Technische Universität Braunschweig

IBPC 2023

INTERNATIONAL BATTERY PRODUCTION CONFERENCE

7 to 9 November 2023

CONFERENCE BROCHURE

WELCOME

Dear IBPC2023 participants,

Batteries are a key driver of the global mobility revolution and the core of the energy transition. The battery industry has seen significant progress in production capacities, technological progress in terms of specific energy capacity and fast charging ability, cost reduction as well as raw material requirements in recent years. An end of the innovation power and production capacity increase is not yet in sight. Consequently, we are experiencing a fast innovation rate regarding new materials, production technologies as well as cell and pack designs that need to be transferred from lab-scale to industrial mass production. However, especially the energy requirement and sustainability of battery material and cell production have to be decreased significantly. At the same time, the new EU battery regulation puts a special focus on circular economy of batteries and sustainable. Recycling capacities enabling circular economy need to build up. Because of the importance of resilient supply chains, the development of a European battery economy gains increasingly more attention.

Thrilled with the success of the last five IBPCs with up to 280 participants and about 50 exciting presentations including six plenary talks on recent advancements in battery production, we are delighted to welcome you to the IBPC 2023 in Braunschweig to discuss recent developments and research around circular battery production including recycling and circular economy. This year's plenary talks, presentations and poster sessions address the innovative electrode production of classical lithium-ion batteries (LIBs) as well as next-generation and solid-state batteries, cell design, cell performance and diagnostics, formation and aging, sustainable production, circular economy, the development of recycling processes and battery factory design with associated supply chains. In addition to the production, this year's programme places a special emphasis on recycling topics, as these are becoming increasingly important in the industry and require innovative solutions.

We are delighted to welcome speakers and their presentations that deal with the entire battery value chain up to battery recycling and are looking forward to their contribution to the battery production community. We are particularly thankful for the support of our partners, especially VDMA Battery Production. A special thank goes to our gold sponsors Bio-Logic Science Instruments SAS, Bühler AG, Coperion GmbH, Customcells Itzehoe GmbH, EIRICH GROUP, Netzsch Feinmahltechnik GmbH, NETZSCH-Gerätebau GmbH, Volkswagen AG and our silver sponsors Arranged BV, Buss AG, Mixaco Maschinenbau, Werner Mathis AG, Lead Intelligent Equipment GmbH, Retsch GmbH and Zeppelin Systems. Their support enables us to maintain the high quality of the conference. We warmly welcome you and wish you a pleasant stay in Braunschweig with many interesting talks and exciting discussions.

Prof. Dr.-Ing. Christoph Herrmann & Prof. Dr.-Ing. Arno Kwade

BATTERY LABFACTORY

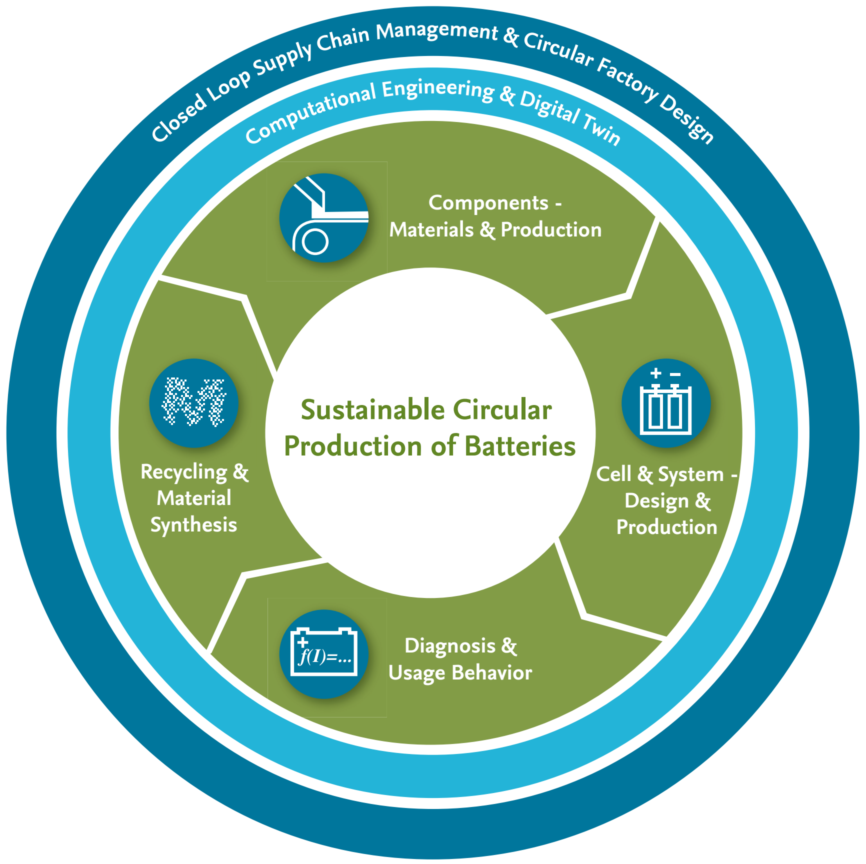
The Battery LabFactory (BLB) stands for an open research infrastructure to investigate and develop electrochemical storage devices from laboratory to pilot plant scale. The research spectrum covers the entire value cycle, from material, electrode and cell manufacturing, up to recycling as well as the subsequent active material resynthesis from recycled raw materials. With this research spectrum, the BLB aims to enable a sustainable circular production of battery cells.

The BLB holds the production infrastructure and characterizing equipment to develop large-sized batteries as well as battery modules and packs. This allows the research on fundamental and application-oriented aspects. The scope of the BLB is to establish a knowledge-driven electrode and cell production to accomplish a fast transfer of R&D into technical or pilot scale production processes. For this purpose, engineers and scientists with different areas of expertise join forces in the transdisciplinary team of the BLB. In detail, 9 institutes of the TU Braunschweig, two from TU Clausthal and one from LU Hannover combine their knowledge and scientific competence. Furthermore, the Fraunhofer Institute for Surface Engineering and Thin Films IST and the Physikalisch-Technische Bundesanstalt Braunschweig (PTB) complete the joined Battery LabFactory Braunschweig.

The BLB represents an open platform for R&D on processes, cell design, diagnostic and simulation of todays and future battery technologies.

BLB BATTERY LABFACTORY BRAUNSCHWEIG

Sustainable Circular Production of Batteries



CONTENT

PARTNERS

Arranged is an active but very discrete player in the filtration of European coatings. Through a long experience in different coating applications, ranging from photographic film, printing plates, automotive coatings to digital printing inks, we have the knowledge to support battery cell makers in improving their production yields by reduction coating defects. We are hands-on focused, deliver quick solutions for testing in the lab, and provide means for scale-up to production level. We know what critical process details to focus on and how to achieve a speedy and efficient result for your coating process. Arranged provides consultancy, offers competitive filtration products for cathode and anode slurry filtration, and designs fully automated filtration units. We have two offices, Arranged Belgium and Arranged Germany.

www.arranged.be/en/filtratie/filtration-applications/anode-and-cathode-coating-lithium-ion-cells/

BioLogic designs, manufactures and markets ultra-precise and ultra-accurate measurement instruments and their control and analysis software, in particular for the battery industry.

A product portfolio of potentiostat-galvanostats, battery cyclers and impedance analyzers satisfies the needs of industrial R&D in new energy storage technologies, fuel cells, photovoltaics, corrosion and biosensors.

Our user-friendly instruments and dedicated software have been developed in partnership with the scientists and R&D laboratories that develop and test batteries worldwide.

www.biologic.net

Every day, billions of people come into contact with Bühler solutions to cover their basic needs for food and mobility and more. Our technologies are in your smartphone, solar panels, diapers, lipstick, banknotes, the foods you eat, and the vehicles you drive. Bühler offers a wide range of solutions for the crucial process steps in LIB cell production. As a global leader in wet grinding and dispersing technologies, Bühler provides reliable, scalable and industry-proven solutions for wet grinding of active materials and precursors as well as continuous mixing of electrode slurries for lab, pilot and large-scale production.

www.buhlergroup.com

BUSS is an international market leader in compounding systems for demanding applications. As the originator of co-kneader technology, BUSS can offer unique compounding solutions that set the standard for heat or shear critical applications in the plastics, aluminum, chemicals and food processing industries. BUSS's core expertise is in providing customized and application-specific solutions for advanced compounding tasks to meet stringent process technology and product quality requirements and ever greater market demand for sophisticated technology. “Swiss quality” explains why BUSS compounding systems perform so well, are a reliable investment and have made the company a leading supplier of advanced compounding technology.

www.busscorp.com/products/compeo/

About Coperion

Coperion is a global industry and technology leader in compounding and extrusion systems, sorting, size reduction and washing systems, feeding systems, bulk material handling and services. Coperion develops, produces, and services plants, machinery, and components for various industries and employs 5,000 people in its three divisions and in its 50 sales and service companies worldwide.

For the battery industry Coperion offers first-class, reliable technology for manufacturing top-quality battery compounds. As a system provider our solutions encompass the entire manufacturing process for battery compounds: from bulk material handling to precise feeding and extrusion- including containment concept planning and implementation for every step. Focusing on a continuous production approach of battery masses, Coperion offers an innovative and efficient way of manufacturing.

www.coperion.com

About CustomCells

CustomCells puts premium battery cells on the road, on the water, and in the air. As one of the leading companies in the fields of development and series production of special lithium-ion battery cells, CustomCells is setting the pace for a comprehensive technological transformation. CustomCells employs more than 200 highly qualified employees and operates development and production sites in Itzehoe and Tübingen. The company supports its customers along the entire value chain – from the initial idea, through prototyping and series production, to project planning and commissioning of customers’ own gigafactories. As a recognized premium partner of major automotive manufacturers, CustomCells is also significantly driving the electrification of the aviation sector with its solutions.

More information: www.customcells.com

PARTNERS

EIRICH

Whether you manufacture lithium/sodium ion batteries for electric vehicles or develop electrical energy storage systems, Eirich offers you solutions for the entire mixing process in electrode production. Due to their unique functional principle, Eirich mixers have been successfully used along the entire production chain for electrical energy storage systems for decades. Mixer are installed for preparation of anode and cathode raw materials, the production of coating slurries for electrodes and separators, semi-dry, paste-like mixes to powdered and structured dry mixes for dry electrode production (DBE). With a network of competent partners, we also supply turnkey systems from raw material preparation to the interface in electrode production. As a technology partner with proven material and process expertise for the battery cells of today and tomorrow and many years of experience in laboratory and production applications, you can trust us. Challenge us- we will be happy to help you design your manufacturing process optimally.

www.eirich.com

LEAD

Established in 2002, Lead Intelligent Equipment (LEAD) is one of the world's largest suppliers of new energy manufacturing equipment. With a focus on designing, engineering, and building cutting-edge manufacturing solutions, LEAD serves many of the world's largest automotive, renewable energy, and technology companies. LEAD´s expertise lies in serving eight specialized manufacturing sectors: lithium-ion EV batteries, EV module and pack equipment, solar PV panels, 3C equipment, hydrogen fuel cells, laser precision processing, connected factories, and smart logistics.

In 2021, as part of its expansion strategy, LEAD established a German subsidiary headquartered in Nuremberg. LEAD´s commitment to global expansion is evident through the establishment of 15 subsidiaries and 50 service outlets across Europe, America, and Asia. With a global footprint, LEAD boasts extensive production and research and development (R&D) facilities spanning over 1,000,000 square meters. These state-of-the-art spaces are where a dedicated team of over 21,000 employees collaborate to drive innovation and develop industry-leading solutions.

www.leadintelligent.com

Mathis
Werner Mathis AG, Switzerland www.mathisag.com

Werner Mathis AG, a known player in the Battery sector, designs and manufactures R&D and Pilot Scale coating and drying machinery in Switzerland. Our special designed coating head offers a variety of coating technologies, such as slot die and knife coating, movable cart includes vessel, filters, pump, and control system. Coat weight measurement, surface inspection, laser marking, thickness measurement, OPC UA and data management. Mathis dryer includes other technologies which can be combined allowing energy efficiency, different atmospheres as argon, dry air, LEL control, microenvironment available. Mathis offers solvent recovery system technologies, regenerative thermal oxidation (RTO) and catalytic oxidation system (CT).

www.mathisag.com

MIXACO® MASCHINENBAU

MIXACO is one of the leading manufacturers of mixer systems worldwide with more than 55 years of experience in mixing. As a completely independent, family-managed company located in Neuenrade, Germany, we can fully concentrate on our core competence, i.e. development and production of industrial mixer systems. More than 7,500 MIXACO mixers of the highest quality made in Germany ensure the optimum efficiency in production processes of our customers. Our global sales and service network allows us to be on-site at our customers premises, everywhere in the world. We understand the claim made in Germany as our brands commitment to quality. In this way we will wholeheartedly meet the expectations of our international customers in the future as well.

With pleasure we manufacture your dry mixer for electrode production or raw material structuring, for the laboratory and the production.

www.mixaco.com

NETZSCH

NETZSCH Technology is a world leader in the field of thermal characterization of almost all materials. We offer complete solutions for thermal analysis, calorimetry (adiabatic and reaction calorimetry), the determinaton of thermophysical properties, rheology and fire testing.

www.grinding.netzsch.com

Retsch® part of VERDER scientific

True to the guiding principle "Enabling Progress", VERDER SCIENTIFIC sets standards in high-tech equipment for solid matter quality control and continuously improves battery technology for a more efficient use of resources and securing maximum sustainability.

The well-known scientific companies under the umbrella of VERDER SCIENTIFIC offer sophisticated and reliable products, providing one-stop solutions in various applications. RETSCH, one scientific manufacturer, is the leading provider for neutral-to-analysis sample preparation and characterization of solids. Having a century of experience under its belt, RETSCH offers equipment with unparalleled performance, operating convenience, safety, and longevity.

www.retsch.com

PARTNERS

Battery Production

The VDMA Battery Production department is the partner for all questions relating to machine and plant construction in the field of battery production. The member companies of the department supply machinery, plants, machine components, tools and services for the entire process chain of battery production: From raw material preparation, electrode production and cell assembly to module and packaging production. The current focus of VDMA battery production is on Li-ion technology. We research technology and market information, organize customer events and road shows, hold our own events, such as the annual conference, which has established itself as an important industry meeting place, and are in dialogue with research and science on current topics and on joint industrial research.

www.vdma.org/batterieproduktionsmittel

The world's changing – and we're changing with it. We're placing the focus on e-mobility, the digital transformation of our brand and smart mobility. But we want to be more than Europe's largest carmaker. We want to deliver the ideas and solutions for resource-friendly mobility and networked traffic systems in big cities and small towns all over the world.

The Volkswagen Passenger Cars brand is present in more than 150 markets throughout the world, produces at over 30 locations in 13 countries and delivered around 4.9 million vehicles in 2021. Around 184,000 people currently work at Volkswagen worldwide. And we want you to be one of them.

www.volkswagen-karriere.de/de.html

About Zeppelin Plant Engineering

Zeppelin Systems specializes in the design, construction, and technological upgrading of industrial plants for storing, conveying, mixing, dosing, and weighing high-quality bulk materials and raw materials. With around 1,700 employees worldwide, Zeppelin Systems provides daily solutions for customers in the plastics, chemicals, rubber, and tire industries. Customers in the food industry also value Zeppelin Systems' many years of technological know-how and experience in delivering turnkey solutions. From plant planning and project implementation to after-sales service including process optimization – Zeppelin Systems is an integrated solutions provider, delivering complete solutions from a single source. Every Zeppelin plant is characterized by tailored features to meet specific customer requirements, smart automation solutions, and comprehensive service. We refer to this as the embodiment of engineering art, and we apply it to the entire life cycle of a system. With roots in Germany and global operations at more than 20 sites around the world, Zeppelin Systems makes industrial-scale testing available to its customers, thereby facilitating the assessment and sustainable optimization of their plant design. Zeppelin Systems also develops and manufactures mechanical and plant engineering components that can be seamlessly integrated into third-party systems. We Create Solutions for our customers every day. For more information, visit www.zeppelin-systems.com.

Battery Production

VDMA Battery Production

The VDMA department is the direct contact for all questions relating machine- and plant construction. The member companies of the department supply machinery, plants, machine components, tools and services for the entire process chain of battery production: From raw material preparation, electrode production and cell assembly to module and packaging production. The current focus of VDMA Battery Production is on Li-ion technology. Our activities:

- We research technology and market information: (Roadmap Battery Production Equipment 2030, process brochures, business climate survey)
- We operate the Online Industry Guide, where you can find the expertise of our members in the field of battery production: https://vdma-industryguide.com/
- We supervise fairs (CIBF, Battery Show USA) and hold our own events, such as the VDMA Battery Production Annual Conference: Established itself as an important industry meeting
- We are in dialogue with research and science on current topics and on joint industrial research and we have a cooperation with the Fraunhofer Research Institution for Battery Cell Production FFB
- We represent our industry in politics and the public

If you have any questions, please do not hesitate to contact us!

Website: https://vdma.org/batterieproduktionsmittel

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>extruders >feeders >components >pneumatic conveying >complete systems

COPERION TECHNOLOGY FOR CONTINUOUS PRODUCTION OF BATTERY MATERIALS.

+ Complete high containment systems from one single source
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+ Containment secure material handling

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Coperion is the worldwide market leader for extruders, feeders and material handling at the highest technical level. We provide continuous production technology for maximum product quality. **www.coperion.com/battery-materials**

coperion
confidence through partnership

arranged.
COATINGS FILTRATION

An integrated method for filtration will take your productivity a big step ... forward

Arranged is for a cell battery manufacturer relatively unknown. Correct, we started our battery maker market approach this year and are confident we can offer a valuable package for your industry.

We are an experienced filtration partner for coating applications in Europe. We have understood what goes wrong in the present cathode and anode coating lines often installed by turn-key companies or engineering firms. The defects are typical for every coating application.

Let me explain.

What can we learn from printing plate coating?

Same as in your application, they coat on a metallic substrate (Aluminium). An air inclusion in the coating means the manufacturer must scrap such a printing plate. Because where there is no coating due to the presence of an air bubble, no inks will adhere = a printing defect on paper. One tiny air bubble means a large 1 m^2 printing plate will be rejected. With our know-how, customers have reduced scrapped products drastically.

What can we learn from digital inks?

Cathode and anode slurries are dispersions, just as digital printing inks are. Only the scale is different, where digital inks contain nanometer pigments, battery slurry particles are in the micron range.
Yet the requirement is the same: remove the unwanted and disturbing particles from the slurry before these are coated on the substrate. Consider this: the job can become heavily complex with the combination of solvents, particle concentration, and viscosity. With digital inks, we have resolved many filtration issues and enhanced productivity; we can do the same for battery slurries.

How can we improve our process line, and what is the impact on filter service life and productivity?

Well, this magic we will disclose in a face-to-face meeting at your location.
We bring our 30 years of coating filtration experience with us.

ARRANGED BV - Bilzen - Belgium :

assist@arranged.be / T +32 89 656321

ARRANGED GmbH - Stolberg - Germany :

em@arranged-gmbh.de / T +49 2402 9791 562

URL

PROGRAMME

CONFERENCE DAY 1 | Nov. 7th

8:00 I Arrival of Attendees

9:00 I Welcome by the Conference Chairs

9:15 I Keynote by Dr. Stefan Jung (BMBF)
Towards a Technologically Sovereign European Battery Value Chain - The R&D Approach of Germany's BMBF

9:50 I Break

10:00 I **Parallel Sessions**

Continuous Slurry Mixing
Room Maschinenhalle I Chair: Prof. A. Kwade

Continuous Processing of Negative LIB Electrodes using an Innovative Compounding System
Kristina Borzutzki, Fraunhofer FFB & Krischan Jeltsch, Buss AG

Investigations of a continuous dispersion process for paste formulation in the production of lithium-ion batteries and analysis of a cleaning procedure
Kevin Raczka, KIT

Continuous slurry mixing process in large-scale electrode production.
Adrian Spillmann, Bühler AG

Material Development and Production
Room Nimes I Chair: Dr.-Ing. S. Melzig

Graphite Production Technologies for Batteries – State of the Art Review
Bahman Yari, Hatch

Mechanofusion for lithium-ion battery cathode manufacturing
Guo Jung Lian, University of Sheffield

Synthesis of layered oxide cathode active materials from secondary resources
Martin Menzler, Fraunhofer IST

10:45 I Discussion

11:00 I Break

11:15 I **Parallel Sessions**

3D-printing and structuring of electrodes
Room Maschinenhalle I Chair: Dr. rer. nat. M. Kandula

Targeted Structuring of High-Energy Lithium-Ion Electrodes – An Innovative Method Without Loss of Material
Michael Bredekamp, TU Braunschweig I iPAT

3D-printed hydroborate based all-solid-state sodium-ion batteries
Jan Thomas, Fraunhofer IFAM

Dry Coating – is it really a benefit to more cost efficient and sustainable battery production?
Noah Rieple, P3 automotive GmbH

Machine Learning in Battery Cell Production
Room Nimes I Chair: Prof. K. Dröder

Framework and demonstrator for AI-based quality assessment in battery cell production: an implementation in KIproBatt
Xukuan Xu & Michael Möckel, Technische Hochschule Aschaffenburg

Improving Yield Through AI / ML Driven Automated Rootcause Analysis in EV manufacturing
Kalle Ylä-Jarkko, Elisa IndustrIQ, Helsinki

Large area evaluation of jelly roll alignment using machine learning methods
Andreas Kopp, Hochschule Aalen

12:00 I Discussion

12:15 I Lunch Break

13:15 I Poster Session

14:45 I Keynote by Dr. Elixabete Ayerbe (CIDETEC)
CIDETEC towards a digitalization of the battery manufacturing plant

15:20 I Keynote by Dr.-Ing. Linus Froböse (Skeleton Technologies)
Ultra fast charge and discharge in seconds with Supercapacitors and Superbatteries

15:55 I Break

16:10 I **Parallel Sessions**

Traceability and Ontologies in Battery Cell Production
Room Maschinenhalle I Chair: Prof. G. Garnweitner

Traceability in battery production: Enabling deep insights into the correlation between process and product parameters
Hai Yen Tran, ZSW

Battery Value Chain Ontology (BVCO) – Towards an Ontology for Lithium-Ion-Batteries in a Circular Economy
Lukas Gold, Fraunhofer ISC

Image-based Traceability in Electrode Production
Johannes Lindenblatt, TUM

Material Production and Characterization
Room Nimes I Chair: Prof. S. Zellmer

Effect of the PEO molecular weight on the composite cathode performances
Maica Morant, CIC energi gune

Advantages of Particle Size and Shape Analysis for Battery Manufacturing Performance through the use of Dynamic Imaging Technology
Colin Dalton, JM Canty Dublin

Design to cost Ni, Mn and Co-based battery materials for EVs mass adoption in Europe
Guillaume Lefèvre, Umicore

16:55 I Discussion

17:10 I Break

17:25 I **Parallel Sessions**

Innovations in dry and wet electrode production
Room Maschinenhalle I Chair: Prof. A. Kwade

Exploring the IR Drying Process in in Li-Ion Battery Electrodes; an experimental and computational chemistry approach
Larisa von Riewel, Hereaus

Multilayer slot coating – Opportunities for Battery Electrodes
Harald Doell, TSE Troller AG

Improvement of dry electrode manufacturing with powder characterization
Salvatore Pilliterri, Granutools

Investigation of Electrochemical Performance and Morphology of Multilayer Electrodes with Graded Porosity
Fatjon Maxharraj, Fraunhofer IKTS

Recycling I (Disassembly and environmental impact)
Room Nimes I Chair: Prof. B. Yagmurlu

Process Development and Characterization for Automated Disassembly of End-of-Life lithiumion Batteries Achieving Efficient Recycling
Shubiao Wu, TU Braunschweig I IWF

Closing The Loop For Lithium-Ion Batteries In Europe? Opportunities And Challenges
Nils Steinbrecher, TES-AMM

A modular demo disassembly of retired electric vehicle battery
Kai Liang Tan, ARTC

Challenges and Strategies for Sustainable Recycling of Lithium-Iron-Phosphate-Batteries (LFP)
Nils Wieczorek, Stiftung GRS Batterien

18:25 I Discussion

18:40 I Prof. Arno Kwade & Kashfia Mahin
Optimizing Battery Production Costs: Introducing Kostentool Ekozell

19:00 I Apero

PROGRAMME

CONFERENCE DAY 2 | Nov. 8th

8:30 I Keynote by Prof. Aubrey Mainza (University of Cape Town)
Raw Materials for Battery Production – Opportunities and Challenges

9:05 I Keynote by Prof. Jürgen Fleischer (KIT, wbk)
Productivity vs. Flexibility: Resolving the Conflict of Objectives Through Agile Battery Cell Production

9:40 I Break

9:50 I **Parallel Sessions**

Solvent-free and Solvent-reduced Electrode Production	Sustainability in Battery Cell Production
Room Maschinenhalle I Chair: Prof. A. Kwade	**Room Nimes I Chair: Prof. T. Spengler**
Printing technology as green alternative for Li Ion Battery electrode production *Daniela Fenske, Fraunhofer IFAM*	A blockchain platform demonstrator to increase transparency and to enhance more sustainable battery material value chains *Maximilian Rolinck, TU Braunschweig I IWF*
Assessment of high-mass-loading NMC and graphite electrodes produced via dry electrode manufacturing *Edouard Quérel, Empa & Valentin Dolder, Bühler AG*	Advancements in Cost-Efficient and Sustainable Li-Ion Battery Manufacturing: Insights from the BatWoMan Project *Bernd Eschelmüller, AIT Austrian Institute of Technology GmbH*
Solvent-free process for the roll-to-roll production of nickelrich cathodes for LIB *Alice Hoffmann, ZSW*	A critical evaluation of system implications on the environmental targets of the new EU Battery Directive *Steffen Blömeke, TU Braunschweig I IWF*

10:35 I Discussion

10:50 I Poster Session

12:20 I Lunch Break

13:20 I Keynote by Dr. Torsten Brandenburg (BMWK)
Resilience and sustainability of the European battery ecosystem

13:55 I Keynote by Dr. Yvan Reynier (CEA)
CEA battery activities: What is the right R&D scale to serve a growing industry?

14:30 I Break

14:40 I **Parallel Sessions**

Electrode, Cell and Module Diagnostics	Characterization, Formation and Aging
Room Maschinenhalle I Chair: Prof. C. Schilde	**Room Nimes I Chair: Prof. M. Kurrat**
Inline X-ray Metrology for Battery Cell Production – Possibilities, Limits and Contribution to Process Improvements *Hagen Berger, Exacom GmbH*	Combined Machine Learning and Electrochemical Impedance Spectroscopy for Battery Degradation Analysis *Binbin Zhu, TU Braunschweig I InES*
Detecting and modeling defect structures in battery cells *Alexey Telegin, Keysight*	Investigation of Li Plating and Fast Charging for Li-ion Batteries with a Physico-chemical Modeling Approach Complemented by Electrochemical and Optical Operando Experiments *Niklas Bless, TU Braunschweig I InES*
Why the Xray source matters for high-resolution CT *Mats Sjöstedt, Excillum AB*	What conditions have to be met for EIS-Measurements to be valid? General remarks from the field *Julia Berlin, BioLogic*

15:25 I Discussion

15:40 I **Parallel Sessions**

Inline-analysis and Water Effects in Electrode Production	Production of SSB Cells
Room Maschinenhalle I Chair: Dr.-Ing. K. Banov	**Room Nimes I Chair: Dr. rer. nat. P. Michalowski**
Rheological Design of Battery Electrode Slurries *Carl Reynolds, University of Birmingham*	Influence of Pressure in ASSB Assembly: Scalable Concepts to Improve Cell Performance *Lovis Wach, TU Munich*
Inline Quality Measurement in the Continuous Mixing Process as a Key for a Steady and High Product Quality *Thorsten Stirner, Coperion GmbH*	Development of a scalable production process of sulfide-based solid electrolytes and characterization of product properties *Michael Grube, Fraunhofer IST*
Post-drying: simulation and experiments of micro- and macro-scale mass transport *Thilo Heckmann, KIT*	Challenges of Compressing Sulfide-Based Separators for Solid-State Batteries *Carina Amata Heck, TU Braunschweig I iPAT*

16:25 I Discussion

16:40 I Break

16:50 I **Parallel Sessions**

Industrial Session	Components for Next-Generation Batteries
Room Maschinenhalle I Chair: Prof. C. Herrmann	**Room Nimes I Chair: Chair: Dr. rer. nat. P. Michalowski**
Production of dosable structured dry battery electrode (DBE) mixes in a one-pot process with Eirich intensive mixers *Stefan Gerl, Maschinenfabrik Gustav Eirich GmbH & Co KG*	Transport Properties of Hard Carbons *Giar Alsofi, University of Birmingham*
Boosting Efficiency and Sustainability: Netzsch's Pioneering Techniques in LFP and LMFP Battery Production *Maximilian Münzner, NETZSCH-Feinmahltechnik GmbH*	Industry-near processability of sulfurized polyacrylonitrile based electrodes *Robin Moschner, TU Braunschweig I iPAT*
Introducing the Center of Excellence Battery: Cell- and Battery Development for the Volkswagen-Group *Dr. Dominik Koll, Volkswagen AG*	Thin film lithium metal anodes for solid-state batteries manufactured via sputter deposition *Julian Brokmann, Fraunhofer IST*
Staying at the Edge of Time: From Analytical Instruments Manufacturer to Integrated Solutions Provider *Julia Berlin, BioLogic*	

17:35 I Discussion

17:50 I **Room Maschinenhalle** Conversion for dinner	**Room Nimes** Innovation culture in battery technology *Jan Diekmann, Custom Cells*
18:10 I **Room Maschinenhalle** Conversion for dinner	**Room Nimes** Plenary Discussion, Arno Kwade & Christoph Herrmann Various speakers

18:55 I Break

19:30 I Gala Dinner

PROGRAMME

CONFERENCE DAY 3 | Nov. 9th

8:30 I Keynote by Dr. Pieter Verhees (Umicore)
Challenges for battery recycling in Europe

9:05 I Break

9:15 I **Session**
Safety in Production and Use
Room Maschinenhalle I Chair: Dr.-Ing. F. Lienesch

Health and Safety in Battery Cell Production
Martin Föhse, Pilz GmbH und Co. KG

Comparison of Thermal Runaway Early Detection Using Different Electrical Measurement Methods
Torben Jennert, TU Braunschweig I elenia

9:45 I Discussion

10:00 I Break

10:15 I **Session**
(Urban) Factories and Supply Chain
Room Maschinenhalle I Chair: Prof. C. Herrmann

Comparison of battery supply chains regarding their environmental and socio-economic impacts
Jan-Linus Popien, TU Braunschweig I AIP

Closing the Gap between Lab Scale Development and Industrial Technology: Cathode Materials Pilot-Plant “Powder-Up!”
Peter Axmann, ZSW

Procedure for considering the required flexibility in production operations during factory planning using the example of the Fraunhofer Research Institution for Battery Cell Production FFB
Natalja Rube & Jakob Palm, Fraunhofer FFB

A scalable assessment framework for estimating battery resource potentials in urban environments
Katja Knecht, TU Braunschweig I ISU

Seminar 9:15-11:00
Introduction, material overview & electrode production
Room Nimes I Prof. A. Kwade

11:15 I Discussion

11:30 I **Session**
Recycling II (Materials)
Room Maschinenhalle I Chair: Dr.-Ing. H. Zetzener

From end-of-life batteries to high quality graphite-developing a recycling process focused on anodic materials
Fernanda Padilha Noronha & Anna Rollin, TU Braunschweig

Transforming Waste into Opportunity: Sustainable Black Mass Recycling and Beyond
Alexander Zeugner, HC Starck

Comprehensive model-based environmental impact evaluation of recycling process chains
Abdur-Rahman Ali, TU Braunschweig I IWF

Electrochemical performance of active materials from spent LiBs regenerated with a direct recycling approach
Marilena Mancini, ZSW

12:30 I Discussion

12:45 I Poster Prizes

13:00 I Virtual Tour BLB

13:30 I Lunch

Seminar 11:15-12:00
Introduction, material overview & electrode production
Room Nimes I Prof. A. Kwade

Seminar 12:00-12:45
Automated Cell Assembly
Room Nimes I Do Minh Nguyen

Seminar 12:45-13:30
Digitalization
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PRESENTATION ABSTRACTS

Continuous Slurry Mixing

Continuous Processing of Negative LIB Electrodes using an Innovative Compounding System

Kristina Borzutzki, Krischan Jeltsch, Markus Eckstein, Dominik Kramer, Andreas Niklaus
Fraunhofer Research Institution for Battery Cell Production FFB

To meet the growing demands on lithium- ion batteries, process costs (including process time, energy demand material scrap) need to be reduced. In this regard, innovative continuous mixing processes which are considered as promising alternatives compared to the conventional batch-type process, are of high interest [1].

