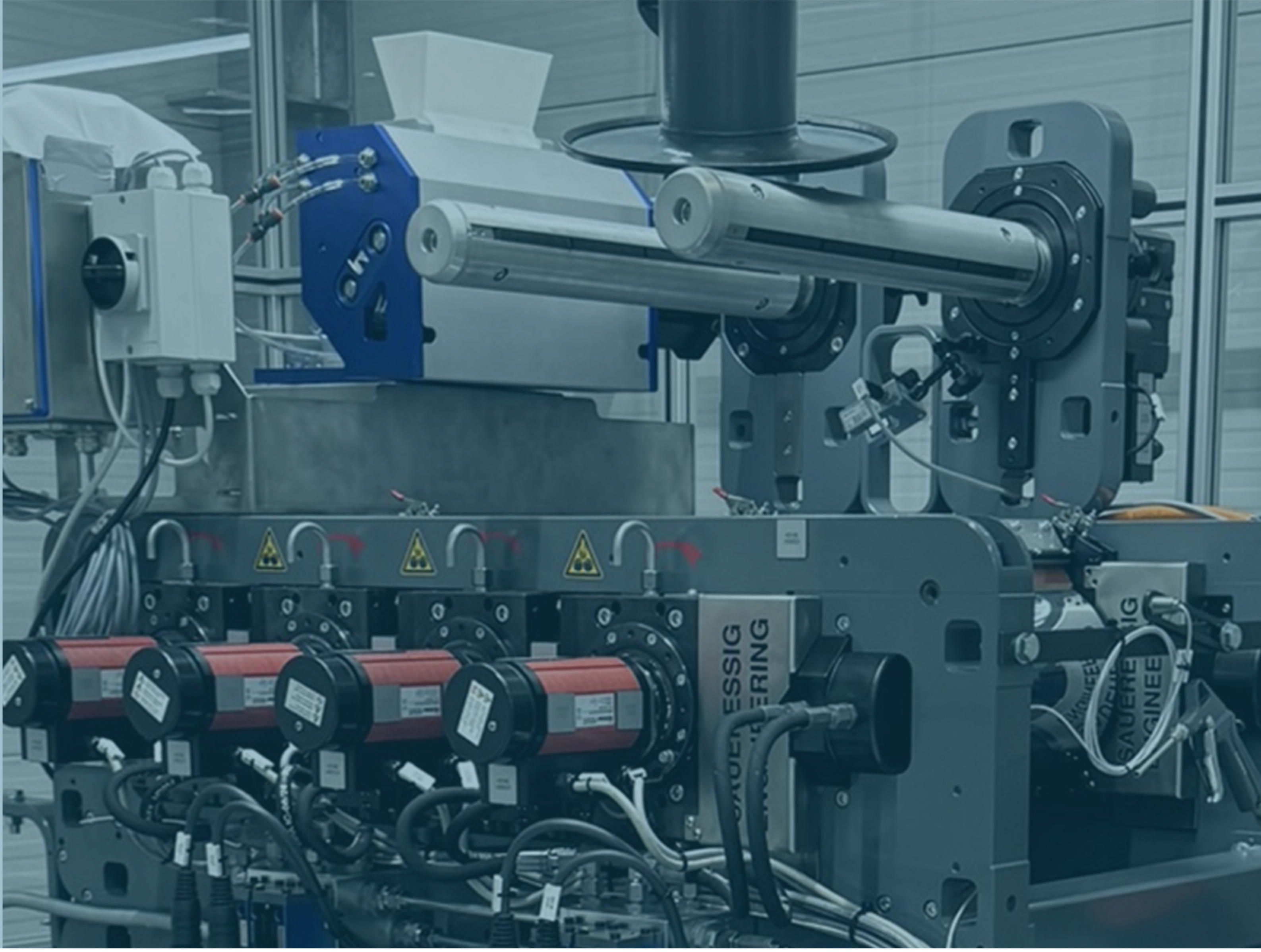

Industrialization concept for the dry coating of battery cathodes

GEFÖRDERT VOM

Bundesministerium
für Bildung
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Findings from a research project.

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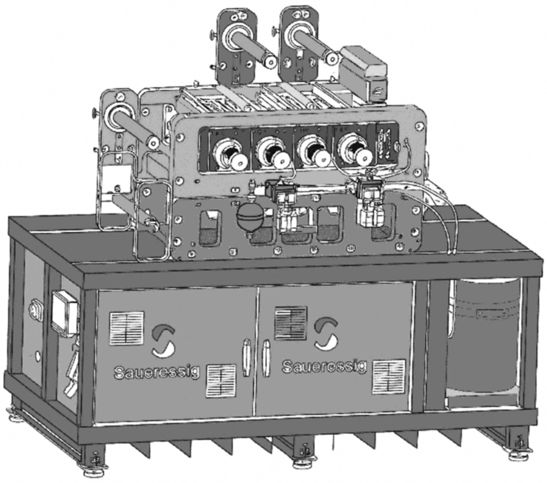

Content

Introduction

The rapid advancement of battery technology, coupled with the increasing demand for high-performance energy storage systems, presents substantial challenges to industry, research, and society. The manufacturing process of battery electrodes is receiving particular attention, as these electrodes play a critical role in determining the performance, sustainability, and cost-effectiveness of batteries, thereby making them essential to electromobility and other applications within the energy transition.

Compared to conventional methods, dry coating is an innovative electrode manufacturing process that eliminates the need for solvents, thereby enabling a substantial reduction in energy consumption during production. In addition, it eliminates the need for complex drying processes as well as for solvent recovery and disposal, offering both ecological and economic advantages. As part of the research project "*Process and Material Development of Lithium-Ion Battery Cathodes for Large-Scale Dry Coating Technology*" (*ProLiT*), investigations were conducted into dry coating methods for lithium-ion battery cathodes, and a corresponding industrialization concept was developed.

The project unites a diverse consortium of industrial and scientific partners, encompassing the full range of expertise necessary for a comprehensive approach to the development of calender-gap-based dry coating technologies [1]. The consortium includes **materials manufacturers**, *Daikin Chemicals* (PTFE binder development) and *IBU-tec* (LFP cathode active material development), **universities**, *Technische Universität Braunschweig* with the *Institute for particle technology* (process and plant development (batch mixer, calender), scaling) and *Universität Münster* with the *Münster Electrochemical Energy Technology Institute* (formulation development on a laboratory scale (batch mixer), electrochemical analyses in multilayer pouch cells), **machine and plant manufacturer**, *Maschinenfabrik Gustav Eirich GmbH & Co. KG* (*Eirich* mixer, development, consulting), *Coperion K-Tron (Switzerland) GmbH* ((dosing technology, development) and *Matthews International Corporation with Saueressig Engineering* (calender, plant development) and **cell manufacturer** *CustomCells* (process development (extrusion), electrochemical analyses in pouch cells) as well as an OEM with cell assembling expertise.

The aim was to implement scalable and competitive processes using a hybrid approach combining material, process, and plant development. The development was conducted in close collaboration within the consortium, with the evaluation of the calender gap-based dry coating process for battery electrodes (DBE) performed in comparison to solvent-based reference processes, considering factors such as product quality, resource efficiency, and sustainability.

To scale up the calender gap-based dry coating process, a concept for an industrial production line with a capacity of 1 GWh was developed, which is presented in this whitepaper. This concept builds upon the findings obtained in the *ProLiT* project and encompasses both pouch and cylindrical cell formats.

The focus is placed on the process steps relevant to commonly used cathode materials such as LFP and NMC. Beginning with material handling and proceeding through raw material mixing to film and electrode formation via calendaring, all critical process stages were systematically analyzed and evaluated regarding efficiency and sustainability. Additionally, overarching factors such as energy balance, personnel requirements, and equipment maintenance were examined. Since battery factories are usually designed for the production of cells of a defined size and with an annual output of several GWh, large production capacities are realized in modular GWh blocks. Within these blocks, the capacity of the systems is limited, so that the blocks are in turn divided into lines and installed in parallel. Many production machines available on the market achieve a production capacity of around 1 GWh. Therefore, the *ProLiT* project focused on this practical scale in order to gain realistic and directly applicable insights for the industrial implementation of dry coating.

Dry coating process

The dry coating process for electrodes starts with the mixing and functionalization of active material, conductive additives, and a suitable binder such as PTFE. Due to its ability to form fibrils under shear and temperature, PTFE can cross-link particles of the active material and conductive additives by binding the particles to the network formed by the fibrils via Van der Waals forces. After the binder has been fibrillated in the mixing process, the powder mixture is fed into the calender gap in a controlled manner in order to achieve a uniform film thickness and surface loading during film formation. In the calender, the powder is formed into a film in the initial “powder-to-film” step in the first gap pass by shearing and temperature of the calender roll pair. The calendering process is accompanied by further fibrillation of the PTFE binder and more intensive cross-linking of the electrode components. In order to obtain a specific film thickness and areal loading, the initially formed film can be further sheared between several roller pairs and the film thickness reduced. The formed film is then cut at the edges depending on the cell format and laminated onto a current collector between a roller pair to produce the battery electrode.

Appropriate processes and machine concepts have been proposed, for example, by *Maxwell Technologies* [2] and *Fraunhofer IWS* (*DryTraec*®) [3]. In terms of plant engineering, the film formation and lamination processes can be separated or both processes can be implemented in a single machine. However, there is currently no standardized process or generally preferred number of calender rolls.

Despite their advantages, dry coating processes also present specific challenges. Achieving a fine and uniform distribution of the binder within the powder mixture is particularly difficult when using highly cohesive and fibrous binders such as PTFE. Moreover, the precise dosing of the electrode mixture into the calender roll gap and the subsequent compaction of the powder into a stable electrode film require careful process control to ensure uniformity across the electrode’s width, length, and thickness, reliable adhesion to the current collector, and an optimal pore structure within the electrode.

