Diode Laser Drying of Electrodes for Lithium-Ion Batteries

Paving the way for energy-efficient and economical battery production
“We focus on delivering processes and innovations for an economical and ecological sustainable battery cell production”
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1. Status Quo and Challenges of Electrode Drying

Batteries are everywhere in our daily lives, and their importance continues to increase. In particular, the lithium-ion technology has many applications in our everyday lives nowadays, such as stationary energy storage, in the electronics segment, or in the field of electric mobility.

Due to the rising costs of fossil fuels and the transition to e-mobility as a result of the set climate targets, an increasing number of battery production facilities has been announced worldwide. Currently, the production of lithium-ion batteries has reached an unprecedented level. As a result, the demand for low-cost and at the same time high-quality battery cells continues to grow globally. This has led to an increasing competition between established and new cell suppliers. A key part of this competition involves the development of innovative and future-oriented manufacturing technologies. Among many objectives, the main target of these novel production methods often is to reduce the production costs while at the same time increasing the cell performance. Furthermore, national legislation regarding compliance with environmental protection, work safety, and CO₂ restrictions in production also have a decisive role in the establishment of new production lines.

A promising approach for the reduction of costs within the manufacturing process can be found in the optimization of the drying process of the electrodes. In this process step, solvents are removed from the wet slurry film that is coated on both sides of the current collector foils (usually copper for anodes and aluminum for cathodes). The slurry thereby contains the active materials which give the battery cells their electrochemical properties. The previous addition of the solvent favors the material characteristics during the earlier mixing process as well as during the application of the slurry. Accounting for about one quarter of the operating costs, the drying process is one of the most cost-intensive production steps. The incurred high operating costs are primarily due to the significant energy demand covered by natural gas within the drying process step using current production technologies.

As a further challenge, conventional drying machines require large amounts of production space. The high system footprint primarily results from the long lengths of drying sections required by conventional technologies. To meet throughput targets, dryer lengths can reach up to 50 to 100 meters.

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**Energy shares in battery cell production**[1]

- **Drying**: 27% of energy consumption, high potential for energy savings in the drying process step
- **Vacuum drying**: 9% of energy consumption
- **Assembly**: 25% of energy consumption
- **Formation**: 5% of energy consumption
- **Dry rooms**: 26% of energy consumption
- **Handling**: 5% of energy consumption
- **Other**: 5% of energy consumption

**Cost shares (CapEx+OpEx) in battery cell production**[2]

- **Electrode production (other)**: 18% of cost consumption
- **Drying**: 21% of cost consumption
- **Cell finalization**: 41% of cost consumption
- **Assembly**: 20% of cost consumption

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*Incl. Coating

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*Figure 1: Energy and cost breakdown in battery cell production*
DIODE LASER DRYING OF ELECTRODES FOR LITHIUM-ION BATTERIES
PAVING THE WAY FOR ENERGY-EFFICIENT AND ECONOMICAL BATTERY PRODUCTION

Facing the challenge of double-sided foil coatings along with the long drying distances, often a multi-level dryer design or air floating units are applied. As a consequence, both solutions result in a significant increase in equipment complexity. The space requirement and thus the costs are often further increased by the multiple installation of dryers to achieve targeted production capacities. Furthermore, anodes and cathodes are typically processed separately on different manufacturing lines, which also increases equipment amount. Besides the use of different solvents, the prevention of cross-contamination as well as different environmental requirements are generally reasons for the separate processing of anode and cathode foils.

The drying process of the electrodes also has a significant impact on the quality and performance characteristics of the battery cells. Currently, the convection drying method marks the most widely used drying technology. Apart from the high space requirement, this technology is characterized by further challenges such as low energy efficiency. Other challenges include inhomogeneous heat fields, slow and inaccurate control characteristics, lack of material-optimized heat alignment, slow production ramp-up as well as the heat dissipation into the surrounding production area.