In addition, the mixing process significantly impacts the quality of the electrode paste and subsequently of the final battery performance. [2,3] Therefore, it is of particular interest to gain deep knowledge of the mixing process and to reveal specific product-process correlations. Recently, several studies have been performed on electrode paste production utilizing a widely used twin-screw extruder system in the field of continuous mixing processes for battery manufacturing. [1-3] Nevertheless, a variety of different production techniques for continuous mixing including multi-screw extruders or oscillating kneaders are generally suitable for the production of battery electrode compounds. Though, to date these alternative technologies are rarely exploited. In this contribution, a continuous screw-based oscillating kneader system is utilized for aqueous processing of Gr-based electrode pastes. Taking into account the results of previous studies on twin-screw extruders [4,5], various critical process parameters such as the screw speed, throughput and explicitly the kneading concentration are varied to explore the process and to understand its potential. To corroborate the quality of the electrode pastes, their viscosities and particle size distributions are determined and correlated to specific machine parameters such as the engine power. Further, for a comprehensive process evaluation, electrodes are fabricated, and their electrochemical performance is validated.

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Investigations of a continuous dispersion process for paste formulation in the production of lithium-ion batteries and analysis of a cleaning procedure

Kevin Raczka, Juan Meza, Hermann Nirschl
Karlsruhe Institute for Technology

Electromobility and the storage of regeneratively generated electrical energy have high demands regarding the performance and costs of lithium ion cells. They require an in-depth understanding of the material properties of the raw materials and the procedural processes for manufacturing the electrodes. Numerous parameters must be measured and controlled in product development and later production in order to selectively set specific cell properties and at the same time establish an understanding of a stable continuous manufacturing process. Therefore, this research project aims to reduce production costs and increase the performance of battery cells. The concept relies on innovative and agile plant technology that allows flexible formats with the possibility of rapid recipe changes for continuous cell production. A twin-screw extruder is used for the production of the desired electrode slurry which corresponds to the first manufacturing step. The process control strategy of the extruder system is based on an adaptive, digital concept to ensure high quality battery slurries with the highest degree of automation and minimum energy input with the aim of minimizing raw material wastage or electrode slurry losses.

The efficient and resource-friendly process control is intended to reduce the respective downtimes and set-up times by up to 20 % compared to a standard batch process. Furthermore, with the help of an automated cleaning procedure, a faster recipe change should be made possible, which reduces the cleaning time by up to 20% compared to manual cleaning of a batch process. Thereby, the analysis of the residual concentration in the process room is essential in order to avoid possible cross-contamination.

The presentation will cover conclusions about the characteristic quality criteria for the electrode slurry such as viscosity or particle size distribution. First cleaning attempts were made using turbidity measurements in order to identify the quality of different media regarding the remaining concentration while cleaning and the decisive parameters such das flow rate or rotation speed of the twin-screw extruder. The findings obtained characterize the key influences necessary to control in order to reach a fully automated, agile battery manufacturing process.

Continuous slurry mixing process in large-scale electrode production.

Adrian Spillmann
Bühler AG

Over the last couple of years, continuous mixing has been fully adapted by the battery industry for the production of LIB electrode slurries. Bühler has been pioneering the continuous twin-screw mixing technology which combines all unit operations in a single continuously operated device. The result is a very high productivity per mixing line, elimination of batch-to-batch variations and reduced operating cost.

In this presentation, we will elaborate on the OPEX saving potential by comparing real production data. Due to energy savings by a factor of four, the operation cost of the electrode slurry production section can be significantly reduced compared to conventional batch mixing. In addition, further reduction in TCO is achieved by lower number of operators and higher production yield of the continuous electrode slurry manufacturing approach.

Material Development and Production

Graphite Production Technologies for Batteries – State of the Art Review

Morvarid Bajgiran, Bahmam Yari, Sina Kashani, Mark Bellino
Hatch

The surging demand for graphite in the battery market, fueled by the rapid growth of electric vehicles and electronics, presents a significant challenge for the industry. To address this challenge and attract new investments, it is essential to identify the most suitable graphite production technologies. Utilizing the Kepner-Tregoe decision making methodology, this study conducted a comprehensive assessment of the commercialized and emerging technologies used for production of battery-grade graphite. The analysis considered multiple evaluation criteria, including technical feasibility, scalability, economic viability, environmental impact, health and safety considerations, and the availability of the feedstocks. The choice of feedstock significantly influences the selection of the production technology. Natural and synthetic graphite processing triggers variations in the technique to upgrade carbon precursors into a battery-acceptable graphite. The characteristics and availability of the feedstocks also plays a crucial role in determining the performance and efficiency of the production process. Consequently, the technology assessment carefully examines the compatibility of each production technology with the available feedstocks, enabling a comprehensive evaluation of all relevant factors. The study findings could support informed decision-making processes, and guide the strategic allocation of resources to meet the escalating demand for the battery-grade graphite.

Mechanofusion for lithium-ion battery cathode manufacturing

Guo Jung Lian, Milan K. Sadan, Xuesong Lu, Denis Cumming, Rachel Smith
University of Sheffield

High specific energy and density is a key requirement for lithium-ion batteries (LIB) to fulfil the performance demand of electric vehicles. In LIBs, the cathode is often the limiting factor due to the low electronic conductivity of active materials. Conductive additives (e.g., carbon black) are commonly used to enhance electronic conductivity within electrode structures. However, their presence reduces the total energy density and is therefore kept to a minimum, typically within 2 wt% in commercial electrodes. In conventional wet slurry mixing and coating, the electrode structure is often a relatively uncontrolled distribution of the active material, conductive additives, and binder. This poses challenges when attempting to spatially design the distribution of conductive additives in electrodes.

Particle engineering has great potential to tailor the desired structure for active materials. Previous studies have hypothesised that conductive additives should be distributed in a way such that both long and short-range electrical pathways are present to enhance the overall performance of the electrode. Recent literature has utilised mechanofusion as a pre-processing technique to apply coatings to active materials using high shear and compression forces.

In this work, we systematically extend mechanofusion approaches to control the degree of carbon black (CB) deagglomeration as a method of manipulating the contributions of short-range pathways in cathodes. The findings indicate successful deagglomeration and coating of CB onto the surface of NMC622 particles, with varying coating characteristics affected by CB loading, mixing time and intensity. By measuring the electrical conductivity of coated particles, the percolation threshold for C65-coated NMC622 particles and its sensitivity to different process parameters was investigated. Lastly, the electrochemical performance was evaluated to understand how coated particles affect electrode performance through deliberately manipulated electrical networks.

Synthesis of layered oxide cathode active materials from secondary resources

Martin Menzler, Elisabeth Glatt, Sebastian Melzig, Sabrina Zellmer
Fraunhofer Institute for Surface Engineering and Thin Films IST

The application of sustainable resource strategies is becoming increasingly relevant in the field of battery production. Cathode active materials in particular contain important, globally finite resources. It is therefore crucial to recover these raw materials. The importance of the battery recycling is becoming further apparent due to the EU-required recycling quotas and the use of recycled materials. Among others, nickel-rich layered oxides have attracted great interest as cathode active materials due to their comparatively high energy density. Efficient recycling and resynthesis processes for these materials are therefore unavoidable. The aim is to reconvert cathode active materials such as Li[NixCoyMnz]O2 (NCM), LiCoO2 (LCO) or Li[NixCoyAlz]O2 (NCA) from end-of-life batteries to metal salts (e.g. nickel sulphate) in order to resynthesize cathode active materials with equal electrochemical performance as the material from primary sources. Currently, the recovery of cathode active materials is still not widely established for impure material streams as the recycling route is subject to certain fluctuations due to the varying raw material qualities. As a consequence, it is essential to establish efficient as well as scalable process routes for the production of cathode active materials from secondary raw materials.

In this study, certain kinds of cathode active materials, for instance NCM 622, NCM 811 and NCA have been synthesized on a laboratory scale using primary metal salts as well as secondary metal salts obtained by hydrometallurgical treatment (e.g. nickel sulphate, cobalt sulphate, lithium carbonate). This makes it possible to assess the differences between the use of primary and secondary materials in terms of their impact on the production process and the product properties, particularly regarding the role of impurities. The applied synthesis method is a two-step hydroxide coprecipitation, a subsequent spray drying process and a (two step) calcination. Crucial process parameters (e.g. pHvalue, temperature, educt dosing, reaction and aging duration) and formulation parameters (e.g. educt concentration) have been varied in order to determine significant process-product interdependencies. Within this study, the starting materials, intermediates and final products were analyzed regarding their chemical composition (ICP-MS / ICP-OES, EDX), morphology (REM), crystal structure (XRD) and particle size distribution (laser diffraction).

As a conclusion, this study investigates the effects of varying starting materials (obtained from primary and secondary resources) on the synthesis process and the resulting product properties.

3D-printing and structuring of electrodes

Targeted Structuring of High-Energy Lithium-Ion Electrodes – An Innovative Method Without Loss of Material

Michael Bredekamp, Peter Michalowski, Arno Kwade
TU Braunschweig I Institute of Particle Technology (iPAT)

The development of battery systems for mobile and stationary applications is an essential step towards a sustainable energy industry. Therefore, the lithium-ion battery cell is the subject of current research in industry and science. The rate at which lithium ions are intercalated is largely determined by the porosity of the electrode and leads to a decrease in the specific power density, especially with increasing electrode loading (thickness). The introduction of vertically-oriented structure pores, which provide fast transport pathways for Lithium-ions can maximize the rate-performance of electrodes while holding a higher energy density. For this reason, the targeted structuring of electrodes is a promising approach to improve the high-current capability of lithium-ion batteries by reducing cell internal resistances. The current state of research is laser structuring, in which an improvement in the rate capability has been proven. However, the process results in substantial material losses, thereby reducing theoretical capacity and increasing cost.1,2.

In the work that will be presented, a novel structuring process using liquid injection is introduced. This sustainable method enables the creation of pores locally in the electrode coating without material loss. By injecting a liquid excipient, the active material is only displaced directly after coating. During the drying process, the excipient disappears from the electrode, creating pores with a spacing of about 400 µm (center to center) and a pore diameter of about 100 µm. After calendering, the pores are not completely closed, leaving conductive paths for the cations. To evaluate this novel process, experimental data of structured graphite anodes (6 mAh/cm²) were compared with non-structured reference electrodes. The structured electrodes were characterized by electrochemical impedance spectroscopy (EIS) and physical tests. In addition, electrochemical tests were performed in pouch cells. The results show a significant increase in rate capability of 20% at a C-rate of 1C.

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3D-printed hydroborate based all-solid-state sodium-ion batteries

Jan Thomas, Ingo Bardenhagen, Julian Schwenzel
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In the search of new electric storage technologies, sodium-ion batteries (SIBs) have attracted huge interest due to the possibility to create high performance batteries without scarce elements. However, the theoretical energy density of the liquid electrolyte system is only around half of that of a lithium-ion battery. One way to tackle this issue can be the application of a sodium metal anode. Similar to the lithium system this seems to be possible only with a solid electrolyte.

Beside the, for the lithium system commonly investigated, classes of oxides, sulfides and polymers hydroborates have been identified as another class of solid electrolytes. Hydroborates have shown excellent ionic conductivities over 1 mS/cm at room temperature with an electrochemical stability window of 0 – 3 V vs Na/Na+, thus making them perfect for the usage of metallic sodium [1]. Moreover, they can easily be processed by dissolution and precipitation, which allows for advanced processing techniques.

In this contribution, we are going to present the application of screen-printing for the processing of all-solid-state SIBs based on hydroborates. This technique is especially suited for producing customized cell SHAPES AND sizes, while manufacturing the cells layer-by-layer. A glovebox system consisting of three interconnected boxes for paste preparation, material printing and cell assembly will be used to simulate an encapsulated process chain. We will show the printing process of electrodes as well as separators and first morphological and electrochemical results for these components.

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Dry Coating – is it really a benefit to more cost efficient and sustainable battery production?

Noah Rieple
P3 automotive GmbH

With the increased demand for lithium-ion batteries for electro mobility and stationary storages, concerns about high energy consumptions during battery production arise. In particular the energy intensive drying process to evaporate the solvents after coating of the electrodes contributes significantly to the manufacturing cost and carbon footprint. By employing PTFE (Polytetrafluoroethylene) or alternative binder systems, the toxic solvents can be eliminated using a dry coating process and the energy consumption can be significantly reduced. Furthermore, the dry coating approach allows for thicker electrode layers and, thus, higher energy density of the battery cells. This presentation will give an overview of current market developments and shed light on the current challenges associated with dry coating, in particular the issues associated with the impact of lithium loss on the cell design due to PTFE side reactions, as well as concerns about PTFE supply chain. Will dry coating actually be cheaper than conventional electrode manufacturing? And does it in fact have a positive impact on the carbon footprint of a battery?

Machine Learning in Battery Cell Production

Framework and demonstrator for AI-based quality assessment in battery cell production: an implementation in KIproBatt

Xukuan Xu, Lukas Gold, Simon Stier, Andreas Gronbach, Michael Möckel
Technische Hochschule Aschaffenburg

As process monitoring has made large amounts of data available along the production process in battery cell production, AI-based data processing solutions are increasingly used for early determination of expected product qualities.
Within the project KIproBatt, an implementation of a semantic dataspace for the LIB assembly line at Fraunhofer-ISC for physical sensor data and images has been achieved. The collected images allow the AI-based segmentation of surface defects and to quantify the stacking accuracy of the electrodes during the assembly process. Correlations between process data and electrochemical features are extracted using machine learning methods, from which early quality indicators can be defined.

Improving Yield Through AI/ML Driven Automated Rootcause Analysis in EV manufacturing

K. Ylä-Jarkko, R. Heikkilä, S. AbbasZadeh, A. Liski, M. Krsteski
Elisa IndustrIQ

Implementation of AI/ML methods is necessary for Lithium-Ion Battery (LIB) manufactures to solve the yield issues and high manufacturing costs. Currently up to 40% of the produced cells can be either defective or requiring post-production fixes [1]. Detecting failures within the production process itself poses challenges because the intricate combination of raw materials, physical interactions, and process parameters can only be reliably observed at the final stages of cell production during the formation phase leaving no room for recovery or rectification [2]. This late detection results in the wastage of substantial amounts of raw materials and consumed electricity, leading to significant financial losses.
In our solution we have developed AI/ML algorithms for early classification of battery cells during the formation phase according to their expected lifetime to reduce wastage of raw materials, machine operation time, and energy consumption. After detecting anomalous battery cells our algorithms transform this information into quantifiable knowledge so that actions to continuously improve the productivity of the manufacturing line is possible. Achieving accurate and automated root cause analysis for poorly performing cells during the formation phase is crucial for both profitability and customer satisfaction, as it directly impacts yield and overall product quality. For this we are collecting all the historical factors (raw materials, cell design parameters, process parameters and intermediate product features and measurements) related to the production of the cell in question so that the root cause of anomalous behavior can be harvested from the thousands of variables. Inline automated Root Cause Analysis utilizing interpretable machine learning algorithms and multidimensional discrimination methods can scan through the whole process history consisting of thousands of process parameters and intermediate product features in seconds and provide potential root cause in seconds compared to hours or days it would normally take from analytically skilled process engineer.

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Large area evaluation of jelly roll alignment using machine learning methods

Andreas Kopp, F. Trier, A. Jansche, T. Bernthaler, G. Schneider
Hochschule Aalen I Materials research institute (IMFAA)

Li-ion batteries play a major role in the building of a green and emission-free economy. The quality and lifetime of a battery are mainly determined by the morphology of the electrodes and the stack of electrodes or jelly roll. The distribution of material within electrode coatings, homogeneous coating layers and good cell balance are favorable for a homogeneous current distribution, good utilization of active material, and long life [1-3]. We demonstrate a workflow for analyzing cross sections of whole round cells and large-scale light microscope images. We use machine learning algorithms to segment the microscopy images into Al and Cu current collectors, and the anode and cathode coating. The analysis of the segmented image allows the measurement of the thickness of current collectors, electrode coatings, and the geometry of the jelly roll over the whole sample area by a fully automated approach. Visualization of the results helps identify inhomogeneities and deviations in the battery microstructure and provides important information about the production quality and stability of the production processes. These tools can be used for quality assessment of whole Li-ion batteries or for the evaluation and development of new production processes. As a result of stresses arising during the cycling of Li-ion batteries, the microstructure changes over the lifetime. With this workflow, these changes can also be measured and quantified. The method shown helps to understand the correlation between the microstructure, performance, and lifetime of lithium ion batteries.

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Traceability and Ontologies in Battery Cell Production

Traceability in battery production: Enabling deep insights into the correlation between process and product parameters

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Center for Solar Energy and Hydrogen Research Baden Württemberg (ZSW)

The market for lithium-ion battery applications has grown tremendously in recent years. To serve additional market, further reduction of production costs is essential. By integrating digitization concepts into an automated battery cell production line, the overall costs of battery manufacturing can be significantly lowered by increasing the in-spec production rate. To ensure a trouble-free operation of the production line in combination with a high in-spec product rate, a large quantity of data reflecting both process and product parameters along the whole manufacturing process is mandatory. Automated data collection by integrated sensors provides such information and all data must be stored into a dedicated data warehouse. Such data will then enable employees to make conscious decisions for process improvement already during operation. In this work, we present a tracking and tracing system based on DataMatrix-Code (DMC) implemented throughout the entire batter-cell manufacturing process at our research production line in Ulm (FPL/ZSW). In the electrode coating line, a DMC associated with a timestamp and related process/product parameters is marked on the tab area each 85 mm (see Fig. 1). The position of the mark is stored in a database together with linked production data from the subsequent processes, such as calendering, cell assembly and cell-formation. This data-driven approach enables deep insights into the complex correlation between process and product performance parameters.

Acknowledgements

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Battery Value Chain Ontology (BVCO) – Towards an Ontology for Lithium-Ion-Batteries in a Circular Economy

Lukas Gold, Simon Stier

Fraunhofer Institute for Silicate Research ISC

With increasing requirements from national and European funding agencies for research data management in new projects, the use of ontologies to apply FAIR data principles has become prevalent. Ontologies help structure and define language terms in specific fields of research, facilitating the exchange and reuse of structured research data linked to these terms.

The field of lithium-ion batteries (LIBs) is rapidly advancing, given its significance in enabling carbon-neutral transportation for the 21st century. To harness the potential of artificial intelligence (AI) in LIBs' development, production, and recycling, machine-readable data is crucial. The European Commission recognizes this and imposes regulations, such as the product/battery passport and increased demands for life cycle assessment (LCA).

While existing ontologies like BattINFO (Battery INterFace Ontology) focus on processes within LIBs, our work presents an ontology dedicated to the entire lithium-ion battery value chain, encompassing raw materials, battery cell component processing, assembly testing, battery cell usage, and recycling back to raw materials. Our approach builds on established ontologies like EMMO (Elementary Multiperspective Material Ontology), and BattINFO and introduces GPO (General Process Ontology) and BVCO (Battery Value Chain Ontology) to extend the scope.

Notably, we provide detailed descriptions of the production process, employing a meta-level to capture general production processes and sublevels to account for specific differences in cylindrical, prismatic, and pouch cell production.

Moreover, we are actively working on enhancing process understanding by incorporating input parameters and output characteristics, enabling modeling of the correlation between process parameters and final product performance. This correlation is pivotal for improving production quality, reducing costs and waste, and achieving more economic and sustainable production practices.

Image-based Traceability in Electrode Production

Johannes Lindenblatt, Rüdiger Daub

Technical University Munich I Institute for machine tools and industrial management

The high complexity of lithium-ion battery production is characterized by a large number of process steps with numerous process parameters. Big Data approaches and artificial intelligence primarily drive the resolution of these complex parameter correlations. By creating large transparent data sets from production data, correlations and relevant parameters can be identified, resulting in optimization and increased efficiency of lithium-ion production. While the mapping of production data to individual electrode sections is currently performed by markers, advances in computer vision and computing power offer the implementation of a non-invasive, markerfree solution using camera images. This paper presents a concept of unique identification and assignment of electrode sections using image matching to enable the traceability of electrode sections. Therefore, photos from the pilot production line are acquired in-line, allowing the application and evaluation of artificial intelligence to show the readiness of different classical and learning-based image matching approaches for the traceability of electrode sections.

Material Production and Characterization

Effect of the PEO molecular weight on the composite cathode performances

M. C. Morant-Miñana, J. Martin-Ortiz, J. Blanco, M. Armand, L. Otaegui, A. Villaverde

CIC energi gune

To enter the mass market, the manufacturing of solid-state cathode electrodes needs to ensure continuous lithium ion and electron conducting paths inside the electrodes due to low fluidity of the solid powders present in the mixture. Therefore, special attention must be paid to the manufacturing methods and parameters, which are of high importance for the electrode architecture and consequently, for the cell performance. The electrode uniformity, composition, particle size and distribution are mainly related to the mixing process of the slurry which is affected by the operating variables (volume, intensity, and time) and fluid properties (density and viscosity). In the case of polymeric composite cathodes, the viscosity is highly related to the Mw of the polymer which can be strongly affected by the shear of the technique.

In this study, the effect of the PEO (poly ethylene oxide) Mw on the electrode architecture will be presented. PEOs with molecular weights of 700 kg mol- 1 and 400 kg mol-1 will be employed to maximize the number of contact points among the active material, the conductive additive, and the catholyte. Interestingly, the decrease of the molecular weight of the polymer will allow for slurries with higher solid contents (ca. 50 wt%) that will result in composite cathodes with very smooth surfaces, low porosities but poor adhesion to the current collectors. Finally, the electrochemical performance of each cathode will be studied proving how the viscosity of the slurries will affect the cell cyclability.

Advantages of Particle Size and Shape Analysis for Battery Manufacturing Performance through the use of Dynamic Imaging Technology

Colin Dalton, Tod Canty

JM Canty

One of the most important factors in optimization of the cell performance of lithium-ion batteries is the particlesize distribution of the active material. Small particles with narrow distribution lend themselves well to better cell performance than larger, coarser particles. However, if the active material particle size is too small, it can have a negative effect on the cell performance. Not only is the particle size crucial to the cell performance but surface roughness and shape information is important as it impacts on the packing density and viscosity of the particle slurry.

High magnification 2-Dimensional optical imaging techniques for characterizing particle size, shape and surface roughness are crucial for optimizing the performance of the battery cell. Traditional 1-Dimensional particle counting methods are unable to characterize between particles, misrepresent droplets and bubbles as particles and are unable to provide surface and shape information. They are often limited to off-line lab environments where a process sample is taken to a lab and timely control is difficult. These methods do not provide continual analysis of the battery slurry.

High magnification dynamic imaging through the use of Canty's vision-based systems provides at-line, real time analysis of size and shape of the particle slurry. Critically, the 2-Dimensional system is capable of distinguishing solid particles from other particles/droplets in addition to reporting surface and shape information of the particulates. This reduces the likelihood of characterization errors and enhances reproducibility, repeatability and accuracy. The visual capability allows the user to input his or her knowledge of the process to work in making meaningful analyses decisions. Imaging filters can be applied to the analysis that can distinguish solids from droplets/bubbles, thereby doubling the capability of the instrument over non-visual equipment, which cannot make this distinction.

This paper describes a high magnification dynamic imaging system used for measuring slurry particle size in providing a true 2-dimensional size and shape analysis. The paper will also outline the critical steps in measuring, sampling and analysis utilizing both lab and in-line systems.

Design to cost Ni, Mn and Co-based battery materials for EVs mass adoption in Europe

Guillaume Lefèvre
Umicore

Cathode active materials are the major contributor to EV-battery cost and the key technology lever of their performance. Therefore, it is the critical river of long-term battery technology strategy. So far, two development paths have emerged, performance and cost-effective EV batteries and Ni, Co, Mn-based (NMC) materials are the only technology offering solutions for both. On one hand, high-Ni NMC materials are favoured for design to performance. On the other hand, medium-Ni NMC high-voltage as well as promising High-Li and Mn (HLM) materials are favoured for design to cost.
Umicore as a global leader in the battery cathode active materials manufacturing space with over 20 years of experience, is developing NMC materials to serve automotive customers. This talk will deep-dive on Umicore's design to cost roadmap which offer competitive solutions for various metal price scenarios without jeopardising performance. Particular attention will be given on High-Li and Mn (HLM) materials which benefit from NMC supply chain and prospects of high recycling value. It will be demonstrated why they attract the interest and development efforts of cell makers and OEM for low-cost EVs.

Innovations in dry and wet electrode production

Exploring the IR Drying Process in in Li-Ion Battery Electrodes; an experimental and computational chemistry approach

Larisa von Riewel
Hereaus

The drying of electrodes is an essential and limiting process step along the manufacturing chain of lithium-ion batteries. Electrode properties and process speed are significantly restricted by heat and mass transfer mechanisms in conventional convective drying. To overcome these problems, we considered infrared radiation (IR) as a promising approach.
Consequently, we investigated the IR drying as a complementary technology to the current convective drying methods in Li-Ion battery manufacturing process, with focus on enhancing the production speed lines while keeping or even improving the quality of the electrodes after drying. Furthermore, we developed integration options to improve drying process using IR as a booster or retrofitting the existing convection ovens and checked the performance of the cells.
Specifically, we investigate several parameters like cracking, binder migration, adhesion of active layer onto the substrate and lifetime as a function of distinct slurry drying rates (low or high) for both anode and cathode.
Our results are based on experimental tests and analytical studies performed in the lab and on production lines. Furthermore, we gained a fundamental understanding of the governing processes performing microscopic simulations of the slurry drying process using multiscale-simulation methods from computational chemistry.

Multilayer Slot Coating - Opportunities for Battery Electrodes

Harald Doell
TSE Troller AG

Premetered coating in the slot format is an attractive method to apply single or multilayer structures of functional layers to continuously running substrates or in a sheet based process. Single layer slot coating in the meantime is well known and recognized in order to apply very thin layers in the field of organic electronic and very precise layers in the field of batteries too.
The main advantages of premetered coating methods shall be repeated hereunder:
· Coat weight or film thickness is well specified within operating range of process
· Formulation changes or changes of operating conditions do not affect average coat weight
· Reactive liquids (multi- component) systems can be coated even over longer campaigns
· Excellent uniformity of coated film in both, cross-web and machine direction
· Multiple layers coated simultaneously
The possibility to apply multiple layers simultaneously was very common in the photographic industry for several decades. These structures of sometimes ten or more layers were coated in one coating pass mainly to fulfil economical requirements but also for technical reasons. In general multilayer coating methods are attractive in different aspects:
· Functions of complex layers can be split into mono-functional structures. Thus chemistry of the single layers can be less complex and less compromises in the design have to be accepted
· An optimized structure of the coated film including specific functionality can be coated
· Thin and ultra thin individual layers can be achieved
· Usually it is more economical to apply multiple layers simultaneously than one by one, even when the investment cost for the equipment is higher and maybe the coating speed is lower
· The multilayer coating methods are well known and understood
One motivation is to develop battery cells with lower weight at comparable capacity or higher capacity at similar weight. Other opportunities are using different materials in the individual layers to optimize for example binder migration or other features of single layer structures.
Coating of multilayer structures of course is only one part of the process, drying is another important step. Due to the mostly present requirement to evaporate the solvent of the bottom layer through the entire package the layer structure, the selection of solvents and the drying process itself is important to develop too.
TSE Troller has a long experience in supplying multilayer coating dies. For feasibility tests there are narrow dual layer slot dies available which can be used either for electronic and optical layers with dry thicknesses far below 100nm or also for rather thick layers for battery slurries.

Improvement of dry electrode manufacturing with powder characterization

Salvatore Pillitteri, Marcella Horst, Aurelien Neveu, Filip Francqui
Granutools

Electrode production is a critical step, determining the battery properties. At the start of production, raw materials are generally mixed dry in powder form and then added to a solvent to produce a slurry. This slurry is spread on a current collector to create an electrode. However, new dry processes are more and more preferred for ecological and financial reasons. In these processes, no solvent is used, and the powder material stays dry from the beginning to the end. In such cases, the flowability of the powder material is a new parameter to consider. Consequently, powder characterization becomes more and more important for electrode manufacturing improvement.
Polytetrafluoroethylene (PTFE) is a polymer binder that shows good results to produce electrodes in dry processes. This binder is added in powder form to the active material and the conductive additive. The powder blend is mixed and undergoes stress to fibrillate the binder, creating fibers of PTFE between particles. After fibrillation, a thin film is produced from the powder blend and connected to a conductive sheet to create an electrode. The length and the number of fibers depend on the mixing conditions and are responsible for the consistency of this film. Adequate consistency of the electrode film is important for subsequent process steps to avoid errors in battery performance. Moreover, the flowability of the powder blend is also changed due to these fibers. Therefore, it is important to characterize the powder material during the mixing step to evaluate the fibrillation rate.
In this work, we investigated the effect of the mixing time during fibrillation on the powder properties. Powder blends were prepared with lithium iron phosphate (LFP), carbon black, and PTFE and mixed during different mixing times at a constant mixing intensity. The powder density and packing dynamics were measured with a tapped density method (GranuPack, Granutools, Belgium) as well as the flowability with a rotating drum method (GranuDrum, Granutools, Belgium). Changes in these powder

properties were observed to be affected by fibrillation. Therefore, we highlight in this work that adequate characterization methods to evaluate fibrillation will help in improving dry processes for electrode production.

