up to 10% with a median answer of 5.5%.
2.2	Assumption: A non-okay cell is introduced into the formation and charged.When would this cell be recognized, on average, or at what point within the cell finalization would this be desirable?	On average, the non-okay cell will be detected right after the formation. Depending on the defect, earlier or later detection is possible.It is desired to recognize the non-okay cell earliest.
3	**Inline early quality determination during the formation process**	
3.1	Sort the following measurement techniques according to their potential for inline early quality determination during formation, and which of these are currently used in large-scale production?	EIS is the most suitable technology, followed by DC-data. Ultrasonic and X-ray data are considered not suitable for early quality determination.Only voltage/current curves and cell temperature is currently recorded during the formation.
3.2	The data currently collected inline during formation are sufficient for an early quality determination during formation.	The data currently collected during the formation are not sufficient for EQD. However, with increased data evaluation, DC data might be sufficient.
3.3	Which criteria are improved by using suitable measuring technology for EQD during the forming process?	With suitable inline measuring techniques, especially process speed and cell quality can be increased.
3.4	Sort the criteria by relevance in large-scale production in the field of formation.	Battery cell quality and safety are the most important features, followed by process speed.
3.5	If measurement technologies such as EIS can significantly improve the formation regarding various criteria, why do you think they are not yet used in large-scale production today?	Especially because of high integration cost, EIS is not integrated yet. Lack of knowledge about this technology and the estimation of the necessity, whether added value is given or not, are other frequently mentioned reasons.
3.6	Which production errors can be detected during the formation process with the help of currently collected parameters and which production errors would be desirable to detect?	Currently a separator rip and metal chips can be detected during formation. However, all possible defects are desired to be detected.
3.7	What would happen to a cell that were classified as non-okay during the forming process?	Actions are highly dependent of machine configuration. With no safety issues given, the cell remains in the formation chamber and the channel is stopped. Otherwise, the whole batch is stopped and scrapped.
4	**Live control of the formation process**	
4.1	Battery cell parameters collected inline are used in large-scale production for live control of the formation process.	Currently, inline collected data are not used for live control of the formation.
4.2	The process can be optimized regarding the adjacent criteria by live control using inline measurement data of formation.	With a live control, especially process speed and battery cell quality are improved.
5	**Overall optimization needs of the cell finishing process chain**	
5.1	How do you assess the possibilities of EIS measurement to enable the previously addressed use cases of early quality determination, defect detection, and live control?	Inline EIS measurements during the formation process empower early quality determination and production error detection.
5.2	Weight the optimization needs of the formation process according to their relevance.	Cost reduction, early quality determination, and production error detection are the main optimization needs of the formation process.

5. Discussion

The results shown were achieved based on a high diversification of the industries involved. However, mainly European companies were surveyed, so the answers mainly apply to the European region. It would be interesting in future research to assess the role of cell finalization optimization in the Asian and American regions and whether the results shown here are also valid there.

Implementation of EQD systems presents significant advantages in process speed and battery quality, with minimal impact on safety considerations when they are integrated in the formation process with no process interruption. However, live-controlled formation processes face challenges in equipment capability and computational demands, hindering widespread adoption in series production.

Ultimately, the optimization needs in the cell finishing process chain pivot around cost reduction and early quality determination, with equal emphasis on production error detection. Electrochemical impedance spectroscopy (EIS) emerges as a key player in early quality determination, showcasing substantial potential for production error detection.

However, the integration of EIS technology into an uninterrupted formation process presents a non-trivial challenge and has yet to be implemented in large-scale production settings. Figure 5 outlines a proposed framework for incorporating EIS-based quality prediction into the uninterrupted formation process, which is segmented into three key components.