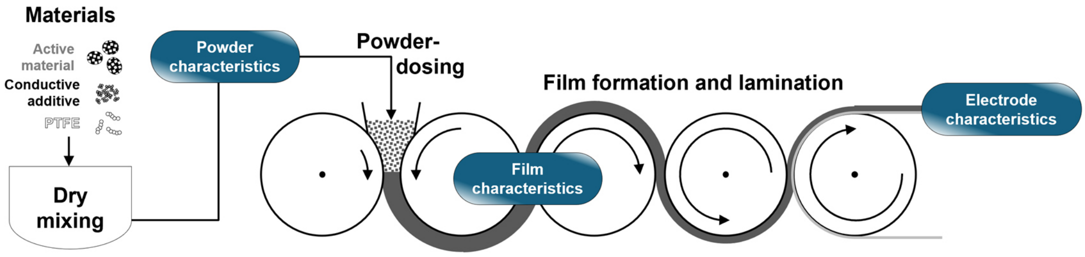

Figure 1: General process chain of calender-gap-based dry coating (created by M. Nickl)

The process investigated in the *ProLiT* project employs PTFE as a binder to achieve a homogeneous distribution and a stable network in the electrode mixture through fibrillation. A multi-roll calender (>8 rolls) was used to produce the cathodes for multilayer cells, combining film formation and lamination onto the current collector foil. Another special feature of the *ProLiT* project is the newly developed dosing technology, which continuously and controllably feeds the electrode mixture into the calender gap.

Gigafactories

The following considerations are based on a production line size with an annual capacity of 1 GWh. The question was raised regarding the quantities of material that would need to be processed for this capacity and the machine sizes available to the industrial project partners for this purpose. Two key challenges arise when selecting the machine technology: On the one hand, there are significant size gaps among the available machines, with certain models capable of achieving throughputs many times higher than the capacity required for 1 GWh. However, the next smaller model would either be too small to meet the required throughput or, operating at nearly full utilization, would run too close to its maximum performance limit. On the other hand, individual machine concepts are limited by their maximum performance, meaning that higher throughputs cannot always be achieved even with larger machines. In such cases, it becomes necessary to operate several machines of the largest available size in parallel.

One possible approach is to design individual production lines with defined performance, where one machine is installed for each process step. The machine with the lowest performance determines the overall output of the line. This concept offers a high degree of flexibility for scaling and expansion, as the desired plant capacity can be more easily adjusted by operating multiple lines in parallel. However, this approach may result in high space requirements and increased investment costs, particularly for very large capacities. Alternatively, economically optimized machine sizes can be implemented for the individual process steps, allowing the number of parallel machines per step to vary. This, however, requires careful planning of material flows and a well-designed plant logistics system.

The findings obtained from a 1 GWh production line can generally be transferred to larger production units, such as 10 GWh. This requires a detailed understanding of the necessary throughput capacities (e.g., in kg/h or m/min), as well as the corresponding cell formats and machine parameters. Based on this information, the overall production capacity can then be scaled accordingly by multiplication.

Cell format & properties

for an annual plant output of 1 GWh

Cell properties and formats

For the basic considerations, two NMC-based cell formats were selected: a 4695-round cell with approx. 30 Ah, a diameter of 46 mm, and a height of 95 mm, as well as a pouch cell with approx. 90 Ah (350×100×68 mm). These are shown schematically in Figure 2.

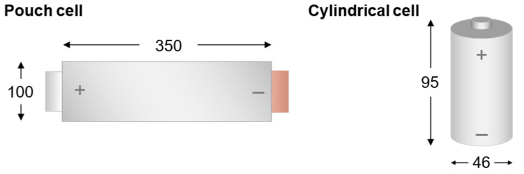

Figure 2: Cell formats of pouch cell and cylindrical cell

As part of the project, both NMC and LFP cathodes were investigated, while graphite anodes were only considered to a limited extent. The reference formulations for the cathodes are shown in Table 1 below.

Table 1: Cathode formulations

Cathode	Active material / %	Carbon Black / %	Binder (PTFE) / %
NMC	97	1.5	1.5
LFP	97	1.5	1.5

Plant throughput for an annual production of 1 GWh

To calculate the required throughput capacities of the plant, the electrode and cell parameters listed in Table 2 were defined as boundary conditions. A uniform areal capacity of approximately 4 mAh/cm^2 was specified to enable a comparable evaluation of the NMC and LFP cathodes. Due to the differing specific capacities of NMC and LFP, variations in electrode thickness are unavoidable.

Table 2: Properties of NMC and LFP cathodes

Parameter	Unit	Active material	
		NMC	LFP
Specific capacity	mAh/g	~200	~150
Areal capacity	$\text{mAh}_{\text{AM}}/\text{cm}^2$	~4	~4
Mass loading	$\text{mg}_{\text{AM}}/\text{cm}^2$	~23	~28
Voltage	V	3.8	3.3
Density	g/cm^3	~3.2	~1.9
Thickness	µm	~73	~150

For an annual production capacity of 1 GWh, assuming 350 operating days per year and continuous 24/7 operation, the resulting material consumption and throughput are shown in Table 3.

Table 3: Material consumption and throughput for 1 GWh/a production of NMC and LFP cathodes

Parameter	Unit	Active material	Carbon Black	Binder (PTFE)
NMC cathode				
Material consumption	t/a	~1300	~20	~20
Throughput	kg/h	~160	~2.5	~2.5
LFP cathode				
Material consumption	t/a	~1800	~30	~30
Throughput	kg/h	~220	~3.5	~3.5

The proportion of recycled material generated during film formation in the multi-roll calender, such as separated edge strips, can be reintroduced into the active material-carbon black mixture together with fresh PTFE during the mixing process. For the cell formats used in the *ProLiT* project, pouch cells account for an estimated 5.7 % of the recycled material, while round cells contribute around 8 %. Additional losses occur during calender start-up and shutdown, estimated at approximately 5 %, as well as from coarse material collected by the protective sieve between the buffer container and the dosing unit. This results in a potential maximum recycling rate of up to 15 %, corresponding to an increase in material throughput in the mixer from 160 kg/h to 189 kg/h, using NMC as an example.

However, dust emissions captured by filters at the dosing unit, mixer, or calender are not recycled, as their composition is uncertain and they likely contain mainly fine particles such as carbon. This material is therefore discarded. Based on positive operational experience, it is assumed that almost all other material is successfully utilized, thereby improving overall process efficiency.

Figure 3: Process equipment and automation technology in a modern industrial battery materials production environment at a gigafactory site. Image provided by Maschinenfabrik Gustav Eirich GmbH & Co. KG.

Plant concept

The following plant design is based on the findings of the *ProLiT* project and the defined boundary conditions. It includes the integration of either a twin-screw extruder or a batch mixer (here: *Eirich* mixer). The concept is supplemented by the necessary peripheral systems for the storage and dosing of raw materials, as well as recycled material. Furthermore, the transport, intermediate storage, and dosing of the fibrillated mixture for subsequent processing in a multi-roll calender are considered. Figure 3 provides a schematic representation of the plant concept.

The plant concept is described in detail below and essentially consists of the following components:

1. **Raw material handling:** Raw material feeding for input materials and recycled material with intermediate silos.
2. **Solid material dosing** into a mixing system.
3. **Mixing system** (extruder or batch mixer (here: *Eirich* mixer)) **and functionalization of the powder mixture** taking place there.
4. **Material transfer to intermediate silos** with protective sieving at the discharge on the material feeding/ powder dosing side.
5. **Powder dosing into the calender gap** across the required roll gap width.
6. **Film formation in the multi-roll calender.**
7. **Return/recycling of edge trims** from the calender and coarse material from the protective sieving back into the mixing process.
8. Finished double-sided coated electrode.

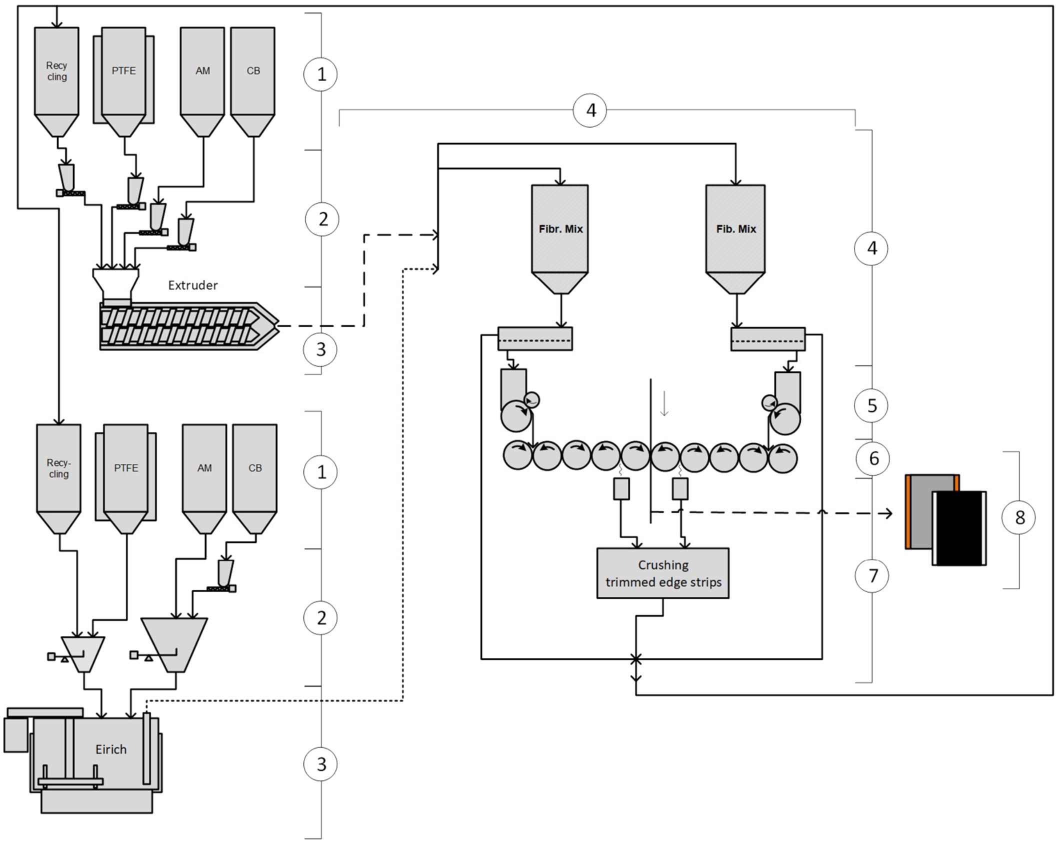

Figure 4: Plant concepts for extruders and batch mixers (here: Eirich mixer) for the dry coating process developed in the ProLiT project (created by S. Gerl).

