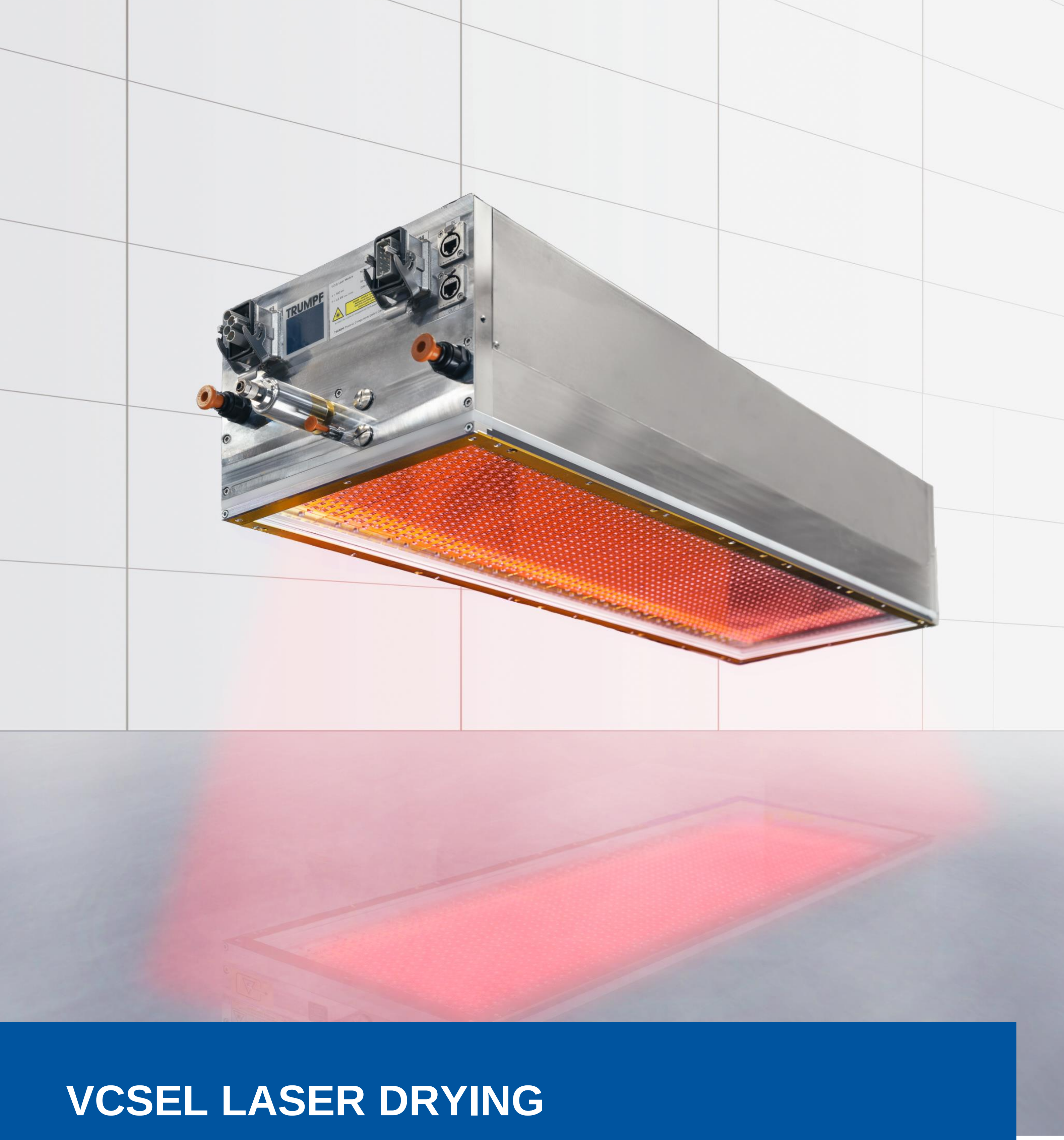
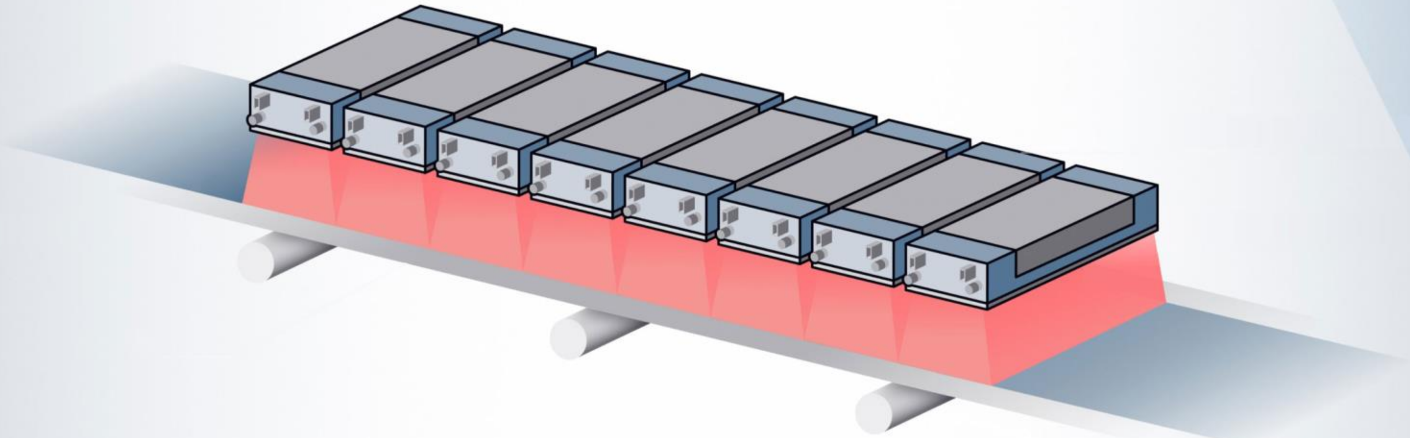


VCSEL LASER DRYING
IN BATTERY PRODUCTION

A solution for cost-effective electrode manufacturing

> *“Laser drying technology represents a significant leap forward in the manufacturing of battery electrodes, offering a solution for a cost-effective and ecological sustainable battery production.”*
>
> Prof. Dr. Achim Kampker, RWTH Aachen University



> *“We consider laser drying technology as an innovative advancement in battery manufacturing. Our VCSEL solutions allow significant CapEx and OpEx reductions.”*
>
> Dr. Rolf Apetz, TRUMPF

MANAGEMENT SUMMARY:
ELECTRODE DRYING WITH VCSEL TECHNOLOGY

KEY TAKEAWAYS

Laser drying processes for battery electrode drying can:

- reduce OpEx by up to 40%.
- decrease the CO_2 footprint by up to 40%.
- lower CapEx by up to 40%.
- reduce the equipment footprint by up to 50%.
- maintain comparable electrode and cell quality.