The application of diode lasers for highly efficient drying of electrodes represents an attractive solution to increase battery quality and performance. Compared to other drying technologies, the diode laser technology is characterized by its high-power density thus compact design. At the same time, it provides a high degree of homogeneity along with the possibility of location-selective energy input. The adaptive alignment of the laser beam can also be used to specifically address the different properties of the active material layer as well as the solvent contained. In the following sections, this technology will be closer explained, and potential implications for future battery production will be described.

The 2020s are expected to mark the decade in which lithium-ion battery energy storage will become an integral part of everyday life, finding application in vehicles, consumer goods, power tools, and many more segments. Especially for emerging markets, demands are expected to grow in double digit rates over the next years, driving today’s and future need for battery cells. Innovative production technologies thereby play a key role in ensuring a sustainable production in the future.

Figure 2: Wet coated electrode foil at the PEM institute of RWTH Aachen University
“Electrode drying is one of the quality-determining process steps in battery production”
“Customized solutions for an efficient and sustainable battery production worldwide”
2. Diode Laser Drying Solution

Already today, a paradigm shift in modern production is prominent. Therefore, the optimization of process efficiency in the direction of CO₂-neutral production is increasingly attracting attention. This often includes the electrification of the production equipment. The semiconductor-based conversion of electricity into laser radiation promises a reduction in dependence on fossil resources and thus a turnaround in the sector of industrial drying. Therefore, laser drying could become a key technology in the construction of future battery production lines.

In addition to the laser source and the control module, further key elements of diode laser systems include the cooling unit, fiber optic cables, and the homogenizing processing optic. Ultra-wide beam optics as well as maximum output capacities of over 20 kilowatts per laser unit also allow the drying of coating widths far beyond current production standards. In addition, the use of the zoom optics allows a high degree of flexibility in adjusting the beam width. Therefore, different coating widths can be covered within one laser module. With a range of 900 to 1,080 nanometer, the typical spectral range of the emitted laser radiation lies within the near infrared area.

Furthermore, different spot sizes and working distances can be effortlessly realized with homogenizing process optics. This provides a high degree of flexibility in designing new drying systems as well as in the integration into existing machines. The high working distance enables a remote installation of the optic outside of the evaporation chamber, which is a key factor for enabling ATEX compatibility. Furthermore, the high freedom in laser spot design allows for an efficient arrangement of the solvent extraction system.

The adjustment of the outgoing hot and thus highly energetic mass flows thereby represents an important key component in increasing process efficiency. The laser spots are being designed in width and length to the electrode size and ideal nozzle distance for fume extraction, enabling spots of e.g., 1,400 x 300 mm².

Unlike other drying technologies such as drying with infrared lamps, the laser radiation also penetrates emerging solvent vapors virtually unhindered due to its low wavelength. This effect further benefits the control and thus efficiency properties. With an electrical wall plug efficiency of over 50%, high-power diode lasers with edge-emitting semiconductor structure also represent the most efficient laser technology currently available.
Another fundamental advantage of the diode laser technology lies in their ability to apply energy with high accuracy. Due to the distinct focusability of the laser beam as well as the possibility to switch it on and off within less than a millisecond, always the exact amount of energy is introduced into the wet film. This allows for an optimal adjustment of the drying intensity depending on the specific material and solvent properties. In addition, the electrode foil can be thermally relieved by the avoidance of unnecessary energy input. With the additional implementation of inline sensors, the optimum process window can be adhered even closer. Inline coating thickness sensors or thermographic cameras, for example, can be used to address coating deviations. Using suitable machine-learning (ML) algorithms, the system is also capable to further improve the drying process on its own.

As a further advantage, the system capability of fast and effortless on and off switching significantly simplifies the machine ramp-up. Therefore, even after long standstill, no costly and time-consuming reheating is required. Furthermore, the fast start-up and shut-down phases significantly simplify the execution of machine stops due to maintenance work or malfunctions in the machine. This enables further savings in time and resources.