1. RAW MATERIAL HANDLING

ACTIVE MATERIAL – NMC and LFP

The powdered active material (AM) is typically supplied in large containers (big bags) with welded aluminum liners and a capacity of around 500 kg. Emptying is performed manually at big bag stations into level-monitored buffer silos with a capacity of at least 1.5 times that of a big bag.

Industrially relevant NMC cathode materials with high nickel content, particularly NMC811 and above, are highly sensitive to moisture. To prevent premature aging during storage and processing, it is therefore crucial to minimize exposure to ambient humidity as much as possible.

As an alternative to a dry room, a controlled microenvironment could offer a more energy-efficient and cost-effective solution. Due to the carcinogenic properties of NMC, containment at the feeding station (OEB3/OEB4) should be ensured, for example through dust-tight docking combined with additional enclosure, such as a glove box.

Unlike NMC cathode materials, LFP cathode materials do not exhibit significant capacity loss due to temperature or humidity influences. Consequently, neither noticeable degradation nor premature aging is expected upon contact with ambient air. However, LFP is hygroscopic, which can cause cohesive behaviour during handling, potentially affecting downstream processing and requiring the material to be dried again. In addition, LFP is sensitive to UV radiation and is therefore stored in big bags with aluminum liners that provide effective protection against light exposure. These liners also prevent moisture ingress during storage, avoiding agglomeration that could complicate handling and processing. From both an energy and economic standpoint, a controlled microenvironment may represent a practical alternative to a conventional dry room for LFP. Nonetheless, it should be carefully evaluated whether such a setup is truly necessary, given the short residence times in the buffer silo and the rapid processing throughput. Since LFP is not classified as a hazardous material, the big bag station can be designed far more simply than for NMC, reducing safety requirements and enabling easier handling during emptying and dosing.

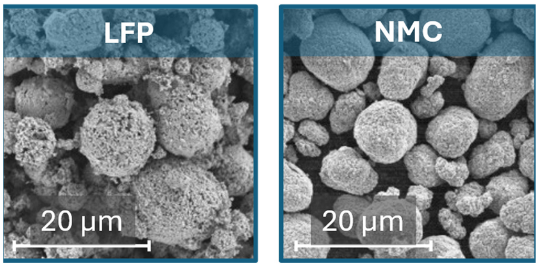

Figure 5: SEM images of polycrystalline LFP and NMC raw materials.

CONDUCTIVE ADDITIVE – Carbon Black

Due to its low bulk density of 30 to 60 g/L, carbon black is supplied in vacuum-packed paper bags containing 5 to 10 kg. Owing to its high specific surface area (50–2000 m^2/g), carbon black readily absorbs moisture from the ambient air. It is therefore advisable to use a controlled microenvironment both during bag emptying and while storing the material in the buffer silo to minimize exposure to air humidity and preserve its material properties. Because of the low bulk density (0.08-0.16 g/cm^3) and the corresponding dosing volume, the refill cycles must be carefully considered.

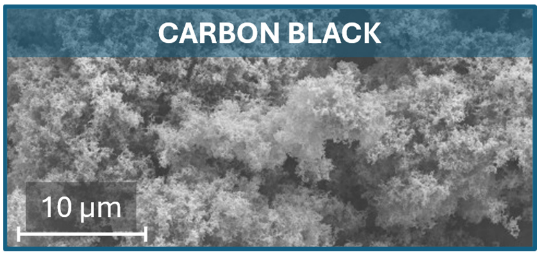

Figure 6: SEM images of a type of Carbon Black

In conventional industrial electrode production based on wet film coating, carbon fibers such as carbon nanotubes (CNTs) or carbon nanofibers (CNFs) are increasingly used to enhance the electrical conductivity of electrodes and thereby improve their performance. However, due to their biopersistent nature, handling CNTs and CNFs requires strict safety precautions, and they were therefore not used in the *ProLiT* project.

BINDER – PTFE

PTFE is supplied as a coarse powder, typically in 25 kg drums that, unlike PVDF containers, do not include an inner plastic liner. As a result, the material cannot be removed directly and must either be scooped out at a bag-filling station or processed using specialized drum-emptying equipment. Larger containers, such as 100 kg drums, are unsuitable for handling PTFE, as the material can become heavily compacted at the bottom due to its own weight and high ductility. No special precautions regarding humidity are necessary, since PTFE is not hygroscopic. The material can therefore be handled openly at a feeding station equipped with an inlet flap. However, during material transfer, there is a risk of electrostatic charging, which requires appropriate safety measures. These include grounded feeding stations and antistatic tools to ensure safe operation.

The properties and handling of PTFE are highly temperature-dependent. Temperatures above approximately 20 °C can already cause fibrillation of the PTFE raw material during the dosing process. The resulting agglomerates of compacted

PTFE can negatively affect both the mixing process and subsequent film formation. Therefore, the cooling chain should remain uninterrupted during storage and transport, maintaining temperatures below 20 °C to prevent material alteration. For raw material dosing, material temperatures between 0 °C and 10 °C have proven effective. Since PTFE has low thermal conductivity, containers must be stored under cooled conditions for a sufficient period after transport to ensure the material is fully chilled.

The simplest solution is to provide a cooled room for storage, material feeding, the buffer silo, and the dosing unit. Since agglomeration of PTFE can occur, sieving or dispersion is required when transferring the material into the silo. To prevent unwanted compaction during transport and storage in drums of the PTFE, and thus potential discharge issues in the buffer silo, the silo capacity should be limited to the equivalent of one or two container volumes. For material discharge, vibration feeders are preferred over screw feeders, as they enable gentle dosing of the material and help prevent clumping.

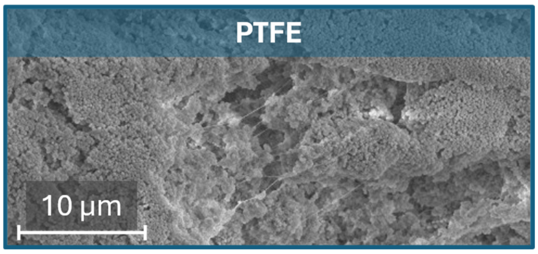

Figure 7: SEM images of a type of PTFE

2. SOLID DOSING INTO A MIXING SYSTEM

In a continuously operating **extruder**, the individual formulation components are simultaneously fed into the mixing process through dedicated dosing points. It is crucial to use highly precise feeders with minimal time-dependent fluctuations in the individual solid mass flows to maintain the formulation reliably within the specified tolerances. State-of-the-art systems use gravimetric dosing technology, continuously measuring the weight loss of the feed hopper, which calculates and controls the mass flow based on this data. In a **batch mixer** (in this case, an *Eirich* mixer), the raw materials are weighed in dosing containers according to the formulation and subsequently fed into the mixer. Since the formulation is weighed on a batch basis, fluctuations in mass flow during the dosing process are irrelevant. The formulation accuracy depends solely on the total dosed quantity, not on a constant discharge rate. This reduces the demands on dosing control and makes it easier to verify formulation accuracy. Additionally, the dosing process for the next batch can begin while the current batch is still being mixed, significantly reducing mixer filling times.

3. MIXING SYSTEMS AND FUNCTIONALIZATION OF THE POWDER MIXTURE

The main objective of the mixing process is to achieve a homogeneous distribution of the electrode components, to adequately disperse the highly agglomerated conductive additives (typically conductive carbon black and, increasingly, CNTs), and to optimally fibrillate the PTFE binder for the subsequent dry coating process.

EXTRUDER

The extruder is a highly flexible mixing system that can be configured for various formulations and operating modes. In the current plant concept, each component of the formulation is assigned its own dosing unit, allowing either the collective feeding of reactants through a central hopper or controlled feeding at different positions along the extruder. Additionally, premixes can be prepared and introduced in the desired ratios. The adjustable dosing points, flexible screw configuration, and precise temperature control of individual extruder sections enable the process to be optimally tailored to the specific requirements of dry coating.