Investigation of Electrochemical Performance and Morphology of Multilayer Electrodes with Graded Porosity

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Multilayer cathodes (electrode composed of multiple stacked layers) have emerged as a promising approach to enhance the electrochemical performance of Li-ion batteries. [1] One of the key advantages of multilayer cathodes is their ability to mitigate the specific limitations that typically occur in single-layer cathodes. Using multilayer electrodes with graded porosity both energy and power density can be improved. To improve the power density, it is beneficial to have a higher porosity near the separator which increases the transport rate, while maintaining a greater amount of active material towards the current collector will help retain a higher energy capability. [2,3] But this can be achieved only with the correct porosity grading, and this is why it is important to investigate the morphology of electrodes, because by understanding it we can optimize the design.
In this work we report manufacturing of graded porosity (bi-layer) electrodes while keeping constant parameters such as areal capacity, thickness and overall porosity. The bi-layer electrodes are tested and compared with a reference single layer electrode. The porosity of bottom layers varies from 10% to 35% and the top layers from 35% to 42% with an overall porosity of 35%. Also, electrodes with other parameters, e.g. different overall porosity or thickness are manufactured and tested. Optimized recipe of NCM 622 as active material and PVdF as a binder is used for electrode processing, while coating of the electrodes is done using doctor blade. Coating and calendaring of electrodes is done in two steps. The first step is coating and calendering of the first layer and afterwards on it the second layer is coated and calendered. It is important to note that at this step the manufacturing process for these advanced electrodes does not require any new equipment, but for a later scale up some equipment adaption might be needed. Different methods are used to study the properties of the electrodes. For tortuosity studies ELCells are prepared and measurements are done using electrochemical impedance spectroscopy (EIS). Half cells (coin cells) with lithium metal as anode are prepared for rate capability tests. Pore size distribution, conductivity measurements and adhesion tests are also carried out and compared with single layer reference electrodes.
This work discusses the influence that graded porosity electrodes have on electrochemical and morphological properties e.g. rate capability, cycle stability, pore size distribution and tortuosity.

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Recycling I (Disassembly and environmental impact)

Process Development and Characterization for Automated Disassembly of End-of-Life lithiumion Batteries Achieving Efficient Recycling

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Disassembly of lithium-ion batteries (LIBs) which in End-of-Life phase is a crucial step in the pretreatment processes of LIBs recycling and requires efficiency in order to achieve adoption within industrial processes. Necessary are high purities as well as material separation rates of recycled active materials. Up until now, research addressed the dismantling of spent battery packs into modules, which are later shredded and separated in (pyro-)chemical processes. However, there is limited investigation into module and cell disassembly in the LIBs recycling field, particularly in the context of automated approaches for cell disassembly to enhance the effectiveness of subsequent chemical treatments.
This research focuses on the identification of the structure of various commercial battery cells using CT scans and establishes a general model for structural description of the cells. Based on this model, an analysis of the theoretical processes for disassembling different cells and separating their components is conducted, leading to the development of automated disassembly process concepts. Selected cell types are subsequently disassembled in partially automated procedures and different components are characterized with the mass variation analysis. The study quantitatively investigates the disassembly processes, evaluating parameters such as disassembly time, cost, and potential for automation. Moreover, the presented work introduces a reverse production process model, contributing to the expansion of LIB recycling regarding the depth of disassembly processes. With the topics explored within this research, the feasibility and potential of novel automated disassembly procedures at cell level are investigated, providing insights into improving material recovery and achieving higher recycling rates.

Closing The Loop For Lithium-Ion Batteries In Europe? Opportunities And Challenges

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TES Sustainable Battery Solutions is one of the very few recycling companies who was able to fully close the loop for Lithium-Ion batteries in Asia. One of our client's new handphone batteries have now recycled battery material from their old phones included. While this is amazing, is this also possible already in Europe? If not, why is this? Additional questions to be discussed are the different battery chemistries we have and will have in Europe. How will they be recycled if the valuable metals in future EV batteries are reduced to a bare minimum? Those questions and related opportunities and challenges in battery recycling will be shared and discussed.

Retired Electric Vehicle Battery Disassembly Demo Line

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Amidst the global land transport electrification, the demand for high voltage lithium-ion (Li-on) battery is expected to grow 30% annually from 2023 to 2030 to reach a market size of 4.7TWh. At the end of a Li-on battery's useful life – typically after 8 – 10 years, the retired battery still has much residual performance and value. The increasing focus on sustainability has driven development towards reusing (back to the same application), repurposing (for other applications) or recycling (material value recovery) retired batteries. The end-of-life (EOL) pathway primarily depends on the state-of-health (SOH) of a battery, on top of economic and environmental considerations. With an expected increase in EOL batteries over the coming years, there is an urgent need to develop solutions to improve the efficiency of EOL battery processing.
In Singapore, strong regulatory push by the government means that by 2040, there will be an estimated 10 GWh of EOL EV batteries annually. Regardless of its EOL pathway, an EV battery typically undergoes pre-processing – including disassembly, diagnostics, and sorting. Most current processes are performed manually, resulting in low productivity and poor safety. Given Singapore's small land area and high labour costs, we propose to introduce modular disassembly cell design and increase the automation level especially during disassembly. With this objective, we designed and built a conceptual modular disassembly system to demonstrate the disassembly and testing of an EV battery (Nissan Leaf Gen 2, Nissan) – from pack to cell level. To improve the safety and productivity, we integrated numerous technologies and solutions in our demonstration system. A few of these are highlighted below.
The first is to implement automation for repetitive unbolting and pick-and-place tasks. Contrary to assembly, a key challenge in disassembly automation is the required flexibility to address varying input components. Batteries have various models and designs, with different fastener sizes and locations. We developed a vision-guided unbolting process to address the varying conditions. A vision system attached onto the robotic arm first captures images of the battery. A pre-trained shape identification algorithm detects the bolts and transmits their pose information. The robot arm then moves to the respective locations and

executes the unbolting tasks with an unbolting end-of-arm tool (EOAT). We have achieved >95% detection accuracy and process reliability. In addition, we have implemented automation to the general pick-and-place of components, such as brackets, bus bars and modules.
Secondly, on difficult-to-automate tasks, we have implemented virtual reality (VR) solutions to aid in manual disassembly. These tasks include wire handling, bus bar removal and connector removal. Through wearing a VR headset, the operator would be able to perceive a 3D rendering of the battery and follow the pre-programmed disassembly instructions. Finally, we have introduced autonomous mobile robots to improve the cell modularity. Flexibility in material transfer between the disassembly and testing stations will greatly improve the capability to handle batteries of different designs and batch sizes.
In summary, our conceptual EV battery disassembly system managed to reduce process time by more than 50%. Despite the progress, many challenges remain in disassembly. A higher automation level is desired. We will develop more robotic EOATs to execute tasks such as connector and wire cutting, and small item pick-and-place in constrained environment. To implement vision guidance more reliably, a deep learning model could be considered. This potentially allows the detection of previously unseen odd-shaped components, and could classify the EOL condition of the components.

Challenges and Strategies for Sustainable Recycling of Lithium-Iron-Phosphate-Batteries (LFP)

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The world of batteries is in a state of flux. Only a few years ago electric vehicles were not deemed viable for the future, e-bikes were considered to be purely for senior citizens, and stationary battery storage systems were a niche product. Nowadays, however, not a week goes by without hearing about a project to build a gigafactory for manufacturing cells, owning an e-bike is part of a sustainable lifestyle, and the demand for battery storage systems can no longer be met. If we put the above into figures, this means that in Europe the number of new electric vehicles on the road will rise from approx. 2,200,000 currently to 6,500,000 by 2026. In the same period, e-bikes will more than double – from 5,000,000 to around 11,000,000. And the quantity of home energy storage devices will treble from 300,000 to 900,000.
Besides the increasing demand for batteries, the most common cell chemistry has also changed. Whereas NMC technology used to be seen as the undisputed pioneer, LFP technology is now gaining ground. The rising demand and growing supply of battery products is certainly welcome. However, there are many questions concerning the retention and recycling of batteries that still need answering.
• In Europe, there is currently insufficient recycling capacity available for lithium-ion batteries (LiB), and too few projects are being planned to cope with the rising quantities.
• Recycling technologies in use today concentrate first and foremost on NMC batteries and are not suitable for LFP batteries.
• It still remains to be seen how EU regulations can be implemented and achieved regarding the use of recycled materials.
To be in a position to answer these questions, GRS Batteries has developed a concept for recycling LFP batteries the "Green Mass Project". This concept encompasses the complete recovery path, from recycling to new production. The primary objectives are as follows:
• Processing and recycling of LFP batteries and the recovery of lithium.
• Proof of the feasibility of using recycled lithium for the production of new batteries.
• Introduction of a certification method to verify that recycled lithium has been used in the production of new batteries.

Solvent-free and Solvent-reduced Electrode Production

Printing technology as green alternative for Li Ion Battery electrode production

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The need for more ecological and sustainable production technologies is a general demand for competitive battery manufacturing factories in the future. The energy consumption and carbon dioxide emissions are cost-driving factors and at the same time have high increasing social impacts. Solutions for making electrode production greener can be realized by avoiding or replacing toxic and harmful materials, e.g. by aqueous processing. Also less solvent requiring processes may lead to less extensive drying efforts. Screen-printing technology for electrode manufacturing combines both environmental benefits and enables for thick film electrode production with high areal capacities especially for high energy cells (up to 5…8 mAh/cm2). In this work it will be shown that the solvent amount can be decreased by about 20% by processing of highly filled pastes. In addition, it is possible to enable a multilayer printing and therefore sequential and fast drying as well as near-net-shape printing leading to less waste upon production. The thickness and high areal capacity of the printed coatings lead to new design aspects of the electrode structure affecting full cell performance. Some insights will be given with regard to current-rate capability, useable capacity, porosity and efficiency of ion-exchange pathways. The screen-printing process is a scalable and established series production technology. The high accuracy, energy efficiency and low emissions are strongly in line with the goals of green production.

Assessment of high-mass-loading NMC and graphite electrodes produced via dry electrode manufacturing

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Empa

Dry battery electrode (DBE) manufacturing is emerging as an alternative technology to wet electrode manufacturing, widely employed in the lithium-ion battery industry today. DBE manufacturing eliminates the need for toxic solvents in electrode production and the energy-intensive drying step, thereby reducing the environmental impact of electrode production and cutting through large capital expenditures in factories.[1,2,3]
Within the scope of the InnoSuisse Flagship project Circubat,[4] we develop a DBE manufacturing process for NMC and graphite electrodes. Our DBE manufacturing process consists of two steps: (1) mixing of electrode active materials, polytetrafluoroethylene (PTFE) binder and conductive additives in a twin-screw extruder; (2) electrode film formation from the dry mixture using calenders with differential roller speeds and lamination onto current collector foils.
In this tandem presentation, we demonstrate that our extrusion-based DBE technology can produce electrodes with an areal capacity of 5 mAh cm-2 or more. Electrodes are characterized in terms of their microstructure and electrochemical performance in lab-scale batteries, encompassing key aspects such as rate capability and capacity retention. We make a comprehensive comparison of the DBE electrodes against wet coated electrodes fabricated using identical active electrode materials, mass fractions, and mass loading.[5] We conclude with an outlook on the scalability of the DBE technology, with the ambition to translate our promising laboratory results to gigafactory scale.
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Solvent-free process for the roll-to-roll production of nickelrich cathodes for LIB

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Climate targets lead to a continually growing demand for lithium-ion batteries (LIB) produced by energyefficient processes with a low CO2 footprint. In state-of-the-art production, LIB cathodes are produced by wetcasting of suspensions containing the hazardous, toxic solvent N-methyl-pyrrolidone (NMP) which has to be evaporated and recovered. By a solvent-free electrode production process, as much as 12,900 metric tons of CO2, 4,100 metric tons of NMP and more than 42 million kWh of energy can be saved per 100,000 PHEV battery packs with state-of-the-art chemistry per year.[1]
Solvent-free processes described in literature or patents usually demand a preceding production of granulates[2] or several additional production steps[3-4]. In this contribution, we present a highly efficient, continuous and industrial-suited process for the solvent-free production of nickel-rich NCM cathodes for LIB. In our process, a flat cathode composite is generated from

a mixture of loose powders by extrusion through a slot die and is transferred directly onto an aluminium current collector run roll-to-roll.

However, the innovative process entails special challenges. Measures to encounter them are presented and the impact of process parameters on the quality of the electrodes is analyzed. The functionality of the solvent-free process is demonstrated at the example of a double-side coated electrode with high areal capacity produced roll-to-roll. The composite is thinner than 200 µm per side containing as much as 89 % active material. In galvanostatic cycling, the electrode shows good utilization of the active material and an adequate rate capability. References

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Sustainability in Battery Cell Production

A blockchain platform demonstrator to increase transparency and to enhance more sustainable battery material value chains

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The rapid growth in battery production capacity to meet the increasing demand for electric mobility and energy storage solutions leads to significant environmental impacts. To address this challenge, there is a need to enhance the development of sustainable battery value chains. Various legal and corporate initiatives address this need, for example the German Supply Chain Act or the EU Battery Regulation. As a result, a quantification of environmental impacts connected to the battery production and single batteries is necessary. On the one hand, this requires more transparency along the entire value chain and, on the other, a valid database. Recent literature indicates high variances in environmental assessment results due to changing production routes and material supply. However, availabe dataset are currently mostly based on assumptions and generalisations. Hence, the existing do not suffice for reporting of environmental impacts of batteries from varying value chains due to the lack of representativeness and data gaps. Against this background, the talk will emphasize the potential of blockchain technologies to increase data transparency in battery material value chains. It will present recent results from the BMBF-funded project SUSTRAB, that develops a platform to demonstrate how blockchain technologies may be used to provide verified and consistent datasets, as well as to automate reporting mechanisms. At the example of lithium production, an overview of variations in material production routes and accompanying environmental impacts will be given and exemplary data transactions to the proposed platform concept will be presented. This takes into account the issues of data privacy, governance and levels of aggregation. As an outlook, the talk motivates to develop mutual solutions for an improved crossorganisational data exchange, to achieve transparency on environmental impacts and thus to enable a fair comparison of products.

Advancements in Cost-Efficient and Sustainable Li-Ion Battery Manufacturing: Insights from the BatWoMan Project

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The overall goal of BatWoMan is to develop innovative, cost-efficient, and sustainable Lithium-Ion battery manufacturing concepts. This presentation provides insights into new approaches and technologies pursued by the BatWoMan project, highlighting their potential to contribute significantly to the European Union's ambitious goal of achieving a carbon-neutral energy storage system production, while fostering economic viability and environmental sustainability.

BatWoMan focuses on three main technology efforts. Firstly, the development of energy-efficient processes for electrode manufacturing, eliminating volatile organic compounds and preparing highly dry mass containing slurries up to 70% and 80wt% for anode and cathode, respectively.

Secondly, the project is implementing innovative dry room-reducing concepts that lead to much lower cell production costs, and drastically reduce the carbon footprint of the whole battery manufacturing process, since the dry room operation is a massive cost driver considering the whole battery production value chain. Depending on the production line the costs for the dry room operation can reach 30% of the total production line costs [1]. A battery data space, providing relevant information of the materials and the carbon footprint of the individual production steps, is created to ensure the traceability and state determination of the produced battery cells for costumers and second life users.

Lastly, the BatWoMan project establishes low-cost and energy-efficient cell conditioning methods including wetting, formation, and aging processes. New three-dimensional electrode designs improve the cell conditioning steps and ensure the optimal performance and extensive lifetime of lithium-ion cells. By developing these approaches, the project enhances the overall sustainability and economic viability of future greener batteries at cell level.

This way, BatWoMan will lead to an estimated cell production cost reduction of 63.5% and cell production energy consumption reduction by 52.6% and therefore enable a European leadership position in sustainable battery production.

Acknowledgments

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A critical evaluation of system implications on the environmental targets of the new EU Battery Regulation

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The European passenger car sector is transforming towards battery electric vehicles to reduce CO2-eq emissions and meet climate targets. However, necessary battery production is resource and energy intensive and uses many materials such as Lithium, Cobalt, and Graphite which are critical in the European market. This results in a shift of the product-related impacts from the usage towards the production stage. As a response policy, the upcoming EU Battery Directive forces the usage of recycled materials from spent batteries in new batteries to limit materialrelated CO2-eq emissions and material criticality. Many parameters influence the availability of recycled materials and its usage in new batteries.

Current approaches are often based on "black-box-models" to quantify the availability of recycled materials in different markets which limits the consideration of spatial, product and process-specific differences and the environmental potential of the recycled materials. Further, Life Cycle Assessment studies often consider detailed descriptions of underlying processes for specific battery production and recycling routes but missing an overall market perspective over time to include the availability of used batteries. Hence, integrating different assessment models is necessary to quantify the amount of recycled materials used and its potential to decarbonize EUs transport sector.

Our approach combines country-specific vehicle market models based on a System Dynamics approach with detailed battery production and recycling Life Cycle Inventories to quantify material flows and stocks over time. Based on these quantities, available recycling technologies and underlying efficiencies are used to quantify the material-specific recycling material flows. Afterwards, the future recycled material share in new batteries is calculated and compared with the targets of the upcoming EU Battery Directive.

The assessment of different scenarios supports future policy decisions and the identification of critical system components throughout the transition towards circular battery production. In summary, our approach and results enable the review of the current legislation regarding their ambitions and feasibility, and evaluate the environmental impacts of primary and recycled material shares in circular battery production from an overall market perspective.

Electrode, Cell and Module Diagnostics

Inline X-ray Metrology for Battery Cell Production – Possibilities, Limits and Contribution to Process Improvements

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X-ray systems are currently widely used in different applications, offline as well as inline. Typical features to inspect are e.g., the overhang of the anodes compared to cathodes, the overall alignment of jelly roll or stack, wrinkled electrodes, particle contamination among others.

In battery cell production environments typically 2D x-ray imaging is used independently of the cell format, to keep the cycle time of the production line. This is a feasible approach typically only for wound cells since they are rotational symmetric. The disadvantages of using 2D imaging are acceptable for wound cells.

This is a completely different story with stacked cells. The common testing approach is here to capture 2D images over a corner. The number of electrodes has a very high influence on the recognition of electrodes in the image. The more layers of electrodes are used in a stack the more disadvantageous this method becomes due to the parallax effect of the x-ray beam. This can be overcome by a fast inline CT that captures the cell in 3D and analyzes slices of this volume in more than one dimension.

The biggest challenges here are the requirement to meet typical cycle times as well as providing a solid absolute accuracy as well as repeatability of the results, which means having a local resolution of the entire systems that allows to qualify the x-ray image chain as a measurement system following typical MSA rules, e.g., VDA5.

Reliable results from the x-ray inspection systems contribute to overall process improvements on yield and efficiency. If all results are being used in a digital process model that acquires data from the entire production floor and cross correlating x-ray results with machine parameters and maintenance status of the other involved machines as well as raw material data, production drifts can easily be detected as well as the necessity of parameter changes.

Normal inspection methods allow for only single product evaluations while the approach of proven metrology systems allows process control and characterization of the entire production process. This is achieved by not only distinguishing between good and bad, but rather by characterizing defects into different classes and observing these classes not only product by product, but over the entire production cycle.

Detecting and modeling defect structures in battery cells

Alexey Telegin
Keysight

Not every cell that is produced will be a good cell. Various defects can appear in the cell, introduced by material or process problems as the electrodes are made, as the cells are assembled and filled, and as they are put through the electrical steps during formation and aging.

For R&D: Early detection of defect structure means shorter time to discovery of what causes defects.

For Manufacturing: Early detection of defect structures in the cells means that cells can be pulled out of the mainstream process flow sooner, resulting in less wasted resources spent on sending bad cells through the long formation and aging process steps. Furthermore, early detection and removal of defective cells increases factory safety as those defective cells are not subjected to the electrical steps during formation.

This presentation will explore 3 measurement technologies that can be used for early detection of defect structures in cells:

1. High Voltage Separator Defect Detection
2. Electrochemical Impedance Spectroscopy (EIS)
3. Direct Self-Discharge Measurement (SDM)

Using a sophisticated physics-based model of the cell, these measurements can be analyzed and interpreted to determine if defect structures exist in the cell.

Why the Xray source matters for high-resolution CT

Mats Sjöstedt
Excillum AB

To get better higher yield and OEE in the production the Battery imaging is a growing field for x-ray inspection, both for high-speed inspection in production lines as well as for research and development. With recent developments in liquid metal high-power x-ray tubes, 3D battery inspection with scan times in the second range is becoming possible. Advance high-resolution imaging for industrial inspection has been made possible using the MetalJet Xray source. Here we demonstrate what us unique with the MetalJet technology and how this enables 1-second CT scanning of an EV battery cell. We will share how a MetalJet E1+ with an emission power of 1 kW and 30 µm spot size enables that the battery cell can inspected in almost the same pace as the production of the battery cell.

Characterization, Formation and Aging

Combined Machine Learning and Electrochemical Impedance Spectroscopy for Battery Degradation Analysis

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Solid-state batteries (SSBs) are considered as one alternative to conventional lithium-ion batteries as they enable safer operation. A detailed look into the reaction kinetics and the possible aging mechanisms of the solid electrolytes (SEs) and the interface of SE and active material at the composite electrodes was of major interest in recent years12. Cell scale modeling and prediction of the cell performance and the degradation however are lacking, although they would offer fast evaluation beyond material-intensive and time-consuming experiments. Besides, diagnosis with non-destructive tests is crucial for the development, design, production and application of SSBs. For example, cells with degradation need to be identified by battery management systems and balanced for the safety of the entire stack.

Herein we characterize a type of commercial solid-state batteries3 using electrochemical impedance spectroscopy (EIS) and train a machine learning model to diagnose their state-of-health (SoH) throughout cycling. The SSBs used have multilayered electrodes with a ceramic SE. To shorten the measurements period, the experiments were conducted with distinct formation and cycling protocols, which leads to faster and various degradation modes during their lifetime. The SoH of the tested SSBs ranges from 40% to 140% SoH for a rated capacity of 200 µAh. The EIS data was collected intermittently between the 5th cycle and the 100th cycle, and was organized into 108 datasets for training and validation. The machine learning (ML) model was then trained by using the EIS data and operating parameters as input values and the SoH during cycling as output property. The EIS data was preprocessed and selected with a feature selection model. Significant features, e. g., impedance data from a certain frequency range, were selected and analyzed qualitatively. The applied feature engineering transfers data from non-gaussian into gaussian distribution, which enables the usage of Bayesian ridge regression algorithms to avoid overfitting. Furthermore, the distribution of relaxation time (DRT) method was adopted to generate equivalent circuit model (ECM) for this SSB type. The equivalent circuit

model of a battery consists of sources in series or parallel connected, e.g., internal resistances, capacitances or constant phase elements. We analyzed the change in resistance and constant phase element at different frequency range to study the aging influence. Despite the manufacturing tolerance and inherent production deviation among the cells, the model achieves a root mean squared error of 2.5% for the SoH diagnose during validation. To predict the future SoH after 10 more cycles, it achieves a root mean squared error of 2.7%. Furthermore, the feature analysis reflects the dominating changes in certain frequency ranges. The tested SSBs have stronger correlations between the impedance in the high frequency range and their SoH prediction.
All in all, the herein presented work highlights the promise of combining data-driven modeling with EIS characterization to predict the performance of complex electrochemical systems, and can be expanded to other cell geometries and further battery technologies.

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Investigation of Li Plating and Fast Charging for Li-ion Batteries with a Physico-chemical Modeling Approach Complemented by Electrochemical and Optical Operando Experiments

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Fast charging plays a crucial role in meeting the demands of lithium-ion batteries in automotive applications. The successful implementation of electric vehicles relies on the design and development of appropriate battery cells and charging protocols. However, fast charging presents a significant challenge due to the risk of lithium plating, which can lead to capacity loss, decreased performance, and safety concerns.
In this work, we propose a physico-chemical modeling approach to analyze lithium plating and fast charging strategies for lithium-ion batteries. Our approach integrates electrochemical and optical operando experiments to complement the model.
The modeling framework builds upon the commonly used Doyle-Fuller-Newman approach and extends it with a surface reaction model specifically designed for lithium plating. This model captures both the plating and stripping reactions as side processes to intercalation, distinguishing between reversible and irreversible plating.
To validate and parameterize the model, we conduct optical operando experiments using an optical test cell and a light microscope. Alongside electrochemical measurements, these experiments provide valuable information on the reversible and irreversible plating behavior. Key aspects include the onset of lithium plating, reversibility, plating and stripping kinetics, and the quantification of plated and stripped lithium.
Furthermore, we investigate various fast charging protocols using the developed model to assess the risk of lithium plating under different operating conditions. We also analyze the impact of general cell aging on charging behavior, a crucial factor during battery use. To address this issue, we propose an age-adaptive fast charging strategy, which is compared to a corresponding static charging protocol.

What conditions have to be met for EIS-Measurements to be valid? General remarks from the field

Julia Berlin
BioLogic

Electrochemical Impedance Spectroscopy continues to become more and more important for battery testing. The next trend is to automate measurements and analysis. But for measurements to be valid, caution must be taken that these are recorded under valid conditions, especially when no human eye has a look over the results. This talk gives an introductory overview of the four validity criteria of impedance measurements and shares tipps and tricks from the field how to decoy invalid experiments and reach proper analysis results fast.

Inline-analysis and Water Effects in Electrode Production

Rheological Design of Battery Electrode Slurries

Carl Reynolds, Giar Alsofi, Halima Khanom, Emma Kendrick
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Battery electrodes are manufactured industrially by coating slurry onto a foil current collector. The rheology and surface properties of the slurry are key to determining the final coating microstructure, and the choice of coating process (slot die, blade coating, 3D printing) changes the requirements for the slurry signifcantly. Here, we discuss the key properties required for coating via these different processes, and define design principles for the slurry rheology, using experimental results to show the impact of rheology on the coating manufacture. We then discuss formulation approaches, demonstrating changes in additives, weight solids and binder systems, that can be used to achieve the target slurry rheology. By designing the rheology of the slurry, the coating process can be optimised and multi-level structuring from particle to coating can be achieved, improving performance, sustainability and efficiency of manufacturing.

Inline Quality Measurement in the Continuous Mixing Process as a Key for a Steady and High Product Quality

Thorsten Stirner
Coperion GmbH

Coperion offers contained systems for the continuous production of battery electrode slurry: from bulk material handling to high accuracy feeding and mixing. The continuous mixing process using a twin screw extruder offers significant advantages compared to the conventional batch process such as material efficiency, reduced solvent content, process stability as well as flexibility. By combination of dispersive and distributing mixing, the extruder generates a very homogeneous coating paste. Due to the self-cleaning design of the extruder, cleaning is reduced to a minimum as well as downtime compared to the batch mixing process. To make full use of all benefits a continuous quality control of the product is essential. Common inline measurements comprise the density, viscosity, and particle size distribution. A new possibility is spectrophotometry. By measuring the colour of the slurry, predications about homogeneity, composition and consequently the process stability is ensured.

Post-drying: simulation and experiments of micro- and macro-scale mass transport

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For competitive battery cells, an important prerequisite is energy savings in the cell production. An essential cost factor in the manufacturing process of Li-ion batteries poses the humidity management and the post-drying process. In this post-drying process, moisture adsorbed from the air gets removed from the compounds of thhbre battery by a high energy input. Otherwise, the absorbed moisture reacts with the electrolyte during the operation of the battery, leading to its degeneration. Literature has revealed a connection between electrochemical performance and the remaining moisture content. To remove the moisture cost efficiently from the compounds of the battery, this process step needs to be thoroughly understood. Therefore, a precise and comprehensive simulation along with knowledge of the sorption equilibrium of water and the kinetics of mass transfer reveals optimization potential of energy consumption and process acceleration.
This work investigates the water mass transport in porous electrodes during the post-drying experimentally and theoretically. Time-resolved drying curves are measured with a magnetic suspension balance at variable temperatures and pressures. Furthermore, as physicochemical basis for transport phenomena, sorption equilibria of the compounds of a Li-ion battery have been ascertained and provide the basis for the interpretation of the drying curves.
The focus lies on the influence of the micro- and macro-scale that are relevant for the desorption processes during post-drying. The micro-scale e.g., the hydrophilic, polymeric binders and the macro-scale e.g., the gas phase of the porous electrode are combined into a simulation model that accounts for transient mass-transport phenomena on both scales. Precise drying experiments validate this simulation. The presented results provide the basis for modelling post-drying and sorption processes during moisture management at an industrial scale.

This work contributes to the research performed at CELEST (Center for Electrochemical Energy Storage Ulm Karlsruhe) and Material Research Center for Energy Systems (MZE). The authors would like to acknowledge financial support of the Federal ministry of Education and Research (BMBF) via the ProZell cluster-project "Epic" (Grant number: 03XP0295A).

Production of SSB Cells

Influence of Pressure in ASSB Assembly: Scalable Concepts to Improve Cell Performance

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Technical University of Munich

Sulfide-based all-solid-state batteries (ASSBs) promise higher safety, longer life cycles, and higher energy densities compared to conventional lithium-ion batteries. However, their commercialization faces multiple challenges, one of which is inadequate cycling performance due to interface issues between the all-solid components. Multiple assembly strategies exist to tackle these problems. Lamination of two or more layers can be used during production to increase the contact area between components. Different methods to compact single components or laminates exist and must be evaluated thoroughly on their influence on cell performance.
This talk aims to present scalable strategies to improve the cell performance of sulfide-based ASSBs by implementing lamination and other methods of compacting one or multiple components. The implementation of these concepts in multi-layer batteries will also be covered in this scope. The concepts presented build on the initial experimental investigations that have already been carried out. These include the lamination of components by uniaxial pressing on a laboratory scale and the electrochemical analysis and cycling of pouch cells built with these. It was shown that laminating sulfide-based composite cathodes with a sulfide-based separator significantly improves the cycling stability of the cells compared to cells built without a lamination step.

Development of a scalable production process of sulfide-based solid electrolytes and characterization of product properties

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Fraunhofer Institute for Surface Engineering and Thin Films IST

On the way of developing and establishing all-solid-state battery (ASSB) technologies on a larger scale – especially those based on sulfide-based solid electrolytes – the demand for industrial production processes highly increases [1-3]. Currently, there are many challenges and the upscaling of the solid electrolyte (SE) synthesis for sulfide-based ASSB is a key challenge, due to low material availability and lack of processes. Aiming at the availability of high-conductive SE, the focus of this work was to evaluate and establish a scalable and continuous mechanochemical process for the synthesis of sulfide-based SE.
Sulfide-based SE are currently being researched with high effort because of their very high Li+ conductivity and suitable mechanical properties in ASSB electrodes, but their syntheses are mostly reported with long process times and they often require toxic and inflammable solvents [1,2,5-7]. In a previous work [8], the solvent-free mechanochemical synthesis of Li_3PS_4 was investigated and highly optimized in lab scale via high energy ball milling. A deeper understanding of process-structure-product-relations was gained by experiments and associated simulations of stressing conditions with the discrete-element-method (DEM). The insights of the experimental and simulation results revealed a direct correlation between the stressing conditions at different parameter sets and the obtained product properties.
In this work the upscaled mechanochemical process for Li_6PS_5Cl, suitable continuous processing strategies in scalable mill types and material properties in different production atmospheres and after varied post-treatments are presented, to further facilitate the industrial production of ASSB.