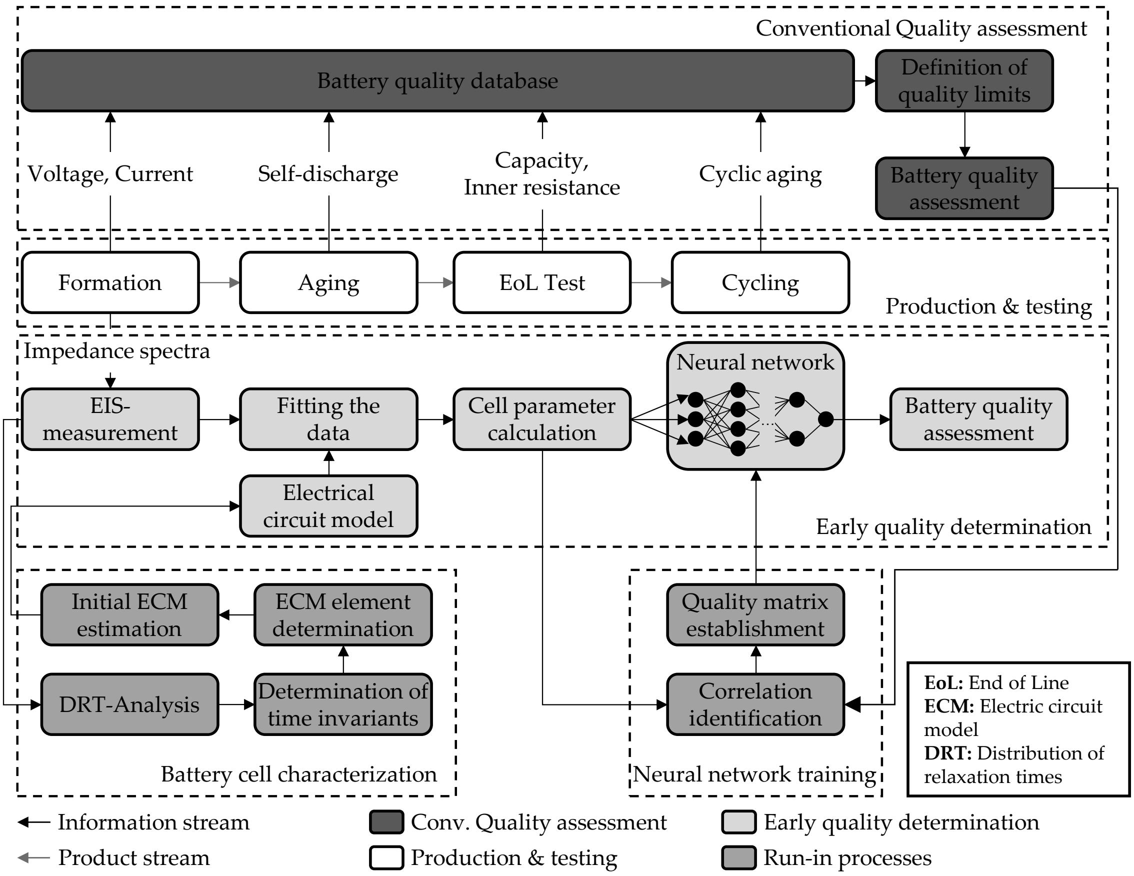

Figure 5. Implementation concept for an EIS-based early quality determination.

The first component in Figure 5, "common quality determination", encompasses the standard processes undertaken to assess battery cell quality. While aging and end-of-life (EoL) testing are integral parts of battery production, cycling is additionally employed to enhance the certainty of the quality assessment for the battery cells.

The second component in Figure 5, “early quality determination”, focuses on utilizing EIS for quality prediction during the formation process itself. Impedance spectra are captured at predefined intervals during formation. These spectra are then employed to fit an electric circuit model (ECM). The parameters of the ECM can subsequently be inputted into a neural network, which calculates the quality of the battery cell.