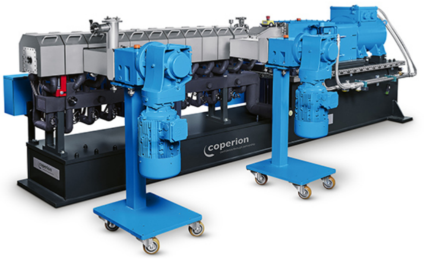

Figure 8: Twin-screw extruder from Coperion GmbH

At the beginning of the processing section in the extruder, dispersion of the raw materials, particularly the conductive additive and PTFE, takes place. PTFE fibrillation occurs in the middle section of the process at elevated temperature and shear. Within the extruder, PTFE fibrillation is achieved by selecting a suitable screw configuration and adjusting the process parameters (e.g., rotational speed and temperature). In the last third of the processing section, the product is cooled, and the resulting agglomerate size is reduced using appropriate screw elements (e.g., toothed mixing elements). If the reduction of the resulting macroscopic agglomerates of the fibrillated powder mixture is not sufficient for the subsequent process steps (dosing and film formation), further agglomerate size reduction can be carried out in a mill or mixer. Any local wear on screw elements or within the housing caused by shear stress and abrasive products can be minimized by using suitable materials of construction.

Since, unlike suspension preparation for wet-processed electrodes, no inline or online measurement methods for quality control currently exist for mixtures used in dry-processed electrodes, material-specific limits for dosing fluctuations must be defined. If these limits are exceeded, the affected product must be removed from the process.

For application in a 1 GWh-scale facility, a 58 mm extruder can be employed. According to the manufacturer's specifications, this extruder is capable of achieving the required throughput of 165 kg/h or higher.

BATCH MIXER

In batch operation, for example using an *Eirich* mixer, the PTFE binder can be added to the mixer together with the active material and conductive additives for processing. However, a two-stage mixing process has proven to be more effective, in which the active material and conductive additives, particularly the conductive carbon black, are first dispersed before the PTFE is introduced. The two-stage mixing process developed within the *ProLiT* project is described in greater detail in the section "research results".

Since the material temperature typically rises during mixing, the batch mixer should be equipped with a cooling system to lower the temperature after fibrillation, break up agglomerates, and cool the mixture to below 35 °C during processing. The final temperature at the end of the mixing process should ideally be between 30 °C and 35 °C, as higher temperatures may cause undesirable phase transitions in the PTFE.

The impact forces of the particles on the tools and container can cause significant wear, particularly at high circumferential speeds of the mixing tool. In contrast to batch mixers with stationary containers, container wear is relatively low. The mixing tool itself, which is exposed to high mechanical stress, is designed with high wear resistance to minimize metal abrasion.

For use in a 1 GWh plant, a 500 L mixer would be employed, which, when filled with 500 to 600 kg of NMC mixture, would provide an available cycle time of up to 3 to 3.5 hours at a required mixing capacity of 165 kg/h. In practice, the batch time is approximately 60 to 90 min due to extended cooling times, resulting from the reduced heat exchange surface area compared to smaller laboratory or pilot units. This corresponds to a potential throughput of about 2.5 to 3.5 GWh per machine. The maintenance intervals for replacing wear parts on the mixing tool are estimated at 3 to 6 months.

Figure 9: Eirich mixer from Maschinenfabrik Gustav Eirich GmbH & Co. KG

4. MATERIAL TRANSFER TO MATERIAL FEEDING SIDES/POWDER DOSING

At the end of the mixing process, the prepared mixture is transferred to the application or dosing unit of the multi-roll calender, preferably by pneumatic conveying. Since the application and dosing units specified in the plant concept (see Figure 4) at both ends of the calender have only very small storage capacities, regular refilling is required to ensure a continuous and uninterrupted material flow into the calender gap. The mixture produced continuously in the extruder or in larger batches using batch mixers is temporally stored in a buffer-hopper which decouples the upstream and downstream processes. In the case of feeding from a batch mixer, the buffer silo must be capable of holding at least half of one batch volume, as the calender features two material infeed points for coating both sides of the battery electrode, with one batch distributed between the two ends. For an extruder, the buffer silo can be designed smaller. However, the larger the silo, the more the pre-fibrillated mixture tends to form agglomerates under its own weight. Discharge aids, such as agitators or fluidization systems, can be employed to ensure reliable material flow from the silo. At the silo outlet or during feeding into the dosing unit, larger agglomerates must be strictly avoided, as they can negatively impact dosing accuracy increase calender roll wear. Therefore, the agglomerate size should preferably remain below 500 µm and must not exceed 1000 µm. To achieve this, the installation of a protective screening system between the silo and dosing unit is recommended for both mixing methods (extruder and batch mixer).

5. POWDER DOSING INTO THE CALENDER GAP

The requirements for dosing the fibrillated mixture into the calender roll gap are demanding. On the one hand, the pre-fibrillated material from the mixer is often not free-flowing and must be processed carefully due to its tendency to agglomerate. On the other hand, the material must be distributed evenly across the roll width and with a constant fill level, as variations in the fill level within the calender gap influence the coating quality (film thickness and surface weight). This highlights the importance of dosing accuracy, which must be closely coordinated between the electrode manufacturer and the equipment suppliers for the calender and dosing system.

As this specific combination of requirements could not be met by the standard product range of *Coperion K-Tron*, a new dosing concept was developed as part of the *ProLiT* project.

The resulting roller feeder (see Figure 10) features two synchronized rollers rotating in the same direction. The dosing roller contains cavities, and its rotation discharges the pre-fibrillated material. The second, smaller roller scrapes excess material from the cavity tops, preventing compacted material from entering the discharge gap and minimizing compression of the pressure-sensitive material. The roller feeder is mounted on a scale that continuously measures the weight loss, allowing rapid mass flow corrections through speed adjustments.

Accurate and continuous feeding enables a minimized material bed within the calender gap. As a result, thinner films can already be produced after the first calender pass, and the final film thickness can partly be achieved with fewer calendering steps. For fill-level control, the height of the material bed in the calender gap can be measured and kept constant via a secondary feedback loop. The dosing concept (in both width and throughput) is suitable for both pouch and cylindrical cells, as a uniform material distribution across the entire gap width is required in both cases, with trimming occurring only after film formation.

Within the project, combined operation of the roller feeder and calender achieved accuracies better than 0.5 to 1 % at a dosing rate of 20 kg/h. This applies to both the dosing rate of the roller feeder and the variation in film thickness across the film width and length. The feed hopper should be designed as small as possible to ensure precise gravimetric control while maintaining a reasonable number of refill cycles. Refilling is performed using either a vibratory or screw feeder, depending on the material properties. For materials that are difficult to dose, a screw feeder is preferred but should be configured to convey the powder as loosely and with as little pressure as possible to prevent agglomeration. A refill time of only a few seconds is desirable, and the pre-dosing system should be dimensioned accordingly.

The *Coperion K-Tron* roller feeder can be completely emptied by opening the calender feed gap, allowing the material to fall downward, where it is extracted and recirculated below the rollers.

When using PTFE binders, the material temperature must be kept below 30 °C before dosing to prevent changes in the PTFE structure, which would otherwise increase the cohesiveness of the mixture. It has also been shown that cooler material can be metered more accurately, while warmer material is better suited for higher calendering speeds. Therefore, it may be beneficial to warm the material slightly using infrared emitters as it falls between the feeder and the calender. In general, the drop height of the powder or granulate should be kept as low as possible.

Figure 10: Roller feeder from Coperion K-Tron

6. FILM FORMATION IN A MULTI-ROLL CALENDER

A multi-roll calender can be operated flexibly and, in the present concept, enables double-sided electrode coating for use in battery cells. Material feeding takes place at the first and last roll gaps, allowing the film processed through multiple calender gaps to be laminated onto a current collector foil coated with carbon in the center of the calender. A multi-stage compaction process for the production of single-sided coated electrodes is also possible. In the *ProLiT* project, a four-roll calender was initially used. However, it was found that a single “powder-to-film” step was not sufficient to achieve coating thicknesses below 100 µm for high-performance battery cathodes. Therefore, for the production of multilayer cells, a multi-roll calender with more than eight rolls from *Saueressig/Matthews Engineering* was employed.

In the first calendering step, the loose powder at approx. 30 °C is processed under shear and friction (caused by different roll speeds) into a film that adheres to the faster rotating roll heated to around 100 °C. The shear induced within the calender gap further fibrillates the pre-fibrillated PTFE in the powder (batch mixer) or granulate (extruder), creating particle interlinking and film formation. The resulting film is subsequently passed through additional roll gaps, where further shearing reduces film thickness and surface weight. During the compaction of the powder and thinning of existing films, frayed edges of less compacted material may form; these must be trimmed off, as they can cause instabilities in the subsequent roll gaps.

Before film lamination onto the carbon-coated current collector foil, performed between a pair of rolls rotating at the same speed, further film processing steps such as edge trimming or cutting continuous films into strips may be required to achieve the desired cell format. Figure 2 shows the cell formats used in the *ProLiT* project, while Figure 11 schematically illustrates the configuration of their cathodes.

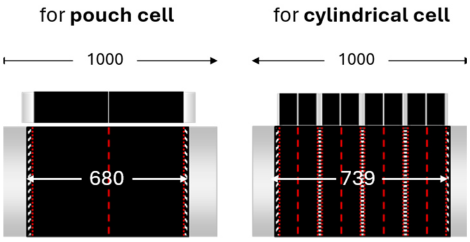

Figure 11: Cutting of the cathode film for pouch cells and cylindrical cells

For pouch cells, coating widths of 330 mm per cathode are achieved. Using a 1000 mm roll, a continuous web with a 660 mm coating width can be produced and then split in the center to yield two electrode webs for pouch cells. For 4695 cylindrical cells, narrower coating widths of approximately 85 mm per electrode are required. With a 1000 mm roll width, four parallel webs of about 170 mm each can be produced simultaneously and subsequently divided, enabling the production of eight electrode webs for cylindrical cells in a single coating pass. The entire roll width can either be coated, removing the edge later from uncoated foil, or pre-trimmed before coating. The edge cuttings are removed by special suction units and recycled into the mixing process to minimize material losses. Simultaneous lamination of both electrode sides is preferred, as sequential lamination is technically more demanding and can compromise coating symmetry. Since each material variation or new formulation requires individual process adjustments, calender setup and optimization are essential.