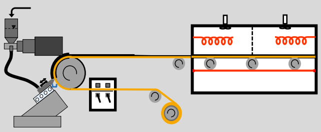
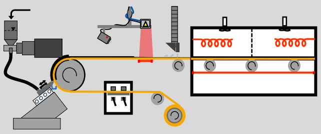
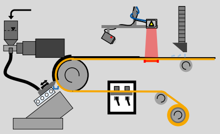
	Convection	Hybrid (Laser & Convection)	Laser stand-alone
Drying concept			
Process output	Web speed: 1.4 m/min Drying time: 92.57 s	Web speed: 2.8 m/min Drying time: 51.21 s	Web speed: 0.8 m/min Drying time: 17.25 s
Electrode quality	Adhesion: 0.51 MPa Res. Moisture: 0.47%	Adhesion: 0.52 MPa Res. Moisture: 0.37%	Adhesion: 0.46 MPa Res. Moisture: 0.63%
Cell quality	Formation efficiency: 82.04% Internal resistance: 12.99 Ω Cycle Stability: 91.99%	Formation efficiency: 81.93% Internal resistance: 12.62 Ω Cycle Stability: 93.66%	Formation efficiency: 83.23% Internal resistance: 12.1 Ω Cycle Stability: 89.09%

Figure 1: Comparison of three drying methods

CONTENT

MOTIVATION AND CHALLENGES IN THE DRYING PROCESS OF BATTERY ELECTRODES

RISING DEMAND AND SHIFT IN PRODUCTION DYNAMICS

The global landscape of lithium-ion battery (LIB) production is undergoing a significant transformation driven by the surge in demand propelled by the rapid growth of electric mobility (e-mobility). This demand surge, fueled by the increasing adoption of electric vehicles (EVs) worldwide, presents both opportunities and challenges for stakeholders across the supply chain.

The exponential growth of the EV market has catalyzed a surge in demand for LIBs. This demand trajectory is underscored by the establishment of new gigafactories, with a strategic focus on regions such as Europe, North America, and Asia. Notably, there is a discernible shift from centralized Chinese production towards localized manufacturing in key markets. This shift, as evidenced by announcements in industry publications like Battery News, is expected to reshape the dynamics of LIB production in the coming years.

COST DYNAMICS AND MARKET PENETRATION

Despite the promising prospects of e-mobility, the high costs associated with LIBs pose a significant challenge to the widespread adoption of EVs. LIBs account for approximately 31.5% of the total cost of battery electric vehicles (BEVs), making cost reduction imperative for market penetration (see figure 2). A detailed breakdown of cell costs reveals that cathode active materials constitute a substantial portion, representing 51% of the total cell cost.

While economies of scale offer a pathway to reduce costs, achieving a sustainable reduction in manufacturing costs remains a differentiator for cell manufacturers.

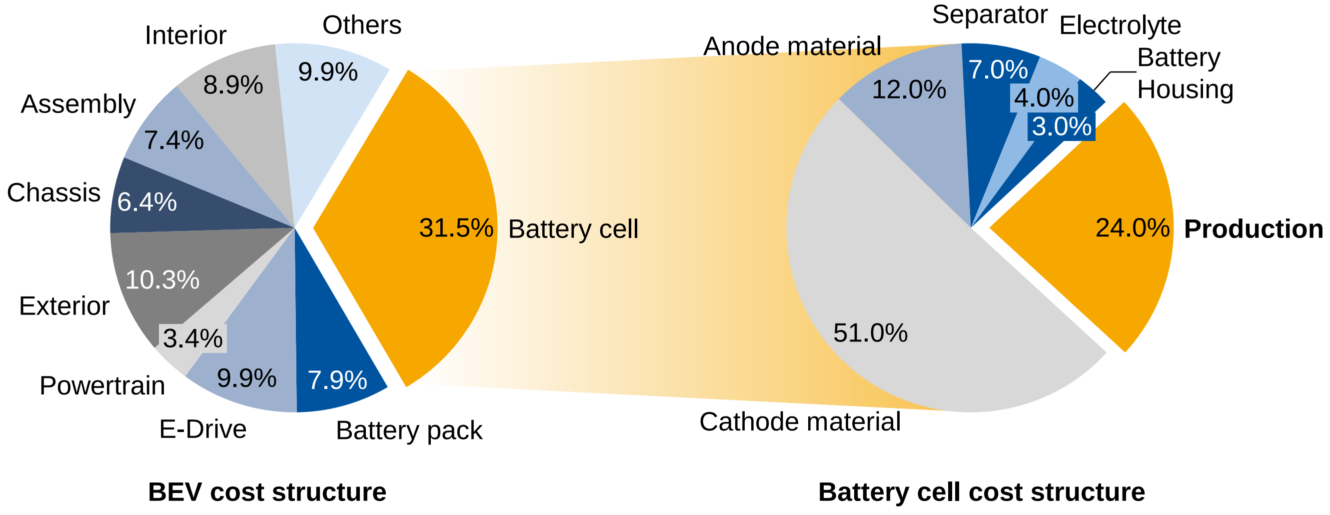


Figure 2: Cost structure Battery Electric Vehicle (BEV) and battery cell [1,2]

INTENSE COMPETITION AND MARKET DYNAMICS

The intensifying competition among battery cell manufacturers further complicates the landscape. In regions like Europe, established Asian manufacturers compete with emerging local players, leading to a significant increase of production capacities (see figure 3). However, there is a looming concern regarding overcapacity and the ability of all market participants to withstand the competitive pressures.

APPROACHES TO COST REDUCTION AND TECHNOLOGICAL INNOVATION

Addressing the cost challenge necessitates a multifaceted approach. Leveraging economies of scale, adopting innovative production technologies, optimizing energy consumption, and minimizing scrap are key strategies to drive down production costs.

PRESSURE ON MACHINERY AND EQUIPMENT SUPPLIERS

The competitive landscape extends beyond battery cell manufacturers to encompass machinery and equipment suppliers. In this context, innovative process technologies emerge as a potential differentiator for equipment integrators. The ability to offer cutting-edge solutions that enhance efficiency and reduce production costs positions machinery suppliers as strategic partners in the quest for competitiveness.

STATE-OF-THE-ART BATTERY PRODUCTION DRYING PROCESS

The drying process in battery production plays a pivotal role, yet it presents significant challenges in terms of energy consumption, operational costs, and environmental impact. Understanding the current state-of-the-art in drying technology is essential for addressing these challenges effectively.

