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Mini-Environments In Lithium-Ion Battery Cell Production: A Survey On Current State, Challenges And Trends

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Abstract

The demand for lithium-ion batteries increases rapidly. Possible improvements of the production technology are seen as key lever to improve sustainability and cost. The production of lithium-ion battery cells is complex and highly influenced by the production environment. Large parts of the production processes must take place in so-called clean and dry rooms to strictly control particles, temperature, and humidity. Especially the dehumidification of air for dry room conditions requires significant amounts of energy. Moreover, contaminants are emitted in certain processes that must not interfere with operational safety. A possible improvement is given with so-called mini-environments. This concept, roughly described as encapsulation of the individual process step, offer numerous theoretical benefits such as improved process control, enhanced product quality, increased worker safety and reduced energy consumption. The concept of mini-environments in battery cell production is not yet established. This paper presents the findings of an industry and institute survey with key stakeholders from the battery machinery, clean- and dry room, and encapsulation industries. The results show that while the potentials of mini-environments in battery cell production are recognised, many hurdles must be overcome before successful implementation. For example, adapted holistic production systems and new logistic measures must be developed.

Keywords

Mini-Environments; Battery Cell Production; Production Environment; Industry Survey; Sustainable Production

1. Introduction to mini-environments in battery cell production

The manufacturing of lithium-ion battery cells requires to strictly control particles, temperature, and humidity of the production environment [1]. Among other negative influences, moisture leads to the decomposition of the electrolyte which results in shortened lifetime and reduced capacity of the battery cell [2,3]. Airborne or process emitted molecular and particulate contamination can also lead to defects and thus high reject rates [4,5]. Figure 1 gives an overview of the process steps in the production of lithium-ion battery cells, which can be divided into three stages: electrode production, cell assembly and cell finishing. Depending on the materials, dimensions and cell format, not only the process chain but also the individual process steps can differ significantly. In electrode production, anodes and cathodes are produced from the

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input materials. Both electrodes are then assembled with a separator, electrolyte, and a housing. In cell finishing, cells are electrochemically activated, checked, and packed. [6]

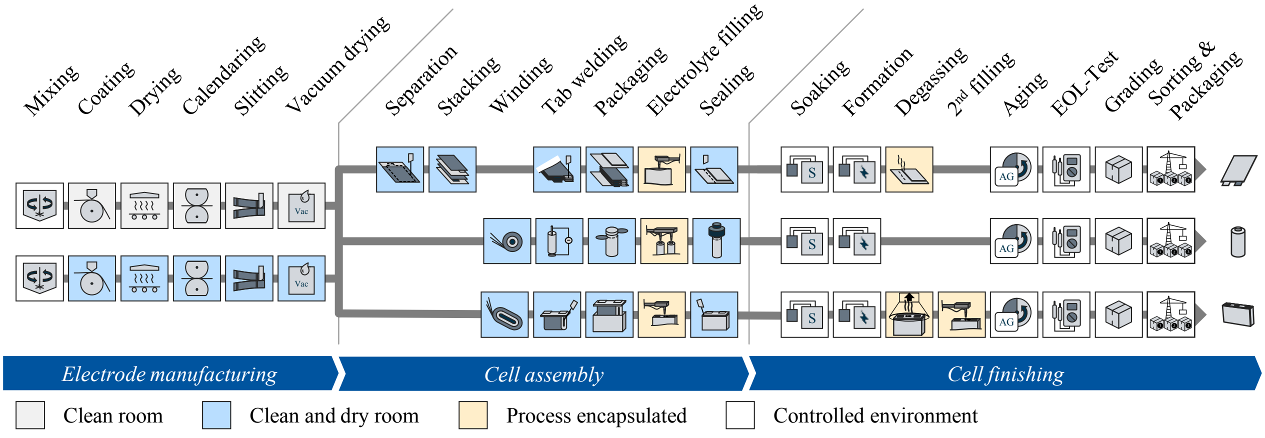

Figure 1: Generic process chain and necessary production environment to produce a lithium-ion battery cell [6]

As seen in Figure 1, the processes are currently placed in facility-integrated clean and dry rooms which are used to control particles, temperature and humidity. Those rooms must be tailored to meet the requirements of individual materials, processes and production characteristics. [7,1,8] Only the electrolyte-processing steps are additionally encapsulated in low-pressure or inert atmosphere due to the electrolyte's high reactivity with moisture. Conventional clean and dry rooms account for 26% to 53% of the overall energy consumption depending on the use case and production conditions [9–11]. At the same time, the sensitivity of future battery materials towards the influence of the production environment will continue to increase [12–14].