Regarding maintenance, it has been observed that NMC mixtures are particularly hard and abrasive, resulting in maintenance and roll replacement intervals of approximately six months. Higher line loads further reduce operational lifetime. Chrome-plated rolls can help minimize abrasion issues, whereas spray-coated rolls are problematic due to their porous structure, which can cause material adhesion and local compaction.

For production scale-up, the use of multiple calenders is preferred over increasing roll width beyond one meter. Larger roll diameters would allow higher line loads and thus higher throughput but would also increase investment and maintenance costs.

For an annual output of 1 GWh, a dry coating speed of 17 to 21 m/min is sufficient, though coating speeds of up to 50 m/min at 100 °C and above are feasible. The facility layout ideally requires a tall room design with sufficient clearance above the calender to accommodate unwinding and rewinding stations for the current collector foil, powder dosing units, protective sieving, and collection or intermediate silos for the electrode mixture, factors that make integration into existing buildings more challenging.

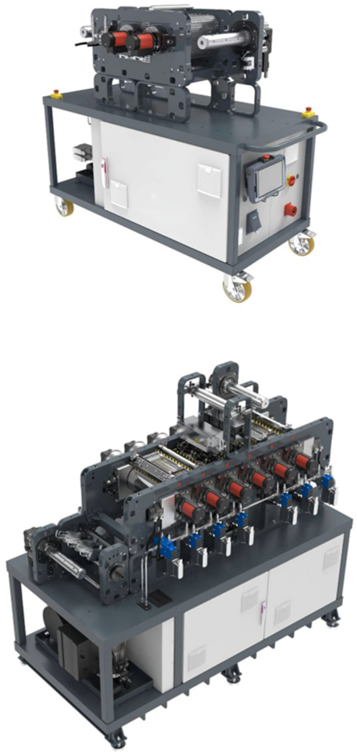

Figure 12: Two- and six-roll calender systems from Saueressig/ Matthews Engineering

7. RECIRCULATION OF THE CUTTINGS

The *ProLiT* project did not include an investigation of the process step for returning edge trimmings or recyclate. However, the following considerations for a holistic plant concept are based on findings obtained from the project and on results evaluated in parallel by partner institutions and companies as part of other research activities. In the present plant concept, edge trimmings and central cuttings of free-standing films generated during the film formation process are extracted. This material is not directly re-calendered but is first homogenized with fresh material in batch mixing systems, such as the *Eirich* mixer. The direct addition of recyclate during PTFE incorporation is particularly effective, as it ensures uniform distribution within the mixture. In extrusion processes, the addition of recyclate to the active material is also feasible; however, extruders are generally less suitable for dispersing free-standing films or recyclate due to their lower tool speeds compared to batch mixers.

Quality control

(in-line / on-line)

Ensuring consistently high product quality requires the targeted implementation of suitable inline or online monitoring methods throughout the entire electrode production process.

a. Coatability of powder mixture

There is currently no direct measurement method available for determining the coatability of fibrillated powders or granulates. Likewise, no inline measurement systems specifically developed for dry coating processes are available for quality assurance purposes. In practice, torque and power curves of mixers and extruders recorded during the mixing process have been used as indirect quality indicators, as they provide insights into the intensity and progress of fibrillation and mixing. In connection with the *Eirich* mixing process, an inline measurement method based on the mixing tool can be employed. To determine the proportion of plastic deformation in the composite from rheological data and to derive conclusions about the processability and fibrillation progress of the binder, a specific measurement sequence can be performed in the mixer. In this sequence, torque is recorded at defined tool speeds, and a flow curve is derived from these data.

The lack of standardization in the dry coating process makes it considerably more difficult to develop and select suitable measurement methods. Nevertheless, the analyses described here and those mentioned in the next section enable targeted monitoring of powder and electrode properties in order to ensure consistently high product quality in continuous processes and to identify potential problems at an early stage.

b. Dry-coated electrode

As with wet coating, the current collector foil can be inspected for surface irregularities prior to lamination, and QR codes can be laser-marked onto the foil to identify defective or accepted electrodes. Measuring instruments designed to determine the areal mass across the electrode width (after lamination), as well as optical measurement systems developed for the quality control of wet-coated electrodes, should also be suitable for use with dry-coated electrodes after appropriate adaptation.

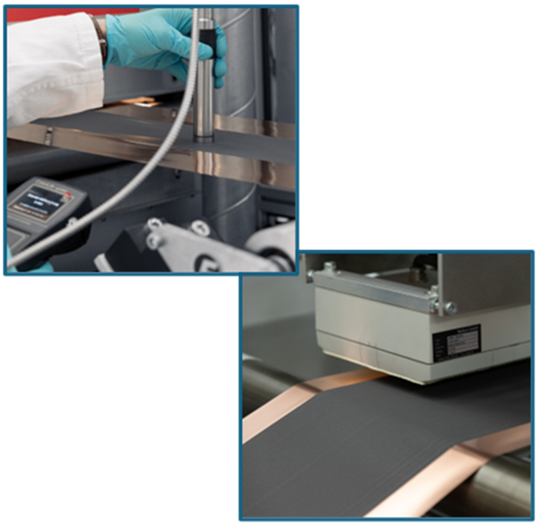

Figure 13: Symbolic images of quality control during electrode production (photos by Marek Kruszewski/TU Braunschweig)

Industry relevant research results

The following section summarizes the key findings of the *ProLiT* project that are particularly relevant to the industrial implementation of the described dry coating process.

I. Materials & powder characterization methods

Similar to established practice in the wet coating of battery electrodes, setting up separate production lines for anodes and cathodes is also recommended for the industrial implementation of dry coating processes. This approach prevents cross-contamination between different types of active materials and eliminates time-consuming setup procedures when switching the current collector foil from copper (anode) to aluminum (cathode).

PTFE exhibits unique properties **as a binder** that significantly influence its fibrillation behavior and, consequently, the resulting electrode characteristics. This material has long been used in calender-slot-based dry coating processes for battery electrodes. The fibrillation of PTFE is temperature-dependent and occurs through the application of shear forces, during which the initially agglomerated PTFE particles are transformed into long fibrils. These fibrils form a three-dimensional network connecting the active material particles and the conductive additive. The use of PTFE enables a reduction of binder content in dry coating to approximately 0.5-2%, compared to wet coating, which typically requires 1-5% PVDF binder on the cathode side. This reduction of inactive material contributes to an increase in the energy density of battery electrodes.

The **different active materials** require material-specific adjustments to the process parameters and formulations, as their particle size, density, and morphology as well as flowability, and interactions with the conductive additive and PTFE binder differ fundamentally [4,5]. A study [4] conducted within the framework of the *ProLiT* project showed that the platelet-shaped structure of graphite significantly slows down PTFE fibrillation during the batch mixing process compared to spherical, highly porous LFP. Due to its high fine-particle content and more porous surface structure, the LFP used in the project exhibits a prolonged PTFE fibrillation time, whereas spherical NMC, with its higher particle density and more efficient compaction characteristics, leads to accelerated PTFE fibrillation during mixing. These material-specific differences necessitate precise coordination of mixing time and intensity as critical process parameters. A further study shows that insufficient mixing time results in incomplete fibrillation and uneven material distribution, whereas excessively long mixing times can cause fragmentation of the active material particles. For both process control and electrochemical performance, similar to wet coating, the stability of the active material under shear stress during mixing and film formation is crucial. Damage to the active material caused by high shear forces at elevated mixing intensities leads to the formation of fine particles within the mixture. This affects the fibrillation behavior and homogeneity of the compound and may induce undesirable side effects during cell cycling due to the increased specific surface area. Another *ProLiT* study has demonstrated [6] that larger active-material particles of the same type transfer more intense shear forces to the PTFE, promoting increased fibrillation and resulting in improved network formation and optimized properties of the electrode film.

The choice of **conductive additive** also affects PTFE fibrillation. A *ProLiT* study demonstrated that, at the same PTFE content, conductive carbon black with lower bulk density, higher specific surface area, and higher oil absorption exhibits more favorable processing characteristics and results in superior electrochemical performance due to more advantageous electrode structures. This improvement can be attributed to the enhanced dispersibility of the carbon black within the mixture, which allows the fabrication of homogeneous, thick electrode films without binder migration issues commonly observed in thick, wet-coated electrodes.