To establish the ECM and the neural network, support processes such as “battery cell characterization” and “neural network training” are deployed. “Battery cell characterization” is essential for defining the components of the ECM and their initial values. This can be achieved through a Dynamic Response Test (DRT) analysis [24]. “Neural network training” involves correlating the battery cell quality determined through “common quality determination” with the cell parameters calculated using the ECM and impedance spectra within a quality matrix.

Once the ECM and neural network are configured and parametrized, only the “early quality determination” component is required in the production process to assess the battery cell quality. As of now, this conceptual framework has not undergone experimental validation. Therefore, it is upon future research to verify the viability of this approach through the production of battery cells incorporating integrated EIS measurements, along with the requisite battery models and neural network.

6. Conclusions

The study delves into various facets of the cell finishing process chain in battery production, offering valuable insights into critical aspects that impact both cost and quality. Notably, the formation and aging processes emerge as resource-intensive stages, contributing significantly to the overall capital expenditures. Expert estimates indicate an average CAPEX share of 35.63%, while potential cost reductions are most pronounced in the formation and aging processes.

Reject rates during the formation process reveal variations from 0.01% to 10%, highlighting disparities in battery quality among manufacturers. Early detection of defects, especially major short-circuits, is crucial for both safety and production efficiency. Inline early quality determination (EQD) technologies, as depicted in Figure 5, underscore the potential for advancements, with electrochemical impedance spectroscopy (EIS) offering high EQD potential despite limited current usage due to integration costs and knowledge gaps. Additionally, direct-current parameters show promise but face computational complexities.

In future research, the American and Asian market should be observed as well. Early quality determination during formation should be validated and implemented in future.

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Data Availability Statement: Data are available on request from the authors.

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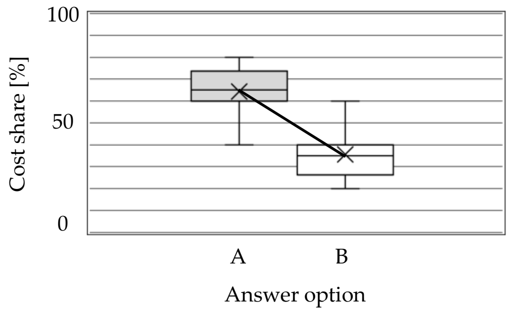
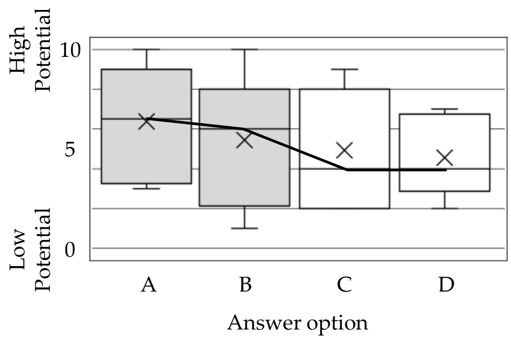
Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A



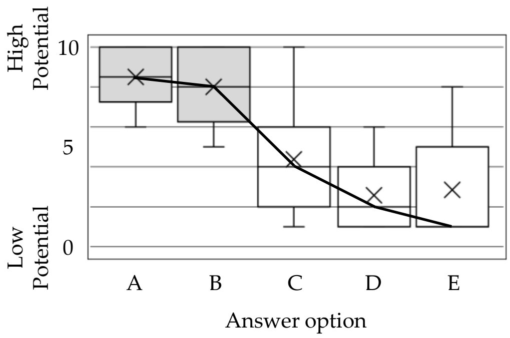
Answer option	Average [%]
A: Electrode production & Cell Assembly	**64.38**
B: Cell finalization	35.62

Figure A1. Question 1.1—How high do you estimate the investment cost share (CAPEX) of cell finalization for battery cell production to be?