One possibility to reduce energy consumption and improve the condition of the production environment is given with so-called mini-environments. Figure 2 illustrates the concept of mini-environments compared to conventional clean and dry rooms. According to the ASSOCIATION OF GERMAN ENGINEERS, a mini-environment is a limited, separated product environment to protect the product from contamination [15]. Applied to battery cell production, this means that particle, temperature and humidity control does not (purely) take place on a room level but within a limited volume around the process. Currently, mini-environments are not established in industrialized battery cell production due to multiple reasons (see chapter 3). In the semiconductor industry on the other hand, mini-environments are already fully developed and integrated, with the key differences to battery cell production being very high degree of standardization and low requirements on ambient humidity. Only very few publications exist in the context of mini-environments for battery cell production. [16] KIM YU GON and EBERHARDT et al. published patents that describe the state of the art of mini-environments in battery cell manufacturing [17,18]. Furthermore, HELLER et al. discussed various terminologies regarding new airtight housing or encapsulation concepts for battery production [19].

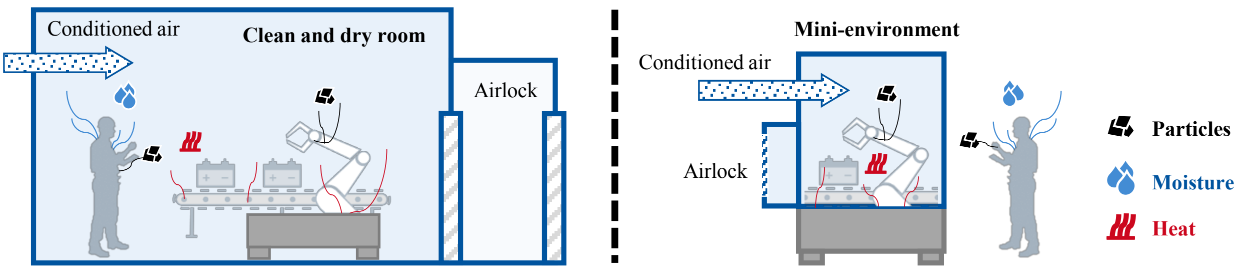

Figure 2: Schematic illustration of a conventional clean and dry room (left) and a mini-environment concept (right) for battery cell production

2. Survey

A comprehensive industry and institute survey was conducted to identify the current status of mini-environments in battery production. The survey was conducted in April and May 2023 and therefore reflects the status on given matter at this time.

To prepare the survey, a comprehensive literature and patent research was conducted. An extensive questionnaire with 76 questions divided into 13 clusters (matching subchapters in chapter 3) was formulated. For each cluster, 4-8 questions were asked divided into quantifiable questions e.g., “at what dew point and particle cleanliness requirement does a mini-environment make sense?” and qualitative questions e.g., “how should a logistic interface look like?”. Forty-five relevant companies and institutions with focus on the European market were identified and contacted to inquire survey participation. In the end, the authors conducted twenty-six digital face-to-face interviews. Figure 3 shows the number of companies and institutes that participated in the survey divided by company profile and origin. The share of participating companies in comparison to the inquired/existing companies is approximately the same in each category.