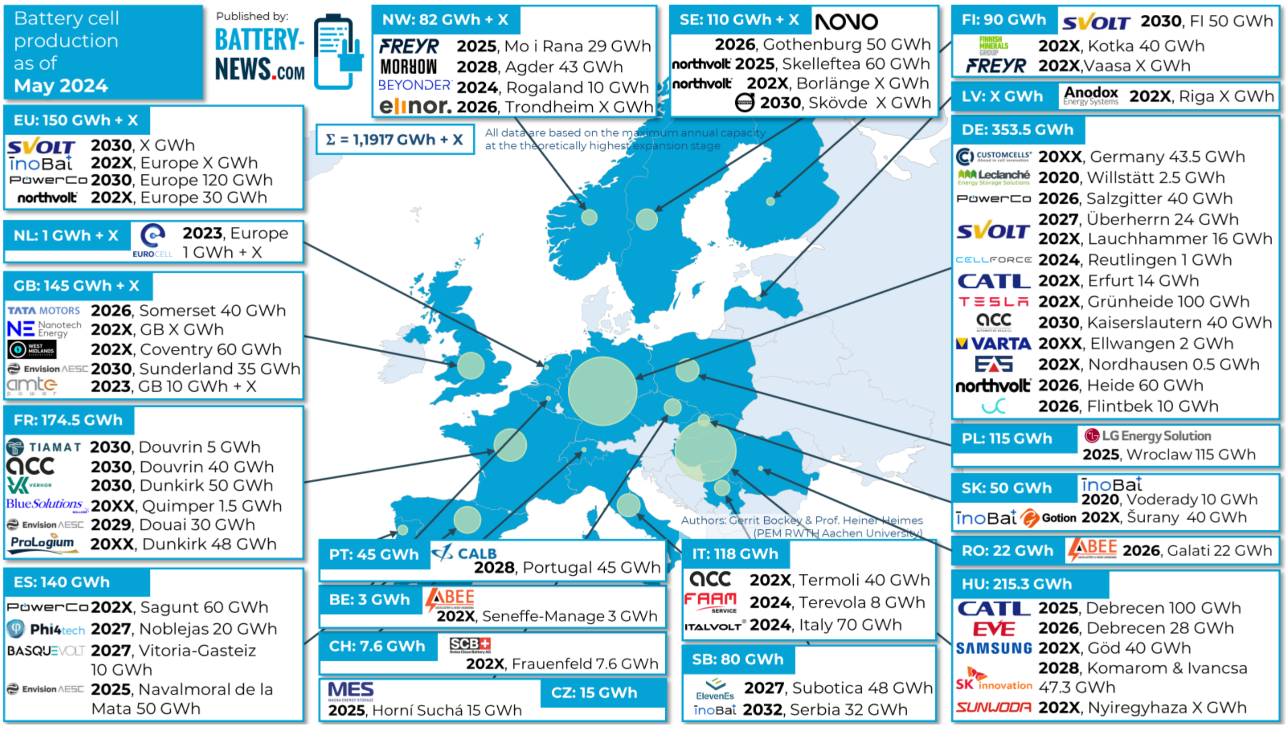


Figure 3: Announcements battery cell production capacity in europe [3]

DRIVERS FOR HIGH ENERGY CONSUMPTION

Three primary drivers contribute to the high energy consumption in cell production: drying, cell finalization, and clean and dry rooms. Among these, drying stands out as a major contributor to operational expenditure (OPEX) costs and carbon footprint. Therefore, focusing on energy-saving potentials in the drying process is paramount for improving overall efficiency.

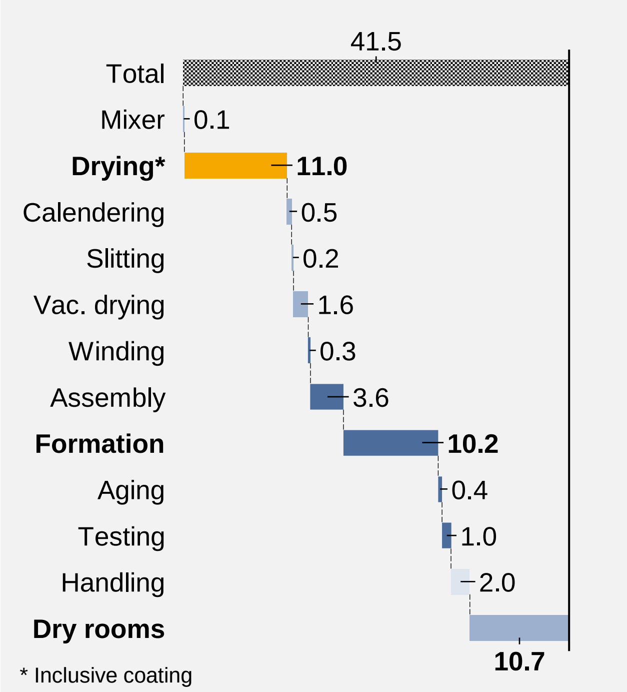


Figure 4: Energy consumption in kWh per kWh produced battery cell capacity [4]

CURRENT DRYING TECHNOLOGIES

The state-of-the-art drying process involves convection drying, typically executed in a multi-stage process. This process operates at web speeds ranging from 35 to 80 meters per minute in a continuous production line. The drying equipment can accommodate film widths of up to 1.5 meters, with drying sections extending up to 100 meters length. During drying, the active material is exposed to hot air, facilitating the evaporation of moisture. [5] Despite its prevalence, the drying process poses several challenges:

- **Energy Efficiency**: Drying accounts for approximately 27% of the total energy consumption in cell production, making it a focal point for efficiency improvements. [6]

- **Footprint:** The need for extended drying sections, sometimes reaching up to 100 meters, results in a significant physical footprint within the production facility. This space requirement contributes to higher operational costs and limits flexibility in plant layout.

- **Costs:** Both capital expenditure (CAPEX) and operational expenditure (OPEX) associated with drying equipment are substantial, comprising approximately 21% of the total manufacturing line costs, according to estimates by the Boston Consulting Group (BCG). [7]

- **Quality Concerns:** Achieving uniform drying across the width of the film poses a challenge, leading to quality issues such as inhomogeneous residual moisture and high scrap rates. Factors such as binder and carbon black migration at high drying rates and coating cracking at elevated thicknesses further complicate the process.

- **Process Control:** Currently, process adjustment in drying is largely based on empirical knowledge. Implementing inline control is challenging due to the extended heating and cooling cycles of the oven, necessitating innovative solutions for real-time process control.

NEXT-GENERATION VCSELS: TECHNICAL INSIGHTS AND ADVANCEMENTS

The next-generation Vertical-Cavity Surface Emitting Laser (VCSEL) TruHeat 5010 (see figure 5) is a low power density infrared laser source designed for the drying of battery electrodes. The VCSEL modules emit laser light perpendicularly (figure 6) from the laser's surface. By arranging the VCSELs in arrays, a large area can be uniformly illuminated. Thus, VCSEL technology offers an energy-efficient and scalable solution for industrial battery production.