Pilot-scale test series at the Chair of “Production Engineering of E-Mobility Components” (PEM) of RWTH Aachen University showed that by use of diode lasers energy consumption could be reduced by up to 85% on a small-scale research line without an energy recovery system. When integrated into series production, particularly the utilization of hybrid drying solutions, in which the advantages of different drying technologies are combined, appears to be promising for further improvements in terms of cost savings and quality. Additionally, diode lasers offer the potential to double production throughput. In the pilot scale trials of stand-alone laser drying, it has been shown that the drying time can be reduced by more than 80% [3].

In the course of the trials, the effects of laser processing on graphite anodes with different binder systems as well as Si-C anodes and LFP cathodes were examined. Furthermore, both hybrid and stand-alone laser drying was investigated.

The validation of conventional and laser-dried electrodes thereby showed that a comparable electrode quality can be achieved. Similar results were measured in terms of surface quality and residual moisture. While the stand-alone laser drying showed slightly lower adhesion results due to possible binder migration, the hybrid process achieved equivalent and even higher adhesion in comparison to convection-dried electrodes. Even in the comparison of cut samples under the scanning electron microscope (SEM), no significant differences could be identified. Furthermore, using the proper system adjustment, stable adhesion without degradation of the binder could be observed with the SEM and the thermogravimetric analysis (TGA). The electrochemical comparison of conventionally and laser-dried electrodes shows similar behavior. Regarding electrode capacity, internal resistance and electrical conductivity, similar performance characteristics were measured among the different dried samples.
The drying process using diode lasers can be divided into four different thermal zones (figure 7). The first zone depicts the heating zone, where the temperature of the wet coating layer gradually increases. Next follows the constant temperature zone, where most of the solvent is evaporated. Within this zone, the advantages of the diode laser, such as high homogeneity and fast controllability, can be fully utilized. Next comes the maximum temperature zone. Since the residual solvent in this zone is very small, the energy introduced by the laser can no longer be dissipated by the evaporation. As a consequence, in case of improper process adjustment, the active material layer may heat up. Meanwhile, the last zone represents the cool-down area. Within this zone, the electrode is no longer under laser radiation and accordingly releases the absorbed thermal energy back into the process environment.

The schematic illustration of the wet-coating drying process according to KUMBERG et al. [4] is shown in figure 8. Within this illustration, the drying process is divided into five phases. The microstructure of the particle layer thereby plays a crucial role in the electrical and ionic conductivity of the electrodes and is significantly influenced by the drying process. Thus, in the course of the third phase, capillary transport of smaller particles to the surface can occur within the active material layer as a result of the emptying of the water-filled network. These smaller particles especially include the binding material as well as carbon black components of the coating.

To improve electrode performance, an even distribution of all active material components is essential. Particularly in the third drying phase, the wet layer is highly sensitive to rapid drying due to capillary transport. By combining different drying technologies in so-called hybrid drying methods, synergies can be created which further improve the drying process. For example, within the first and second drying phase, the high-power density combined with the high accuracy of the diode laser could be used for efficient and uniform pre-drying of the wet film. Following this, in the third and fourth phases convection drying could be applied to prevent capillary transport through slower drying. This could further reduce transport effects such as binder migration. Lastly, a further diode laser module could be introduced in the transition from the fourth to the fifth phase in order to allow particle components that have already migrated towards the surface diffuse back through the input of energy.
3. Implications for Future Battery Production

The implementation of laser drying as a promising drying alternative in electrode production offers the potential to revolutionize the electrode manufacturing for lithium-ion batteries (LIBs). For the industrialization of this technology in hybrid drying concepts, there are basically three main use cases chosen by cell manufacturers:

- **Throughput increase**
- **Footprint reduction**
- **Quality improvement**

Figure 9 shows the influence on the relevant Production Key Performance Indicators (KPIs) “CapEx”, “OpEx”, “Footprint”, and “Quality”, calculated on the basis of the experimental investigations of the three hybrid drying configurations tested on the research line at PEM of RWTH Aachen University. To increase throughput (use case 1), existing convection dryers with a drying length of 70 to 100 meters on a series production level are supplemented by upstream laser modules to double the web speed. This requires large-area laser spots with a length of about 14 meters. Per kilowatt-hours of battery capacity produced, hybrid drying with diode laser systems in this configuration would result in significant energy savings of nearly 20% due to the high energy efficiency of the laser systems. Current diode lasers with a wallplug efficiency of 52% are likely to be improved even more in the coming years due to further product innovations.

<table>
<thead>
<tr>
<th>Use-Case</th>
<th>1: Throughput Increase</th>
<th>2: Footprint Reduction</th>
<th>3: Quality Improvement</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Concept</strong></td>
<td>Laser system integration in front of standard convection dryer (14 m Laser + 70 m convection dryer)</td>
<td>Laser system integration in front of shortened convection dryer (7 m laser + 35 m convection dryer)</td>
<td>Laser system integration after standard convection dryer (70 m convection dryer + 0.25 m laser)</td>
</tr>
<tr>
<td><strong>Pros</strong></td>
<td>Higher energy efficiency</td>
<td>Higher energy efficiency</td>
<td>Increased drying quality possible with inline control</td>
</tr>
<tr>
<td></td>
<td>90% to 100% higher throughput on slightly increased footprint</td>
<td>Approx. 50% less footprint with same throughput</td>
<td>Slightly higher energy efficiency</td>
</tr>
<tr>
<td><strong>Cons</strong></td>
<td>- 19% increased total drying lengths (but significant throughput increase)</td>
<td>- Similar throughput</td>
<td>- Similar footprint</td>
</tr>
</tbody>
</table>

**Influence on Production KPIs (Coating/Drying only)**

| CapEx | -22% | -19% | -5% |
| OpEx | -19% | -28% | -5% |
| Footprint | -43% | -49% | -6% |
| Quality | Slightly increased or similar | Slightly increased or similar | Significantly increased (post-drying for inhomogeneous drying possible) |

Assumptions:
- Wet film thickness: 160 µm (per side)
- Solvent content: 52%
- Foil width: 1.500 mm
- Web speed convection dryer: 80 m/min
- OEE: 0.9
- Electricity cost: 0.13 €/kWh

**Diode Laser data:**
- Wallplug efficiency diode laser: 0.52

* Compared to state-of-the art convection dryer and normalized to one kWh of produced battery capacity

Figure 9: Implication of diode laser systems in battery production
Energy savings of this magnitude mean several million euros per year in cost savings for the anode and cathode line in a gigafactory. This configuration would also have a large impact on Capital Expenditures (CapEx) due to economies of scale. Thus, the potential for CapEx reduction is 22% with a footprint reduction of 44% per kilowatt-hour of battery capacity produced due to the significantly lowered drying time.

In use case 2 (Footprint Reduction), several laser modules are integrated in front of a shortened convection oven. For this purpose, the footprint can be lowered overall to almost 50% of the original drying line with a comparable throughput. As a result, Operational Expenditures (OpEx) can be reduced by almost 30% compared to a giga-scale convection dryer. With an almost maintenance-free service life covering 5 to 10 years 3 shift operation and thus negligible maintenance costs, OpEx almost entirely results from the necessary energy consumption at megawatt scale. Moreover, due to the compact equipment footprint and cost-effective megawatt-scale diode laser systems, a 19% reduction in CapEx is feasible in use case 2.

The third use case (Quality Improvement) consists of a laser module integration downstream of the dryer with the aim of post-drying possible inhomogeneities in the convection-drying process. This helps to ensure sufficient and uniform drying quality especially against the background of increased coating thicknesses for high-energy cells which can result in challenging drying processes. Controlling the laser via a closed-loop inline process control system with appropriate measurement equipment can offer a decisive advantage for improving process quality in electrode production.