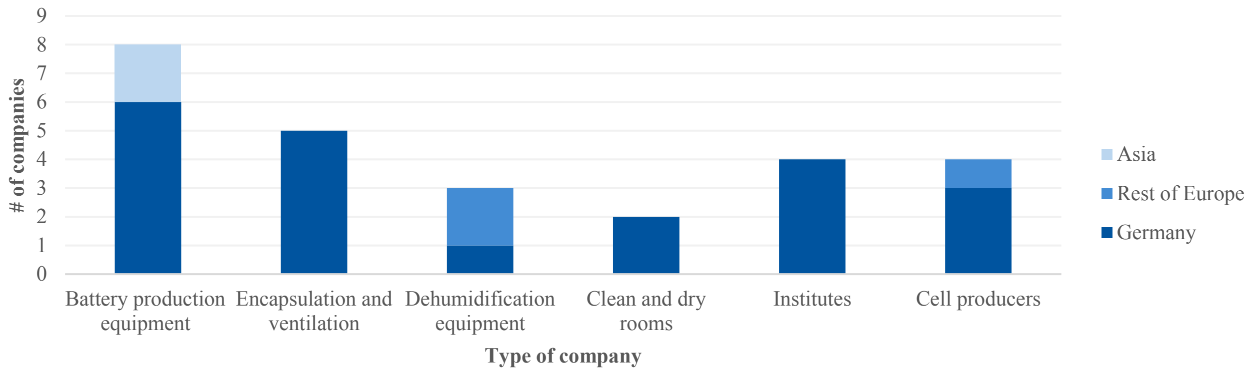

Figure 3: Survey participants divided by type of company and origin (of mother company)

3. Results

The results of the survey are presented below, broken down into the 13 survey clusters. It turned out that only very few of the participating companies already have experience with mini-environments in general. Most of the companies that have experience come from the glovebox or semiconductor industry. Only few companies have developed initial mini-environment prototypes specifically for battery cell production. Thus, the results of the survey rather represent a comprehensive aggregation of knowledge, experiences, opinions, and expectations. Quantifiable answers could only be retrieved by very few participants.

3.1 Concept understanding and definition

Based on the statements of the interviewees, two conceptual approaches exist:

C1. Mini-environment as technically tight enclosures similar to currently available gloveboxes. It can be set up in a grey room and thus aims to replace large clean and dry rooms. Reconditioning upon opening is a key concern. Inert gas may be used.

C2. Mini-environment as an extended machine enclosure concept in comparison to current machine housings, aiming to increase or improve isolation of the process and exclude humans. In this case, some sort of clean and dry room with lower requirements are still necessary. A precise concept vision does not exist yet.

The dimensions of mini-environments are considered to match current machine housings. Mini-environments are seen as an intermediate step towards even smaller process enclosures like micro-environments.

3.2 Application scenarios

Mini-environments are predominantly seen for use in cell assembly. The critical step of electrolyte filling already uses glovebox-like enclosures (C1) today. Implementing mini-environments is generally considered easier for processes with smaller footprint than for those with larger equipment.

The assessment of potential mini-environment application scenarios varies significantly based on the two described concepts as outlined in 3.1:

1. Glovebox-like mini-environments (C1) are already implemented in research laboratories and small-scale production. This concept is predominantly seen limited to this production scale.
2. The yet broadly undefined extended machine enclosure concept (C2) is considered useful for high-volume production with extensive automation. The prevailing opinion is that this concept is most effective when coupled with high automation and precise process control.

3.3 Quality and measurement

The improvement/stabilization of environmental conditions is seen as one of the top three potentials of mini-environments. Especially the advanced separation of operators from the process reduces possible negative influences and therefore increases quality consistency. All types of contamination (humidity, particles, temperature) are considered easier to remove in mini-environments than in larger rooms, mainly due to better and more controlled airflow, which can be simulated in advance. Based on improved/stabilized environmental conditions, a potential scrap reduction during operation was deemed realistic but could not be quantified because of possible contrary effects by necessary enclosure openings.

With regards to measurement, participants stated that temperature, humidity, and particle detection can be inline. Currently used particle traps should be reconsidered as they necessitate openings of the mini-environment. In comparison to current sensor placements to monitor environmental conditions, sensor placement moves closer to the process with shrinking encapsulation volume. Therefore, environmental product requirements can be monitored more precisely. On the other hand, higher complexity applies for data collection and processing, especially regarding frequent mini-environment openings and the resulting variety of states. Almost all respondents stated that the costs for testing humidity, particles, and temperature would not significantly differ from conventional clean and dry room concepts.

3.4 Accessibility

Accessibility is perceived as one of the top three challenges for implementing mini-environments. Companies in the semiconductor industry tend to view the challenges as somewhat lower. Cases that require mini-environments to be opened are given with emergencies, cleaning, maintenance, malfunctions and partially for logistic processes. Overall, accessibility for material supply and logistics are seen as not yet resolved but potentially solvable (see 3.5). A lack of concepts for maintenance, cleaning, etc., is considered critical. Placing mini-environments in a clean and dry room is a straightforward option to minimize negative impact when opening is necessary. Innovative approaches like mobile protective tents were mentioned.