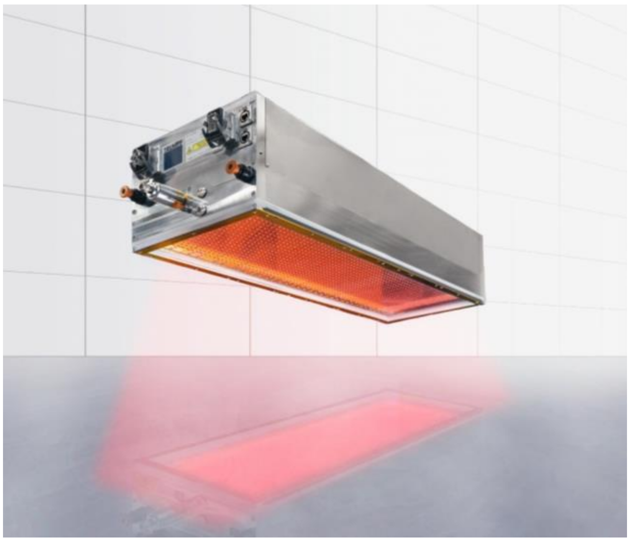


Figure 5: TruHeat VCSEL 5010

DESIGN OF A VCSEL

The basic structure of a VCSEL (see figure 6) includes a gallium arsenide (GaAs) substrate, an active region and Distributed Bragg Reflector (DBR) mirrors. The GaAs substrate provides mechanical support and aids in heat dissipation. The central active region is flanked by two DBR mirrors that reflect light and create resonance. Metal contacts on the top and bottom enable voltage application to control current flow through the active area.

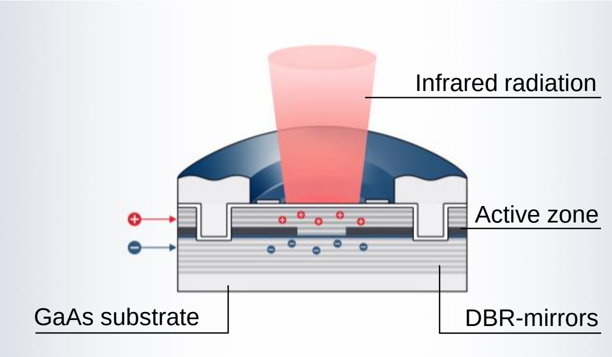


Figure 6: Schematic design of a VCSEL

FUNCTIONALITY OF A VCSEL

When voltage is applied to the contacts, current flows through the active region, injecting electrons and holes into the quantum wells where they recombine and emit photons. The DBR mirrors reflect these photons, causing them to pass through the active region multiple times and generate additional photons, amplifying the light. The DBR mirrors reflect and amplify light at a specific wavelength. If the gain exceeds the losses, laser resonance occurs, producing coherent light. A small portion of this light escapes through the partially reflective upper mirror and is emitted from the VCSEL surface.

Individual VCSEL are characterized by their small size and moderate power output of typically 10 mW. However, VCSELs can be like light emitting diodes (LED) fabricated into large arrays. Multiple chips containing these arrays can ultimately be integrated into a single water-cooled sub-module. This scalability enables the creation of high-power VCSEL-based heating systems that can be scaled up to several tens of kilowatts of output power. [8]

FUNCTIONAL DESCRIPTION OF THE TRUHEAT MULTI-JUNCTION VCSEL

A multi-junction VCSEL contains multiple active regions separated by tunnel junctions. Each active region houses a quantum well or quantum dot structure where laser generation occurs. Tunnel transitions facilitate the movement of charge carriers between active regions with minimal power loss, which can increase the energy efficiency over 60%. [9] A new generation of VCSEL laser modules has been developed for drying lithium-ion battery electrodes. Compared to previous VCSEL systems, these modules prioritize lower power density and higher energy efficiency, achieved through the integration of multi-junction VCSELs, optimized cooling systems, efficient power electronics, and low ohmic losses.

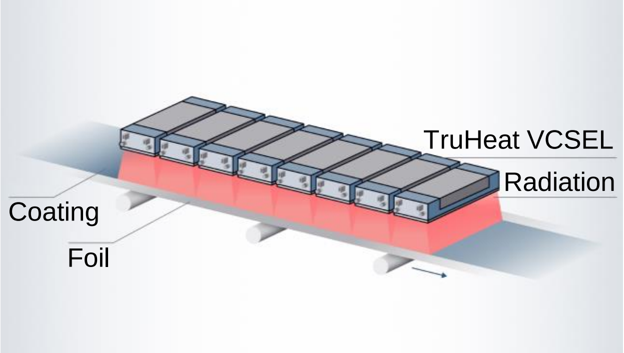


Figure 7: Integration of VCSEL modules

Each module consists of several sub-modules, each of them housing many VCSEL array chips. The front side of the submodules is gold-coated to reflect laser light from the uncoated areas of the battery electrode foils. These foils, whether copper (anode) or aluminum (cathode), exhibit high reflectivity for the laser beam at 980 nm. Electronics on the submodules back enable individual control of multiple zones within a module.

TECHNOLOGY ADVANCEMENTS OF NEXT-GENERATION

Integrability: Employing multi-junction VCSELs allows for a reduction in working distance of up to 100 mm without the need for additional optics. With a low height of just 200 mm, the VCSEL module requires only 300 mm of space above the coating for integration. This compact design, coupled with integrated electronics, offers advantages for both integration into new systems and retrofitting existing production lines.

Zone controllability: Each individual module can be precisely controlled within 10 milliseconds through multiple independently controllable emission zones, each with a width of 32.5 mm. The total emission area of a TruHeat VCSEL 5010 module is either 210×780 mm^2 (short version with 24 zones) or 210×1560 mm^2 (long version with potentially 48 zones). Connecting multiple modules in series allows for control of laser intensity both within and across the web direction. The homogeneity, with a variation of ± 2.5% and reaching up to 3 W/cm^2, ensures uniform drying and consistent electrode quality.

Efficiency: Next-generation VCSEL technology achieves a wall-plug efficiency exceeding 50%, signifying progress towards a more environmentally sustainable battery manufacturing process and providing an advantage in cost reduction. This enhanced efficiency is primarily attributed to the utilization of multi-junction VCSELs. Furthermore, VCSELs present production benefits owing to their LED-like manufacturing process, which enables high-volume, cost-effective fabrication using established semiconductor techniques.

APPLICATION OF VCSEL LASER DRYING IN BATTERY PRODUCTION

VCSEL laser drying enables a direct energy input via laser radiation into the coating material. Operating at a wavelength of 980 nm, VCSEL lasers enable nearly 100% absorption of infrared radiation by common active materials such as graphite and lithium iron phosphate (LFP). This results in significantly elevated drying rates and higher energy efficiency.