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Challenges of Compressing Sulfide-Based Separators for Solid-State Batteries

Carina Amata Heck, Timon Scharmann, Markus Osenberg, Alexander Diener, Ingo Manke, Peter Michalowski, Arno Kwade
TU Braunschweig I Institute of Particle Technology (iPAT)

Solid-state batteries are a promising advancement over conventional lithium-ion batteries by replacing the liquid electrolyte with a solid material to improve safety and power density. Compared to oxides and polymers as potential electrolyte materials, sulfide-based electrolytes offer the highest ionic conductivity.[1] However, challenges in terms of scale-up of the battery production and high sensitivity against moisture have to be solved.[2] An important process step here is the densification of electrodes and separators to achieve a high power density, as well as high ionic conductivity.
Therefore, basic investigations in terms of a densification of Li_3PS_4 (LPS) and Li_6PS_5Cl (LPSCl) based separators by uniaxial pressing and calendering were carried out. Slurries based on hydrogenated nitrile butadiene rubber (HNBR) as binder and p-xylene as solvent were prepared using a dissolver. Resulting densities, mechanical properties, as well as ionic conductivities were analyzed and correlated with the obtained microstructure, which was investigated by scanning electron microscopy.
For example, LPS separators showed a 26 % improvement of the ionic conductivity by increasing the uniaxial densification stress from 25 MPa to 200 MPa. Due to high embrittlement of LPS in compressed state observed for both uniaxial pressing and calendering, LPSCl separators were found to be more suitable for calendering as an industrial relevant densification strategy. Here, porosity was reduced down to 11 %. However, particle breakage for the tested LPSCl material, as identified by synchrotron analysis, in combination with elastic deformation probably hindered an increase in ionic conductivity due to slight contact loss. To obtain a more detailed understanding, densification of LPSCl was also analyzed by uniaxial pressing. Moreover, this work addresses arising challenges related to temperature impact and layer thickness, as well as possible solutions to facilitate the scale-up of sulfide-based solid-state batteries.

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Industrial Session

Production of dosable structured dry battery electrode (DBE) mixes in a one-pot process with Eirich intensive mixers

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Completely dry electrode (DBE) manufacturing is being adopted by an increasing number of battery manufacturers, raw material suppliers and research institutes worldwide due to its obvious cost advantages. Various direct powder-based manufacturing processes such as
•Dry coating with e.g., high voltage induced application of homogenized powder mixtures onto the current collector followed by thermomechanical compression or
•Free standing electrode film formation with fibrillated powder mixtures
are competing for the best technical solution. In all cases, the prerequisite is a homogeneous powder mixture that does not segregate during electrode processing. To achieve this, the mixture usually must be structured so that the properties created during the mixing process are fixed in the mixture. This can be achieved in a first step by coating the active material with conductive additives, which, depending on the mixing intensity, can produce different particle structures that significantly influence

the resistance of the electrode. Any polymer binders required must be incorporated in such a way that they can be processed at least without segregation during powder dosing or powder application or, for free-standing film formation, by fibrillation to form a polymer network in which the active materials and conductive additives are embedded like a spider's web. These elastically plastic mixtures, which behave like a jelly, must be brought into a form that is easy to dose, e.g., in calender gaps.

The Eirich mixer, with its special mixing principle and resulting adaptable high shear forces, can perform particle coating or fibrillation and structuring in addition to particle mixing in the same machine for both anode and cathode. Laboratory and pilot scale trials for dozens of customers on both polarities have demonstrated the performance and scalability of this advanced preparation technology for the future of dry battery electrode manufacturing.

Pilot plant concepts sold and currently in order processing for medium batch sizes around 30-50 kg up to giga-scale pilot plants with 600 kg batch sizes are presented.

Boosting Efficiency and Sustainability: Netzsch's Pioneering Techniques in LFP and LMFP Battery Production

Dr. Maximilian Münzner
NETZSCH-Feinmahltechnik GmbH

LFP (Lithium Iron Phosphate) batteries offer advantages such as a long lifespan, safety, a wide operating temperature range, fast charging, low self-discharge, environmental friendliness, and versatility in various applications.

For the production of LFP and the next-generation LMFP batteries, preliminary grinding steps are necessary to achieve a particle size below d50 < 380 nm before the spray drying process. The current state-of-the-art grinding method involves the use of pin-type mills. However, is this the most optimal approach for production?

Netzsch has developed a new wet grinding process for LFP and LMFP materials. One of the primary cost factors in the production process is the energy consumed during grinding. With the DISCUS mill from Netzsch, energy consumption can be reduced by half while achieving higher throughput. Previous pin mills experienced operational issues due to clogging of external cooling systems. Thanks to the low energy consumption of the DISCUS mill, additional coolers are not required, minimizing downtime and ensuring increased production output. To further reduce required production space, energy costs, maintenance expenses, spare parts, and necessary investments, the DISCUS mills are manufactured in a size of 1200 L.

Following the heat treatment of LFP and LMFP materials, an additional deagglomeration step is necessary to reach the final particle size. Fluidized bed jet mills enable high productivity of 500-1000 kg/h or more with particle sizes below d50 < 1 µm. CGS Jet mills from Netzsch offer significant advantages, including contamination-free and autogenous grinding. The process is continuous due to automatic dosing and discharge through the classifier wheel, giving narrow particle size distributions.

In addition to individual machines, Netzsch also provides complete turn-key solutions encompassing powder handling, transport, control systems, and steel structures.

Introducing the Center of Excellence Battery: Cell- and Battery Development for the Volkswagen-Group

Dr. Dominik Koll
Volkswagen AG

The Center of Excellence Battery gives an introduction to the exciting world of cell- and battery development in the Volkswagen Group. With our young and innovative team we are working at the heart and soul for VWs' transformation towards electromobility. We would like to show you our tasks, portfolio and give a glimpse to what the future has in store for us.

Staying at the Edge of Time: From Analytical Instruments Manufacturer to Integrated Solutions Provider

Julia Berlin
BioLogic.Deutschland

Shaping the Future. Together. Normally, that's what our instruments do for the research of our customers. But in the last 12 months, the continuous requests for automation and integration has transformed our company from providing stand-alone laboratory solutions to providing battery cyclers and potentiostats that can be coupled with various other analytical and software technologies to satisfy the needs for in-situ measurements, integrated solutions and automation. This presentation gives an overview of the different integration approaches we utilized to satisfy different customer demands and solutions that came true because of these efforts. Next step: A vision of the journey to automated high-precision cyclers for pilot-production environments, built by a scientific instruments' provider.

Components for Next-Generation Batteries

Transport Properties of Hard Carbons

Giar Alsofi, Carl Reynold, Luke Sweeney, Emma Kendrick
University of Birmingham

Sodium-ion batteries (SIBs) have gained significant attention as potential replacements for lithium-ion batteries (LIBs) due to their abundant and cost-effective components, as well as their similar working principles. Hard carbons have emerged as the leading anode material for SIBs, offering a balance of cost, performance, and availability. Despite considerable research efforts, the underlying mechanism of HC remains a subject of debate.

To gain deeper insights into the charge transfer mechanism and associated kintetic limitations during the cell's charge and discharge, this study investigates hard carbons at different temperatures. The transitions between stable and unstable phases, which have not been addressed in the existing literature, are observed. By exploring the thermodynamics and kinetics of the cell using techniques such as Galvanostatic Intermittent Titration Technique (GITT) and Electrochemical Impedance Spectroscopy (EIS), valuable insights can be obtained regarding the limitations to ion transport.

EIS, in particular, provides essential information, including the exchange current density, which measures the rates of reaction for sodium intercalation into the carbons, the kinetics has been studied at different temperatures, and the EIS provides additional information upon the time constants associated with the charge transport mechanisms. Furthermore, tthe investigation of different types, and sources of hard carbon will enhance our understanding of the factors influencing cell performance.

The knowledge gained regarding the limitaitons to charge transfer will greatly contribute to the design of more suitable hard carbons, leading to improved overall cell performance in SIBs.

Industry-near processability of sulfurized polyacrylonitrile based electrodes

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Polymer-based sulfur active materials are able to suppress the polysulfide shuttle degrading the capacity of classical carbon-based sulfur materials. This is due to their intrinsic inner structure where smaller sulfur chains are covalently bound to the polymer backbone. The most common of this material class is sulfurized polyacrylonitrile (SPAN) which has an aromatic backbone structure. [1–4] The drawback of these materials, in turn, is the dead mass of the polymer backbone reducing the specific capacity and the energy density. However, the better longterm cycling stability is not the only benefit of SPAN as a sulfur active material. Transferability to established production equipment and scalability of the whole process chain from pristine materials to finished cells is extremely important for the industrial breakthrough of new active materials. For example, during our investigation, water-based SPAN slurries showed very favorable behavior in the mixing stage with a very distinct shear thinning behavior leading to a good sedimentation stability as well as a good coatability. This is further reinforced by a very beneficial complex shear rate behavior.

Besides production parameters the composition and structure of the binder and conductive network was investigated as well. During this research, we found that the structure of this network is essential for the electrical conductivity of the electrode since the SPAN material itself has limited electrical conductivity. Regarding 3Dmaterials classical carbon black is the most advantageous in this regard benefiting from its hierarchical particle structure and the small primary particle size, which fits quite well in the complex pore structure of SPAN electrodes.

This research study using a commercial SPAN material by Adeka (sulfur content of 38 wt.-%) and 90 wt.-% SPAN in the final electrode shows that SPAN as an exemplary polymer-based sulfur active materials is easy to process and easy to scale for sulfur-containing next generation batteries. Furthermore, in lab cells, it shows a capacity retention of more than 98% after 100 cycles using carbonate and ether based electrolytes, which proves its longterm cycling stability and the successful suppression of polysulfide formation.

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Thin film lithium metal anodes for solid-state batteries manufactured via sputter deposition

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The electrification of mobility is one of the main drivers of the increasing demand for batteries, in this area in particular are high gravimetric and volumetric energy densities (ED) of batteries necessary. The use of solid electrolytes (SE) in solid-state batteries (SSB) enables improved ED, operational reliability, shelf life and C-rates by replacing the inflammable liquid electrolyte. Additionally, the use of SE enables the utilization of metallic lithium anodes. To achieve an increasement of energy density, which, however, goes hand in hand with challenges in complying with safety guidelines is a key requirement in the field of SSB. Therefore, it is important to develop innovative technologies that improve the safety of next-generation LIBs while taking ecological and economic aspects into account and, at best, contribute directly to an increase in energy density. A decisive factor for increasing the energy density is the reduction of the amount of lithium used to a minimum through the use of the thinnest possible layer thicknesses. The aim of the work is to establish a manufacturing process for thin lithium metal anodes on different metal current collectors with a high coating rate of > 200 nm/min. A physical vapor deposition process, magnetron sputtering, is used for coating lithium with layers below 20 µm. During the investigations it was possible to identify working windows for the production of anodes for the use of different collector materials. In addition, the anodes have been characterized in terms of their mechanical and electrochemical properties. As a result, it has been possible to make recommendations for the use of different types of current collector foil on the anode side in solid-state batteries which can be adapted to new cell chemistries in the future.

Safety in Production and Use

Health and Safety in Battery Cell Production

Martin Föhse
Pilz GmbH und Co. KG

Though in Europe there are many activities in research and development of battery cell production for quite a long time, there still is a significant leak of knowledge regarding mass production in scale of Giga factories. This also applies to most aspects of health and safety when adapting processes to industrial manufacturing conditions. Battery cell production involves several significant hazards, partly new to, for instance, companies in the automotive industry.

This presentation will cover all relevant health and safety aspects, specific for battery cell production. The main topics are working in clean and dry rooms, handling of hazardous substances, production machinery safety as well as risks of fire and explosion. Not only respective challenges will be discussed, but also some approaches for risk reduction measures will be given.

For instance, purchasing production machinery by so far unknown Asian suppliers can result in critical misunderstandings. Best practices will be described how to perform a purchasing process to ensure safe machinery and to fulfill European legislation. Furthermore, some aspects are discussed to combine highly efficient and energy saving processes with improvements in regards of worker's safety at the same time.

Comparison of Thermal Runaway Early Detection Using Different Electrical Measurement Methods

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Lithium-ion cells are significantly affected by temperature, which affects most of the important cell parameters such as performance, capacity loss, aging behavior and safety issues. Therefore, monitoring the temperature is critical to ensure optimal and safe operation of the cell.

In this study, we investigate the early detection of thermal runaway in lithium-ion cells using electrical measurement methods. Specifically, we compare the effectiveness of current interruption (CI) measurements and electrochemical impedance spectroscopy (EIS) in detecting and predicting thermal runaway events.

Thermal runaway is a critical phenomenon characterized by a rapid rise in temperature within a cell, leading to cascading thermal and chemical reactions that can cause cell failure or even hazardous situations. Timely detection of thermal runaway is critical to prevent serious consequences and to take effective countermeasures.

CI measurements involve interrupting the current flow through the cell at regular intervals and monitoring the voltage response. This method allows the internal resistance to be evaluated and can provide information about the thermal behavior of the cell. EIS measurements allow analysis of the impedance response of the cell over a range of frequencies, which allows identification of changes in the electrochemical processes of the cell.

To compare these two methods, we performed experiments on different lithium-ion cells under different temperature conditions and compared the main effects on the measurement methods.

Our results show that both CI measurements and EIS measurements have the potential to detect thermal runaway. On the one hand, we found that EIS has higher sensitivity in detecting subtle changes in the impedance response of the cell over a range of frequencies, which allows identification of changes in the electrochemical processes of the cell. On the other hand, CI measurements are easier to realize than EIS measurements with the hardware of a conventional battery-mamagenent system, which makes CI measurements particularly interesting for subsequent applications.

Overall, our study highlights the importance of early detection of thermal runaway in lithium-ion cells and shows possibilities for thermal runaway early detection using CI and EIS.

(Urban) Factories, Upscaling and Supply Chain

Comparison of battery supply chains regarding their environmental and socio-economic impacts

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The design of battery supply chains has a significant impact on the environmental footprint of a battery, e.g., through the electricity mix at different locations. Therefore, it is of high relevance for OEMs to reduce the environmental footprint along their supply chains, especially as legal regulations such as the upcoming European Battery Regulation force them to do so. Furthermore, the regulations also include rules to ensure social conditions, so social impacts of battery supply chains also need to be assessed. In addition to these two dimensions of sustainability, it is important for OEMs to obtain batteries at a competitive price, which highlights that all three dimensions of sustainability must be considered together.

Therefore, the aim of this study is to assess battery supply chains including battery raw material extraction and refining, production, and battery recycling in terms of their environmental and socio-economic impacts using the Life Cycle Sustainability Assessment. In this assessment, different scenarios are analyzed to derive recommendations for action to design more sustai-

nable supply chains. First, we consider the current state, which has a strong Asian focus. Second, we consider a European supply chain design to show the differences in the possible designs.
The results of the study show that production in Europe has a high potential to reduce environmental and social impacts. However, costs will increase if we produce in Europe because the cost structure is higher, for example, in terms of labor costs. Furthermore, the results show that there are trade-offs between the three sustainability dimensions. Therefore, the results of the LCA need to be incorporated into further decision-making methods that take into account both stakeholder preferences and regulatory requirements.

Closing the Gap between Lab Scale Development and Industrial Technology: Cathode Materials Pilot-Plant “Powder-Up!”

Peter Axmann, Markus Hölzle
Center for Solar Energy and Hydrogen Research Baden Württemberg (ZSW)

High performant LIB require new, high performant, cost efficient and sustainable materials. Cathode materials are the dominant component in a battery cell regarding cost, key battery parameters and safety.
Currently, the speed of materials development is limited and there is a scaling gap between laboratory research and technical scale: new developments from research institutes are usually only available on a gram scale, insufficient for real-size battery cells or to answer production related questions. Furthermore, latest commercial product generations or products under development are not provided to research institutions. This especially affects the supply of existing pilot research lines for cell production, e.g. the FPL at the ZSW, or, still under construction, the FFB.
Closing this material scaling gap is a prerequisite to establish an internationally competitive battery industry research and production environment in Germany and Europe. Based on > 25 years of experience in the development of cathode materials with particle design up to a kg-scale, ZSW is now building a modern and efficient centre for the development and upscaling of cathode materials to the 1 kg- 10 kg- 100 kg scale, called “Powder-Up!”. Tailor-made powders will be developed for and provided to research partners and industrial partners for cell development. Powder-Up! will operate equipment identical to machines used in related cathode materials industry to guarantee powder production under industrially relevant conditions. Development will be sped up by using new types of high throughput equipment and parallel synthesis.
The presentation will give an overview about the individual process steps, scientific and technical challenges and concepts for new materials. We will discuss concepts for new materials and possibilities for collaboration.
Powder-up! is supported by the BMBF under the Umbrella Concept Battery Research, Funding Program “ForBatt” (03XP0448), and by the WM BW.

Procedure for considering the required flexibility in production operations during factory planning using the example of the Fraunhofer Research Institution for Battery Cell Production FFB

Natalja Rube, Jakob Palm
Fraunhofer Research Institution for Battery Cell Production FFB

When the first battery cell is produced, the factory planning has already been completed for a long time. The
factory planning has a direct influence on the battery cells that have already been produced and those that are still to be produced. The scope of factory planning also includes later changes in the factory. The flexibility defined during factory planning - referred to here as the flexibility corridor- enables or hinders changes to the product, machinery or process that can be implemented either with little or much effort. In addition, the factory planning carried out beforehand, defines how complex it is to subsequently expand this flexibility corridor.
First, the benefits are explained, why it makes sense to consider and evaluate the flexibility corridors as early as the factory planning phase. For each production step of a lithium-ion battery cell, the individual requirements for, e.g., electricity, central cooling and heating, water, compressed air and gases are shown quantitatively, which can be specified in the factory planning.

The requirements of all production steps are then considered, and a qualitative assessment is made of how complex it would be to change these requirements later. The flexibility corridor is shown for every requirement of every production step.
This possible flexibility is hardly needed for many production steps. In order to assess this, future technological developments are analyzed and the need for a flexibility corridor is qualitatively assessed. The comparison of the possible and required flexibility corridor as well as the prioritization of these corridors according to relevance enable the parameters to be defined in factory operation to be evaluated for future production operations as well.

A scalable assessment framework for estimating battery resource potentials in urban environments

Katja Knecht, Philipp Grimmel, Grace Abou Jaoude, Mark Mennenga, Olaf Mumm, Jan Felix Niemeyer, Sandro Süß, Ryan Zeringue, Christoph Herrmann, Vanessa Carlow
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Due to new laws and regulations introduced to achieve Carbon Neutrality, the number of electric vehicles and other electric means of personal mobility are expected to increase. The ensuing demand for scarce materials required in their production will put further pressure on world markets and supply chains. In addition, a significant amount of batteries is bound in consumer products, such as portable, rechargeable consumer electronics, and in industrial applications, that also increasingly contribute to waste streams. Although the establishment of circular battery production and economy in Europe and Germany is of utmost importance, little information is available on the existing and expected volumes of batteries and their presence in urban areas, which are key to support it.
In this presentation, we showcase a novel, systematic approach that allows to estimate battery volume and resource potentials in urban environments. As a framework for spatial exploration and aggregation, we employ an advancement of the TOPOI method that analyses and categorizes settlement units based on a set of spatial indicators derived from geospatial datasets as well as information on, e.g. land-use, building types and functions, population, and transport infrastructure. In combination with additional datasets, such as household data and information on the ownership of cars and electronics, this approach allows us to estimate the existing battery stock across local scales. A case study of Lower Saxony, Germany, exemplifies the approach. Our results emphasize the significance of spatially-refined case studies to understand battery stocks across the built environment and highlight the need for further strategies to support the recovery and reuse of scarce materials. Considering spatial information on end-of-life products can enable the detailed planning and operation of decentralized strategies for disassembly, recycling and retrieval of batteries, e.g. in form of micro circulation factories.

Recycling II (Materials)

From end-of-life batteries to high quality graphite - developing a recycling process focused on anodic materials

Fernanda Padilha Noronha, Sukanya, Anna Rollin, Harald Zetzener, René Wilhelm, Michael Kurrat, Arno Kwade
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Li-ion batteries (LIBs) demand and sales have had exponential growth in 2021, nearly 10% of global car sales were electric. This scenario generates critical problems for producers, i.e. waste management of end-of-life LIBs and scarcity of primary materials. Therefore, developing a circular battery production and recycling chain is crucial to meet the climate and sustainability goals. LIBs recycling processes reported in the literature combine mechanical, thermal, and chemical treatments, leading to desired recycling targets and decreased impurity contents. In most LIBs recycling routes, discharged and deactivated modules are crushed in the early stage, leading to significant impurities in the recovered black mass. However, the key processes focus on recovering the metals due to their scarcity and economic value. On the other hand, graphite, is also crucial, signifying 12 to 21 wt% of the battery.
Within this context, this work proposes deep dismantling process up to the anode level. Additionally, a wet mixing step is added to the classical dry mechanical route (shredding, drying, and sieving). The aim is to increase the quality of the recovered black

mass by gaining benefit of the water-based binders, increasing the recovery rate and reducing the efforts or even eliminating the hydrometallurgy process-step within the complete process route. To achieve an even higher quality of the recovered graphite and optimally reduce the amount of impurities, the material is acid leached and oxidized on the surface by treating it with a mixture of H2SO4:HNO3 (3:1). The graphite is then used in three-electrode test cells to evaluate the effects of reconditioned graphite on the performance and lifetime of lithium-ion batteries. For this purpose, electrochemical characterization methods such as capacity and C-rate tests as well as microscopic post-mortem analysis methods are used to compare mechanically recycled material and reconditioned graphite with the reference material.

Transforming Waste into Opportunity: Sustainable Black Mass Recycling and Beyond

Hady Seyeda, Julia Meese-Marktscheffel, Alexander Zeugner, Armin Olbrich, Jeroen Volbeda, Hagen Poddig, Johanna Köthe
HC Starck

In a world driven by increasing mobile energy demand, the proper management of end-of-life (EoL) batteries has become an urgent priority. This presentation introduces the long-lasting relation between H.C. Starck Tungsten (HCS) and battery materials, as well as its current efforts to implement a sustainable recycling of black masses – a byproduct of lithium-ion battery recycling containing most of the critical raw materials (Li, Ni, Co, graphite). The presented initiative focusses on developing an innovative and resource-efficient hydrometallurgical process to transform black mass into different battery grade chemicals and the subsequent upscaling to pilot and production scale. It will be shown how innovative approaches towards lithium separation and solvent extraction can help to overcome hurdles inherent to state-of-the-art technologies and process routes.
In addition, the holistic approach of HCS towards its new role in the battery industry is to be elucidated. Besides the basic hydrometallurgical business of HCS and the mentioned black mass recycling, this includes the vertical integration towards precursors for cathode active materials (pCAMs), the development of enhanced cathode active materials (CAMs) using tungsten chemicals and the activities around anode active materials (AAMs) and the cell producer Nyobolt.

Comprehensive model-based environmental impact evaluation of recycling process chains

Abdur-Rahman Ali, Felipe Cerdas, Christoph Herrmann
TU Braunschweig | Institute of Machine Tools and Production Technology (IWF)

There is an evident requirement for a comprehensive model-based tool to effectively evaluate the environmental impacts associated with recycling process chains. Addressing this need, the SIMTEGRAL project introduces a Python-based tool that integrates various bottom-up modeling approaches, encompassing the entire spectrum from battery cell design and manufacturing to vehicle use phase. By incorporating recycling routes, the tool enables the calculation of the recycling footprint for each cathode chemistry and recycling path. Validation of the results has been undertaken, highlighting the numerous benefits offered by this integrated approach, including the dynamic selection of battery cell composition, vehicle choice, and recycling route selection. By utilizing this tool, stakeholders can gain valuable insights into the efforts and credits associated with different recycling routes, thereby enhancing their understanding of sustainable practices in recycling.

Electrochemical performance of active materials from spent LiBs regenerated with a direct recycling approach

M. Mancini, J. Martin, M. Hoffmann, P. Axmann, M. Wohlfahrt-Mehrens
Center for Solar Energy and Hydrogen Research Baden Württemberg (ZSW)

Future LiBs production in Europe strictly depends on the availability, cost and sustainability of critical elements such as Li, Co, Ni and graphite. Recycling plays a major role to ensure availability of raw materials and sustainability of LiBs market in the next future, driven especially by price increase and new EU regulations. [1] Most common recycling approaches at the industrial scale aim to recover the transition metals and Li via pyroand/ or hydrometallurgical methods, whilst carbon components are generally not recovered due to their low economic value. Direct recycling represents an alternative approach that is gaining increasing interest. [2] Main target of direct recycling is a short close loop via regeneration of the cathode active material without dissolution into its single elements. The original cathode structure and its functionalities are preserved and reactivated to enable the direct use of the regenerated cathode for the production of new electrodes. The energy need of direct recycling is lower compared to other recycling strategies and the process can be extended to the graphite anode material by providing a decisive contribution to the material sustainability and availability for future batteries. In this presentation, we report about direct recycling of both anode and cathode active materials at a lab-scale, with validation of the approach by closing thee loop from end-of-life LiBs to application of the recycled materials in new Li-ion cells. We discuss about specific challenges and process efficiency at a lab-scale. The approach allows transferring of the developed methods from model materials to aged active materials of different origin. Moreover, we have tested the active materials for their processability and performance in commercially valid electrode and cell formats. We show very promising electrochemical performance of recycled anode and cathode materials in new Li-ion cells, by providing the proof-of-concept of the recycling process.

[1] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52020DC0474
[2] Y. Wang, N. An, L. Wen, L. Wang, X. Jiang, F. Hou, Y. Yin, J. Liang, Journal of Energy Chemistry 55 (2021) 391–419.
Acknowledgements:
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INNOVATION CULTURE IN BATTERY TECHNOLOGY

Dr. Jan Diekmann, Ioana Moldoveanu, Dr. Felix Steinke
Customcells Itzehoe GmbH

Advancing development of lithium-ion technology enables the electrification of more and more applications. However, a large part of the production capacity is still not to be found in Europe. Innovation in technology and process engineering is perceived as an opportunity to change this situation by creating unique selling propositions and technological advantages.
The question is how an ongoing innovation can be achieved and what is actually innovative. This presentation will look at statements, like organizational processes, team composition, or attitude on building an innovative culture and within corresponding examples to provide the basis for a subsequent discussion. For CustomCells, it is not possible to execute customer projects without a constant advance in technology. In this talk, we focus less on the technical content and much more on the corresponding mindset.

Production of lithium-ion batteries

Trailblazing process technology for perfect electrode mixes

Gigafactories for battery production place new demands on processes - especially in the processing of electrodes. The quality of the electrodes influences the performance of your storage cells. The processing of a first-class electrode mix - slurry, plastic body or even structured dry mix - is a demanding task. Trust a technology partner with in-depth material and process knowledge as well as decades of experience.

EIRICH

Eirich Mixer and MixSolver® with EvacMix® technology and you benefit from:

Perfect coating slurry
Agglomerate- and bubble-free

Homogeneous powder and structured dry mixes
For powder electrode coating up to free standing films

Easy scale-up
From lab scale to gigafactory

Sustainable single-pot process
Efficient and environmentally friendly

High-performance batteries
Mixing technology for highly reproducible processes

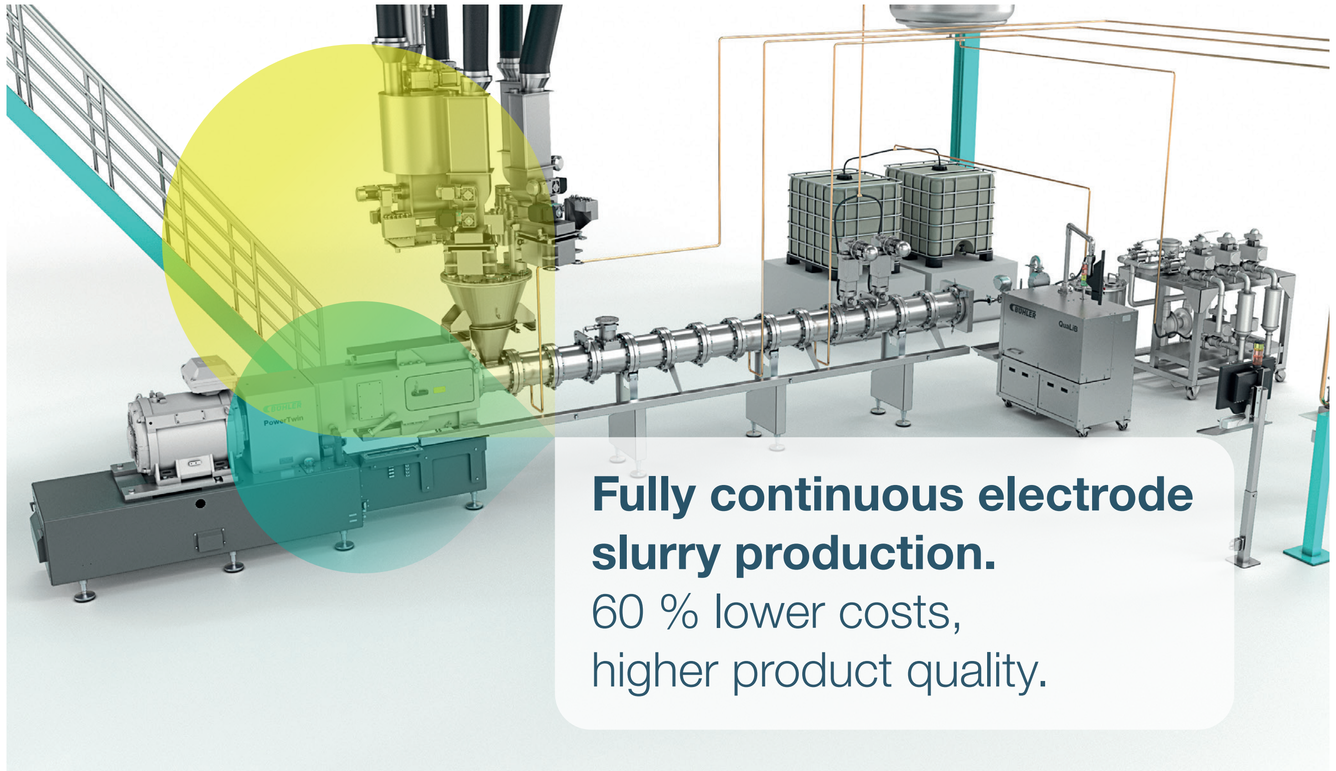
Clean turnkey solution
Strong capabilities for metering and handling

Continuous coater supply
The best of batch and conti

Highly dosable structured dry mixes
With optimal active material carbon coating and binder fibrillation

Future-oriented concept
For wet- and dry-processed electrodes

Unique mixing technology



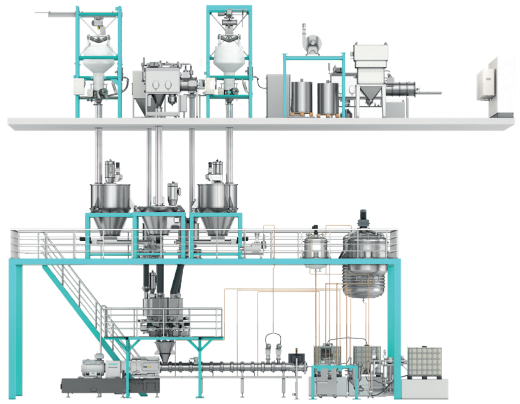
Fully continuous mixing technology for both conventional electrode slurry and solvent-free electrode masses

Bühler offers a wide range of solutions for the crucial process steps in LIB cell production. As a global leader in wet grinding and dispersing technologies, Bühler provides reliable, scalable and industry-proven solutions for wet grinding of active materials and precursors as well as continuous mixing of electrode slurries for lab, pilot and large-scale production.