One of the top three challenges in implementing mini-environments in battery production is seen with reconditioning times after enclosure opening. To reduce reconditioning times, smart opening mechanisms and boost modes have been suggested, but detailed concepts are yet to be developed. Reconditioning times between 3 minutes (mainly C2) and 8 hours (mainly C1) can be achieved today and are dependent on:

- The difference between inside and outside conditions during the time of opening. General rule: the larger the difference between those conditions, the longer the reconditioning times.
- The maximum achievable air exchange rate of the mini-environment. General rule: the higher the air exchange rate, the shorter the reconditioning times.

While not all companies consider standardizing accessibility components necessary, most see some level of standardization as desirable. Developing a singular functional accessibility concept is perceived as more important than a universally applicable standard.

3.5 Interconnection and interfaces

The interconnection of multiple processes with mini-environments is perceived as more complex compared to conventional clean and dry room setups. Physical interfaces are seen as one of the top three challenges for implementing mini-environments in battery production. Unresolved issues primarily relate to airlock concepts between individual mini-environments. The semiconductor field provides valuable know-how, including (partially) standardized load ports for material infeed. Here, challenges are mainly seen in roll-to-roll processes.

Airlock concepts become challenging, especially when trying to standardize interfaces across different process sections e.g., from electrode manufacturing to cell assembly. Standardization is considered less important in this area than for accessibility. Nevertheless, many companies express a desire for standardization in mini-environment interconnection. Custom interfaces are estimated to be technically feasible today.

Airlocks should be designed as compact as possible to minimize the needed conditioned air. It is assumed that interconnecting airlocks between two mini-environments do not require separate ventilation systems but are ventilated with conditioned air from the mini-environments itself. With increasing interconnecting airlock volume, survey participants see higher likelihood of separate ventilation systems. Discontinuous airlock operations are not seen as a difficulty for mostly continuous working dehumidifiers. Pressure relief and pressure retention valves can be employed for compensation.

3.6 Energy and costs

Costs are categorized in investment costs and operational costs, with the latter primarily depending on energy costs.

Overall investment costs are estimated to increase for mini-environment concepts that additionally require a clean and dry room (mainly C2). Overall investment costs are estimated to decrease for mini-environment concepts that can operate without an additional clean and dry room (mainly C1).

Operational cost is believed to decrease significantly with mini-environments with energy saving potentials from reduced dehumidified process volume. This is seen as one of the top three potentials of mini-environments. The amount of energy saving potential is significantly dependent on the production environment requirements. The higher the requirements the higher the possible energy saving potentials are assessed. With lower production environment requirements, the expected energy saving potential also decreases. That leads up to the point where mini-environments have no advantage over conventional clean and dry rooms. A quantification of the requirements at this point could not be made due to a general lack of existing business case calculations and prototypes.

Although acknowledging the theoretically benefit of reducing energy cost, most companies noted that other factors such as yield rate have a much higher impact on operational cost of current battery productions.

3.7 Enclosure and air handling

The assumed requirements for enclosure vary significantly depending on the mini-environment concept. While the glovebox-like concept (C1) involves technically tight enclosures, other mini-environment concepts (mainly C2) mention currently unquantifiable but in the future to be defined leak rates. Pressure induced flow direction of air due to a leakage rate of the housing is considered to be more relevant for particles than for humidity. Here, the flow direction is mainly based on the partial pressure differences of water inside and outside the housing. In battery production, glovebox gloves are only used in positive pressure concepts, which are found only in the glovebox-like concepts (C1). For large-scale applications, gloves are generally considered impractical.

According to company statements, the smaller volume of mini-environments allows for process-oriented airflow patterns in comparison to conventional clean and dry rooms. There is no standardized rule for air handling in mini-environments, and each concept needs to be individually designed in terms of e.g. air flow, ventilation and filtration. Participants are uncertain whether air from the mini-environment needs to be fully exhausted or can be recirculated after treatment. For safety reasons, most concepts currently involve exhausting all air.

It is believed that not every mini-environment requires its own air conditioning/dehumidification unit. Several mini-environments can be supplied by a single unit to enhance overall system efficiency. However, this increases the piping complexity. Employing more units to supply fewer mini-environments could enhance flexibility. Most survey participants consider moisture accumulation non-existent in mini-environments due to partial pressure of water and corresponding immediate distribution of humidity in the small environment.