Essential for an efficient and successful calender gap-based dry coating process is the **identification of process-structure-property relationships** that enable

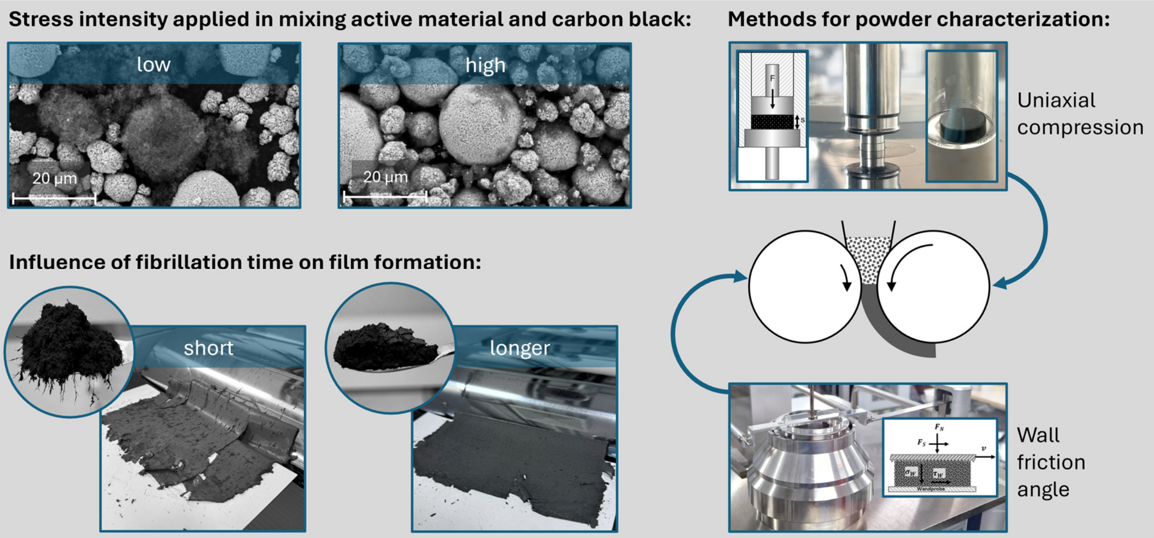

Figure 14: Selection of key findings: effect of the intensity of premixing active material and carbon black as well as fibrillation time on microstructure and film quality of NMC cathodes. Also shown are exemplary methods for powder characterization, such as uniaxial compression and wall friction angle (created by M. Nickl)

the prediction of how powder properties influence subsequent film formation in the calender nip. This requires **powder characterization methods** that can ideally be applied in-line or on-line during production. Although, as previously noted in the "Quality Control" chapter, quantifiable methods remain limited, the *ProLiT* project has identified several promising measurement techniques that allow correlations between powder properties and those of the resulting film or electrode. Uniaxial compression measurement proved particularly valuable, as it enables direct correlations with film and electrode porosities [4]. The resulting compression stresses revealed material-specific differences. An NMC-based powder mixture requires higher compaction stresses to achieve the same compression depth and, under identical calendering conditions, produces thicker films than a graphite-based mixture, which can be compressed to the same thickness even at lower compaction stresses. Additionally, ring shear cell measurements were conducted to determine the wall friction angle on samples of the calender surface materials, which directly correlate with the film thicknesses observed during the initial film formation process (powder to film) [4]. The measurements revealed that graphite forms thinner films due to its lower wall friction angle, whereas NMC tends to produce thicker films during initial film formation as a result of its higher wall friction angle.

The fibril dimensions and morphology have a significant impact on both the bulk density and the particle size distribution of the mixture. In addition to bulk density measurements, dry laser diffraction analysis (measurement range: 0.1 to 3.5 mm) can serve as a qualitative method for assessing the progress of PTFE fibrillation [4], but it does not permit quantitative evaluation of the exact fibril size, as the technique is calibrated for spherical particles. However, it can also serve as a useful indicator for evaluating the stability of the agglomerates formed. The PTFE fibrils produced in the batch mixing process often exhibit a high length-to-diameter ratio. Dry measurement using dynamic image analysis (measurement range: 1 to 34 mm) is suitable for determining this ratio. Owing to the granule sizes of 0.1 to 4 mm typical of extruder processes, the laser diffraction method is unsuitable, whereas dynamic image analysis and sieve analysis are appropriate measurement techniques. Nevertheless, sieve analysis poses challenges for fine powder mixtures from batch mixers, as the loose, elongated polymer fibrils tend to become entangled and form uncontrolled agglomerates due to vibrations during sieving.

Based on the measured powder properties, the mixing and calendering processes must be adapted or optimized for each active material in order to achieve the best possible electrode properties.

II. Machinery & process conditions

The investigations conducted within the *ProLiT* project focus on three key process steps: the mixing process for structuring the powder mixtures, the metered material feed, and film formation through multi-roll calendering. The process chain was examined using both a batch mixer (*Eirich* mixer) and an extruder process.

The **batch mixing process** developed in the *ProLiT* project for specific active materials and formulations using the *Eirich* mixer follows a structured two-stage process approach [4]. First, the active material and conductive additive are premixed at high speed until a temperature exceeding 70 °C is reached, depending on the active material and the filling degree. Complete, finely dispersed carbon black coverage of active material is not essential, as PTFE adsorbs and desorbs fine particles (<1 µm) via Van der Waals forces during fibrillation and can subsequently release finer

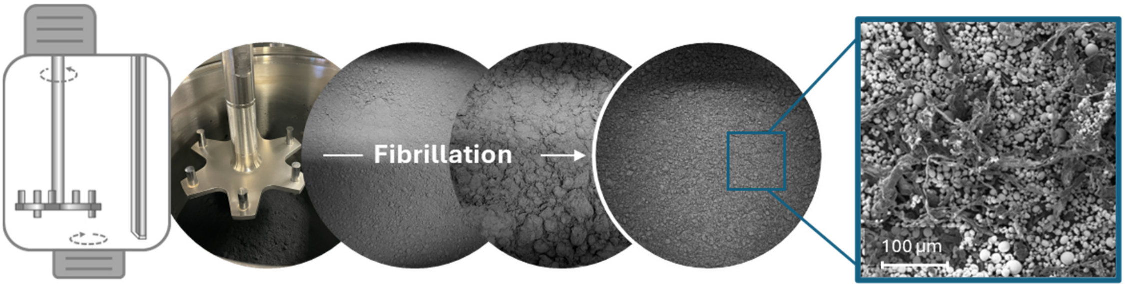

Figure 15: Schematic of a batch mixing process in a 5-liter Eirich mixer with resulting fibril morphology (created by M. Nickl)

fibrils either during mixing or later during calendering. Achieving sufficient dispersion of the carbon black agglomerates is critical: inadequate peripheral speeds result in inhomogeneous carbon black distribution, whereas excessive speeds may damage the active material particles. This pre-structuring phase ensures a homogeneous distribution of both components and the formation of an electrically conductive network. The PTFE binder is then added to the heated mixture and uniformly distributed without initiating fibrillation [4]. The actual fibrillation occurs over a short period under high shear, followed by a low-speed cooling phase down to approximately 30 °C. In general, microfibrils are predominantly formed in the batch mixing process due to the combination of high impact stress and lower shear stress (see Figure 15). If the fibrillation time is too short, an insufficient number of fibrils is formed; if it is too long, over-fibrillation occurs, leading to degraded and excessively thin fibrils, which negatively affect film formation properties. A final, very brief grinding step at high speed defines the desired particle size distribution. During scale-up from a 1 L to a 5 L and subsequently to a 50 L *Eirich* mixer (see Figure 16), process-specific adjustments were required, as the increased weight of the powder mixture in larger volumes accelerated the fibrillation and coiling of the PTFE fibrils.

The **extruder process** allows continuous processing under precisely controlled temperature and shear conditions and, due to the higher shear stresses, can also produce nanofibrils (see Figure 17) [7]. Lower temperatures are suitable for the initial material dispersion to prevent premature PTFE fibrillation caused by the high shear stress constantly present in the narrow gap between the extruder screw and the inner wall of the housing. Special screw components, such as toothed mixing elements, are used to achieve optimal material distribution at low stress intensity. PTFE fibrillation then occurs in the extruder at elevated temperatures, typically above 100 °C, through kneading elements that apply the necessary shear stress. The extruder housing is actively heated in this section. The resulting

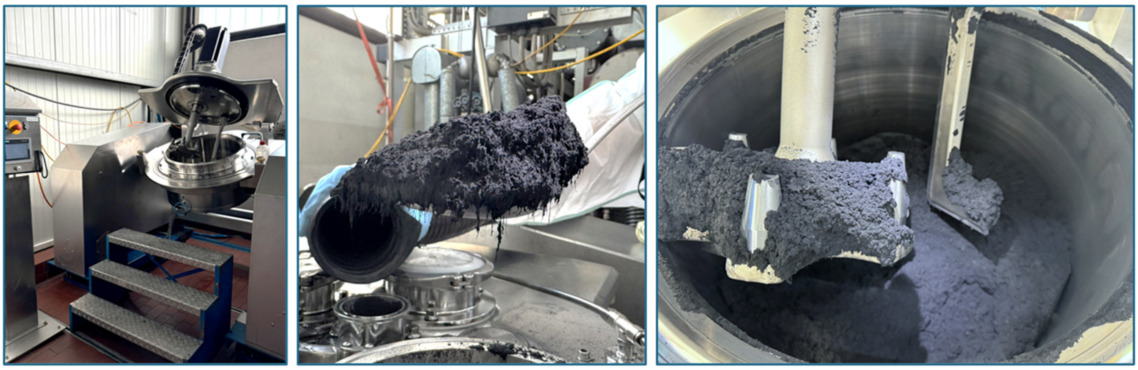

Figure 16: Shown are images taken during the batch mixing process in a 50-liter Eirich mixer at Maschinenfabrik Gustav Eirich GmbH & Co. KG.

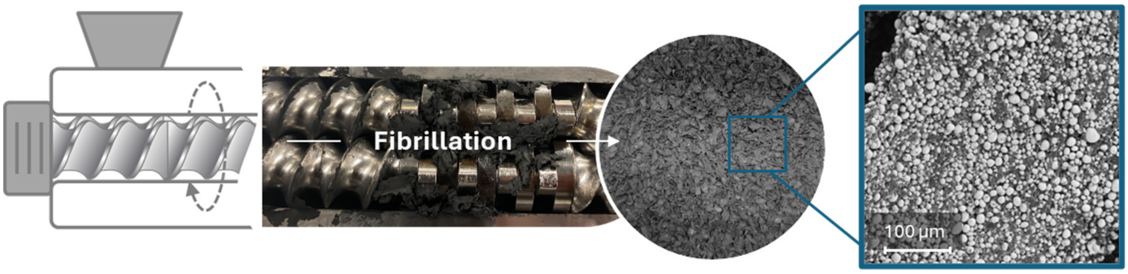

Figure 17: Schematic of a batch mixing process in an extruder with resulting fibril morphology (created by M. Nickl).

kneaded mass enables more efficient energy input than the initial powder mixture but requires precise adjustment of the screw configuration to prevent overfibrillation and material degradation.