KEY ADVANTAGES OF VCSEL LASER DRYING

Increased Drying Rates: The high absorption efficiency translates to faster drying, effectively reducing the overall drying time. This accelerated process minimizes the footprint of drying equipment within production facilities. [11]

Energy Efficiency: VCSEL laser drying allows for a targeted energy input directly into the material being dried, substantially reducing waste heat. This precision leads to a lower energy consumption, contributing to a reduced CO_2 footprint.

Enhanced Controllability: The rapid response time of VCSEL lasers, within milliseconds, offers superior control over the drying process. By integrating appropriate measurement technology and zone control, inline-controlled drying of active materials is achievable.

Compact Design for Retrofit: The compact nature of VCSEL systems facilitates their integration into existing production lines without extensive modifications.

APPLICATION CONCEPTS OF VCSEL-BASED LASER DRYING

Several application concepts can be implemented for VCSEL-based laser drying, tailored to different stages of the drying process (illustrated in figure 8):

Hybrid Approach (Phases 1 and 2): Combines traditional drying methods with laser drying. This method can employ higher laser intensities due to the reduced risk of binder migration during these initial phases.

Stand-Alone Approach (Phases 1 to 5): Utilizes laser drying exclusively across all drying stages. Laser intensities are adjusted to suit the sensitive nature of later drying phases.

In addition to the 2-stage hybrid and the stand-alone laser drying process, other multi-stage laser-based drying processes (e.g. laser-based post-drying) that are tailored to the individual drying phases are also conceivable. To illustrate the efficacy of VCSEL laser drying, three drying concepts are compared, each represented by their characteristic drying curves (see figure 9):

- Convection Drying (1-Stage)
- Hybrid Drying (Laser + Convection)
- Laser Stand-Alone Drying

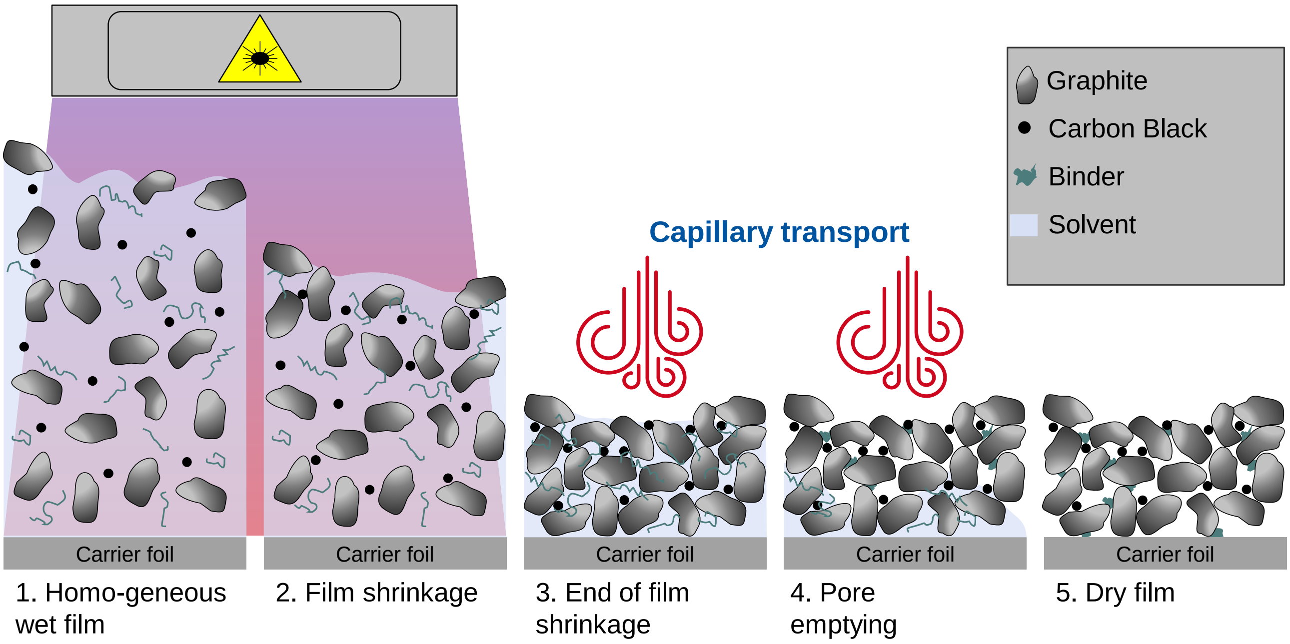


Figure 8: Material kinetic mechanisms of drying process (Hybrid laser- and convection-based process) [10]

The hybrid and stand-alone laser drying processes offer substantial benefits over traditional convection drying:

Accelerated Drying Process: Direct energy input from the laser can increase material temperatures to around 100 °C, compared to the 35-50 °C typical in convection drying. This results in a significantly faster drying process.

Footprint Reduction: The faster drying rates mean a smaller equipment footprint, leading to reduced capital expenditures (CAPEX) and operating expenditures (OPEX) by 30-40%.

Optimized Energy Use: The precise energy application reduces overall energy consumption, enhancing the sustainability of the production process.

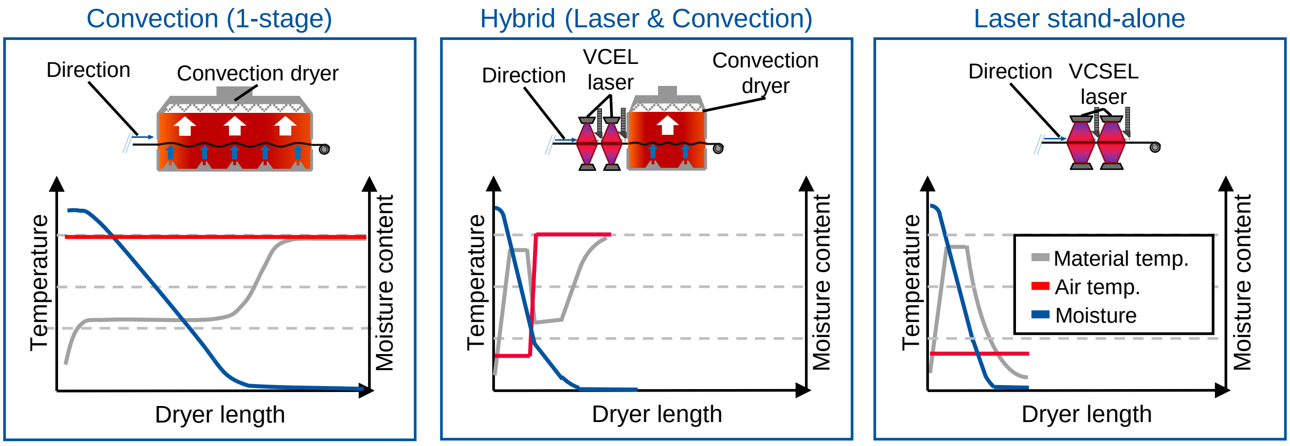


Figure 9: Idealized drying process (Convection, Hybrid, Laser stand-alone)

VCSEL DRYING OF ELECTRODES: EXPERIMENTAL FINDINGS AND ANALYSIS

An experimental study was executed to compare the performance of the VCSEL dryer to conventional convection drying and to evaluate the quality of electrodes dried using both methods. Over 50 parameter sets were conducted in total. Three parameters are analyzed in detail below.