3.8 Safety

Better separation of the operator from the process is seen as one of the top three potentials of mini-environments. General consensus is that the use of mini-environments can increase occupational safety in battery cell production. This is primarily due to the physical barrier provided by the mini-environment between the worker and the product. Generally, safety requirements and resulting measures can vary depending on the mini-environment concept.

It is expected that the occupational safety standard will not increase with the use of mini-environments if they are designed in a positive pressure principle (mainly C1) because contaminants could be pushed out of the mini-environment towards the operator. A safety-beneficial concept is primarily seen in negative pressure concepts (mainly C2) where contaminants are contained inside the mini-environment. Additionally, mini-environments open up the possibility of filtering polluted exhaust air (e.g. NMC exhaust and VOCs) and feeding it back into the enclosure. Thus, the proportion of recirculated air and consequently the energy efficiency potentially increases. Concrete concepts for this aspect are yet to be developed. Even with possible higher occupational safety of mini-environments, it is assumed that the use of personal protective equipment (PPE) is still required.

With the possibility to achieve ultra-low dew points inside and higher dewpoints outside of the mini-environment, mitigated health risks for operators are also considered advantageous.

3.9 Monitoring and control

The participants assessed that the measurement technology used to monitor environmental conditions in mini-environments will not differ significantly from the current technology used in clean and dry rooms. However, the positioning of sensors will be adjusted. Proposed measurement points include the exhaust air of the mini-environment and critical points in the process. Sensor placement in mini-environments will be closer to the point of interest than it is currently customary, enabling more precise measurements. To ensure occupational safety, it is anticipated that more mobile measurement technology will be required, and sample measurements will also need to be taken at various points outside the mini-environments more frequently. For this purpose, e.g., wearable measurement systems can be attached to the operator's clothing.

Participants are unsure whether mini-environments will lead to sensor cost savings. Nevertheless, sensor costs are not considered particularly relevant. A peculiarity of mini-environment sensor technology could be that, upon opening, larger ranges of fluctuations may need to be covered than currently usual.

3.10 Factory integration

Opinions regarding the integration level of mini-environments vary significantly depending on the concept. Generally, mini-environments must be considered in comprehensive factory safety concepts, including emergency exits and fire protection measures. Companies aiming for a glovebox-like approach (C1) tend to believe that mini-environments can be used in a standard production environment and therefore fewer integration effort into the production facility is necessary. With concepts that still rely on clean and dry room (mainly C2), the number of interfaces would increase and the integration into the production facility is assumed to get more complex. In high-volume production scenarios (mainly C2), redundancy e.g., for dehumidifiers should be considered to reduce equipment downtime resulting in increased integration and interface complexity.

Today clean and dry rooms are considered to belong to the building or battery specific infrastructure with close interfaces to the production equipment. In contrary, companies see mini-environments rather belong to the production equipment than as part of the infrastructure. As a result, there is also a responsibility shift for the production environment towards the process equipment manufacturer which is viewed very critically by them.

3.11 Flexibility

Generally, mini-environments are considered to reduce production flexibility due to higher overall complexity of the plant compared to conventional clean and dry rooms.

Initial ramp-ups are also estimated to be more challenging with mini-environments resulting in longer ramp-up times and higher costs. Subsequent starting facilities with the same mini-environment concepts should then require a similar timeframe to current ramp-ups.

In addition, implementing alternative technologies (upgradability) are considered to be more challenging with mini-environments. However, upgradability is generally deemed almost irrelevant in battery cell manufacturing.

Contrary, the smaller air volumes of mini-environments also lead to two factors that could be beneficial for flexibility. Firstly, it is expected that scenarios like night or weekend stand-by operation will be easier and more efficient to implement. Secondly, by separating the process into smaller steps that are separated by mini-environments instead of integrating many process steps into one housing, there is potential for simplified troubleshooting and minimized contamination during openings.

3.12 Future outlook

The current Technology Readiness Level (TRL) of mini-environments in battery production is assessed with varying degrees. TRL ratings ranged from 3 to 9, with most respondents estimating the TRL to be between 4 and 7. While few initial concepts have been successfully demonstrated, near-series testing campaigns have not been conducted and market-ready systems are not yet available. Challenges to improve the TRL are particularly seen in the areas of automation (integration), maintenance and standardization, and in a mindset change required by various stakeholders to implement a new (riskier) concept.