Dosing structured powder mixtures into the calender nip requires conveyor systems specifically designed to accommodate the cohesiveness and flow characteristics of PTFE-fibrillated powders or granulates. The objective is to identify a “sweet spot” between sufficient flowability and the required cohesiveness. Powders with inadequate cohesiveness are easy to dose but exhibit insufficient PTFE fibrillation for effective film formation, whereas highly cohesive mixtures show excellent film-forming properties yet are difficult to feed. Due to the cohesive nature of the fibrillated mixtures, ultrasonic or vibration-based dosing systems proved unsuitable for achieving consistent flow uniformity over time and coating width, particularly in LFP-based formulations. In contrast, the roller feeder developed within the *ProLiT* project enables precise and consistent feeding of optimized powders across the entire coating width and throughout the process. The adjustable filling level in the calender gap directly affects the resulting film thickness.

The **film formation in the multi-roll calender** is influenced by various process parameters. increasing the number of rolls and adjusting the differential roll speeds (friction) enable the production of thinner films at higher process speeds. A study investigating the powder-to-film transition revealed that lower fill levels in the calender gap initially produce thinner films with comparable density, emphasizing the importance of precise dosing. Higher roll temperatures lead to PTFE softening and allow for slightly denser but, above all, thinner films. Increased friction (shear) between the roll pairs results in thinner films at constant density. Higher base speeds can also yield thinner films. However, depending on the powder characteristics, highly porous bulk materials may limit the rate of initial film formation, as air displacement-induced turbulence can cause voids within the film.

Due to the strong interactions between material properties and individual formulations, it is not yet possible to establish generally applicable recommendations for process conditions. Instead, material-specific optimization approaches are required.

Figure 18: Images taken during the dosing process with the roller feeder from Coperion K-Tron, as well as during the film formation and lamination process with the ProLiT calender from Saueressig/ Matthews Engineering (created by M. Nickl)

Energy & life cycle assessment

Energy and resource consumption along the process chain for electrode manufacturing (excluding material production) was calculated for an annual production capacity of 1 GWh. The analysis included electricity, compressed air, and cooling water consumption. The process chains for conventional wet coating and dry coating (Dry Battery Electrode, DBE) were compared (see Figure 19).

Model specifications & assumptions

Electrode production accounting was performed for the two active materials NMC622 and LFP. For dry coating, a material formulation with mass fractions NMC or LFP : PTFE : conductive carbon black = 97 : 1.5 : 1.5 wt% was used. In contrast, for wet coating, a conventional formulation with higher binder and conductive carbon black content (94 : 3 : 3 wt%) using PVDF as binder was defined. Anode production and cell assembly were not included in the accounting. The underlying energy quantities and material flows, unless otherwise stated, were derived from existing literature and studies [8–10]. Life cycle assessment (LCA) calculations were carried out in Brightway 2 using Ecoinvent 3.11. Germany was chosen as the production location. The materials used for electrode manufacturing originate from globally organized value chains. Emissions for the German electricity mix were modeled at 0.380 kg CO2-eq/kWh and for natural gas at 0.202 kg CO2-eq/kWh. The recycling of scrap material was considered for NMC and LFP cathodes with a 15% higher energy demand. For wet processing, a lower scrap rate of 5% was assumed, which, however, could not be directly recycled into the process. For the wet route, NMP recovery was assumed at 99% efficiency, with the respective energy demand included in the model. The greenhouse gas emissions considered for electrode materials are NMC (25.9 kg CO_2-eq/kg), LFP (5.4 kg CO_2-eq/kg), PVDF (55.8 kg CO_2-eq/kg), and PTFE (120.4 kg CO_2-eq/kg [11] and 14.44 kg CO_2-eq/kg [12]).

Energy & life cycle assessment

In the following energy balance, unless otherwise specified, specific energies are given as electrical watt-hours per kilogram of coating. Figure 20 illustrates the percentage energy shares of different process steps along the wet and dry process chains for the manufacturing of battery electrodes with NMC as the cathode active material. The planetary mixer serves as the reference for the wet process route, while both process variants are represented for the *Eirich* mixer and the twin-screw extruder.

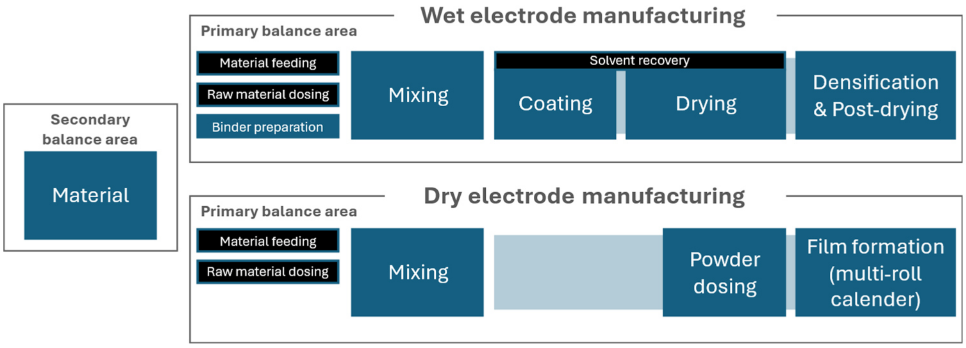

Figure 19: Primary and secondary balance area of wet and dry electrode manufacturing.

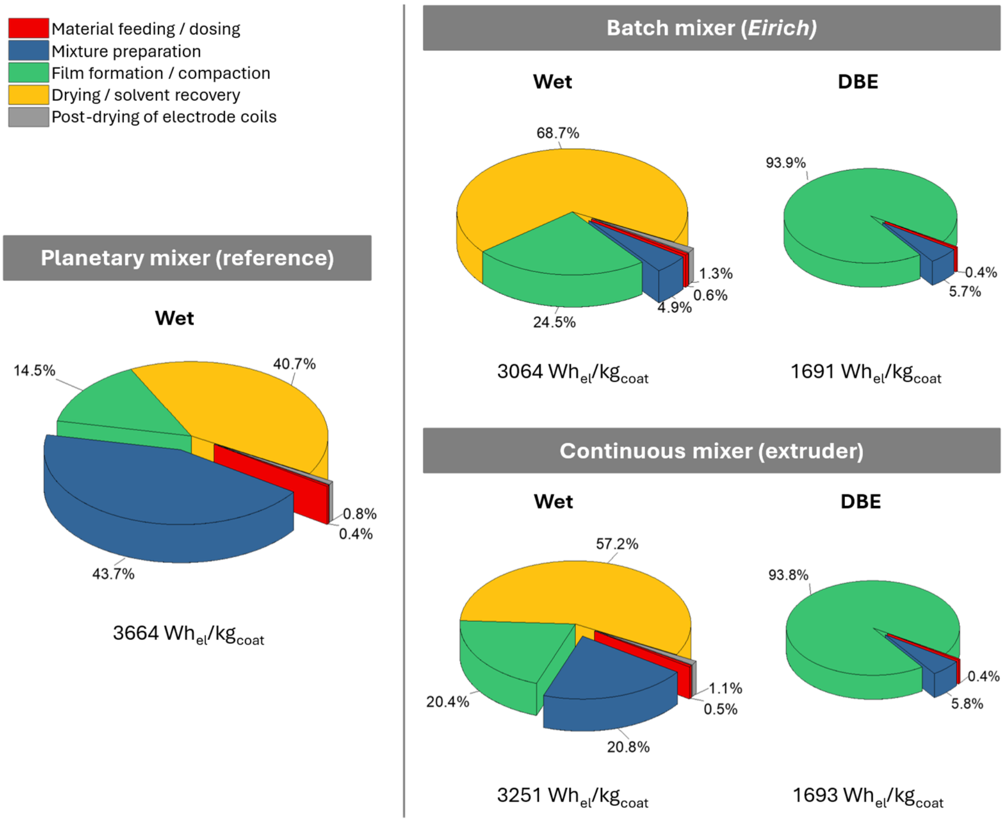

Figure 20: Percentage shares of energy consumption for selected process steps (material feeding/dosing, mixture preparation, film formation/compaction, drying/solvent recovery, and post-drying of rolled goods) along the wet and dry process chains of electrode manufacturing. The planetary mixer is shown as the reference system for the conventional wet process route (for better comparability, thermal energy demand here is converted to electrical equivalents based on a heat pump with a coefficient of performance of three). For the mixing systems Eirich batch mixer and continuous mixer (extruder), both process routes are compared. The specific total energy is expressed as electrical watt-hours per kilogram of coating (Wh$_{el}$/kg$_{coat}$). (LCA by N. von Drachenfels)

In the DBE process, material handling operations such as sack or big bag emptying and dosing require no significant energy input in relation to the overall process. However, since PTFE must be dosed at 8 °C, storage in a cooling silo is necessary. Compared to wet electrode manufacturing, the energy consumption for material handling and dosing is very similar, apart from the additional recycled material.

In the scale-up experiments conducted in batch mode using the *Eirich* mixer, a specific energy demand of approximately 80 Wh/kg was determined, which corresponds to about eight times the energy required for producing a wet mixture in the same mixer. [13]. The extruder consumes approximately 50 Wh/kg for the dry processing (throughput of about 160 kg/h). In direct comparison, the specific energy consumption of the planetary mixer during wet processing is around 250 Wh/kg, clearly highlighting the substantial energy-saving potential of the dry coating process [13].