EXPERIMENTAL SET-UP

Initially, the anode slurry is formulated using an intensive mixer before being applied to the copper collector foil via a slot die. While the coating spanned a width of 160 mm, the collector foil measured 300 mm across. Moreover, the wet film thickness was regulated by adjusting the pump speed, web speed, and slot nozzle distance.

For the first process parameter, electrode drying was conducted using a convection dryer equipped with two independently adjustable heating zones. Electrodes produced for the next parameter set were fabricated using a hybrid laser drying system, combining the VCSEL system PPM430 with a maximum output power of 8.4 kW with convection drying modules. The third process parameter was produced using the VCSEL system in a stand-alone laser system configuration. Figure 10 illustrates the setup for all three parameters.

Table 1 presents the parameter sets utilized in fabricating the examined samples. Throughout this study, the settings of the convection dryer remained constant. Consequently, the web speed for the convection drying parameter was set to the maximum value capable of reducing residual moisture to below 1%. In hybrid tests, the VCSEL system was activated, allowing for an increased maximum web speed of 2.8 m/min. The laser spot of the system covered the entire coating width and extended longitudinally by approximately 230 mm. For stand-alone drying, the convection dryer was deactivated, and only the VCSEL was utilized for drying.

Table 1: Summary of the analyzed parameter sets

Process parameter	Convection	Hybrid	Stand-alone
Web speed [m/min]	1.4	2.8	0.8
Wet film thickness [µm]	180	180	180
Area weight Dry [g/m²]	90.88	88.50	88.03
Temp. heating zone 1 [°C]	120	120	-
Temp. heating zone 2 [°C]	140	140	-
Dryer length [mm]	2160	2160	-
Laser spot width [mm]	-	200	200
Laser spot length [mm]	-	230	230
Laser intensity [W/cm²]	-	2.46	1.08
Areal energy density [J/cm²]	-	12.12	18.68

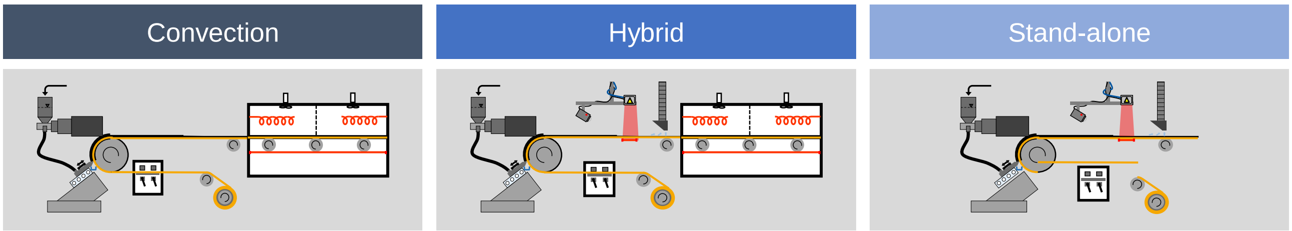


Figure 10: Experimental drying set-up

The slurry composition is detailed in Table 2. A graphite-based slurry was selected for all parameter sets to create the samples. Deionized water, with a weight ratio of 53%, served as the solvent. In addition to graphite and the solvent, the main components included CMC and SBR binders, along with conductive carbon black. Graphite, CMC, and conductive carbon black were added as powders during the mixing process, while SBR was introduced as a 40% solution. Finally, a copper foil with a thickness of 10 µm was utilized as the carrier foil.

Table 2: Composition of the anode slurry

	Graphite	SBR	CMC	Carbon black	DI water
w_{solid} [%]	94.0	3.0	2.0	1.0	-
w_{total} [%]	42.3	3.4	0.9	0.4	53.0

Key evaluation metrics for the samples include adhesion forces between the carrier foil and active material layer, residual moisture content, electrochemical performance, and SEM measurements. Adhesion force was measured using a tensile testing machine, while residual moisture was determined via Karl-Fischer titration. Electrochemical performance was assessed using coin cells assembled with graphite-based anodes and NMC622 cathodes for cycle stability and internal resistance evaluation. SEM imaging captured "top view" and "cross-section" images at various magnifications.

TEST RESULTS OF THE EXPERIMENTAL STUDY

Figure 11 illustrates the drying time and performance of the three drying concepts. The hybrid VCSEL system reduced drying time by approximately 45% compared to convection drying. Stand-alone VCSEL drying further decreased the drying time by over 80%.

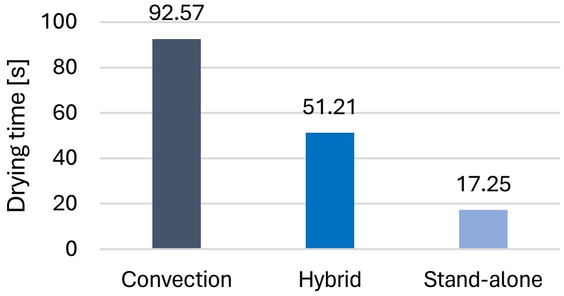


Figure 11: Comparison of drying time

As indicated, a shorter drying time increases the average drying rate, raising the risk of binder migration. The adhesion test indirectly measures the binder content between the substrate and coating. Figure 12 presents the adhesion measurement results for the three drying concepts.

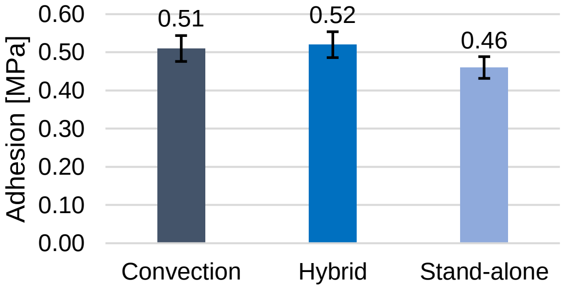


Figure 12: Comparison of adhesion force

It is evident that the adhesion of the hybrid concept remains at a comparable level despite the significantly shorter drying time. The adhesion of stand-alone drying is approximately 10% below the reference value of convection drying. Particularly for the stand-alone drying concept, varying the laser intensities in the web direction could potentially yield improved adhesion results.