In the future, efficiency improvements of diode laser systems through new product innovations and lower production costs due to scaling effects will contribute to a further reduction in CapEx and OpEx compared to standard convection dryers. For instance, new inline measurement technologies and integration of intelligent laser controls with ML algorithms as well as the identification of unknown product-process interactions could further improve product and process quality in electrode manufacturing.

Due to the massive OpEx in electrode manufacturing, the implementation of use case 2 is the most promising due to the highest cost-saving potential. Initial concepts also show a combination of use cases 2 and 3 in order to meet both goals of cost reduction and quality improvement in the same way. The integration of the laser can more than compensate the investment costs for diode laser systems due to the low equipment footprint, which requires fewer components. As a result, the initial CapEx for a hybrid laser drying system is reduced by 5 to 22%, depending on the system concept.

In addition, it is conceivable to further reduce the share of the convection dryer in the drying process and to substitute it completely in the long term. This would result in a further reduction in equipment footprint and energy consumption for electrode drying.

The integration of laser-based drying technologies has the potential to revolutionize electrode manufacturing. Different system concepts and sequences of drying technologies allow to address different objectives such as footprint reduction or quality improvements. Depending on the selected use case, significant CapEx and OpEx savings up to 30% can be realized.
The drying of electrodes for LIBs is the most expensive process step in the entire battery production, accounting for over 20% of the total production costs. The process innovation of laser drying offers great potential to revolutionize electrode manufacturing. The main advantages of the diode laser drying technology are high energy efficiency due to direct energy input as well as footprint reduction and possible quality improvements. Depending on the selected hybrid drying configuration, this results in up to 30% lower OpEx on a gigafactory scale, which can realize cost savings of several million euros per year and per line. Quality improvements in the drying process can be achieved by homogeneous and targeted energy input into the electrode surface. For example, post-drying after the convection dryer can compensate for inhomogeneities in the drying process and potentially contribute to a quality improvement of this process.

Moreover, thanks to their compactness and adjustable working distance, laser systems can also be installed in existing drying equipment. In the future, the already high energy efficiency and process quality could be further improved through new laser product innovations as well as inline quality controls in combination with ML algorithms.

On a research line scale, laser drying has already proven its suitability with comparable electrode qualities and significantly reduced drying times, so that the next step will be to industrialize the technology on a series scale.

**Key Takeaways:**

- Hybrid laser drying processes can reduce OpEx for drying battery electrodes by almost 30%.
- Hybrid laser drying processes can reduce the footprint in the drying of battery electrodes by almost 50%.
- Due to the low equipment footprint and efficient energy input of the laser-based drying systems, CapEx savings of about 20% can be realized.
- Quality improvements in electrode drying can be achieved by integrating large-area and homogeneous diode laser spots.

**Sources:**

[1] Degen et al. (*Life cycle assessment of the energy consumption and GHG emissions of state-of-the-art automotive battery cell production*) 2022

[2] Küpper et al. (*The future of battery production for electric vehicles*) 2018


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Aachen, May 2023
Imprint

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

LASERLINE GmbH, based near Koblenz, Germany, started in 1997 as one of the pioneers in the field of high power diode lasers. The company was able to position itself within a very short time as a technology leader for directly applied diode lasers through products of the highest beam quality and highest efficiency. Roughly 6,500 Laserline high-power diode lasers have been installed worldwide, demonstrating their performance in a wide variety of processes and 24/7 serial applications. Currently diode laser beam sources up to 60 kW are realized as well as the highest electrical efficiencies in the laser market. In the past, LASERLINE has developed a core know-how for homogeneous beam shaping of diode lasers in the kW power range and secured it by means of intellectual property rights.

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ISBN: 978-3-947920-39-6

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