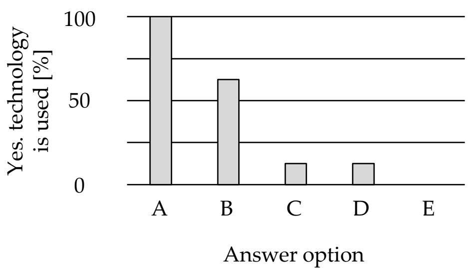
Answer option	Median
A: Aging	**6.5**
B: Formation	**6.0**
C: Wetting	4.0
D: EoL test	4.0

Figure A2. Question 1.2—How high do you estimate the cost saving potential (CAPEX) of the sub-processes in cell finalization to be?



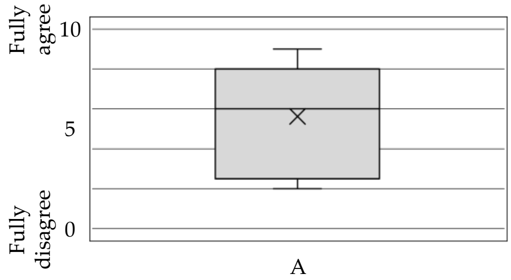
Answer option	Median
A: EIS	**8.5**
B: DC-Measurement	**8.0**
C: Temperature	4.0
D: Ultrasound	2.0
E: X-Ray	1.0

Figure A3. Question 3.1.1—Sort the following measurement techniques according to their potential for inline early quality determination during formation.



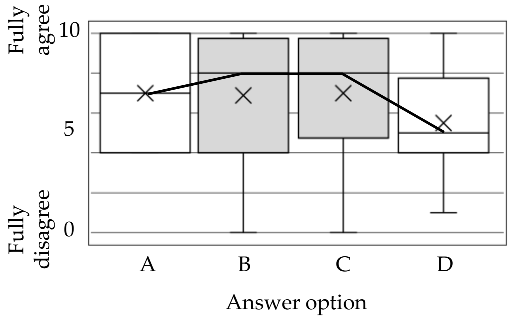
Answer option	Percentages
A: DC measurement	**100**
B: Temperature	**62.5**
C: X-Ray	12.5
D: EIS	12.5
E: Ultrasound	0

Figure A4. Question 3.1.2—Which of the measurement technologies are currently used in large-scale production?



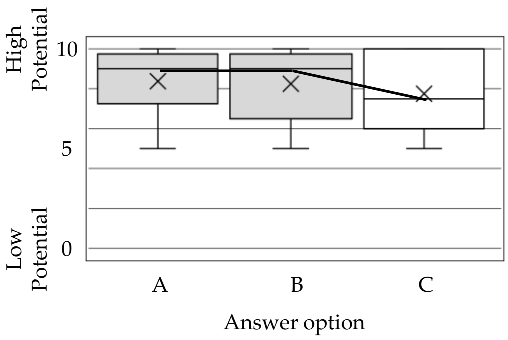
Answer option	Median
A: Data is sufficient	6

Figure A5. Question 3.2—The data currently collected inline during formation are sufficient for an early quality determination during formation.



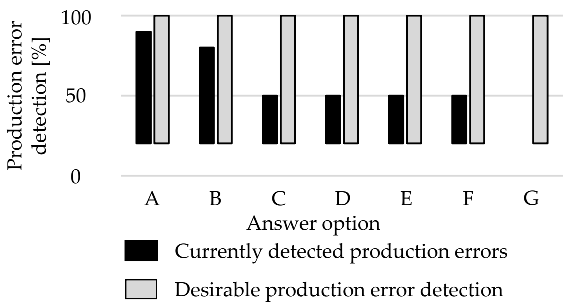
Answer option	Median
A: Know-How	7.0
B: Process speed	**8.0**
C: Battery cell quality	**8.0**
D: Safety	5.0

Figure A6. Question 3.3—Can process know-how be increased by using suitable measuring technology for early quality determination during the forming process? If yes, which criteria are improved as a result?