In the test campaign, the target residual moisture value was set at less than 1%. All drying concepts successfully met the target value. Both the convection-dried and hybrid-dried parameters even achieved residual moisture values of less than 0.5%, as depicted in figure 13. This indicates that complete drying is attainable in both hybrid and stand-alone drying configurations.

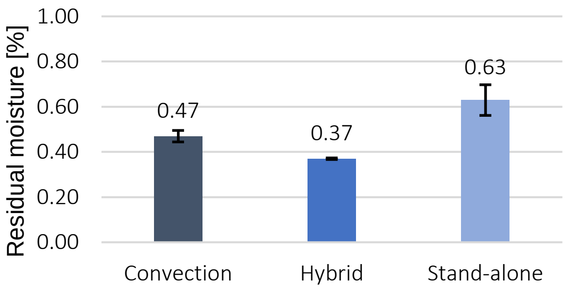


Figure 13: Comparison of residual moisture

Coin cells were assembled using NMC622 cathodes and the graphite-based anodes to assess the electrochemical performance of parameters generated with the convection, hybrid, and stand-alone drying methods. Formation, pulse tests, and cycle stability tests were executed. The internal resistances of the cells can be determined from the pulse test outcomes. Observations regarding the long-term behavior of the cells can be made from the cycle stability tests. However, only 20 cycles were conducted in the experimental study.

Figure 14 displays the average formation outcomes of five coin cells per parameter. The cells underwent charging at C/20 rate and discharging at 1 C rate. Coulombic efficiencies, calculated as the ratio of discharged capacity to charged capacity, demonstrate similar values across all drying methods. Mean values of specific capacities also exhibit comparable results, albeit stand-alone drying showing a slightly higher specific capacity.

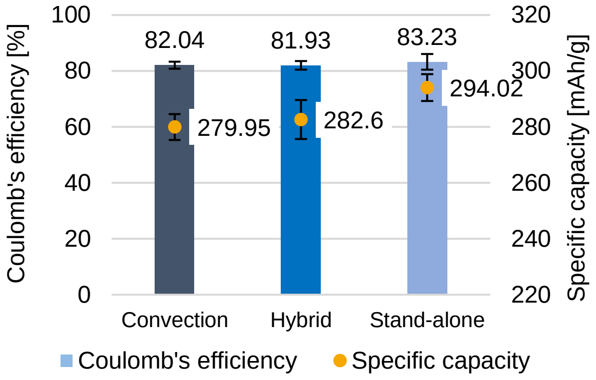


Figure 14: Comparison of coulomb´s efficiency

Following formation, the cells were charged at 0.5 C to a voltage level of 3.6 volts. After a brief rest, the cells underwent pulsing at 0.5 C for 10 seconds. Resistance was computed using Ohm's law. Figure 15 illustrates the findings. The internal resistances of the tested cells are relatively consistent, although conventionally dried cells exhibit slightly higher resistance than those dried via hybrid and stand-alone methods.

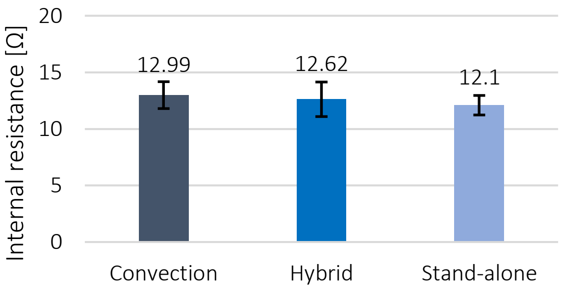


Figure 15: Comparison of internal resistance

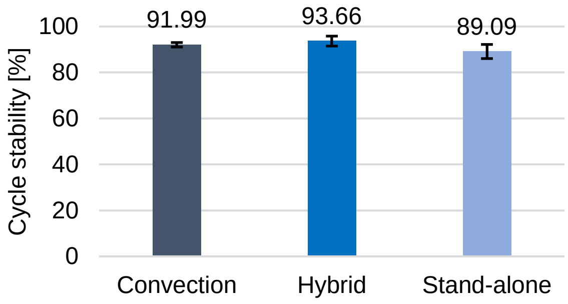


Figure 16: Comparison of the cycle stability

Cycle stability tests were conducted over 20 cycles, involving charging and discharging at 0.5 C. Cycle stability was determined by dividing the 20th cycle's discharge capacity by the 1st cycle's charge capacity Overall, cycle stability is around 90%. Hybrid-dried anodes have the highest stability at 93.66%, while stand-alone dried anodes have the lowest at 89.09%. These results are consistent with the formation test findings (see figure 16). No significant differences in electrochemical performance were observed among the three drying concepts after evaluating the formation, pulse test, and cycle stability test results.

In addition to the adhesion tests, residual moisture tests, and electrochemical evaluations, top-view and cross-section SEM images were captured during the experimental study. Figure 17 presents panoramic views of the cross-sections of convection-dried, hybrid-dried, and stand-alone-dried anodes. The width of the image permits qualitative assessments regarding the morphology and porosity of the produced electrodes. However, no significant differences are observed among the panoramic images of the differently dried parameters.

Figure 18 presents top-view SEM images magnified at 500x and cross-section images magnified at 1000x. The top-view images indicate that the morphology is similar, suggesting that the active materials and binders have not been adversely affected by the VCSEL irradiation. Similarly, the cross-section images of the parameters from the three drying concepts exhibit comparable morphology and porosity.