Opinions diverge on the necessary time duration until mini-environments can be utilized in mass production of battery cells. Estimates range from approximately 2 to 3 years as a minimum to 5 years or more as a maximum. It is considered crucial that the mini-environment concept is first implemented and validated in a small series and then in large-scale production.

Regarding the further development of mini-environments, companies pursue two approaches:

- Companies develop concepts and validate them through demonstrators.
- Development is carried out by universities and research institutions and transferred to the industry.

3.13 Industry landscape

The survey results show that in the development of mini-environment concepts on the one hand equipment manufacturers often wait for a specific inquiry from producers and on the other hand producers expect fully developed and tested concepts from equipment manufacturers. Equipment manufacturers are particularly concerned about the possibility to be pushed into more responsibility by the producers when jointly delivering the process equipment and the equipment for process environment.

For this reason, concept development and hardware demonstration from research institutions were seen as valuable. In general, deeper cooperation and partnerships between stakeholders, especially between producers and equipment suppliers, were considered desirable.

Currently, leading companies in the mini-environment field are primarily considered to be traditional glovebox manufacturers and companies from the semiconductor industry.

4. Discussion and recommendations for action

It can directly be concluded that the concept of mini-environments for battery cell production is still in an early phase. Few companies have experience in the field of battery production in an industrial scale at all. This is also demonstrated by the fact that no quantifiable evaluation is possible for this broad-based industry survey. Holistic knowledge of current battery production processes is still limited and uncertainty about future improvements high. While some experiences from other industries and early-stage concepts exist, there is no uniform understanding of the topic across the industry.

The following recommendations for actions are derived from the results of the survey:

- Development of holistic mini-environment concepts (C2) for each process step individually paired with an industry wide discussion about concepts to interlink the mini-environment concepts for each process step into a complete mini-environment process chain. Uncertainty can even be more reduced if authorities are part of the discussion e.g., regarding occupational safety and standardization.
- Cooperations between multiple companies e.g., equipment manufacturer and enclosure specialists or research institutes and producers should be stimulated to ensure a transfer from requirement definition, over development into implementation.
- Funding of application-oriented research in the field of mini-environments for battery production to do preparatory work that the industry can use to decrease risk of own investment by e.g., a business case calculator that is able to compare capex and opex of different mini-environment concepts to conventional clean and dry rooms for different environmental requirements.

5. Conclusion and outlook

Mini-environments are a promising concept to reduce energy consumption and to increase product quality and operational safety in battery cell production. Currently, only few research publications and industrial concepts exist. Therefore, a comprehensive industry and institute survey was conducted to identify the current status of mini-environments in battery production. With this paper, for the first time, not only individual sub-topics of mini-environments like housing or material transfer are discussed but a comprehensive aggregation of knowledge, experiences, opinions, and expectations are covered with all involved players from process to building. The survey revealed that there is little and no uniform understanding of the topic across the industry. Simultaneously, the potential of mini-environments is recognised and interest in further developments is high. Derived from the results, recommendations for action were given that directly imply a need for further application-oriented research in the field of mini-environments for battery cell production.

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References

[1] Pinho, J., 2021. Dry Rooms: Why They Are Needed and a Review of the Complex Issues Associated With Building Them - Particularly the Large Ones Required to Mass Produce Lithium Batteries. A123, Watertown MA, 3 pp. https://www.scs-usa.com/docs/ABT_John_Pinho_Technical_Report_October_2010.pdf. Accessed 4 August 2023.

[2] Eser, J.C., Wirsching, T., Weidler, P.G., Altvater, A., Börnhorst, T., Kumberg, J., Schöne, G., Müller, M., Scharfer, P., Schabel, W., 2020. Moisture Adsorption Behavior in Anodes for Li-Ion Batteries. Energy Technol. 8 (2), 1801162.

[3] Stich, M., 2019. Wasserverunreinigungen in Lithium-Ionen-Batterien. Dissertation, Ilmenau.

[4] Grabow, J.; Klink, J.; Benger, R.; Hauer, I.; Beck, H.-P., 2023. Particle Contamination in Commercial Lithium-Ion Cells - Risk Assessment with Focus on Internal Short Circuits and Replication by Currently Discussed Trigger Methods. Batteries 9 (1), 9.