Large-scale electrode slurry production.

Due to fully automated operation and inline quality control (QuaLiB), the Bühler continuous electrode slurry mixing process enables a significant reduction in energy consumption and increase in the production yield of the electrode production. In addition, the technology is proven for the dry electrode manufacturing process (DBE).

- Shorter mixing time and consistent product quality
- High productivity up to 2500 l/h per line and scalable process
- Significantly less waste and higher energy efficiency
- Lower operation costs thanks to high level of automation



- > 10 years of process know-how in the LIB industry and > 70 continuous LIB mixing lines in operation from lab to giga factory scale
- Proven for the conventional slurry process and ready for future manufacturing technologies such as the dry electrode process

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BÜHLER

POSTER SESSION I Day 1

Battery production 4.0, modelling, simulation and digital twin

BP_1.1 Scalable energy models for battery cell production
Gabriela Ventura Silva, TU Braunschweig I IWF

BP_1.2 Intelligent Ramp-up Control for Cost Reduced and Flexible Production of Future Battery Cells – InTeAn
Rui Yan LI, RWTH Aachen University I PEM

BP_1.3 Challenges of Traceability in Continuous Mixing Process
Simon Otte, KIT I wbk

BP_1.4 AI-based intelligent quality assurance and process monitoring for continuous, solvent-free electrode manufacturing
Philipp Heugel, Fraunhofer ICT

Battery supply chains and factory designs

BSC_1.1 Technology Potential Analysis and Development of Mini-Environments for Intralogistics in Battery Cell Production
Max Niggestich, Fraunhofer FFB

BSC_1.2 Analysis of the economic, environmental and social trade-offs of implementing resilience measures in circular battery production
Moritz Proff, TU Braunschweig I AIP

Cell assembly

CA_1.1 Design and performance analysis of a high-speed sealing mechanism for pouch cells
Benjamin Schumann, TU Braunschweig I IWF

CA_1.2 Holistic Analysis of Stacking Approaches for Battery Cell Manufacturing and Development of a Procedure Selection Methodology
Matthias Miggelt, Fraunhofer FFB

CA_1.3 Current state of development of Fraunhofer FFB cell designs
Franziska Klein, Fraunhofer ICT

CA_1.4 Novel Anode Embedding Method of FBG Sensors for Enhanced Diagnostics
André Hebenbrock, Clausthal University of Technology I EST

CA_1.5 Cost assessment for the contacting process in battery cell production
Matthias Smulka, RWTH

Electrode production

EP_1.1 Optimized inline monitoring of the drying process of battery electrodes
Jonas Mohacsi, KIT | TFT

EP_1.2 PVDF Binder Mapping Optimisation for NMC Cathode Microstructure
James Parker, University of Sheffield

EP_1.3 Metal-On-Polymer CurrentCollectors: An Innovative Roll-to-Roll Production Process
Claus Luber, Fraunhofer FEP

EP_1.4 Continuous processing of LFP-based aqueous cathode pastes for lithium-ion batteries
Hannah Mittag, Fraunhofer FFB

EP_1.5 Hybrid Laser Drying of LFP Cathodes for Lithium-Ion Battery Electrode Production
Sebastian Wolf, RWTH I PEM

EP_1.6 Characterization of longitudinal wrinkling during calendering of NMC811 cathodes
Ann-Kathrin Wurba, KIT

EP_1.7 Analysis and Comparison of Convective, Laser and Near-Infrared Anode Drying at the Lithium-Ion Battery Production
Raoul Höller, Fraunhofer FFB

EP_1.8 PA novel design and manufacturing process of Si-based anodes using nature inspired polydopamine
Jingyu Xie, Landshut University of Applied Sciences

EP_1.9 The role of binder properties and additive distribution in dry cathode manufacturing by compaction in a calender roll mill
Andreas Gyulai, KIT I IAM-ESS

EP_1.10 Enhanced dispersion of Ni-rich cathode inks with experimental ElectroRite® Additives for improved electrochemical performance
Joanna Galantowicz, University of Birmingham

EP_1.11 Influence of Lithium-Ion Electrode Production Steps on the Effective Thermal Conductivity
Julia Gandert, KIT

EP_1.12 Advancements in continuous extrusion coating of battery electrodes: Process development and pilot-scale scaling
Granit Jashari, Fraunhofer IKTS

EP_1.13 Increasing your OEE by advanced sensors
Jens Reiser, Precitec GmbH & Co. KG

EP_1.14 Mitigation of Binder Migration in the Drying Process by Use of Additives
David Burger, KIT I TFT

Electrode, cell and module diagnostics during production

DDP_1.1 Improving battery cell quality prediction in the end-of-line manufacturing step using chromatic confocal distance sensors
Daniel Nusko, Fraunhofer ISE

DDP_1.2 Exploring the Impact of Electrode Topography on Battery Performance: Insights from 3D-Profilometry
Artur Scheibe, RWTH I PEM

Formation and aging

FA_1.1 Influence of the vinylene carbonate concentration on the formation process
Philip Niehoff, University of Münster I MEET

FA_1.2 Impact of SiOx in SiOx/graphite-composite electrodes on the formation process
Maik Stamm, University of Münster I MEET

Material development and production

MDP_1.1 Challenges and approaches to realize next-generation lithiumsulfur batteries
Eun Ju Jeon, TU Braunschweig I iPAT

MDP_1.2 Carbon produced from atmospheric CO2 via a novel CCUS process- a promising electrode material for supercapacitors
Neele Uhlenbruck, KIT I ITES

POSTER SESSION I Day 1

Production of next-generation batteries

NGB_1.1 Dry coating of sulfide-based components for All-Solid-State Batteries
Arthur Dupuy, Fraunhofer IWS

NGB_1.2 Biopolymer gel electrolytes for zinc-based batteries
David Lammers, TU Braunschweig I ibvt

NGB_1.3 Production of PEO-based composite cathodes for all solid-state batteries using scalable, solvent-free polymer extrusion
Katharina Platen, Fraunhofer IFAM

NGB_1.4 Influence of Pressure in ASSB Assembly: Scalable Concepts to Improve Cell Performance
Lovis Wach, Technical University of Munich

Recycling, circular economy and sustainability

RCS_1.1 Concept of a Mechanical Cell Disassembly as an Enabler for Direct Recycling
Sebastian Henschel, KIT I wbk

RCS_1.2 Purification of organic electrolyte components from high-voltage lithium-ion batteries
Martin Wolke, TU Braunschweig I ICTV

RCS_1.3 Impact of dismantling level on black mass in mechanical battery recycling process
Steffen Fischer, TU Braunschweig I iPAT

RCS_1.4 Enhancing efficiency and sustainability in mechanical recycling of lithium-ion batteries: Insights from a digitalized pilot plant
Dennis Beusen, TU Braunschweig I iPAT

RCS_1.5 Influence of comminution and drying parameters on the properties of lithium ion battery black mass
Jannik Born, TU Braunschweig I iPAT

RCS_1.6 Drying of electrolyte solvents from porous electrodes and separators for recycling processes of lithium-ion batteries
Lukas Lödige, KIT I TFT

RCS_1.7 Comminution of polymers for the recycling of battery periphery in a hammer mill
Sandra Boekhoff, TU Braunschweig I iPAT

RCS_1.8 Assessing the economic and environmental impacts of leasing batteries for electric vehicle fleets: A solution for companies and customers?
Miguel Gonzalez-Salazar, University of Applied Sciences Würzburg-Schweinfurt

System integration and application

SI_1.1 Expansion of silicon containing anodes in pilot pouch cells and its effect on the energy density and module integration
David Dirnbauer, Austrian Institute of Technology

SI_1.2 TranSensus LCA: Towards a harmonized LCA approach for zero emission vehicles
Jana Husmann, TU Braunschweig I IWF

POSTER SESSION I Day 2

Battery production 4.0, modelling, simulation and digital twin

BP_2.1 Ontology-Aware Modeling of Relevant Parameters for Data Preparation in Smart Battery Cell Production
Arno Schmetz, Fraunhofer FFB

BP_2.2 Predictive Analytics Platform for Lithium-ion Battery Cell Manufacturing
Chao Zhang, TU Braunschweig I IWF

BP_2.3 Application of transfer learning in battery cell manufacturing scale-up
Marten Klenner, PowerCo SE

BP_2.4 Modeling the continuous battery slurry mixing process: Material transport and distribution in a twin-screw-extruder
Juan Meza, KIT

BP_2.5 Workflow for Estimation of locally generated Joule Heat during thermal runaway consisting of DEM-simulations of the microstructure and simplified full-cell simulations
Tobias Ohnimus, TU Braunschweig I iPAT

Cell assembly

CA_2.1 Modelling of a Z-Stacking Machine for Virtual and Risk-Free Exploration of Optimization Approaches
Kamal Husseini, KIT I wbk

CA_2.2 Ultrasonic welding of metal-polymer current collectors: Challenges and Limitations
Hakon Gruhn, TU Braunschweig I ifs

CA_2.3 Insertion of Lithium Nitrate as Additive in Li-Ion Battery Cells and its Implications for the Upscaling in Large-Scale Cells
Felix Diller, TU Munich I iwb

CA_2.4 Production of High Quality Pouch Cell Housing through Optimized Deep Drawing Process Control
Nils Schmidgruber, KIT I wbk

Electrode production

EP_2.1 Influence of the Calendering Density on Pilot-Scale Gr/SiO Electrodes
Andreas Röck, ZSW

EP_2.2 From Organic to Water-Based Processing: Pilot Scale Production of High Specific Energy LFMP Cathodes
Vidur Kumar, ZSW

EP_2.3 About the drying behavior of a highly-concentrated granulebased system- A new concept for an energy- and cost-efficient battery electrode production
Kevin Ly, KIT I TFT

EP_2.4 Integration of optical measurement methods into a traceability concept to investigate cause-effect relationships in the context of electrode production in battery cell production
Mark Stringe, Fraunhofer FFB

EP_2.5 Characterization of the induction drying process for the lithium ion electrode production
Tobias Krüger, TU Braunschweig I ifs

EP_2.6 Influence of high-intensive dry mixing carbon black with lithium iron phosphate for lithium-ion battery cathode productions
Simon Raffenberg, University of Münster I MEET

EP_2.7 Experimental study and numerical prediction of coating defects in multilayer slot-die coating of battery electrodes
Alexander Hoffmann, KIT I TFT

EP_2.8 Electrode and Separator Extrusion
Nicolaus Rehse, Collin Lab + Pilot Solutions GmbH

POSTER SESSION I Day 2

EP_2.9 Investigation of Adhesion Strength and Binder Distribution in aqueously processed LNMO Cathodes based on Surface Free Energy
Andreas Weber, KIT I IAM-ESS

EP_2.10 Structure-Property Relationships for Laser-Structured Electrodes in Lithium-Ion Batteries
Maher Kouli, TU Braunschweig I ifs

EP_2.11 Dry mixing and its effect on powder properties for dry coated lithium-ion battery cathodes: A comparison between batch mixing and extrusion
Milena Lux, TU Braunschweig I iPAT

EP_2.12 Influence of Various Polyvinylidene Difluorides on the Carbon Binder Domain for Different Active Material Morphologies in LiNi0.6Mn0.2Co0.2O2-based Positive Electrodes
Johanna Kauling, University of Münster I MEET

EP_2.13 Upscaling and Improvement of Water-based Ni-rich Positive Li-ion Battery Electrodes
Sonja Radloff, ZSW

EP_2.14 Investigation of a high intensity mixing process with powders for the production of dry coated cathodes and anodes
Lukas Bahlmann, TU Braunschweig I iPAT

EP_2.15 Enabling the production of homogeneous high-load positive electrodes by tailoring the electrode formulation – a conductive additive and solvent apporoach
Candeniz Gercek, University of Münster I MEET

EP_2.16 Introducing Processing Additives to Enable Aqueous Processing of LiNi0.8Mn0.1Co0.1O2 for Lithium Ion Batteries A pH Control and Surfactant Approach
Vinzenz Göken, University of Münster I MEET

EP_2.17 Material effects in the production of silicon oxide/ graphite based anodes from laboratory to pilot scale
Anna Gerlitz, University of Münster I MEET

EP_2.18 Development of a module for inline variation of the angle of attack for existing electrode coating systems
Florian Denk, KIT I wbk

Electrode, cell and module diagnostics during production

DDP_2.1 Potential of Computed Tomography Imaging for Detection of Inhomogeneities in Battery Cells
Paul-Martin Luc, Technische Universität Berlin

DDP_2.2 High-speed and high-resolution x-ray tomography for battery inspection
Emil Espes, Excillum AB

Formation and aging

FA_2.1 Accelerated Solid Electrolyte Interphase Formation and its Impact on the Performance of 1 Ah Lithium Ion Battery Pouch Cells
Mika Hellkuhl, University of Münster I MEET

Material development and production

MDP_2.1 New binder adhesion property characterization for a highquality battery production
Anja Rajic, TU Braunschweig I ifs

MDP_2.2 Study on Novel Carboxylated Binder Systems for Electrode Production
Ayşe Yarangünü, TU Braunschweig I ifs

Production of next-generation batteries

NGB_2.1 Requirements Engineering and Management for Production Technology of Solid-State Batteries
Jan Felix Plumeyer, RWTH I PEM

NGB_2.2 Comparison of reaction enthalpies under solvent variation in the wet-chemical synthesis of β-Li3PS4
Aurelia Gries, Fraunhofer IFAM

NGB_2.3 Direct coating of solid electrolyte on cathodes using a slot die
Andrea Wiegandt, Fraunhofer IFAM

Recycling, circular economy and sustainability

RCS_2.1 Electrochemical recovery of metals from battery black mass
Claudia Schulze, Fraunhofer IKTS

RCS_2.2 Enhancing Battery Sustainability: A Novel Sustainability Modelling Platform for Battery Production
Joris Baars, Fraunhofer IST

RCS_2.3 Feasibility analysis of the automated dismantling process for the automotive traction batteries, including a comparative economic analysis
Johannes Feik, DHBW Mosbach

RCS_2.4 Modelling and Flow Sheet Simulation of Mechanical Recycling Processes for Li-Ion Batteries
Franziska Punt, TU Braunschweig I iPAT

RCS_2.5 Towards a harmonized approach for prospective environmental and economic assessments of battery innovations
Kira Patzke, Fraunhofer IST

RCS_2.6 How to quantify recyclability improving design decisions?
Sönke Hansen, TU Braunschweig I IWF

RCS_2.7 Environmental aspects linked to life cycle phases of solid-state-batteries
Nelli Kononova, TU Braunschweig I IWF

RCS_2.8 Effects of different impurities on synthesized NMC particles
Markus Rojer, TU Braunschweig I iPAT

Cell Types, module and pack design and production

CTP_1.1 Identifying the impact of the positive active material on the cell design and battery cell production capacity
Anna Weichert, Fraunhofer FFB

CTP_1.2. Towards Multi-Disciplinary Design Automation of Circular Battery Modules – Framework, Potentials, and Future Research
David Inkermann, Clausthal University of Technology I IMW

POSTER ABSTRACTS I Day 1

Battery production 4.0, modelling, simulation and digital twin

Scalable energy models for battery cell production

Gabriela Ventura Silva
TU Braunschweig | Institute of Machine Tools and Production Technology (IWF)

Battery cell production is characterized by energy-intensive processes that have a significant environmental footprint in the life cycle of batteries. Therefore, research addressing the reduction of energy consumption is crucial for improving sustainability within the battery industry and, consequently, the mobility sector. The energy consumption values presented in the literature vary largely, especially due to the differing assumptions and scopes considered in the assessments. Furthermore, detailed information on the processes and materials investigated is often missing, and only estimated values are presented. This lack of transparency hinders the comparison of different production strategies (e.g., scales, process routes) and material streams (e.g., cell chemistry, solvent types). Moreover, there is a need to investigate the effect of system variations on energy consumption on individual processes as well as on global process chain levels. To tackle this challenge, this work presents process-specific energy models for battery cell production validated against lab and pilot data. Several factors are developed to consider improvements in energy efficiency and material scrap reduction as a function of increased production scales. The results present an assessment of critical parameters and energetic hotspots in battery cell production at different production scales and their comparison with literature data.

Intelligent Ramp-up Control for Cost Reduced and Flexible Production of Future Battery Cells – InTeAn

Rui Yan Li, Jessica Schmied, Daniel Neb, Benjamin Dorn, Heiner Heimes, Achim Kampker
RWTH Aachen University I Chair of Production Engineering of E-Mobility Components (PEM)

The intelligent and flexible ramp-up of production facilities is one of the main challenges in the current production of battery cells. While the decommissioning of various production plants generally proves to be less problematic, the recommissioning of plants and systems often proves to be difficult. The aim of the project applied here is therefore to develop an overall methodology for the rapid (re-)ramp-up of industrial manufacturing process chains. The methods to be developed are to serve as a starting point for the design of a highly flexible cell production line considering different battery cell concepts.
With the use of data-driven methods for modeling and experiment design, the underlying processes are to be actively elucidated, optimized, and prepared for control in an easily understandable manner. Several subprocesses (in particular mixing and coating) are to be considered in isolation from the overall process and the causal influences of manipulated variables on the process dynamics are to be determined. In addition, changes in basic conditions are to be recorded in real-time and readjusted according to the defined requirements. Furthermore, the flexible design of the data infrastructure should guarantee that the developed control processes are versatile.
To develop an initial data basis, the first theoretical process correlations for mixing and coating were established. In parallel, initial ramp-up scenarios were developed, which formed the basis for detailed process planning for the mixing and coating processes in the eLab at RWTH Aachen University. The preliminary tests made it possible to determine initial interrelationships between process parameters such as web speed or web tension and quality characteristics such as wet film thickness or adhesion. Afterward, several offline machine learning models were trained on the initial data basis, to identify and confirm further trends and interdependencies between process parameters and quality attributes. Using these results of the offline models, an online controller was modeled based on a Long Short-Term Memory (LSTM) neural network.

Challenges of Traceability in Continuous Mixing Process

Simon Otte, Dominik Mayer, Jürgen Fleischer
Karlsruhe Institute of Technology (KIT) I Institute of Production Science (wbk)

The production of high-performance batteries requires precise and efficient manufacturing processes. Therefore, deviations from the specifications in the product quality and production parameters must be detected at an early stage and the causes must be traced and eliminated. A traceability system is necessary for this purpose, which makes a crucial contribution to maintaining quality and optimizing battery production. Furthermore, the obligations through the battery passport from 2027 highlights the need for a robust traceability solution. This study addresses the challenges of traceability in the context of continuous mixing, a novel technology used in battery manufacturing. To overcome these challenges, the utilization of digital twin technology and innovative digital solutions is proposed.
One critical step in battery production is the continuous mixing process, where active materials and binders are homogeneously mixed using a twin-screw extruder. A significant challenge lies in achieving real-time visibility of the parameters values, control over the continuous mixing process and process traceability. Traceability in continuous mixing is complicated due to multiple input materials, the highquality requirements for the intermediate product and unknown parameter dependencies. To address this, innovative solutions that enable unique identification and tracking of each input material batch and intermediate product are needed. In this context, solutions from the state of the art and research are considered and possible approaches to finding solutions are developed. New digital solutions enable manufacturers to derive valuable insights from the amount of data generated during the continuous mixing process. For example, new approaches of data storage can contribute to better data integrity with more security and transparency. A digital twin can be used to gain a better understanding of the interdependencies between product, process and plant technology. With appropriate design of a digital twin and a good data set, this is also possible retrospectively. These insights can be used to optimize process parameters and improve overall process efficiency.
Given the newness of continuous mixing technology and the introduction of battery passports, which track critical information throughout the battery lifecycle, a robust traceability solution is essential. The integration of digital twin technology and innovative digital solutions offers a promising approach to address the traceability challenges in continuous mixing. By enabling real-time monitoring, control, and analysis, these solutions enhance traceability, optimize process parameters, and ensure consistent product quality. This research contributes to the advancement of battery production by providing insights into traceability solutions for the mixing process.

AI-based intelligent quality assurance and process monitoring for continuous, solvent-free electrode manufacturing

Philipp Heugel, David Lau, Quan Nguyen, Markus Hagen, Benjamin Schumm, Christian Girsule, Julius Roch, Ingo Bardenhagen, Julian Schwenzel, Frank Sehnke, Nico Klar, Anton Kaifel
Fraunhofer Institute for Chemical Technology ICT

As a state-of-the-art process for the industrial production of battery electrodes, batchwise electrode coatings with solvent-based slurries are currently applied. By using solvent-free manufacturing processes, time-consuming and energy-intensive drying of the electrodes can be avoided which is also reducing production costs. Furthermore, production can be made more sustainable by avoiding the use of toxic solvents such as NMP, which is used especially in the manufacturing process of cathodes. Within the KontElPro project in the InZePro cluster, we use dry processing methods as an alternative to the conventional wet-coating approach. Those techniques can also be used for non-toxic, Co- or Ni-free electrodes, which means that green, sustainable cells can be produced. Furthermore, in order to reduce high scrap rates, the existing and installed production processes are to be supplemented with further process sensors to provide inline information which allows corrective action to be taken during electrode production. The continuously recorded sensor and process data are stored in a central database as well as the electrochemical measurement results of the electrodes produced and tested. With the help of AI, both individual processes as well as complete process chains are to be controlled and optimized. Significant cost savings are therefore possible compared to conventional procedures.

In this work, we not only focus on the continuous and intelligent production of electrodes/electrolytes by extrusion with die and calender but also on solvent-free electrodes with low binder contents produced by the DRYtraec® process. In addition, a sensor concept was developed for realizing intelligent extrusion and dry coating. Based on this, a self-learning control system is being developed, implemented and validated.

Furthermore, a no-SQL database is used which can store data streams from each process sensor, so that this data can be correlated with further off-line analysis and electrochemical results. The database is also the basis for track and trace and the sensitivity analysis of production parameters in relation to target values with data-driven AI methods, in offline and later in online operation for individual as well as for the entirety processes under consideration. Digital twins are created for all processes, which are used to optimize the processes and are continuously improved with active learning.

The aim is to expand existing, innovative and easily scalable methods of solvent-free electrode production (extrusion, dry transfer) with an inline process control and a cross-site, networked database. Automated data evaluation and AI-supported modeling and optimization of processes with digital twins will help make electrode production more efficient, improve quality and reduce waste. Production waste (should some arise) can also be reintegrated into the beginning of the process chain, which further underlines the sustainability approach. The aim is to identify the particularly quality-critical process steps and parameters and to define quality gates by linking process parameters with electrochemical results and by using AI in connection with digital twins. The results show that by using virtual sensors, time-consuming and cost-intensive processes (e.g. quality control by hand using SEM images) can be virtualized. Process-relevant parameters could be identified, which can be used to train the AI.

Battery supply chains and factory designs

Technology Potential Analysis and Development of Mini-Environments for Intralogistics in Battery Cell Production

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Due to the rising interest in electric vehicles, the demand for more efficient battery cells is increasing rapidly. Energy consumption during production is a major driver of costs and CO2 emissions. To fulfill societal demand, higher gravimetric and volumetric energy density of lithium-ion battery cells are required. Since these materials are significantly more sensitive to moisture, the production conditions need to be adapted accordingly. Therefore, the preparation of clean and extremely dry atmospheric conditions is crucial for production of highquality battery cells. The technology approach "Mini-Environment" enables the substitution of conventional clean- and dry-rooms for significant energy and cost savings and especially for intralogistics processes. However, clean and dry room conditions must be maintained not only along the hole value chain but also in the intralogistics area. These areas account for a significant share of the energy demand of the clean and dry rooms. In order to enable battery cell production in mini-environments and thus reduce the energy consumption, an intralogistics solution is needed in which the clean and dry room conditions are maintained. Moreover, there are currently no logistics or airlock solutions for the described use case of interlinking Mini-Environments tailored for battery cell production. Both topics lead to the research question, what are the requirements for a transport and storage system for moisture-sensitive semi-finished products in the battery cell production factory? To answer this question, the method of requirements engineering is used. Which leads to a first conceptual design for a gas-tight, intralogistics mini environment based on morphological box. With this a holistic production analysis is conducted, to highlight the advantages within the different application areas of the concept.

Analysis of the economic, environmental and social trade-offs of implementing resilience measures in circular battery production

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Global crises such as the COVID-19 pandemic, the war in Ukraine, or the chip shortage show how vulnerable global supply chains can be. Such supply chain disruptions particularly affect the automotive industry with its global supplier networks. Within the transforming mobility sector, lithium-ion batteries are at the center of these issues, as surging demand meets supply chains that are highly vulnerable to disruption. Many of the raw materials and components are sourced from centralized and often politically unstable regions worldwide, making disruptions more likely. As a result, companies are looking for ways to make their battery supply chains more resilient to global crises and risks, to avert them where possible, and to withstand and recover from disruptions.

However, these resilience measures impact all three dimensions of sustainability in different ways. For example, the supply bottleneck caused by the blockade of the Suez Canal could have been overcome by a short-term switch to air delivery of parts. This would have resulted in an economic advantage by ensuring the availability of supplies, but it would also have been associated with an extensive environmental impact. In comparison, alternative trading partners would have been much more environmentally beneficial but could have resulted in long-term economic disadvantages due to the loss of existing partners and long durations to start the new supply channel. This illustrates how companies face trade-offs when choosing appropriate resilience measures. Therefore, this poster provides a framework and an initial quantitative analysis to demonstrate the impact of resilience measures in the battery supply chain and how they function in the trade-off between economic, environmental and social impacts.

Cell assembly

Design and performance analysis of a high-speed sealing mechanism for pouch cells

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Large parts of the production process for industrial scale electrodes use roll to roll processes, to maximise productivity. In contrast, current solutions for the subsequent cell production process continue to be characterized by a discontinuous material flow. Consequently, identifying new approaches for continuous handling processes during cell production has a high potential to increase productivity. However, continuous handling processes still have to meet the high requirements on quality and safety. Among others, one major safety risk of the cell production is the occurrence of leakages due to insufficient sealing strength of the pouch bags.

This research presents an approach for a high-speed sealing mechanism for pouch bags with continuous material flow. Potential mechanisms are conceived by analysing and adapting, technologies from highly productive industries such as the packaging or pharmaceutical sectors. A suitable range of the process and design parameters for the high-speed process (e.g. belt velocity, geometry of the sealing element) is selected. This work applies destructive testing to assess the effects of the considered parameters on the sealing strength as a key quality criterion. The test results enable the creation of models for different parameter settings. The influence of different parameters on the performance of the sealing mechanism (e.g. throughput, sealing strength) can then be shown from technical as well as economic perspective. Allowing for an informed adaption of the mechanism to individual quality and productivity targets.

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Holistic Analysis of Stacking Approaches for Battery Cell Manufacturing and Development of a Procedure Selection Methodology

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As a result of the energy transition, the demand for alternative energy sources is increasing, and with it the demand for storage technologies. To be able to supply the growing markets with battery cells in the future, the production capacities must be expanded, and existing technologies further developed. In the state of the art, stacking represents the bottleneck in battery cell production, because is currently done by single sheet stacking or Z-folding. To cope with the high throughput, in large battery factories these stacking plants must be scaled up. The parallelization leads to a high space requirement in clean and dry rooms and consequently to a large amount of dry air, the production of which constitutes a large part of the total energy costs in battery cell production. There are already a number of alternative, faster stacking methods. However, all principles have advantages and disadvantages from a techno-economic point of view. Moreover, there are no actual comprehensive stacking procedure overviews based on patent analysis, which evaluate alternative processes and their technological suitability. Both issues lead to the research question which impact have the different stacking technologies to battery production and what are the relevant evaluation criteria? To answer these questions, a technology analysis with evaluation of the technologies and the impact of their risks and characteristics is required. In summary, there are many stacking technologies, and some of them can increase the speed by a factor of 10 compared to the state of the art, but they still need to be investigated. The advantages and disadvantages of the technologies must be evaluated in a structured way to make targeted decisions for research activities and the applications in the industry.

Current state of development of Fraunhofer FFB cell designs

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Lithium-ion batteries (LIB) have become an integral part of our everyday lives. They are used primarily in consumer electronics, mobility and stationary energy storage. LIBs and their production play a key role in the shift towards more sustainability and climate friendliness. Cell design and cell chemistry, but also technical performance parameters (including energy and power density, lifetime, environmental conditions, safety, costs, ecological footprint and recycling) significantly determine the properties of the battery cell. The potential for making batteries more efficient is far from exhausted, especially in the case of large-format LIBs.

Within the framework of the multi-stage FoFeBat projects, a "battery cell research production" ("FFB") will be established by 2026, in which novel battery cell concepts and processes will be combined and researched with digitalised, flexible and modular production methods. The aim is to reduce the development effort for the highly scaled production of the latest LIB cells, cell concepts and production technologies. During the set-up of the 21700 round cell production, as well as pouch and prismatic production lines for large-format LIBs, in addition to the specification of the equipment (incl. in- and offline measurement technology), cell design and construction of the "FFB" cells will be developed and defined, and sample cells will be produced in iterative steps in order to validate the cell design.

In this poster, the current development status of the "FFB" cell designs of round, pouch and prismatic cells (e.g. cell chemistry, performance parameters, cell geometry inside and outside, technical drawings, etc.), the way to get there (e.g. via patent research and requirements management) as well as initial findings from the validation phase of the sample cells will be shown.

Novel Anode Embedding Method of FBG Sensors for Enhanced Diagnostics

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When operating batteries only a limited amount of measurement data, e.g. cell voltage, current, or tab surface temperature, is typically generated. Particularly for large cell formats, these measurements are strongly restricting the insight into the inner processes of a cell. For an in-depth understanding, in-operando measurements inside the cell are necessary. Embedding fibre Bragg grating (FBG) sensors into the anode material makes it possible to monitor key parameters and phenomena within the battery during its operation. The inert FBG sensors offer a noninvasive and non-destructive means of collecting valuable data without disturbing the electrochemical processes occurring inside the battery.

Integrated FBG sensors have been successfully retrofitted by various groups. However, in the presented work, a novel embedding method as a modification to the established process for cell fabrication at the Battery LabFactory is shown, paving the way for future scalability and reliability of large-scale production. To date, the chosen method ensures the most non-invasive way for integration into the anode active materials layer, and in addition, higher homogeneity is guaranteed compared to operationally expensive retrofit processes.

The embedded optical sensors allow for continuous, real-time monitoring of crucial parameters such as strain and temperature providing a better diagnostic understanding of battery behaviour. This enables a targeted study of the impact of different material compositions on battery performance, aiding in the optimization of cell designs, and increasing battery lifespan. The measurements also provide crucial information about the properties of newly developed materials under realistic operation conditions and therefore show strong potential for ensuring consistent and reliable battery performance.

Cost assessment for the contacting process in battery cell production

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The rapid growth of the electric vehicle market and the increasing demand for renewable energy storage systems have propelled the advancements in battery cell production. Among the various processes involved in battery cell manufacturing, the contacting process plays a crucial role in establishing efficient electrical connections within the cell. As the production volumes surge, it becomes essential to conduct a comprehensive cost assessment of the contacting process to optimize resource allocation and enhance overall production efficiency.