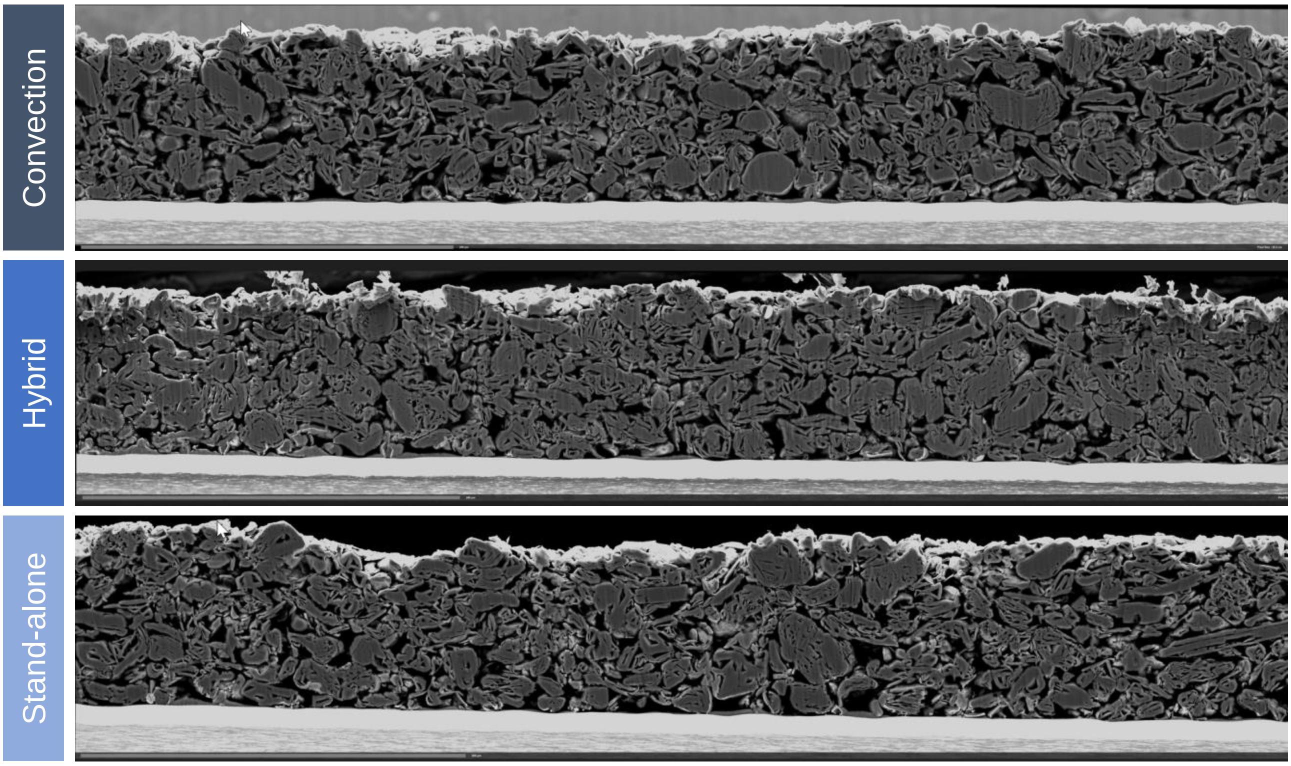


Figure 17: Comparison of SEM panorama images

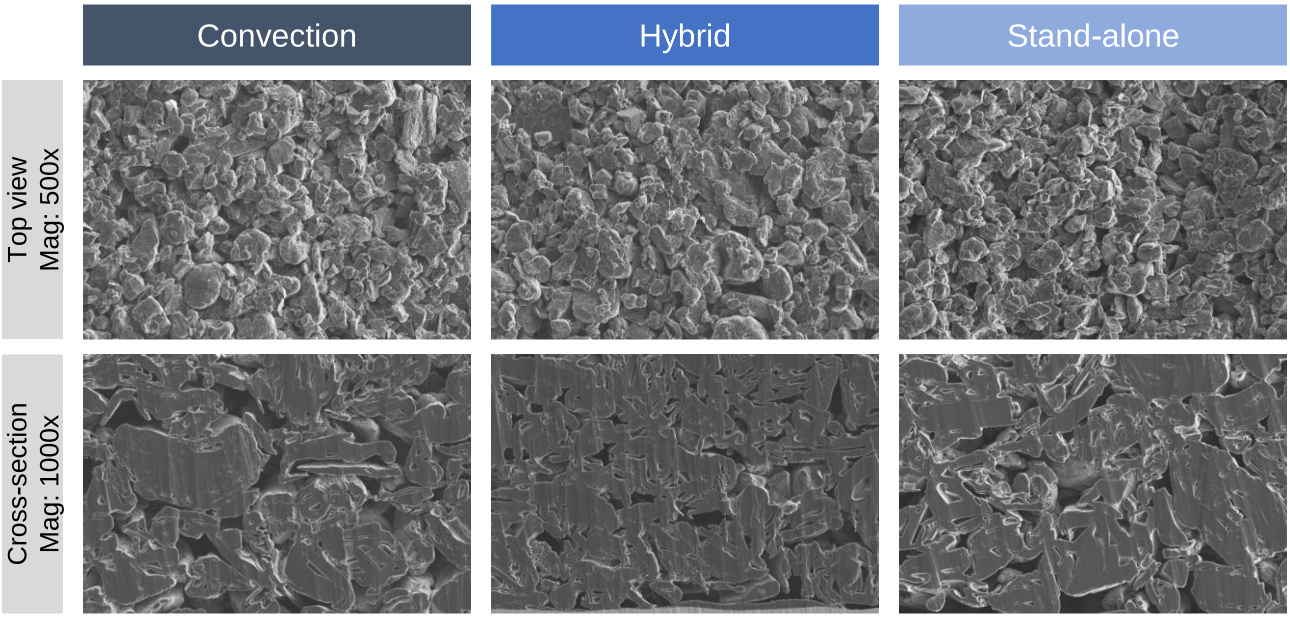


Figure 18: Comparison of top view and cross section SEM images

SUMMARY

The global lithium-ion battery production landscape is transforming due to the rapid growth of electric mobility, driven by increasing electric vehicle adoption. This surge in demand presents opportunities and challenges, catalyzing new gigafactory establishments in Europe, North America, and Asia, and shifting from centralized Chinese production to localized manufacturing. However, high lithium-ion battery costs, constituting about 31.5% of battery electric vehicle costs, pose a significant barrier. Addressing this challenge requires economies of scale, innovative production technologies and energy optimization. Competitive pressures are intensifying, particularly in Europe, where established Asian manufacturers and emerging local players are increasing production capacities. Drying, a major contributor to energy consumption and operational costs, necessitates focus on energy-saving potentials. Improving drying efficiency is crucial, given its significant physical footprint, high costs, and quality control challenges.

Laser drying has the potential to enhance energy efficiency, thereby reducing costs, CO_2 emissions and plant footprint. To validate this potential, an experimental study was conducted comparing conventional convection drying, hybrid VCSEL laser drying, and stand-alone VCSEL laser drying. Using laser drying in the hybrid concept reduced drying time by 45% while maintaining comparable quality in terms of adhesion, residual moisture, and electrochemical properties. Furthermore, no differences were observed in SEM images. With a stand-alone laser drying solution, the drying time was reduced by over 80%. Although this method resulted in slightly lower adhesion values and slightly higher residual moisture levels, no significant differences were detected electrochemically or in SEM images. A reduction in drying time results in either a substantially smaller footprint for the same throughput or a significantly increased throughput within the existing footprint.

IMPRINT

The chair of **Production Engineering of E-Mobility Components (PEM) of RWTH Aachen University** was founded in 2014 by Professor Achim Kampker and has been active in the field of lithium-ion battery production technology for many years. PEM covers all aspects of the development, production, and recycling of battery cells and systems. Due to numerous industrial projects with companies of all stages of the value chain and central positions in renowned research projects, PEM offers extensive expertise.

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ISBN: 978-3-947920-53-2

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