[5] Kehrer, M., Locke, M., Offermanns, C., Heimes, H., Kampker, A., 2021. Analysis of Possible Reductions of Rejects in Battery Cell Production during Switch-On and Operating Processes. Energy Technol. 9 (7), 2001113.

[6] Plumeyer, J.F., Menebröker, N., Clever, H., Kokozinski, L., Wessel, S., Heimes, H.H., Kampker, A., 2023. A Review of Process Innovations in the Cell Finishing of Lithium-Ion Batteries in Large-Scale Production. Hannover: publish-Ing.

[7] Heimes, H.H., Kampker, A., Wennemar, S., Plocher, L., Bockey, G., Michaelis, S., Schütrumpf, J., 2023. Production Process of a Lithium-Ion Battery Cell, Frankfurt am Main. https://www.pem.rwth-aachen.de/global/show_document.asp?id=aaaaaaaabyilawq. Accessed 9 August 2023.

[8] Vogt, M., Koch, K., Turetskyy, A., Cerdas, F., Thiede, S., Herrmann, C., 2021. Model-based energy analysis of a dry room HVAC system in battery cell production. Procedia CIRP 98 (1), 157–162.

[9] Dai, Q., Kelly, J.C., Gaines, L., Wang, M., 2019. Life Cycle Analysis of Lithium-Ion Batteries for Automotive Applications. Batteries 5 (2), 48.

[10] Degen, F., Schütte, M., 2022. Life cycle assessment of the energy consumption and GHG emissions of state-of-the-art automotive battery cell production. Journal of Cleaner Production 330, 129798.

[11] Yuan, C., Deng, Y., Li, T., Yang, F., 2017. Manufacturing energy analysis of lithium ion battery pack for electric vehicles. CIRP Annals 66 (1), 53–56.

[12] Bi, Y., Li, Q., Yi, R., Xiao, J., 2022. To Pave the Way for Large-Scale Electrode Processing of Moisture-Sensitive Ni-Rich Cathodes. J. Electrochem. Soc. 169 (2), 20521.

[13] Busà, C., Belekoukia, M., Loveridge, M.J., 2021. The effects of ambient storage conditions on the structural and electrochemical properties of NMC-811 cathodes for Li-ion batteries. Electrochimica Acta 366, 137358.

[14] Xin, F., Zhou, H., Zong, Y., Zuba, M., Chen, Y., Chernova, N.A., Bai, J., Pei, B., Goel, A., Rana, J., Wang, F., An, K., Piper, L.F.J., Zhou, G., Whittingham, M.S., 2021. What is the Role of Nb in Nickel-Rich Layered Oxide Cathodes for Lithium-Ion Batteries? ACS Energy Lett., 1377–1382.

[15] Verein Deutscher Ingenieure e. V., 2021. Cleanroom technology – Barrier systems - Minienvironments (VDI 2083 Blatt 16.2). VDI Verlag, Düsseldorf.

[16] Korea Air Cleaning Association, 2002. Clean Technology and Management for Indoor Air. Proc. Int.Symp.

[17] Eberhardt, K., Hubalek, K., Handte, J., 2021. Method for cleaning exhaust air produced during a machining process in a clean room/dry room and system for carrying out the method B01D46/42; B01D53/26; F24F7/003; F24F8/10;. https://worldwide.espacenet.com/patent/search/family/080266800/publication/DE102021004571A1?q=DE102021004571A1. Accessed 4 August 2023.

[18] Kim, Y.G. Multi-stage dehumidification system for local area dehumidification of dry room B01D53/26; F24F3/14; F24F9/00;. https://worldwide.espacenet.com/patent/search/family/077926778/publication/US2022373199A1?q=US%202022%2F0373199. Accessed 4 August 2023.

[19] Heller, M., Turhan, H., Holöchter, N., Miggelt, M., Niggestich, M., Schöne, N., Janning, F., Wessel, S., Tübke, J., 2023. Energieeffiziente und qualitätsorientierte Anlagenkonzepte für die Batteriezellfertigung.

Biography

Lorenz Plocher (*1994) has been research associate at the chair of "Production Engineering of E-Mobility Components" (PEM) of RWTH Aachen University since 2020. He studied mechanical engineering with a specialization of vehicle engineering at RWTH Aachen University and power engineering and engineering thermophysics at Tsinghua University, China. His research focus is on holistic production planning approaches.

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