In this study, we present a detailed analysis of the cost factors associated with the contacting process in battery cell production. We begin by exploring the different stages and sub-processes involved in establishing electrical contacts, including pre-welding and tab-welding. By leveraging insights from industry experts and extensive literature review, we identify key cost drivers at each stage and develop a framework for cost assessment.

Furthermore, we conduct a comparative analysis of different contacting technologies, such as ultrasonic welding and laser welding, to assess their cost-effectiveness in different scenarios. We evaluate the initial investment costs, process complexity, throughput, and yield rates associated with each technology option.

The outcomes of this study provide battery cell manufacturers with valuable insights into the cost structure of the contacting process and enable informed decision-making regarding process optimization and resource allocation. By identifying cost drivers and evaluating technological alternatives, manufacturers can enhance their competitive edge, improve production efficiency, and achieve cost reductions in the fast-evolving battery cell production landscape.

Electrode production

Optimized inline monitoring of the drying process of battery electrodes

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The increasing demand for energy storage may position battery cells as one of the main players in the process of the energy transition. As electrification of the transport sector and digitalization continue to advance, the production of battery cells is set to increase significantly. However, to achieve this growth, it is crucial to optimize the manufacturing process by improving energy and material efficiency and ensuring cell quality.

In the manufacturing process of battery electrodes, reducing solvent loading through a suitable drying process is a critical step. One major challenge is minimizing high reject rates, which can significantly impact costs. Therefore, the aim is to achieve full monitoring of the drying process by integrating comprehensive sensor technology. By doing so, deviations from target parameters can be detected and eliminated at an early stage.

In this work, various sensors have been investigated to determine their suitability for inline monitoring of the drying process. They are to be integrated into the housing of a convective dryer developed in-house for a roll-to-roll system on a laboratory scale. This unique system offers special possibilities, including spatial integration of corresponding sensor technology.

An area-resolved measurement of the film temperature can be achieved by using an IR camera, which serves as an indicator of the progress of drying. Another parameter examined is the roughness of the film surface, which increases strongly during the drying process. This can be well resolved using of a scattered light sensor. These measurements are crucial for monitoring a three-stage drying process. Using the latest confocal point sensors, it is possible to monitor the film height distribution on the vibrating belt of the roll-to-roll system. Additionally, a further possibility for measuring the surface roughness could be achieved.

This work contributes to the research performed at CELEST (Center for Electrochemical Energy Storage Ulm Karlsruhe) and Material Research Center for Energy Systems (MZE). The authors would like to acknowledge financial support of the Federal Ministry of Education and Research (BMBF) under project ID 3XP0359A (IQ-El) and 03XP0295A (EPIC).

PVDF Binder Mapping Optimisation for NMC Cathode Microstructure

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In the pursuit of next generation batteries, the lithium-ion battery industry has identified several effective and adoptable battery chemistries. However, increasingly recent data indicates that the techniques used in electrode production and the final electrode microstructure can controls the final performance of the cell [1,2]. With the need for battery production reaching a new height and indicating accelerated future demand, it is important time to review how we can control and optimise microstructures. To gain this deeper understanding of how each process and their process conditions alter the structure of the electrode, we need to develop a enhanced structural characterisation.

This work details out progress in the development of cross-sectional methodology for analysis of NMC622 cathodes. The electrodes were impregnated with epoxy resin and polished for SEM-EDX for binder mapping. The industry adopted binder for cathodes is polyvinylidene difluoride (PVDF) due to its stability at high voltage and good wettability [3,4]. PVDF and the conductive additive are both rich in carbon; therefore, to distinguish the PVDF, fluorine must be imaged. However, fluorine is a highly electronegative and small atom, and these characteristics provide a great challenge in producing accurate EDX data.

In this contribution we provide detailed analysis of the binder location and challenges associated with mapping fluorinated polymers in battery electrodes [5]. Additionally, the false-positives corresponding to manganese and cobalt (present in the NMC active particles) having similar x-ray emission peaks to fluorine is explored [6]. This work explains the decisions made during sample preparation and SEM-EDX analysis to combat these challenges.

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Metal-On-Polymer CurrentCollectors: An Innovative Roll-to-Roll Production Process

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As electro mobility is becoming more and more mature, the demand for safe and environmentally friendly batteries is rapidly growing.

Due to the high market growth of batteries, a shortage of resources, e.g. metals, can be foreseen. To avoid this and to increase intrinsic safety of the battery cells, Fraunhofer FEP, in collaboration with VON ARDENNE GmbH, developed the deposition of thick metal films onto polymer substrates for use as current collectors in lithium ion battery cells as replacement for the metal foils currently used.

Combining the two aspects of novel material combination and novel production technology, the use of an electron beam deposition process to deposit thick metal layers (up to 1 µm thick) on thin polymer substrates (down to a thickness of 6 µm) by using of cost efficient Roll-to-Roll technologies has been demonstrated. To tackle the problem of excessive substrate heating during the process, a novel cooling method, provided by VON ARDENNE GmbH, is being used.

Dynamic deposition rates for Aluminum of around 25 000 nm*m/min and for Copper of around 7 500 nm*m/min for a width of 500 mm were achieved. Current Collectors with sheet resistances down to 35 mOhm per square on both sides (top and bottom) for Aluminium were fabricated.

The shown industry compatible Roll-to-Roll process is fully scalable and the double sided deposition of roll lengths of up to 1000m could already be demonstrated.

Pouchcells were built with aluminium metal-on-polymer current collectors for the cathode and were compared to reference cells. In the poster, we present recent results and possibilities for further upscaling of the process.

Continuous processing of LFP-based aqueous cathode pastes for lithium-ion batteries

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Up to now the discontinuous batch mixing process still represents the state-of-the-art process to produce pastes for lithium-ion batteries (LIBs).[1] Though, as 30%1 of the cost of a lithium-ion battery are related to battery production, cost-saving processes play an increasingly important role. One innovative and promising alternative to the discontinuous batch mixing process in order to reduce material demand, production time and therefore cost is the continuous mixing process. [1,2]

This novel mixing process not only yields advantages with respect to process related costs but could also be particularly beneficial for aqueous processing of cathode materials. Especially due to the reduced time of the mixing process, since one of the remaining challenges in aqueous cathode processing is the time-dependent pH increase [3,4] of the electrode paste upon contact with water as a result of the Li+/H+ exchange [3]. However, due to its innovative character in the battery field, the continuous mixing process has hardly been explored so far. [1] Hence, this work investigates the production of LFP-based aqueous cathode pastes produced by a continuous mixing process using a twin-screw extruder.

To optimize the mixing process regarding a high product quality and compatibility of the slurry with the slot die coater, we performed experiments with varying process parameters, primarily the kneading concentration and solid content, and analyzed the produced cathode slurries. In our analysis, we particularly focused on the relevant properties of the electrode paste (e.g., viscosity and particle size distribution) and several process parameters of the extruder, to understand whether and if so, how the process parameters and product properties correlate. Beyond that cathode electrodes are fabricated and scanning electron microscope examinations are carried out to validate the quality of the electrode and correspondingly the extrusion process-product correlations.

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Hybrid Laser Drying of LFP Cathodes for Lithium-Ion Battery Electrode Production

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Convection drying of electrodes is very cost-intensive as it is characterized by high energy and space consumption. Laser-based drying is a promising enhancement to the conventional drying process in electrode production. Through a direct energy input by means of laser radiation, a reduction of the drying time can be achieved. As a result, cost savings through footprint reduction and energy savings can be realized. For this purpose, various use cases for the integration of the laser system into existing coating and drying lines are possible. The integration of the laser as pre-drying before the convection drying process is particularly promising. Hybrid electrode drying using laser and convection was analyzed with regard to its influence on process performance and electrode quality. To this end, investigations were carried out related to adhesion capability, residual moisture and cell quality. It was shown that significant reductions in drying time can be achieved with comparable quality parameters.

Characterization of longitudinal wrinkling during calendering of NMC811 cathodes

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With the increasing use of lithium-ion batteries (LIBs) in various industries, there is also a growing demand for higher energy densities. Calendering is a critical process step in the LIB electrode manufacturing process as it adjusts the thickness and density of the individual electrodes in a battery cell. This in turn determines the volumetric energy density of the cell. Increasing the volumetric energy density requires higher electrode densities and higher compaction rates which induce higher stresses in the electrode. These stresses lead to deformation and various defects that cause web tears and machine stops. Defects also negatively affect the subsequent process steps and handling operations such as web guiding and winding and increase the scrap rates during the battery cell manufacturing process. Within this work the defect "longitudinal wrinkling" is investigated. The formation of longitudinal wrinkles is well known to electrode manufacturers but is still not fully understood. This work presents a systematic geometrical description of the longitudinal wrinkles for $LiNi_{0.8}Mn_{0.1}Co_{0.1}O_2$(NMC811) cathodes calendered at different roll temperatures, web tensions and densities. The longitudinal wrinkles are measured using a laser triangulation sensor and a 3D scanner. Their geometric values are then correlated with the calendering process parameters. The electrodes are also characterized in terms of their deformation and their mechanical properties. This work can be used as a basis for gaining a deeper understanding of the formation of longitudinal wrinkles. It contributes to reduce the formation of longitudinal wrinkles in the future.

Analysis and Comparison of Convective, Laser and Near-Infrared Anode Drying at the Lithium-Ion Battery Production

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With today's product requirements, cost pressure and increasing environmental awareness, the conservation of resources is a necessity for material-efficient, resource-conserving, and time-, quality- and performance-optimized battery production. The initial drying process of the coating can be identified as a significant cost and emission source due to high energy demands resulting from inefficiencies and heat losses.[1] Shortening drying length, process and ramp-up times would offer significant advantages in process control and flexibility.[2] In this contribution the innovative use of near-infrared and laser radiation for energy input into the coating is being investigated, to mitigate the disadvantages of conventional drying. Thereto radiating modules are placed between the coating-module and the convection oven. By using radiation only for drying, the process can be evaluated against the benchmark of convection drying. Furthermore, a sequential combined drying process can be looked at. The increase in efficiency and savings potentials can be quantified, as well as the increase in throughput by combining said technologies. The target is to achieve optimized process control with a reduction in energy consumption, drying distance, and drying time while maintaining comparable qualitative coating properties. A change in quality due to drying defects can be quantified by the physical properties of the coating (adhesion, conductivity, surface quality, additive distribution) or the performance of functional cells. By considering the technologies both individually and jointly, it is possible to not only compare the drying products but also the drying mechanisms. By analyzing the interdependencies and correlations of input and quality parameters, a statement on the operating conditions and recommendations for action can be given. Not only do those provide insights into the theory of drying but also direct assistance for the practical application of innovative drying solutions.

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A novel design and manufacturing process of Si-based anodes using nature inspired polydopamine

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Silicon (Si), due to its high theoretical capacity (3579 mAh/g), has attracted high interest as an anode active material. However, the large volume fluctuation during charging and discharging process causes mechanical instability of Si-based anodes and leads to particle cracking, SEI instability and electrical disconnection. These have further consequences on the electrochemical performance, especially the capacity decrease in the electrodes and cells.

Besides an optimization based on Si-graphite-composites with limited beneficial from silicon (only around 10% content), the design of Si-based anodes can also be focused on binder and distribution of the components. A novel idea of manufacturing the Si-based electrodes is inspired by a nature material polydopamine (PDA), which is found in mussel adhesive protein. Selfpolymerized PDA as binder additive in electrodes has proven a higher adhesion and led to improvement of electrochemical performance. [1-2] Besides, the study of PDA carbonization has succeeded to obtain a high electrical conductivity up to 1.2 x 105 S/m. [3] Thus, the concept of combining these two possibilities of PDA with Si-based anode is interesting and beneficial, which is reported in this contribution.

A combination of polymerization of PDA and Si-active material mixing may improve the homogeneity of the Sibinder distribution. With a partial carbonization process after electrode coating, a part of the PDA should still maintain its characteristics as binder. Simultaneously, another part of the PDA could break down to carbon material to improve the electrical conductivity in the electrode.

A preliminary test of this novel manufacturing process is reported. Si-core-shell material was mixed with selfpolymerized PDA and coated roll-to-roll using knife coating. Afterwards, the electrodes were carbonized at two different temperatures (300°C and 800°C) with different procedures. Subsequently, the electrodes were tested electrochemically in half-cell format.

Generally, the project succeeded and confirmed the electrochemical functionality of the electrodes. The lithiation capacity of electrodes in the first cycle reached the theoretical capacity (above 3000 mAh/g). All electrodes were able to cycle at different C-rates. The rest capacity after 100 cycles at 1C was up to 550 mAh/g. The whole cycling- and power-test data will be presented at the meeting.

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The role of binder properties and additive distribution in dry cathode manufacturing by compaction in a calender roll mill

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The dry compaction of electrode powders is dominated by the mechanical properties of the used electrode powder blend, and these are strongly influenced by the morphology of the particles and their mechanical and visco-elastic properties. Therefore, one major challenge in powder compaction is the high susceptibility of the process towards changes in the material composition or its mixture homogeneity. Recent developments in dry powder compaction are thus limited to specific materials, such as PTFE with low shear strength, which facilitate the compaction process while establishing mechanical integrity of the formed electrode. To increase the versatility of the dry compaction method, a better understanding of the mechanical properties of additives is necessary, so that additives are not only implemented for their capacity to improve electrochemical performance, but also improve the shear properties of the dry powder blend at the same time.

Therefore, this work investigates the influence of the conductive carbon and binder additives and their distribution on the processibility and shear behavior of the powder blend[1]. Additives with high surface area and irregular particle size, such as carbon black, lead to increased internal friction of the powder blend, while plate-like graphite acts as a solid lubricant. Additionally, when processed at temperatures above the melting point, the binder can act as a lubricant during the dry compaction of the powder. Therefore, binder properties such as shear viscosity and molecular weight were investigated for their influence on the processibility of the powder blends.

These dependencies were investigated for an electrode composition using NMC622, carbon black, conductive graphite and various PVDFs in a mass ratio of 93.5/2.5/1/3 w%, resulting in electrodes competitive to slurry-based electrodes. Finally, the findings were successfully applied in the design and production of other electrode formulations, such as NaVPO4 electrodes.

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Enhanced dispersion of Ni-rich cathode inks with experimental ElectroRite® Additives for improved electrochemical performance

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The fabrication process of electrodes is a highly intricate and multifaceted process that encompasses several stages, including mixing, coating, drying, and calendaring, which ultimately culminate in the assembly of the electrode into a cell. Each of these production stages significantly impacts the overall performance of the electrodes. [1] Firstly, the selection of raw materials for electrode production plays a crucial role. This choice determines the appropriate type of solvent that can be employed and whether the incorporation of stabilizing additives is necessary. [2] Secondly, during the formulation of cathode inks, it is imperative to ensure their stability, particularly in terms of particle agglomeration and sedimentation. This stability directly affects the quality of the final product and must be carefully managed. [3] Thirdly, the processability of cathode inks is important. The coatability, flow and stability of the ink all impact the coating to produce homogeneous coatings with no defects. [4] Lastly, the microstructure and interfaces of the resulting electrode impact both ionic and electrical conductivity. Factors such as the volume fraction of the active material, the pore phase, and the interactions between conductive additives and binders all contribute to the overall conductivity of the electrode. [5,6] Overall, the complex nature of electrode fabrication demands meticulous control and optimization of each production stage to achieve electrodes with superior performance characteristics.

In this study, we explore the impact of the experimental ElectroRite® Additives, in an experimental setting, on the stability, processability, final microstructure of formed electrodes, and overall electrochemical performance. To conduct this investigation, we employ unmodified commercial NMC811 cathode active material, carbon black (CB65) as a conductive agent, and polyvinylidene fluoride (PVDF) binder dissolved in N-methyl-2-pyrrolidone (NMP) solvent. By employing this standardized experimental setup, we can accurately assess the impact of the ElectroRite® Additives on high solid content inks (70 wt.%) while various parameters are being examined. Our investigations have revealed that the incorporation of small quantities of these additives has the potential to enhance the stability of NMP-based Ni-rich cathode inks, by improving the dispersibility of ink components, and enhance their processability, which affects final microstructure. The impact of incorporating experimental ElectroRite® Additives into the Ni-rich cathode inks was initially examined using a Rheometer, enabling the observation of notable alterations in rheological characteristics. Subsequently, the inks were coated onto aluminium current collector, and their microstructure before and after calendaring was assessed through SEM/EDX analysis and Four-point probe measurements. After undergoing calendaring to obtain the desirable porosity of 35%, the electrodes were assembled into a full-cell configuration. Following that, an electrochemical analysis was conducted to evaluate the efficacy and properties of the assembled full-cell system, showing advantages of additives implementation. Finally, our research demonstrates that these additives used in small quantities, have the potential to improve the stability, processability, and overall electrochemical performance of the cells, paving the way for advancements in battery manufacturing technology.

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Influence of Lithium-Ion Electrode Production Steps on the Effective Thermal Conductivity

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Many authors have shown that the mechanical and electrical properties of electrodes are strongly influenced by the production steps like mixing[1-3], coating and drying[1,4,5] and calendering[1,6-11]. These include the effective ionic and electrical conductivity as well as the adhesion strength between coating and current collector. However, there are no studies known that experimentally investigated the impact of the production steps on the thermal material properties of the electrodes. This is why we aim to shed light on the changes of the effective thermal conductivity of electrodes caused by the coating and drying conditions as well as the compression during calendering.

In this context, we investigated one-sided coated electrodes with different active materials. Varying the coating thickness, drying rate and compression force allowed an insight into the impact of the different yet specific production processes. To quantify the effect on the thermal behavior we used the effective thermal conductivity, as it acts as a key property for the heat removal and thermal gradients within batteries. To do so, we measured the specific heat capacity and density of the solid phase for each material via differential scanning calorimetry and gas pycnometry, respectively. The thermal diffusivity was then measured with laser flash analysis for all the differently coated or calendered sheets and materials. Including the gravimetrically determined porosity, the effective thermal conductivity could then be calculated and enabled a comparison between the different materials and production parameters.

This way we can take a look at the dependence on coating thickness and drying rate, which both particularly influence the binder distribution within the coating, and furthermore the alterations for varying compression rates, which significantly influence the porosity. The results indicate correlations with the adhesion strength and electrical properties. However, the different electrodes do not all show the same behavior, indicating a strong influence of the material with its varying particle size, shape and rigidity as well as the composition and fraction of the binder carbon black phase. The independent impact of all these parameters still poses an interesting research topic.

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Advancements in continuous extrusion coating of battery electrodes: Process development and pilot-scale scaling

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LIBs are the leading battery type in the consumer sector and are increasingly used in automotive and stationary storage applications. For further market penetration, the price of cells must continue to decrease, for which both new processes and cell designs are essential. Drying processes require a significant amount of energy, which can be a costly and environmentally taxing endeavor. To mitigate this issue, one approach is to increase the solid content of the material being dried, leading to reduced energy consumption during the drying process. Therefore, the process development for continuous direct extrusion coating of battery electrodes with high solid contents and its subsequent scale-up to pilot scale are crucial steps towards advancing the production of highperformance batteries [1-3].

In recent years, our research has demonstrated the successful production of direct extruded electrodes [4]. This innovative approach has led to a significant reduction in solvent content during the cathode and anode production processes, reaching reductions of solvent up to 10% and 30% respectively, compared to wet film casting methods. This reduction in solvent content has resulted in decreased energy consumption during the drying process. In this study, we focused on investigating the coating of cathode and anode paste formulations with high solid content, specifically over 80 wt% for cathode and 65 wt% for anodes, utilizing a twin-screw extruder. To achieve a uniform distribution of the binder within the paste and enhance the adhesive strength of the coating, we evaluated various binder materials, such as carboxymethyl cellulose with molecular weights, as well as polyacrylic acid, for anode manufacturing via the extrusion process. For cathode manufacturing, we investigated a blended binder system comprising PVDF/additive in NMP, with different ratios, and explored the use of water-based binders mentioned earlier. Rate capability test of the prepared electrodes in test cells was analyzed based on the different formulations employed, and the findings are discussed in detail.

Overall, this low-solvent process offers the advantage of consolidating various steps involved in electrode production, including mixing, coating, and drying. As a result, this streamlined process not only reduces complexity but also leads to cost savings in terms of machinery investment and energy expenditure. Significant parts of this research are funded by the BMBF through the projects Headline (03XP0394I) and OptiEx (03XP0294A).

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Increasing your OEE by advanced sensors

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Precitec stands for the passion for light, which we make use of in the fields of optical measurement, laser cutting and laser welding. This presentation focuses on our solutions for optical sensors. In a first part, the physical background of our sensors such as the chromatic confocal, interferometric or laser photothermal radiometry measuring techniques will be displayed. These techniques enable resolutions < 1 micron.

In a second part we make a journey along the battery process chain to elucidate where our sensors are in use: measurement of real-gap between slot die and roll, measurement of edge superelevation, measurement of thickness of coating in wet and dry condition and with vibration of band, elucidation of the 5 stages of drying, measurement of concentricity of calender rolls, detection of impurities and measurement of cutting burr to name but a few.

In a third part, new trends for laser cutting and laser welding will be displayed. Such as multi-pass cutting of ASSB or cap-to-can welding of 46xx cells.

The presentation closes with an outlook of possible closed-loop strategies for tomorrow's MP lines.

Mitigation of Binder Migration in the Drying Process by Use of Additives

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To meet the increasing demand for batteries, it is important to optimize the battery manufacturing process for efficiency and cost reduction. One of the challenges in roll-to-roll manufacturing is the drying process, which needs to be fast to achieve high throughput with limited dryer length. However, fast drying rates can cause the binder in the electrode coating to migrate, leading to possible delamination and reduced cell performance. The migration behavior of the thickener CMC, binder SBR, and other additives must be considered to get an understanding of the phenomenon. Capillary-driven flow of solvent during drying after the end of the film shrinkage is thought of to be the main cause of binder migration [1].
The composition and processing of the slurry play a key role in binder migration. High shear mixing in a kneader can suppress binder migration by facilitating the interactions between CMC and the partially shred particles' surface [2]. The reduction of particle size itself also may mitigate binder migration completely [3]. If a higher specific surface due to smaller particles is unwanted for SEI formation, another approach can be chosen: The addition of synthetic nano-scale clay can influence the microstructure of the slurries, interacting with CMC [4]. It is important to investigate how the microstructure of the slurries and drying conditions impact the pore emptying and the formation of mechanical properties of the dry electrode.
This poster will discuss the influence of different slurry compositions on the pore emptying during drying at increasing rates. We will compare these findings with the analysis of the coatings' local microstructure, including adhesion strength and image analysis of the pore structure at a coating-glass substrate interface (see Fig. 1). By tracking pore emptying during drying, differences in the increase of empty pores' area can be observed, which indicate slurry- and drying rate-dependent pore emptying behavior. Furthermore, the use of promising slurry compositions in a multilayer configuration will be explored to optimize material usage, such as incorporating additional additives only in the substrate-near layer or reducing the overall passive material content.

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Electrode, cell and module diagnostics during production

Improving battery cell quality prediction in the end-of-line manufacturing step using chromatic confocal distance sensors

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To ensure that defective battery cells are identified at the end of the production, end-of-line testing is performed. End-of-line testing typically comprises of electrical measurements from which the capacity of a battery cell is inferred. However, battery cells with capacity value inside the specification range might present small defects, which are not detectable. The additional contactless measurement of volume expansion of battery cells can give insights into the lithium-ion transport process beyond those provided by electrical measurements alone.
The local measurement of the expansion of the battery cell may provide information about its areal homogeneity, which cannot be obtained from the results of the electrical measurements. For this purpose, we use confocal chromatic distance sensor in the end-of-line. The advantages of the confocal chromatic sensor are the high resolution due to the use of the complete color spectrum and the structurally smaller space requirement of the measuring head. This non-contact sensor does not influence the electrical or mechanical characteristics of the cell in any way, as it does not exert any pressure and does not supply energy to it. The results are fully automated, easy to interpret and require small volume. To determine optimal positions for the measuring points, pressure sensors and digital image correlation through triangulation methods are used. Measurements of the cell expansion taken at the optimized locations, in addition to electrical measurements, are then scaled to be performed over a large number of cells.
This data set can be used initially to observe trends across cells, and eventually to train Machine Learning models that could be used to classify defects, assign grades, or predict lifetimes.

Exploring the Impact of Electrode Topography on Battery Performance: Insights from 3D-Profilometry

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The impact of a heavily fossil fuel-based economy is coming to a fore, stressing and endangering earth's homeostatic ecosystem. To counteract, generation, storage and use of renewable energy sources is encouraged as a key strategy, while most impactful sectors such as manufacturing and transportation find themselves in the spotlight. As a consequence, demand for batteries as a main technology for energy storage is rapidly increasing. Irrespective of the specific sector, high requirements are placed on manufactured battery cells, as simultaneously asked for low costs, high energy and power densities, while at the same time expecting highly secure operation over the entire lifetime.
As the performance of batteries is strongly influenced by the electrode design and topography, submitted poster aims to make a valuable contribution by exploring the impact of electrode topography on battery performance using advanced 3D-Profilometry. Surface features such as roughness, skewness, kurtosis and other are analysed together with coating defects (e.g. pinholes, agglomerates) for both anodes and cathodes at a microscopic scale. Characterization results are then used to hypothesize relationships between electrode topography and key battery performance parameters such as capacity, cycling stability and rate capability. Additionally, the influence of selected electrode manufacturing parameters (e.g. slurry composition, line loads during calendaring, etc.) is considered to give an explanation on obtained electrode topography. Gained insights thereby shed light onto the complex interplay between electrode topography and battery performance.
Overall, the poster highlights the importance of considering electrode topography as a critical factor in battery design and performance optimization. By understanding how surface characteristics affect key performance metrics, researchers and manufacturers can optimize electrode designs and manufacturing processes to enhance battery performance and durability. The knowledge gained from this research has the potential to drive advancements in battery technology, enabling the development of more efficient and reliable energy storage systems for a wide range of applications.

Formation and aging

Influence of the vinylene carbonate concentration on the formation process

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The formation of lithium-ion batteries is a crucial production process due to its direct impact on the performance, capacity, and overall quality of the batteries. The formation process involves the initial charging and discharging cycles that a newly manufactured battery cell undergoes to form passivating layers on the electrode surface. Hence, the formation procedure may be highly dependent on the electrode materials and electrolyte recipe. Here, six different vinylene carbonate concentrations were utilized in 1 Ah winded pouch cells with a graphite anode. The cells were characterized with regard to gassing, electrochemical performance, vinylene carbonate consumption, electrochemical impedance spectroscopy of symmetrical cells and surface analysis.

Impact of SiOx in SiOx/graphite-composite electrodes on the formation process

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The formation of lithium ion batteries (LIB) is a crucial production process due to its direct impact on the performance, capacity, and overall quality of the batteries. The formation process involves the initial charging and discharging cycles that a newly manufactured battery cell undergoes to form passivating layers on the electrode surface. Hence, the formation procedure may be highly dependent on the active materials and electrolyte recipe used. The formation procedure can be designed by choosing different C-rates and voltage ranges and number of cycles.

Here, three different formation procedures were investigated. These procedures include so-called microcycles at different voltage windows, which were correlated with the subsequent aging behaviour. For this, 1 Ah LIB cells with Ni0.8Mn0.1Co0.1O2-containing positive and either pure graphite-containing or 10% SiOx/90% graphitecontaining negative electrodes were used. The tested voltage regimes were a) 3.0 – 3.5 V, b) 3.6 – 3.7 V or c) 4.0 – 4.2 V. The microcycling was stopped when a Columbic efficiency of 99% is reached. The amount of gassing was examined by Archimedes principle. Electrochemical Impedance Spectroscopy (EIS) and extensive current pulse measurements were used to analyse the resistance. Thermogravimetric Analysis (TGA) and X-Ray Photoelectron Spectroscopy (XPS) were carried out to examine the solidified formation products on the electrode surface, while Gas Chromatography of the electrolyte residue is giving insight on the electrolyte decomposition. Additionally, long term cycling is carried out to determine the influence of the different micro-cycling procedures on the performance and resistance.

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Material development and production

Challenges and approaches to realize next-generation lithiumsulfur batteries

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The development of advanced energy storage technologies is driven by the increasing demands for high specific energy, safe operation and cycling stability. Current lithium-ion batteries are limited by their specific capacity. Lithium-Sulfur (Li-S) batteries are emerging as next-generation batteries, offering high specific capacity and the advantage of using non-toxic, abundant sulfur. However, their widespread application is hindered by the so-called "polysulfide shuttle effect", which results in low utilization and loss of active materials, while in terms of Li-metal related Li-S batteries the formation of dendrites is posing severe safety issues.

In this contribution, our works on solving the challenges and facilitating the practical application of Li-S batteries are discussed. In general, an artificial Solid Electrolyte Interphase (SEI) can protect the Li metal already from the first cycle, preventing the growth of Li dendrites. We have successfully developed a 1.7 µm thin, free-standing artificial SEI made of a polymer composite that can be easily laminated onto the Li metal [1]. In particular, a hybrid material of SiO2 nanoparticles embedded in a polyethylene oxide (PEO) matrix resulted in extended cycling stability and better reproducibility of Li-S cells featuring a composite carbon-sulfur cathode with a liquid electrolyte. Our second approach is to replace the liquid electrolyte by a solid electrolyte to improve battery safety and increase volumetric energy density. With the SE2A Cluster of Excellence, a cross-linked copolymer hybrid solid electrolyte that shows promising ionic conductivity of 1.14 × 10-4 S cm-1 at 20 °C was developed [2]. Pentaerythritol tetraacrylate (PETEA) and tri(ethylene glycol) divinyl ether (PEG) were copolymerized to serve as cross-linking matrix to achieve sufficient mechanical strength. Li7La3Zr2O12 (LLZO) particles were covalently bound to the copolymer by a previous surface functionalization step. The cycling performance of Li-S cells was evaluated using the developed hybrid electrolyte (PETEA-PEG-LLZO) together with a composite cathode and a Li metal anode. Thereby, novel composite cathodes based on sulfur as the active material and conductive carbon with solid electrolyte binder (so called catholyte) was developed [3]. The fabricated cells exhibited an initial capacity of 760 mAh g-1 at a C-rate of 0.1 at 20 °C, which proves the suitability of the developed hybrid electrolyte for room temperature applications. Nevertheless, a strong drop in capacity was observed, which we attribute to the shuttle effect. Furthermore, a more facile process, e.g. process that can be carried out under ambient atmosphere, needs to be developed for the commercialization of Li-S batteries.