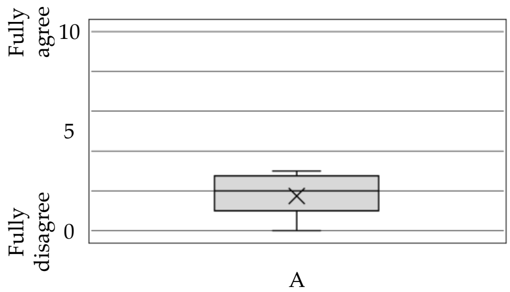
Answer option	Median
A: Safety	**9.0**
B: Battery cell quality	**9.0**
C: Process speed	7.5

Figure A7. Question 3.4—Sort the criteria by relevance in large-scale production in the field of formation.



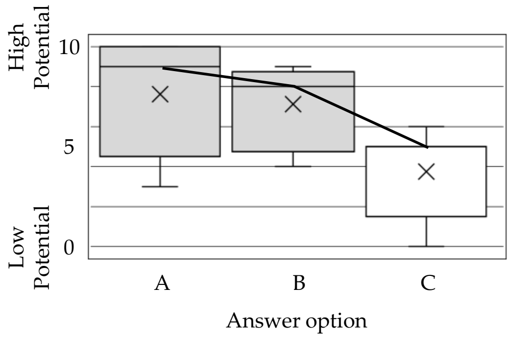
Answer option	Currently detected production errors [%]	Desirable production error detection [%]
A: Separator crack	87.5	100
B: Metal chips	75.0	100
C: Cross contamination	37.5	100
D: Coating defects	37.5	100
E: Insufficient wetting	37.5	100
F: Anode and cathode mutually displaced	37.5	100
G: Agglomerates	0	100

Figure A8. Question 3.5—Which production errors can be detected during the formation process with the help of currently collected parameters? Which production errors would be desirable to detect?



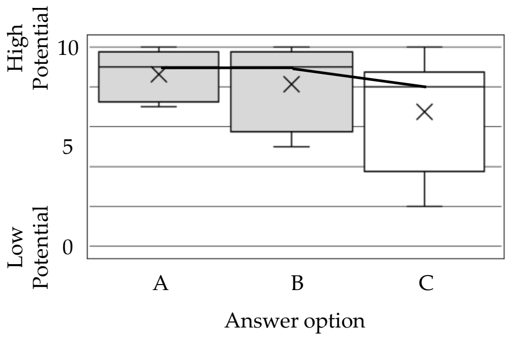
Answer option	Median
A: Usage in large-scale production	2

Figure A9. Question 4.1—Battery cell parameters collected inline are used in large-scale production for live control of the formation process.



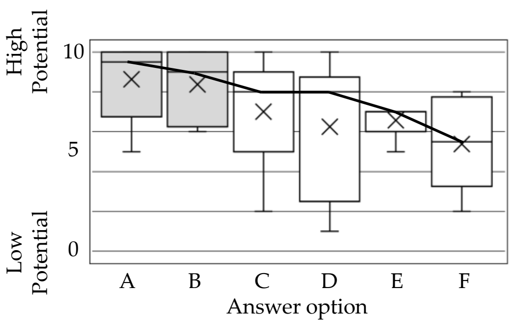
Answer option	Median
A: Process speed	**9.0**
C: Battery cell quality	**8.0**
C: Safety	5.0

Figure A10. Question 4.2—The process can be optimized with regard to the adjacent criteria by live control using inline measurement data of the formation.



Answer option	Median
A: Early quality determination	**9.0**
B: Error detection	**9.0**
C: Live control	8.0

Figure A11. Question 5.1—How do you assess the possibilities of EIS measurement to enable the previously addressed use cases of early quality determination, defect detection, and live control?



Answer option	Median
A: Cost reduction	**9.5**
B: Early quality determination	**9.0**
C: Error detection	8.0
D: Scrap reduction	8.0
E: Process-Know-How	7.0
F: Safety	5.5

Figure A12. Question 5.2—Weight the optimization needs of the formation process according to their relevance.

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