During the subsequent film formation process, the energy consumption is dominated by the multi-roll calender, which requires approximately 400 kW including climate and cooling systems. Based on a throughput of around 190 kg/h, this corresponds to a specific energy demand of about 1500 Wh/kg. In comparison, the major energy consumers in wet coating are the drying and solvent recovery units. Depending on the plant design and operational strategy, drying alone can account for up to 14 kWh/kg, primarily supplied by gas [8,14–16]. For solvent recovery by distillation, the energy demand amounts to approximately 130 Wh$_{Gas}$/kg [17]. Additional significant contributions arise from the densification step using a two-roll calender (approx. 180 Wh/kg) and from the post-drying required for wet electrodes (approx. 460 Wh_{Gas}/kg)[8,14].

The energy shares shown in Figure 20 indicate that DBE dry coating using the *Eirich* batch mixer reduces the energy demand for cathode production by approximately 45 % compared to the wet processing route. Comparable energy consumption levels and savings potentials are observed when using an extruder. In both DBE process routes, the calender represents the dominant energy consumer due to the high power requirements for pressing pressure and temperature control. Furthermore, the increased active material fraction in the DBE process results in a higher cell energy density, leading to an additional reduction in the specific energy demand per kilowatt-hour of cell capacity by about 2-3 %.

While the energy balance clearly demonstrates significant advantages of the DBE process over conventional approaches, a comprehensive evaluation of the process route also requires consideration of the life cycle assessment (LCA). Figure 21 illustrates the global warming potential of the cathode, differentiated by material and process variant. Table 4 presents the relevant impact categories and the achieved improvements, each normalized to cell capacity and differentiated by cathode active material and process variant for the route using the *Eirich* mixer.

The overall results derived from the life cycle assessment (LCA) clearly demonstrate that the dry coating process causes lower environmental impacts across multiple impact categories compared to conventional wet coating. The global warming potential (see Figure 21) associated with the materials and production of the cathode decreases by 8.5 % to 41.4 kg CO_2-eq per kWh of cell capacity for NMC, and by 12.8 % to 20.4 kg CO_2-eq per kWh of cell capacity for LFP.

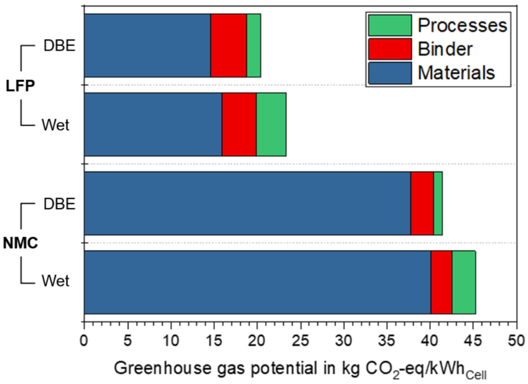

Figure 21: Greenhouse gas potential of the cathode as a function of materials and production variants for the process route using an Eirich mixer (LCA by N. von Drachenfels).

Particularly noteworthy is the comparatively high contribution of the PTFE binder in the DBE route, which amounts to approximately 3 kg CO_2-eq per kWh at the cell level and accounts for about 2-4 % of the total CO_2-eq emissions of a cell. Additional materials, anode production, and cell assembly contribute between 15 and 25 kg CO_2-eq per kWh of cell capacity, depending on the cell design and material selection.

The advantage is particularly pronounced for the consumption of fossil fuel resources (FFP), which strongly

Table 4: Impact categories per cathode active material and process variant for the process route using an Eirich mixer.

Impact categories	Unit	NMC			LFP		
		Wet*	DBE**	Δ	Wet*	DBE**	Δ
Greenhouse gas potential	kg CO_2-eq /kWh_{Cell}	45.22	41.39 | 39.07	-8.5 % | - 13.6 %	23.35	20.35 | 16.63	-12.8 % | - 28.8 %
Freshwater ecotoxicity	kg 1,4-DCB-eq /kWh_{Cell}	5.62	5.27	-6.2 %	1.79	1.57	-12.2 %
Human toxicity potential (cancer)	CTUh	10.57	9.74	-7.9 %	6.88	6.10	-11.3 %
Water consumption	m^3/kWh_{Cell}	3.87	3.67	-5.2 %	0.26	0.22	-15.3 %
Fossil resource scarcity	kg oil-eq /kWh_{Cell}	12.53	10.77	-14.0 %	5.94	4.07	-31.6 %

* with PVDF: 55.8 kg CO_2-eq/kg

** with PTFE: 120.4 kg CO_2-eq/kg (without gas capture) [11] | 14.4 kg CO_2-eq/kg (with gas capture) [12] correlates with overall energy use. For LFP, the reduction in the cathode, normalized to cell capacity, amounts to approximately 32 %, while for NMC it is about 14 %. This improvement is primarily due to the elimination of natural gas use in the cathode production chain within the DBE process. Across all other evaluated impact categories, consistent improvements between 5.3 % and 16.4 % per kWh of cell capacity are observed. These findings are in line with current scientific studies [18,19]. When comparing the LCA results with the wet processing route employing a planetary mixer instead of the *Eirich* mixer, the potential savings further increase by 0.5 to 2.3 percentage points, depending on the impact category.

In summary, the assessment demonstrates that the dry coating process provides ecological advantages regardless of the cell chemistry type. The results thus highlight the significance of the DBE technology as an effective approach to reducing the environmental footprint in cell production.

Transitioning the energy carrier in electrode manufacturing to fully electric operation offers additional potential for lowering greenhouse gas emissions, particularly when utilizing electricity from renewable sources. This also applies to the wet coating process. Further reduction opportunities may arise from improvements in scrap rates, energy-efficient heat recovery, and more accurate determination of PTFE emission factors. Overall, the dry coating process already presents substantial optimization potential for the sustainable industrialization of battery cell manufacturing.

Staffing requirements

The personnel requirements for cathode production differ significantly between the DBE process and conventional wet coating. In the DBE process, a total of one operator is required for material handling and mixer operation, consisting of approximately 0.5 personnel units for system monitoring in the control room and 0.5 for material logistics (e.g., handling BigBags, sacks, and drums). In the calendering section, two operators are assigned to ensure continuous operation and process supervision. In comparison, the conventional wet coating process also requires one operator for the mixing unit and Material logistics; however, an additional operator is required for transporting the slurry from the mixer to the coater as well as for quality control. The operation of the (tandem) coater and dryer requires two further operators, while only one person is assigned to the calendering section. Consequently, the overall personnel demand in the DBE process can be organized more efficiently, primarily due to the elimination of transport and drying steps and the concentration of activities within the calendering stage.

Conclusion & perspective

The *ProLiT* project successfully demonstrated that both LFP and NMC cathodes can be manufactured using the PTFE and calender gap-based dry coating process, even if this requires multi-stage compaction steps. The resulting scientific findings form the basis for the industrialization concept developed, which envisages a scalable implementation of dry coating. The insights gained into process-structure-property relationships between the powder and the resulting free-standing film or finished battery cathode are crucial for industrial scaling, as they enable reliable prediction of film properties and process effects. There is still great potential here for the development of future in-line and online quality control systems, which could contribute significantly to increasing efficiency and reproducibility in large-scale production. Compared to conventional wet coating, the dry coating process described in the industrialization concept enables significant energy savings to be achieved, as other studies have also shown [19], making the method a key element for sustainable and cost-efficient cell production. The developed holistic plant concept for cathode production with integrated recycling of edge trimmings into the mixing process provides a robust basis for industrial implementation. Important aspects for further development that were not focused on in the *ProLiT* project include the systematic recycling of production waste such as edge trimmings, cell format-specific cut-offs, and screen overflow, the recycling of dry-coated battery electrodes, and the development and integration of advanced process monitoring systems. These challenges need to be addressed in future projects in order to exploit the full potential of dry coating. Overall, the industrialization concept developed for dry coating shows great potential for significantly advancing sustainable and economical battery cell production.

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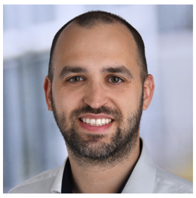
Authors

Prof. Dr.-Ing. Arno Kwade
University Professor
iPAT | TU Braunschweig

Marcella Nickl
Research Associate
iPAT | TU Braunschweig

Dr.-Ing. Stefan Gerl
Head of Process Technology
Maschinenfabrik Gustav
Eirich GmbH & Co KG



Nicolas von Drachenfels
Managing director
Battery LabFactory Braunschweig

Simon Raffenberg
Research Associate
MEET | Universität Münster

Dr. Katrin Junghans
Head of Batteryline
MEET | Universität Münster

Philipp Röring
Scientist Chemical Materials
Matthews Engineering

Dr. Ronny Schlegel
Senior Director
Research & Development
Matthews Engineering

Keith Melton
Sales Manager
Coperion K-Tron
(Switzerland) GmbH

Simon Gröninger
Manager Process
Technology – Battery
Coperion GmbH

Dr. Katja Kretschmer
Head of Cathode Material
Development Division
IBU-tec advanced materials AG

Dr. Sven Klein
R&D Leader
Advanced Battery Materials
Daikin Chemical Europe GmbH

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BLB+ | Braunschweig LabFactories for Batteries and more

Technische Universität Braunschweig
Langer Kamp 19 | 38106 Braunschweig

E-Mail: p.michalowski@tu-braunschweig.de
Web: www.labfactories.de

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CONTACT

Prof. Dr.-Ing. Arno Kwade
University Professor
a.kwade@tu-braunschweig.de

BLB+ | Braunschweig LabFactories for Batteries and more
Technische Universität Braunschweig
Langer Kamp 19 | 38106 Braunschweig
www.labfactories.de