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Carbon produced from atmospheric CO2 via a novel CCUS process - a promising electrode material for supercapacitors

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To mitigate climate change, the transition to a renewable energy system is essential, requiring stationary energy storage to capture the intermittent renewable energy generation. Besides, the development of Carbon Capture Utilization and Storage (CCUS) processes that reduce CO2 emissions by storing and/or using the greenhouse gas are necessary. Here we present a process for the synthesis of solid carbon from atmospheric CO2, which can be utilized in electrochemical energy storage devices. After direct air capture, CO2 and hydrogen are converted into methane, which is then thermally split up into hydrogen and carbon at 1100 °C in a bubble column reactor filled with liquid tin. The carbon (PyroC) thus produced from atmospheric CO2 at the Karlsruhe Institute of Technology is characterized by electron microscopy, then used for the fabrication of electrodes and tested in supercapacitors. The electrodes were prepared by mixing the carbon powder (active material) with polyvinylidene difluoride (PVDF) as a binder in N-Methyl-2-pyrrolidone (NMP) solution. The electrodes were tested in symmetric and asymmetric coin cells with 0.5 M NaBF4 ionic liquid electrolyte. While symmetric supercapacitors with PyroC electrodes showed low capacitance of just over 1 F/g, the capacitance was increased to about 35 F/g total active material by combining PyroC with an electrode made from activated carbon (AC). Coupling PyroC (negative electrode) with AC (positive electrode) also resulted in OCV of approximately 0.5 V. These systems were cycled in voltage range of 0.01- 3 V at varying current densities (0.2, 0.5, 1, 2, 5 & 10 mA/cm2). Cyclic voltammetry (CV) scans (scan rate of 2 mV/s) from 0.01 to 3 V before and after cycling (> 1000 cycles) revealed several reversible and irreversible redox reactions. The results presented demonstrate a promising combination of CCU and energy storage applications, thus addressing several challenges associated with climate change mitigation at the same time.

Production of next-generation batteries

Dry coating of sulfide-based components for All-Solid-State Batteries

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All-solid-state batteries (ASSBs) employing sulfidic electrolytes in electrode and separator are one of the most promising technologies for the next-generation energy storage systems. Safer and with higher energy density than the common lithium-ion batteries, ASSBs have recently attracted great interest from both academic and industrial communities [1]. However, full-scale commercialization is hindered by a lack of process technology that could transfer ASSBs to a higher Technology Readiness Level. Indeed, the incompatibility of sulfidic electrolytes with commonly used solvents (NMP, water) requires new concepts for component manufacturing. Dry electrode processes could potentially eliminate the solvents and further provide savings in energy consumption and equipment footprint [2].

In this study, a scalable and continuous process for sulfide-based materials, in solid-state cathode and separator manufacturing is demonstrated. The patented solvent-free coating technology DRYtraec® is applied here. This calender technology is using a speed differential concept to apply shearing modulus to PTFE-based dry mixtures. Further parameters such as roll speed, temperature, force, gap width and coating width can be tuned, allowing versatile dry film production. While manual manufacturing of dry electrodes were already shown in previous work [3], here a step forward on the prototype-scale production is made.

With a content of 1% PTFE, laminated NMC on Al-foil was obtained, over 325 cm length on 10 cm width. In this work, the relationship between shearing ratio and thickness deviation will be discussed. Mapping over width and length of electrode will be also shown for loading and porosity values. A quasi-linear relationship between shearing ratio (speed differential of the rolls) and loading is thereby demonstrated. Moreover, the influence of DRYtraec parameters into film formation will be presented, especially the strong relation between shearing ratio and roller speed as function of the gap thickness.

In parallel, two types of solid electrolyte layer (SEL) as separator can easily be manufactured with DRYtraec® process: free-standing and laminated. The first one, free-standing film, describe a film which is produced continuously through the gap, without using any mechanical substrate as current collector. The second one, laminated film, describe a film formation on the rolls that will be then transferred on current collector by a lamination step. Synthesis and properties of both of these separators will be further described, as well as theirs scalability opportunities.

Finally, to pave the way for the future development of ASSBs, SEL was directly laminated on cathode material. Electrochemical characterization of each component are being evaluated to highlight the relevance of DRYtraec® process for solid-state batteries manufacturing.

Biopolymer gel electrolytes for zinc-based batteries

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The ever-increasing demand for more environmentally friendly and sustainable alternatives to fossil fuel-based products and processes has also drawn the attention of modern science to biopolymers. Due to various promising properties in terms of biodegradability, functional diversity and accessibility, the importance of biopolymers as alternative materials has increased rapidly. Not only for biomedical, food or packaging applications, but also in battery technology, biopolymers can meet the requirements for safer, more sustainable, and greener battery materials at low costs. As alternatives to today´s predominant Lithium-ion batteries (LIBs), zinc-based batteries are considered suitable candidates for one of the "beyond lithium-ion" technologies due to their safer aqueous alkaline electrolyte as well as lower cost and specific power and energy close to LIBs [1]. Natural biopolymers such as xanthan or alginate are thus herein investigated as replacements for current battery components. In the form of gel polymer electrolytes (GPEs), xanthan and alginate offer a great opportunity to avoid common challenges of zinc-based batteries, such as zinc anode derived dendrite growth or shape-change during battery cycling.

Xanthan and alginate demonstrated their suitability as a GPE in various concentrations in a nickel-zinc battery (NiZnB). Here, the NiZnB with a 200 g L-1 xanthan electrolyte resulted in 200 successful charge and discharge cycles with similar initial discharge capacities compared to the reference NiZnB with a glass fiber separator and a liquid alkaline electrolyte. However, the NiZnBs with biopolymer-based GPEs need improvement in terms of poor capacity retention and lower Coulomb efficiencies compared to the control reference. To this end, we aim to modify the biopolymers in terms of, for example, chain length or molecular weight, which can be controlled by selected cultivation conditions. These results are an important step towards a more sustainable battery development and are beneficial for future zinc-based battery technologies, which face similar challenges as NiZnBs in terms of anode aging.

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Production of PEO-based composite cathodes for all solid-state batteries using scalable, solvent-free polymer extrusion

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All-solid-state battery (ASSB) is the next generation battery technology, where classical liquid electrolytes are replaced with ion-conducting solids improving the safety of such a battery. The functionality of solid electrolytes (SEs) as separator preventing electron transport while conducting lithium ions enables the use of electrodes made of metallic lithium for high energy density ASSBs.

The use of only solid components brings new challenges at the electrode-electrolyte interface. To provide good interfacial contact between the cathode and SE, a composite cathode (CC) consisting of conventional cathode materials and SE as catholyte seems to be promising. Regarding the importance of the transition from lab-scale production to larger scale, scalable process routes for composite cathodes need to be established. The use of a thermoplastic polymer as matrix for SE enables the replacement of conventional solvent-based production methods through solvent-free extrusion. A twin-screw extruder with two feeding units offers the possibility of a separate addition of the cathode components and SE and mixes them continuously to produce homogeneous CCs.

The aim of this work is to produce PEO-based CCs using solvent-free extrusion. To optimize the mixing of the components, a screw configuration consisting with kneading blocks is used. Here, we determine the influence of extruder parameters on the process stability and product quality of produced PEO-based CCs. Optimized process temperature and screw speed are used to avoid degradation of PEO. SEM and electrochemical measurements are examined for product characterization.

Influence of Pressure in ASSB Assembly: Scalable Concepts to Improve Cell Performance

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Sulfide-based all-solid-state batteries (ASSBs) promise higher safety, longer life cycles, and higher energy densities compared to conventional lithium-ion batteries. However, their commercialization faces multiple challenges, one of which is inadequate cycling performance due to interface issues between the all-solid components. Multiple assembly strategies exist to tackle these problems. Lamination of two or more layers can be used during production to increase the contact area between components. Different methods to compact single components or laminates exist and must be evaluated thoroughly on their influence on cell performance.

This talk aims to present scalable strategies to improve the cell performance of sulfide-based ASSBs by implementing lamination and other methods of compacting one or multiple components. The implementation of these concepts in multi-layer batteries will also be covered in this scope. The concepts presented build on the initial experimental investigations that have already been carried out. These include the lamination of components by uniaxial pressing on a laboratory scale and the electrochemical analysis and cycling of pouch cells built with these. It was shown that laminating sulfide-based composite cathodes with a sulfide-based separator significantly improves the cycling stability of the cells compared to cells built without a lamination step.

Recycling, circular economy and sustainability

Concept of a Mechanical Cell Disassembly as an Enabler for Direct Recycling

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In order to enable a circular economy and to reduce the dependency on foreign imports, the new EU-battery directive is setting strict targets for the amount of precious raw materials, which need to be recycled from end-oflife lithium-ion batteries. Starting in 2027, 90% of cobalt and nickel, as well as 70% of the used lithium have to be recycled. In order to fulfill these requirements, new methods such as direct recycling are being developed. Compared to existing pyro- or hydrometallurgical approaches, the direct recycling aims to achieve a functionpreserving material recovery, thus reducing the need for extensive thermal energy or chemical components throughout the recycling process.

One of the requirements for the successful direct recycling is a high disassembly depth in order to reduce the number of materials, which need to be processed together. This work therefore presents a concept for the mechanical disassembly at the cell level. Starting point hereby are individual end-of-life battery cells, and production scraps such as cell stacks which have failed the short circuit test for example. By opening the cells and then separating the components from another, it is possible to retrieve single variety anodes and cathodes, which can then be further processed, by removing the active material from the current collector for example. The concept shown in this work is being designed to handle pouch cells, both with a single sheet stacking and a zfolding configuration.

Purification of organic electrolyte components from high-voltage lithium-ion batteries

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Increasing concerns regarding climate change and energy-dependence have motivated the development of battery recycling processes which can improve resource efficiency and close material loops. For lithium-ion batteries (LIB), EU legislation has targeted a recycling efficiency of 70 % by 2030 [1] resulting in increasing research in battery recycling processes. To achieve the desired recycling targets and a closed material loop, it is necessary to recover and purify the volatile electrolytes. These components constitute approximately 10 – 20 % of the total battery cell mass [2].

The electrolytes consist of solvents, such as dimethyl carbonate (DMC), diethyl carbonate (DEC), ethylene carbonate (EC) or ethyl methyl carbonate (EMC) [3,4], as well as additives such as vinyl carbonate (VC) or fluorobenzene (FB) [3]. Furthermore, impurities may result from undesired reactions and by-product formation during battery cell aging or the recycling process. In the LithoRec II process [5], the volatile organic components of the electrolyte mixture are recovered through drying. However, the presence of impurities inhibits this multicomponent mixture from being directly reintroduced into the material loop. Therefore, the recycled electrolytes need to be separated before reintegration into the material cycle.

This poster contribution refers to the conference topic "Recycling, circular economy and sustainability". It reports simulation and experimental results of the separation and purification of volatile organic electrolyte components using fractionating batch rectification on a selected model mixture consisting of DMC/EMC/DEC/FB. The simulations indicate a separation of DMC, EMC and DEC with a purity of ≥ 99 %. Compared to the experimental findings, which exhibit lower separation performance, it becomes apparent that the simulations tend to overestimate the actual separation performance which suggests the need to refine process and/or simulation parameters.

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Impact of dismantling level on black mass in mechanical battery recycling process

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In recent years, the development of electric vehicles and renewable energy technologies has lead to an increased production of lithium-ion batteries (LIBs). As a result, the amount of end-of-life LIBs will also increase in the near future. Mechanical recycling is a promising approach for the holistic recovery of the valuable metals like nickel or cobalt and other materials from used LIBs. However, the influence of the level of dismantling on the amount of impurities within the recycled material and the recovery efficiency of the mechanical recycling process has not been fully investigated. In this study, the effect of the dismantling level on the mechanical recycling of LIBs, and further scale-up effects to a pilot level process is investigated.

In a laboratory scale process, the recovery efficiency of the black mass is evaluated with respect to impurities for each dismantling level. The results indicate a recovery efficiency of over 98 % for the active material at the cathode level and 95 % at the anode level, with impurities of less than 2 %. In addition, the introduction of an additional screening step reduces impurities by more than 65 %. At the cell level, however, the black mass yield is slightly lower, accompanied by higher amounts of copper and aluminum impurities. Nevertheless, more than 70 % of the black mass can be recovered after the initial grinding and drying step, where drying parameters play a critical role in managing the impurities on the black mass.

In an upscaled recycling process at the pilot level, the recovery of materials at the cell and module level is further investigated. A vacuum shredder is used to recover volatile components of the electrolyte during the shredding process.

In conclusion, our research highlights the significant influence of the dismantling level on the recovery efficiency of mechanical battery recycling. Higher levels of dismantling lead to enhanced recovery efficiency and reduced impurities in the black mass. Our study also examines the impact of process parameters on key properties such as particle size and particle morphology for different dismantling levels. Additionally, the mechanical recycling process demonstrates scalability to the pilot level, offering a sustainable and efficient means of recovering valuable metals from spent LIBs.

Enhancing efficiency and sustainability in mechanical recycling of lithium-ion batteries: Insights from a digitalized pilot plant

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Closing material loops is essential for sustainable electric mobility, particularly to ensure the availability of battery materials. Therefore, efficient recycling systems are necessary, aiming to maximize output quantity and quality while minimizing costs and environmental impacts [1]. One common method for recycling lithium-ion batteries starts with shredding and drying the cells or modules, followed by the mechanical separation of different material fractions [2]. The separation processes primarily focus on extracting the valuable black mass for further processing, such as hydrometallurgy.

However, the entire mechanical process chain is a major challenge due to the batteries' complex material composition. To better understand the intricate processes, a comprehensive knowledge of the influence of process parameters and conditions as well as of input materials, intermediates and final products is essential. This can be achieved by analyzing data from various sensors, control loops, and integrated analytics throughout the process chain, including online, offline, and atline measurements.

This work presents a novel approach for safe and efficient mechanical recycling of spent lithium-ion batteries using a digitalized recycling plant. This approach starts with a combined vacuum shredder and dryer, which process deeply discharged batteries into a safely manageable bulk material on pilot scale. An insight into the digitalization concept of the pilot plant will be given and results from the data analyses will be presented. The results show that the variation of the mixing intensity has a significant influence on the black mass yield and the total resulting product particle size. In addition, the mixing intensity affects the drying time and enables the optimization of the energy-intensive vacuum process through controlled and monitored process control. This improves the overall understanding of the processes, making them more efficient and sustainable by identifying and optimizing energy-intensive processes and increasing the yield of black mass.

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Influence of comminution and drying parameters on the properties of lithium ion battery black mass

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As a result of current global efforts to reduce greenhouse emissions, especially in the automotive sector, the demand for lithium-ion batteries (LIBs) is constantly increasing. As a consequence of this enhanced use of LIBs, the number of end-of-life (EOL) batteries will also grow significantly in the future. Due to their partly toxic components, these batteries pose a potential risk to humans and the environment. Furthermore, LIBs contain valuable raw materials such as nickel, cobalt and manganese, which are only available in limited quantities, especially in the European Union. For these reasons, an effective recycling process with high recovery rates is of immense importance for creating closed material cycles and avoiding raw material shortages.
One approach to recycle LIBs is the mechanical-thermal process route followed by hydrometallurgical processing [1]. In this process, battery cells are first discharged, short-circuited and then mechanically crushed. The comminution parameters must be optimized to increase the yield of particulate battery active material, also called black mass (BM). In the following process step, the crushed battery material is dried at a low temperature in a vacuum atmosphere to separate high-volatile electrolyte components. In the subsequent process step, the lowvolatile electrolyte components, conducting salts and binders are thermally decomposed and the BM is prepared for hydrometallurgical processing.
In this work, a process for the production of an optimised BM for subsequent hydrometallurgical processing with the aim of low contamination is presented. The focus is on the process development for the generation of pyrolysed BM to realise high material recovery rates. The release of electrolyte components through evaporation and thermal decomposition is monitored in all process steps by means of Fourier transform infrared spectroscopy (FTIR). It is shown that even low temperatures under vacuum conditions are sufficient to separate volatile electrolyte components and, in addition, the risk of hydrofluoric acid formation can be minimised. By means of thermogravimetric analysis (TGA), scanning electron microscopy (SEM) and inductively coupled plasma analysis (ICP), the BM is analysed and a strategy for designing the comminution and vacuum drying processes is discussed. In perspective, the overall recycling rate of LIBs can be increased and emissions can be reduced by recovering electrolyte components.

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Drying of electrolyte solvents from porous electrodes and separators for recycling processes of lithium-ion batteries

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The successful development of a sustainable and rapidly growing lithium-ion battery (LIB) market requires efficient recycling technologies for end-of-life batteries. A promising process approach to maximize recovery yields and ensure battery materials quality combines mechanical shredding and separation steps with hydrometallurgical treatment of active materials.. [1] During the shredding phase, the electrolyte, which comprises a mixture of organic solvents and conductive Lithium salt, is released. These solvents not only pose a severe risk to process safety and the environment, but also have an adverse impact on the recovery rate in subsequent process steps. [2, 3]
For this purpose, an intensified drying step is implemented, focusing on the targeted removal of the electrolyte solvents from the crushed material. Optimizing drying time and conditions is critical for economic and environmental considerations. In this study, the drying process is thoroughly investigated to gain a deep understanding of its complexities. The description of this process is intricate due to the presence of a multicomponent mixture with different thermodynamic and material transport properties, as well as the influence of the porous structure of the shredded material. Particularly, the impact of upstream crushing on solvent release is carefully examined.
Drying and sorption experiments will yield data about the mass transfer kinetics and phase equilibria. The volatilization of the organic electrolyte solvents during drying is quantified on a component-specific basis using various experimental setups. [4- 7] Initial results on the solvent evaporation will be presented. The experimental output is integrated into a predictive simulation model to optimize critical process times given by the drying boundary conditions imposed by the process parameters. In the end, the findings gained about the drying in the LIB recycling result in energy and costs reductions and can be leveraged to enhance existing processes and drive the development of innovative industrial-scale plants.

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Comminution of polymers for the recycling of battery periphery in a hammer mill

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With the increasing demands on lightweight construction and low-cost production combined with higher mechanical requirements for components in the automotive industry, the proportion of composite materials made of metal and polymer is rising. The materials used in the component can be interconnected in a form-fit, force-fit or material-fit manner and pose considerable challenges for the recycling of the components after their service life. Actually, shredders are used to crush end of life batteries and add-on parts like power strips, which are sorted in various following process steps to obtain fractions with a minimum contamination. The shredded polymer fraction contains first different types of plastics with different characteristics and second the fractions show a wide particle size distribution. To ensure a high quality, the recyclate must be completely single-sorted and have a homogenous particle size distribution to ensure an easy reuse, e.g. for injection moulding.
In order to enable a material recycling of the polymers, the stress type of impact comminution is investigated in a hammer mill. Two basic polymers have been chosen: PA6 on the one hand and POM on the other, both thermoplastic materials with diffe-

rent material properties. The operating parameters of the mill are kept constant while different pretreatments of the polymers are used to change the fracture properties, using a variation of temperature and moisture. The particle size distribution of the fractions are determined by sieve analysis, comparing the different pretreatments and polymers. The aim is to determine a correlation between the pretreatment and the particle size distribution in order to identify possible process windows for the recycling of hybrid materials.

Assessing the economic and environmental impacts of leasing batteries for electric vehicle fleets: A solution for companies and customers?

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Battery electric vehicles (BEV) powered by renewable energy are expected to enable a large decarbonization of the land-based transport. Recent estimations of the International Energy Agency suggest that BEVs could grow 20-fold by 2030, reaching 200 to 350 million units globally. However, the environmental impacts of BEVs remain a critical concern. Batteries are responsible for 80% of the life cycle environmental impacts of BEVs, mainly due to the extraction of raw materials, manufacture, and charge. Circularity represents a pragmatic concept that strives to prevent the unnecessary exploitation of new materials by prolonging the lifespan of resources and products. Among the various circular business models, battery leasing remains an underexplored area in the existing scientific literature. This study centers around the economic and environmental impacts of battery leasing for electric vehicles as a circular business model and compares them to the linear model of selling-buying batteries. Unlike previous research that focused on either the economic or the environmental aspects, or solely on vehicle leasing, this analysis considers both aspects of battery leasing. A comprehensive approach is employed, combining a battery fleet model, net present value (NPV) analysis, and cradle-to-grave life cycle assessment (LCA). To provide a deeper understanding of the subject, a dedicated battery fleet model is built that incorporates various driving profiles instead of relying on a single 'average' profile used in previous studies. This detailed approach enhances comprehension of how the mileage evolves over time and its implications for cost structures and cost-effectiveness. Modeling a large number of customers with different driving profiles better reflects real-world scenarios compared to using a single 'average' profile. This realistic representation is essential for assessing the life cycle impacts of business models, as it depends on customer preferences and decisions regarding driving distances. The findings demonstrate that leasing batteries can be equally profitable as selling them, with a positive NPV of 6.4 million € and a confidence interval of ± 5.5% at 90% certainty for a fleet of 10,000 battery electric vehicles. However, companies that lease may require higher revenues and face increased tax obligations to achieve the same NPV as selling. To generate additional income, companies would need to charge fees to customers, which may not always be economically beneficial for them. Interestingly, purchasing the battery proves to be the most costeffective option for customers driving more than 10,000 km/year. From an environmental perspective, life cycle assessment (LCA) results indicate that leasing batteries offers no substantial environmental benefits compared to selling them. Although leasing offers advantages such as user flexibility, and promoting battery repair, repurposing, and recycling, there is insufficient evidence to support its cost-effectiveness or significant environmental improvements over traditional buying and selling models. The findings may be relevant for other business models targeting a substantial user base in the BEV domain, such as battery as a service or battery swap. It is important to acknowledge the limitations of this study, which concentrated on Nickel manganese cobalt oxide (NMC) batteries for vehicles in the small segment and conducted the analysis based on driving profiles and conditions specific to Germany. Therefore, further research considering different battery chemistries, vehicle types, and other countries or regions is necessary to provide more conclusive arguments. Nonetheless, as battery prices continue to decline, it is reasonable to expect the economic advantage of purchasing batteries over leasing to persist in the future. Such a scenario would benefit customers by not only providing the perception of more affordable products but also offering enhanced quality and longer warranty periods.

System integration and application

Expansion of silicon containing anodes in pilot pouch cells and its effect on the energy density and module integration

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Silicon containing anodes, due to their high specific capacity, open a pathway to enable Li-Ion Batteries with increased volumetric and gravimetric energy density. This strive is powered by requirements from various Li-Ion Battery applications, e.g. the automotive industry, and is reflected in recent research and innovation funding programs. Among others, the Horizon Europe projects IntelLiGent [1] and SeNSE [2] investigate two types of silicon containing anodes in combination with different Generation 3b Li-ion Battery cathode materials. The large volume change of silicon containing anodes during lithiation and delithiation and the resulting challenges on cell level are well known in literature. However, the investigation usually is carried out at lab scale or at pouch cell level for a limited cycle number [3] [4]. The application of this anode material in the automotive sector results in challenges for module and pack design, therefore the long-term volumetric changes and specifically its thickness are key parameters for the industry.

For this reason, extensive cycling tests are conducted on an industrially relevant level, providing reliable insights in the long-term behavior of silicon containing pouch cells. Furthermore, the reduction in energy density and the context of the cell status (SoC, SoH) and the cell expansion is investigated. Double sided electrodes (silicon graphite composite anodes with 5 wt % to 20 wt % silicon content) with areal loading of 2.0 $mAhcm^{-2}$ to 4.5 $mAhcm^{-2}$ are manufactured and calendered on pilot scale. Multilayer pilot pouch cells of 2 Ah to 10 Ah are manufactured from these electrodes and electrochemically tested. Using an in-house designed setup, the expansion of the cells is tracked in Z-Axis and the pressure on the cell is controlled during formation and cycling. The results show that the expansion of the cell can be split in two components: an irreversible, increasing with number of cycles, and a reversible component, corresponding to the breathing of the cell during each charge and discharge cycle. After 100 full cycles, the cell thickness increases up to 25% in comparison to the thickness before formation.

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TranSensus LCA: Towards a harmonized LCA approach for zero emission vehicles

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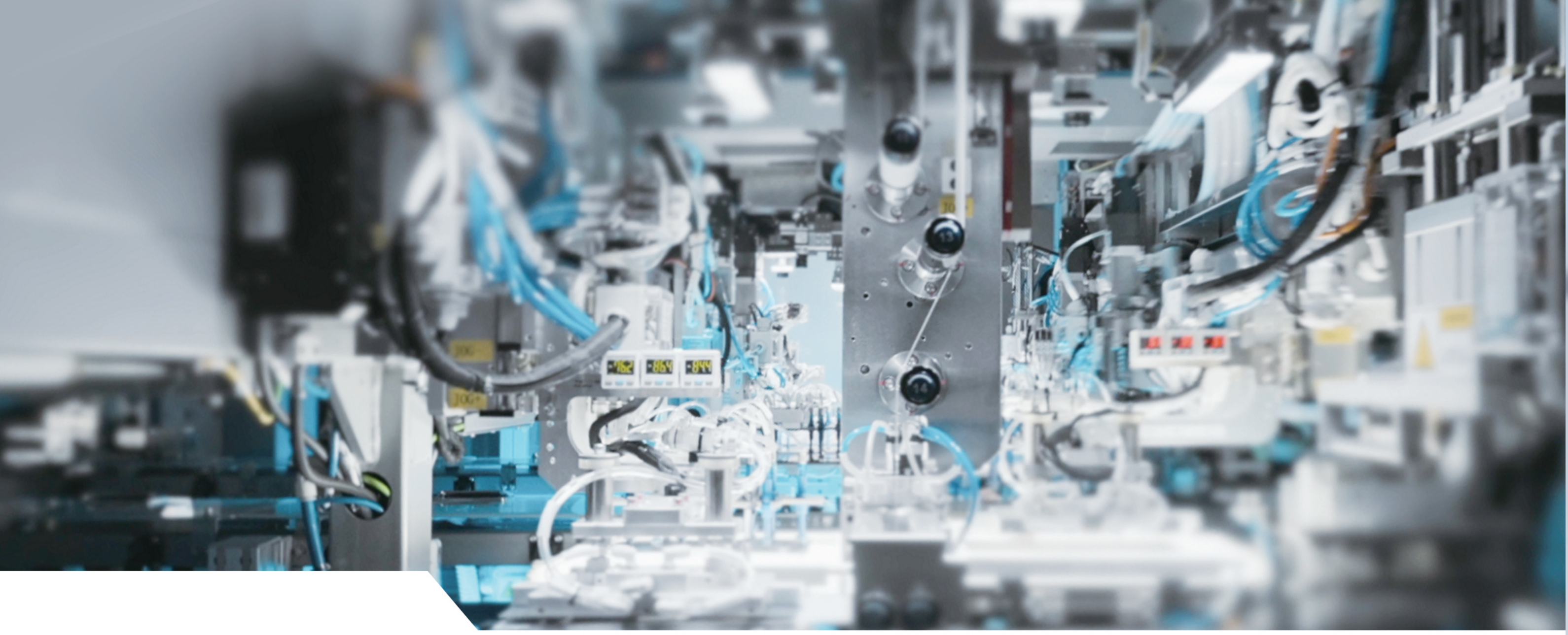
In response to climate change and the resulting demand for sustainability across the entire value chain and life cycle, our road transport system is changing rapidly. New drive systems are achieving steadily growing market shares. At the same time, sustainability targets are being established in more and more legislative initiatives and directives. In order to realistically define these sustainability targets and subsequently track their implementation, a consistent and holistic approach to assessing the environmental, economic and social impacts of technologies and mobility concepts is needed. Currently, there is a lack of a standardized method for sustainability assessment in the mobility sector that is used consistently by all stakeholders. TranSensus LCA aims to develop a basis for a harmonized, widely accepted and applied LCA approach for a zero-emission road transport system across Europe with regard to different LCA types: the retrospective product LCA, the prospective product LCA and the fleet level LCA from an OEM perspective and a market perspective. By bringing together relevant stakeholders from industry and research, transparency in the implementation of LCA will be created and an evidence- and data-based LCA approach will be designed and harmonized that assesses environmental, economic as well as social aspects. The base for the developed guidelines is an extensive review on already existing guidelines, state of the art in research and OEM reports as well as industrial practice. The review highlighted which parts are already quite harmonized and where the most needs and gaps can be found. For example, the two most common system boundaries are cradle-to-gate and cradle-to-grave for ZEVs and batteries. Most vehicle LCAs use kilometer-based FUs. For battery-focused LCAs a commonly applied FU is the energy provided over the service life. However, how to calculate the lifetime of batteries and vehicles is often left open. The options identified in the review build the base to develop the method in TranSensus LCA.



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POSTER ABSTRACTS I Day 2

Battery production 4.0, modelling, simulation and digital twin

Ontology-Aware Modeling of Relevant Parameters for Data Preparation in Smart Battery Cell Production

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Battery Cell production is a key technology for the tackling of major global challenges like the climate crisis. Still, the cause-effect relationships of parameters and their impact on quality indicators and resulting process stability are only limitedly identified and published. Those cause-effect relationships are target of highly active research. An essential part of the work in the data-based analysis of such cause-effect relationships lies in the preparation of the data. In our work, we show how those cause-effect relationships and the relevant parameters can be described by ontologies and integrated into the data ingestion pipeline with reduced effort. Therefore, we propose a ontology-aware data storage and middleware tool chain. We show, how this works in the example of distributes production machine setup. Finally, we show paths for further integration of the concept by machine vendors using standardization approaches for OPC UA Companion Specifications.

Predictive Analytics Platform for Lithium-ion Battery Cell Manufacturing

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Lithium-ion batteries have become a key technological driver for the switch towards electric mobility due to featuring characteristics such as high energy density and safety factor. However, the high energy demand and required material input during production limit the technological potentials which is why the reduction of scrap rates and with this the lowering of the overall production costs and environmental impacts have gained increasing importance. This poster proposes a concept for a predictive analytics platform focused on quality control during the battery cell manufacturing. The platform integrated new battery cell testing tools and modern machine learning methods to support the real-time prediction of final product quality during the processing steps and thus enable the reduction of production waste through a reactive adaption of down-stream processing parameters.
As a use case, the effects of the lamination process of electrodes and separators on cell performance were investigated. More than one hundred cell stacks were laminated under different process parameters and tested at different stages of cell assembly. Using the validated models, the platform demonstrates the potential to predict cell performance in real time and thus reduce material input and energy demand by interrupting the production of critical cells, to conduct a process parameter study for cell production more efficiently, leading to better decision-making regarding adaptation and improvement of the production process.

Application of transfer learning in battery cell manufacturing scale-up

Marten Klenner, Artem Turetskyy
PowerCo SE

The increasing demand for battery cells in the automotive sector forces cell manufactures to accelerate product development and scale-up of their production processes. To achieve this, digitalization expands data acquisition and enables the use of machine learning methods. These methods can be utilized for quality assurance, process optimization, process control and more. For example, a machine learning method allows to accelerate the work of process developers by quantifying the influence of production parameters on product features. With this, the process developer can adjust the production parameters and may reduce the number of experiments. The application of machine learning requires a large amount of data, which is especially difficult to acquire in the prototyping phase of the scale-up of battery cell manufacturing due to the vast number of parameter variations, the complex process chain and the small production quantities. Therefore, there is a need for methods, which are able to train machine learning models on small datasets. A possible method for this is transfer learning which uses parts of a previous model on a new, but similar problem. Utilizing transfer learning becomes even more interesting when applied on production scale-up. For example a machine learning model could be transferred onto a machine with a higher throughput or a model used on coin cells can be reused for prismatic cells. This poster describes different applications of transfer learning in the scale-up of battery cell manufacturing with the scope to accelerate the development processes from laboratory to series production. Furthermore, it introduces challenges in data acquisition, tracking and tracing and modeling needed to overcome in order to utilize machine learning models and transfer learning methods.

Modeling the continuous battery slurry mixing process: Material transport and distribution in a twin-screw-extruder

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The battery slurry mixing process has a major impact on battery cell performance. It also has a significant impact on the downstream production process. Mixing by extrusion provides a flexible method to cover both low and high production rates, facilitating scale-up and reducing long downtime in large industrial applications.
The adaptation of a twin-screw extruder (TSE) for the production of battery slurries was initially carried out through numerical flow simulations of the process based on a laboratory scale extruder. Single elements of the extruder screw were simulated using the Smoothed Particles Hydrodynamics (SPH) method. The SPH method offers high flexibility due to its free surface flow nature and adaptability to complex geometries, allowing the simulation of both fully and partially filled screw sections. Consequently, this approach allowed the investigation of different operating parameters and design concepts for the configuration of the extruder screw.
Based on the simulation results, dimensionless models of the extrusion process are adapted to the machine used. This approach allowed the study of the influence of the process parameters on the energy consumption and the pressure build-up along the screw in a digital framework and prior to experiments, leading to a better understanding of the mixing performance of the extruder.
The description of the material transport through the extruder in terms of the filling ratio allowed the optimization of the screw design and the calculation of the process limits.

Workflow for Estimation of locally generated Joule Heat during thermal runaway consisting of DEM-simulations of the microstructure and simplified full-cell simulations

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The continuously increasing energy density of modern lithium-ion batteries means that battery safety is becoming an increasingly relevant topic. The mechanical stress on the battery in the event of an accident (e.g. of an EV) can lead to a short circuit. In the worst-case scenario, this leads to an uncontrolled thermal runaway, during which more and more energy is released with increasing capacity and energy density. Therefore, during the development process the battery cell must be optimized with regard to safety to minimize the probability of a thermal runaway. For realizing such a safety assessment in the early stages of development, a simulation-based workflow using multi-physics simulations of the full cell is inevitable. An important input for these simulations of the thermal runaway is the heat generated at the point of short circuit. Here, a workflow will be presented that allows estimating the heat generated by coupling DEM and continuum simulations of the microstructure as well as simplified full-cell simulations.
The mechanical impact on the microstructure of the lithium-ion cell due to the misuse scenario is simulated using DEM models. This limits the dimensions of the volume element that can be considered to few hundred micrometres. With the help of continuum methods, it is possible to derive electrochemical properties from the resulting microstructure. In this way, the change of

resistance between anode and cathode can be determined. Finally, this information is used in a simplified full-cell simulation to allow an estimation of the current density at the point of the short circuit and thus a calculation of the generated heat. We present a first concept of a workflow, which provides an estimation of the local heat generated during a short circuit by using different analysis methods for parameterization and calibration and by combining different simulation methods. Besides the general concept, first results will be presented.

Cell assembly

Modelling of a Z-Stacking Machine for Virtual and Risk-Free Exploration of Optimization Approaches

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Within battery cell production, the stacking process step is attributed with high significance. One reason for this is that it involves a transition from a continuous to a discrete production. Therefore, it is crucial that the machines and equipment used for stacking are operated with high throughput capability. Considering the trend of reducing separator thicknesses, setting up the machines for a material change or initial commissioning poses a challenge. Currently, this is done by trial-and-error approaches, where material waste and inefficiency result from choosing incorrect machine adjustment parameters. The utilization of digital machine models offers the opportunity to optimize and accelerate these processes. This poster presents an approach to build a machine model for a Z-Stacker. By considering multiphysical relationships between machine components, control structure and material, stress conditions in the separator can be predicted. Thus, it becomes possible to identify optimal machine adjustment parameters, leading to a reduction in material waste and personnel efforts.

Ultrasonic welding of metal-polymer current collectors: Challenges and Limitations

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Intensive research efforts are currently taking place in the field of metal-polymer current collectors. These new current collectors are intended to replace conventional aluminum and copper foil as they promise weight reduction and safety advantages. However, the introduction of those current collectors require adjustments within the manufacturing process. Here, one of the main challenges is the contacting of those novel current collectors to produce pouch cells. While, thermal processes, such as laser beam welding, are not applicable due to the melting of the polymer core during contacting, ultrasonic welding seems to be a promising contacting technique. However, as the polymer core acts as an insulator there are questions concerning the adaptability of the ultrasonic welding process for the contacting of metalpolymer current collectors. For this reason, the extent to which ultrasonic welding as a cold welding process can be applied to the novel metal-polymer current collectors was investigated. Special attention was paid to the sensitivity of the electrical and mechanical load capacity after contacting depending on the number of plies as well as the influence of the thickness of the metallization. The results show, that ultrasonic welding is suited to contact those novel current collectors and based on these, small Pouch cells for laboratory examination can be produced. However, as the number of joinable layers is limited and the electrical resistance is quite high, the process needs further adjustments to match the industrial requirements.

Insertion of Lithium Nitrate as Additive in Li-Ion Battery Cells and its Implications for the Upscaling in Large-Scale Cells

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To enhance the energy density of lithium-ion battery cells, high-capacity active materials such as silicon are used in lithium-ion battery research. However, the use of these materials is often associated with reduced battery lifespan compared to conventional battery active materials. One approach to mitigate this limitation is the incorporation of additives. Additives are substances that are introduced in small quantities to cell components to augment various chemical reactions within the battery cell, such as the formation of a more stable solid electrolyte interphase. Lithium nitrate (LiNO3) has shown promising properties for improving the performance and longevity of lithium-ion batteries. However, the solubility of LiNO3 in the electrolyte fluid as standard form of additive insertion is limited, necessitating alternative strategies for its effective integration.
This study explored various methods for incorporating LiNO3 into battery cells, utilizing a nickel-rich NCM cathode and a silicon-dominant anode. Alternative approaches were evaluated to overcome the solubility limitations of LiNO3 in the electrolyte. Notably, during the scaling process from coin cells to pouch cells, a significant increase in gas formation was observed during formation, presenting challenges for the scalable implementation of LiNO3 in large-format battery cells.

Production of High Quality Pouch Cell Housing through Optimized Deep Drawing Process Control

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In recent years, the following three relevant designs for Li-Ion battery cells have emerged, which are distinguished by their housing, respectively their geometry and material: Cylindrical and prismatic cells that typically consist of wound electrodes (jelly-rolls) placed in a rigid, metallic housing. In contrast, pouch cells use discrete electrode sheets in stack form. These electrode stacks are heat-sealed into the eponymous pouch foil, a limp multilayer foil, as a housing.
Defects in the pouch film usually result from the production of the individual half-shells. A forming process known as deep drawing is specifically used here. In this process, the pouch foil is clamped in the mould by a hold-down device and formed into the desired geometry by pressing in the internal punch.
The process parameters of the hold-down force and the punch speed have a particular influence on the quality of the half-shells. If the parameters are set incorrectly, defects such as wrinkles or, in the worst case, ruptures can occur. While cracks result in direct leakage of the cells, wrinkles often lead to channel formation in the sealing seams and can therefore also lead to leaky cells. While previous studies have mainly focused on the influence of static parameters in the thermoforming process, this poster looks at the advantages that can be achieved by adaptively adjusting the parameters during the process.
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Electrode production

Influence of the Calendering Density on Pilot-Scale Gr/SiO Electrodes

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With the growing demand for high-energy-density lithium-ion batteries, silicon oxide (SiO) with its high theoretical specific capacity has emerged as one of the most promising anode materials. Nevertheless, its practical use has been limited by disadvantages such as mechanical degradation or poor cycle life1. One of the most viable approaches to address these limitations is the use of graphite-SiO (Gr/SiO) blends as anode material2. A number of publications are referring to this approach, however they mostly relate to electrodes produced in lab-scale only or containing SiO only in low content.
In our work, we investigated Gr/SiO negative electrodes produced in pilot-scale with a SiO content of as high as 18.6 % and a total of 50 % higher specific capacity compared to state-of-the-art graphite anodes. We show how irreversible losses and overall electrode stability can be improved by tailoring its coating density. Furthermore, the relation between electrode density and mechanical properties such as adhesion strength is elucidated. We further analyzed the effect of calendering density on pore size distribution using mercury intrusion porosimetry. Additionally, we investigated the electrical resistances of the electrode

composites, including interface resistance and volume composite resistivity. Moreover, we examined ionic resistance and effective tortuosity through impedance spectroscopy conducted on symmetrical coin cells.
Half-cell characterization with a Lithium reference electrode was used to evaluate specific capacity and initial coulombic efficiency of both anode and cathode, providing valuable insights into the impact of particle cracking on these electrode characteristics. Finally, we will demonstrate an improved charge capacity of the Gr/SiO electrodes in bi-layer pouch cells by up to 30 % compared to cells with pure graphite anode and show its dependency on calendering density. Overall, our findings demonstrate that cautious electrode compaction is crucial to prevent cracking of SiO particles and maintain low irreversible losses.

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From Organic to Water-Based Processing: Pilot Scale Production of High Specific Energy LFMP Cathodes

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In recent years, there has been a growing interest in developing environmentally friendly and cost-effective manufacturing processes for cathode materials used in lithium-ion batteries. Manufacturing Lithium Iron Manganese Phosphate (LFMP) cathodes using water as the solvent provides a safer and more cost-effective alternative compared to traditional organic solvent-based slurries. [1] The olivine LFMP exhibits substantial potential for high-performance lithium-ion batteries, combining the safety characteristics of $LiFePO_4$ with the energy density advantages of $LiMnPO_4$. [2]
This work focuses on the research and development of a water-based LFMP cathode on a pilot scale with industryrelevant mass loadings and areal capacities. [3] In our work, we investigate a water-based binder and electrode formulation that is suitable for this purpose. The LFMP electrodes are characterized both physically and electrochemically using techniques such as scanning electron microscopy (SEM) and energy-dispersive X-ray spectroscopy (EDX) to evaluate their microstructure, morphology, and elemental composition. Electrochemical performance is assessed through as rate capability, cycling stability, and impedance spectroscopy.
As a result, we will demonstrate that LFMP cathodes produced with our water-based process in pilot scale exhibit desirable properties, including high specific capacity, good rate capability, and low impedance. Our findings reveal that the discharge and charge rate capabilities of the water-based LFMP system are either comparable to or better than those of the organic solvent-based system.
Overall, this research highlights the potential of water-based LFMP cathodes for enabling large-scale production of high-performance, safe, and cost-effective lithium-ion batteries.

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About the drying behavior of a highly-concentrated granulebased system - A new concept for an energy- and cost-efficient battery electrode production

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Lithium-ion batteries have become an indispensable part of modern life. Due to their high energy and power density, lithium-ion batteries are expected to be used primarily in the field of electromobility in the future. The desire for higher performance, cost efficiency and safety poses various challenges for the automotive industry and battery research.
The drying process of battery electrodes has an enormous influence on the electrode quality. It determines electrode characteristics and most importantly cell performance. The major problem during drying is the migration of binder to the electrode surface, resulting in an inhomogeneous binder-distribution throughout the film.
As for state of the art electrodes, drying is one of the most cost-intensive process steps, a new approach for reducing the solvent content in electrode-processing and therefore increasing the cost-efficiency for the battery manufacturing process will be investigated in this work. By reduction of solvent content and the usage of granulates in battery-paste manufacturing, the storage stability of the produced electrode pastes is several weeks. This leads to a decoupling of paste and electrode production and a significant increase in production flexibility.
In terms of the drying step it is essential to investigate the influence of the highly-concentrated particulate granular system on the drying process. Especially the influence on pore structure, film consolidation and binder migration is crucial for understanding the drying process. For this purpose, a series of fundamental studies will be conducted. This work presents the experimental methods for the investigation of the drying behaviour under defined process conditions. These are mainly gravimetric drying tests and investigations by means of cryo-SEM for the elucidation of the pore emptying mechanism, as well as investigations with a magnetic suspension balance for the disclosure of the sorption behaviour. First experimental results will be shown.
This work contributes to the research performed at CELEST (Center for Electrochemical Energy Storage Ulm Karlsruhe) and Material Research Center for Energy Systems (MZE). The authors would like to acknowledge financial support of the Federal ministry of Education and Research (BMBF) via the InZePro cluster-project “GranuProd” (Grant number: 03XP0344C). In addition, the authors would like to thank ARLANXEO Deutschland GmbH for providing the binder used in this project.

Integration of optical measurement methods into a traceability concept to investigate cause-effect relationships in the context of electrode production in battery cell production

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Europe is expected to experience a rapid increase in production capacity for lithium-ion battery cells in the upcoming years. However, the application of these cells in the automotive sector leads to significant challenges. The industry demands high safety requirements and quality standards for battery cells. This presents a central challenge due to the complex process chain involved, with numerous cause-effect relationships that extend beyond process boundaries.
Therefore, these complexities contribute to high scrap rates, leading to increased costs due to expensive materials and limited resource availability. For example, defective intermediates can be identified early and selectively removed from the process chain through improved process understanding. Therefore, it is essential to make production processes more efficient and sustainable.
To address these challenges, it is crucial to improve the process understanding by making cause-effect relationships of process and quality parameters more transparent. In this presentation we introduce a concept that makes cause-effect-relationships transparent to enable process optimization even across process boundaries in battery cell production.
To do so, we describe the product-specific traceability of process and inline quality parameters that is used as the basis for process-optimization. The position-accurate traceability of quality characteristics and process parameters enables a high level of transparency. At the same time, cause-effect relationships lead to a better understanding of the process due to the correla-

tion between these variables and the identification of new relevant parameters. Consequently, there is a mutual dependency between both concepts to enable process optimization.
Afterwards, we validate the concept at the coating and drying process of electrodes. By correlating process parameters with measured product characteristics using an in-line line scan camera, an off-line digital microscope and a laser marking traceability system, we create a data base. By analyzing this database, it is possible to identify cause-effect relationships, this can serve as a basis for process optimization, resulting in lower scrap rates, and thus less material consumption.
Finally, we give an outlook on further research which should cover the validation on further process steps and show further enabled use cases that are possible based on traceability.

Characterization of the induction drying process for the lithium ion electrode production

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To match the steadily increasing demand for lithium-ion batteries, all battery production steps have to be enhanced in terms of quality and performance. In this regard, the drying process of electrodes holds great potential for improvement. The main challenge of state-of-the-art convective drying methods is the high energy consumption within the drying step.
This study focuses on the applicability of inductive heating to dry battery electrodes. By placing recently coated electrodes in an alternating electromagnetic field, the metallic current collector is immediately heated due to induced eddy currents. Since the heat is generated within the metallic material of the current collector, the inductive heating process allows for the efficient drying of the coating starting from the interface between the coating and the current collector. This, in turn, could lead to a significant reduction in heating time and energy losses compared to conventional convective drying methods.
However, the negative impact of high drying rates on electrode properties is well known, as binder migration and carbon black segregation may occur. As a result, the drying rate of conventional convective drying processes is limited. This may also be the case when the novel induction-based heating method is applied.
Within this study, stationary inductive drying experiments were carried out at graphite anodes and NMC622 cathodes on a laboratory scale at different drying intensities and drying times. An infrared camera was used to determine the coating's local heat distribution as well as the temporal temperature development during the drying process. In addition, the drying rates were gravimetrically determined as a function of the area-related power input. Finally, the inductively dried electrodes were further examined to investigate the influence of the drying process on their adhesive strength, the electrode structure, and their electrochemical performance. Based on the results, the transferability of the already known impact of the convection heating process on the properties of the electrodes to the inductive heating process is evaluated.

Influence of high-intensive dry mixing carbon black with lithium iron phosphate for lithium-ion battery cathode productions

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Conductive additives, such as carbon black or graphitic particles, play a crucial role in enhancing the electronic conductivity of electrodes in lithium-ion batteries. However, determining the optimal distribution of these additives within the electrode structure is still an ongoing challenge. Particularly for dry processed electrodes, it is necessary to thoroughly investigate the effects of conductive additives, especially for the use of PTFE as binder.
Recent studies on dry electrode processing have adopted a common practice of premixing the active material with conductive additives to establish a strong and efficient conductive network in the positive composite electrode. This approach has been extensively studied and implemented for solid electrolytes, minimizing any interference with the binder's fibrillation process [1]. Nevertheless, the overall impact of premixing active materials with conductive additives, particularly carbon black, remains relatively uncertain. While initial results have been reported for layered oxide active materials like nickel manganese cobalt oxides [2,3], the premixing of olivine-type active materials, such as lithium iron phosphate (LFP), has not been extensively explored yet. LFP is regaining significant interest as a promising cathode active material for various battery applications due to its low cost, high safety, and long cycle life.
This study introduces a high-intensive dry mixing process for the manufacturing of dry as well as for wet manufactured cathodes. The process involves depositing carbon black onto the surface of secondary LFP particles to create a conductive macro-coating. The influence of the rotational speed of the mixers was investigated in terms of powder properties, rheological properties, coating stability, and the electrochemical performance of LFP-based electrodes.

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Experimental study and numerical prediction of coating defects in multilayer slot-die coating of battery electrodes

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Simultaneous multilayer slot-die deposition in battery manufacturing has significant potential for improving product properties and increasing production efficiency while minimizing costs. By employing multilayer configurations, different materials can be precisely distributed throughout the film height, resulting in graded electrodes that benefit from the synergistic effects of each material [1-5]. This approach offers numerous advantages, such as improved adhesion properties, reduced passive material content, higher charge rates, improved safety, and advances in energy and power density. It can also have a positive impact on subsequent process steps, as demonstrated by Kumberg et al [6], who observed significantly reduced minimum drying times with multilayer electrode structures. Another notable advantage is the compatibility of the method with existing equipment, potentially leading to increased productivity. However, successful implementation is highly dependent on the choice of coating fluid and process, with shear-thinning slurries in battery applications presenting additional complexity due to the dependence of viscosity on shear intensity.
This study examines the application of multilayer coatings to battery electrodes and aims to elucidate the differences between coating defects observed in multilayers compared to those commonly encountered in single layer coatings. Emphasis is placed on the influence of the wet-film-height ratio and the viscosity ratio of the individual layers on the appearance of coating defects. In addition, the investigation includes the development of numerical models to predict coating stability. Computational Fluid Dynamics (CFD) simulations are used to gain a deeper understanding of the intricacies of the coating process and to validate the simplified numerical models. To ensure the relevance and applicability of the results, this study systematically investigates model systems with rheological properties similar to battery slurries, allowing effective transfer of the findings to the fluid of choice for practical application.
This work contributes to the research performed at CELEST (Center for Electrochemical Energy Storage Ulm Karlsruhe) and Material Research Center for Energy Systems (MZE) and is funded by the Federal Ministry of Education and Research (BMBF) under Project ID 03XP0402B (ForeCast).

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Electrode and Separator Extrusion

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We will present several approaches to produce electrodes and separators by extrusion. State-of-the-art processes for electrode production of lithium-ion batteries start with the preparation of low viscous slurries in a batch process. The slurry will then be coated via a slot die onto thin metal foils. The coating is subsequently dried to remove the solvent and calendered to adjust the porosity. These processes involve large amounts of hazardous solvents and have a high demand for energy (drying, solvent recovery). COLLIN has built its first electrode coating line in 1999. Since then, we have improved our machines in many ways to deliver a complete solution to produce electrodes with less or even no solvent. The mixing of the electrode material can be performed by continuous compounding of the base ingredients in a twin-screw extruder. Due to high shearing and individual screw design a good dispersion of the active material within the binder is possible. This electrode material can then be applied via extrusion coating onto the metal foil. Because extrusion can work with much higher viscosities than slot die coating the amount of solvent can be reduced dramatically. To produce a homogeneous thickness profile the die design plays an important role to create a well-defined mass-flow at the die gap. Years of experience in combination with modern simulation tools ensure good results. To further optimize the electrode's inner structure and the thickness tolerance one or more calendering steps can be performed. A heavy drying and therefore a solvent recovery is not necessary in this electrode coating process.
To produce electrode patches a continuous extrusion is combined with a shaping tool. This tool has a cavity the size of the desired patch and gives a very precise control over the dimensions of the electrode patch. COLLIN also builds machines to produce separator films based on mono-axially stretched polyolefin films as well as gel-like separators which already contain the electrolyte in the polymer gel.

Investigation of Adhesion Strength and Binder Distribution in aqueously processed LNMO Cathodes based on Surface Free Energy

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This investigation tackles the issue of low mechanical integrity as well as poor rate capability in aqueously processed LNMO cathodes using a combination of CMC and PVDF latex as binding agents. Starting with the examination of surface free energy through sessile drop and Washburn method the interaction or lack thereof between the different components inside the aqueous slurries can be explained. By transferring the findings to different slurry formulations, the adhesion strength of aqueously processed LNMO cathodes could be improved significantly. The influence of surface free energy of the cathode constituents on the distribution of the applied polymeric binders and the resulting microstructures were further evidenced through SEM imaging as well as ionmilled cathode cross-sections. Lastly the electrochemical performance (rate capability and long-term capacity retention over 1000 cycles) of the different cathode compositions was compared in full-cell configuration.
The application of surface free energy is not limited to the example described. This approach can also be used in other systems to better understand and control the interactions between electrode additives and active materials. In this way, optimized additive systems can be developed to further improve electrodes and cells.

Structure-Property Relationships for Laser-Structured Electrodes in Lithium-Ion Batteries

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The significant increase in energy density is a declared development goal for lithium-ion batteries for applications in electric vehicles. This implies the use of electrodes with significantly increased areal capacity and mass loading. Laser-structured electrodes have shown promising results in recent years, enabling electrodes with ultra-high areal capacity of around 8 mAh/cm^2 for lithium-ion batteries. This makes it possible to produce batteries with a much higher energy density compared to electrodes with conventional areal capacity. However, as there are limitations in lithium-ion diffusion due to the thick coating, batteries made with this type of electrode are still difficult to use in applications.
In order to overcome this limitation, the electrodes are laser-structured to improve lithium-ion diffusion. Various publications have shown the effectiveness of the laser structuring process. During the structuring process, there are several parameters that can be modified to influence the surface topography as well as the structuring pattern resulting in changes in the electrochemical properties. As of today, the influence of both, surface topography as well structuring pattern is not yet completely understood, as there are dependencies between both.
This study summarizes recent findings regarding the influence of surface topography and structure pattern on the fast charging capability. Anodes and cathodes were laser-structured with different structural parameters and electrochemically characterized. It could be shown, that significant increases in charging capability can be achieved with suitable structuring patterns and topographies. Based on this, basic advices for the structuring of electrodes can be derived.

Dry mixing and its effect on powder properties for dry coated lithium-ion battery cathodes: A comparison between batch mixing and extrusion

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One of the biggest energy and cost drivers in electrode production is the drying of wet-coated electrodes. Its elimination has great potential for improving the economics, sustainability, and carbon footprint of the battery production. Dry coating of battery electrodes is a promising way to achieve these goals. Dry mixing of the powdered electrode components at the beginning of the process chain has a decisive influence on the dry electrode and its resulting electrochemical cell performance. In this process step, it is important to functionalize the electrode materials to adjust the powder flowability and microstructure for the subsequent process steps. Therefore, the binder must be homogeneously distributed and structured within the powder mixture along with the active material and conductive additives during the dry mixing process. The resulting powder must be able to form a network during film formation, while maintaining sufficient electrical conductivity of the resulting electrode.
The powder structures of discontinuous mixing by a high intensity mixer were compared with a continuous process by a twin-screw extruder. The two processes differ in many respects, but especially in the way they stress the particles. This results in two product types, powder and granulate, which differ in their particle structure. For example, after batch mixing, the PTFE binder is usually present as micro- to macro-fibrils, whereas nano-fibrils can be formed in the extruder. This increases the risk of over-fibrillation, which leads to poor film formation. Process-structure-property relationships were identified using various powder characterization methods (e.g., flow coefficient, Hausner ratio, electrical conductivity, particle size distribution). The resulting products were tested for functionality in a dry coating process based on a calender. The experiments showed that optimum particle sizes and densities exist to achieve an optimum dry film building behavior.

Influence of Various Polyvinylidene Difluorides on the Carbon Binder Domain for Different Active Material Morphologies in LiNi0.6Mn0.2Co0.2O2-based Positive Electrodes

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State-of-the-art Ni-rich positive electrodes (cathode) consist of active material like LiNi0.6Mn0.2Co0.2O2 (NMC622) and inactive materials such as the conductive additive (CA) and the binding agent (BA) polyvinylidene difluoride (PVdF). PVdF, insoluble in most solvents, requires hazardous N-methyl-pyrrolidone (NMP) as a processing solvent. Due to the associated necessary solvent recovery upon drying, it is important to reduce the amount of NMP used during cathode processing. One way to do so is by increasing the solid content (SC) of the electrode paste, however, this is accompanied by challenges as the viscosity limits the SC which can be applied for the electrode coating process.

Depending on the degree of polymerization and the chain length of the PVdF BA molecules, the properties of these vary, hence affecting the viscosity of the electrode paste, the mechanical and electronic properties of the electrode, and the electrochemical performance. A key factor for a battery cell's performance is the ratio of BA amount to surface area (SA) of the solid components within the composite electrode. As the surface area can vary depending on the particle morphology (primary particles show a high SA and secondary particles show a comparably low SA) it is important to understand how the various PVdF BA interact with these morphological differences. Excess of binder content may result in high internal resistances due to hindered lithium ion mobility and additionally reduced electronic conductivity of the composite electrode. Contrarily, an insufficient binder content may lead to inadequate connectivity between the active material and the conductive additive as well as the adhesion of the composite electrode to the aluminum current collector. As a result, the cycling stability can massively deteriorate because repeated volume change encourages contact loss and detachment from the current collector. Thus, it is crucial to understand the network built off of the various PVdF BAs and the CA, the carbon binder domain (CBD), which may show different elasticities and vary in the coverage of the AM depending on the PVdF used.

This study focuses on the influence of the molecular weight of PVdF BAs on the formation of the CBD network and its distribution within the composite electrode, which is investigated by various methods with regard to morphological, physical, and electrochemical properties. These experiments provide insights into how the chain length of the BA affects the coverage of primary vs. secondary NMC622 particles, making it possible to tailor a binding system for a specific AM morphology and the associated electrode composition.

Upscaling and Improvement of Water-based Ni-rich Positive Li-ion Battery Electrodes

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A sustainable and environmentally friendly production process for battery components is a critical factor for the successful contribution of Li-ion batteries to a more sustainable energy supply. While the environmentally friendly water-based process is well established for carbon-based negative electrodes, the same process still poses several challenges for the positive side, especially when Ni-rich materials are used. The main challenge is the detrimental side reaction of Ni-rich cathode active materials (CAM) with water, leading to a raise in pH of the paste above 12. Such high pH leads to corrosion of the Al foil during the coating process and must therefore be prevented.

In recent years, significant progress has been made in the laboratory-scale aqueous processing of cathode electrodes containing Ni-rich active materials such as LiNi0.83Co0.12Mn0.05O2. It is now necessary to demonstrate at production scale that such an environmentally friendly water-based process can deliver cells with competitive performance. We demonstrate the upscaling of an electrode coating recipe based on carboxymethyl cellulose and styrene-butadiene rubber from 250 mL laboratory scale to 10 L production scale by coating a double-sided electrode with a length of 140 m. Several challenges were overcome, such as controlling and stabilizing the pH of the slurry and fine-tuning the mixing and coating times. The H2O-based pilot electrode was characterized in 21700 type cylindrical cells with a capacity of 3.5 Ah. The cells achieved a high capacity retention of 80% after 1000 cycles at 1C/1C cycling.

For these H2O-based cathodes, a greater increase in charge-transfer impedance was observed during long-term cycling. By optimizing the post-treatment of H2O-based electrodes and adjusting the drying temperature, the longterm cycling stability of pouch cells was significantly improved from 1000 to 1700 cycles before reaching 80% capacity retention.

Investigation of a high intensity mixing process with powders for the production of dry coated cathodes and anodes

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Dry coating processes play an important role in overcoming the immense energy and equipment requirements for the electrode drying step in the conventional LIB manufacturing process. The powdered electrode material is applied to a current collector without the use of solvents. As the components of the electrodes are not homogeneously dispersed in a solvent, the mixing process is particularly important, in achieving an optimal electrode structure. The particle structure can be influenced by different mixing strategies during the mixing process to obtain a homogeneous mixture without segregation tendencies. Furthermore, the formulation of the mixture also plays an important role. A particular challenge here is the even distribution of the binder particles to create a stable film composite during calendering and to avoid increased internal resistance.

The effects of various process parameters on the properties of anode and cathode powder mixtures are investigated. The powder systems studied consist of NMC or LFP (cathode side) or graphite (anode side), PVDF and carbon black, which are dispersed in a high-intensity mixer. The resulting powders shall have a beneficial effect on the properties of the subsequent dry-coated electrodes, and process-structure-property relationships shall be evaluated. Therefore, characterization methods determining particle size distribution, powder conductivity and adhesion strength as well asoptical evaluation using scanning electron microscopy (SEM) are used to evaluate the mixtures. The investigations showed that good powder structuring depends on the specific energy applied to the mixture. However, it is important that any carbon black-binder agglomerates are dispersed. Longer mixing times results in better distribution of these agglomerates on the surface of the active materials and influences the compactability. By using two-step processes, where conductive carbon black and binder are added separately to the active material, a favourable surface coating of the active materials with carbon black is achieved, resulting in improved conductivity. Increasing the binder content leads to the formation of coherent electrode films with higher adhesion strength.

Enabling the production of homogeneous high-load positive electrodes by tailoring the electrode formulation – a conductive additive and solvent apporoach

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To facilitate the electrification of the automotive market, low cost and high energy density LIBs produced under the most sustainable conditions possible are required. These objectives are strongly related to the positive electrode. In order to achieve higher energy densities on cell level, the application of high-load positive electrodes is needed. However, to ensure high lithium ion mobility within thick electrodes and obtain a maximized capacity utilization, it is crucial to tailor the electrode microstructure. Another objective for thick electrodes is to prevent binder migration and crack formation. Therefore, the application of high solid contents (SC) during electrode paste processing is necessary. By using nano-scale and micro-scale spherical, linear and three-dimensional conductive additives the adjustment of an appropriate paste viscosity can be facilitated.

The additional introduction of carbon nanotubes (CNTs) benefits the electrochemical performance leading to higher rate capability and increased capacity retention. The rise of the SC in combination with the conductive additive is compared to the benchmark formulation without further additives in terms of electronic conductivity, adhesion, pore structure and electrochemical performance. With an optimized recipe, similar adhesion strength and superior electrochemical performance was achieved.

However, the optimized recipe does not only enable high SC processing, but also leads to composite electrodes with significant higher mass loading, superior electronic conductivity and higher content of active material within the electrode formulation resulting in higher energy density on cell level. In a next step, the state-of-art processing solvent N-Methyl-2-pyrrolidon (NMP) was targeted with the goal of replacing NMP with a non-toxic solvent.
In summary, a comprehensive study on tailoring the rheological and electrochemical properties by processing additives is presented where high-load positive electrodes with significantly increased rate capability and capacity retention were manufactured.

Introducing Processing Additives to Enable Aqueous Processing of LiNi0.8Mn0.1Co0.1O2 for Lithium Ion Batteries A pH Control and Surfactant Approach

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To allow safe, non-expensive processing and recycling of lithium ion batteries (LIBs), research focus is shifting towards using water as processing solvent in LIB production. Aqueously processed electrodes based on Ni-rich active material still suffer from reduced cycle life due to poor solid component homogeneity within the electrode compared to state-of-the-art NMP-processed electrodes. Additionally, lithium proton exchange reactions on the active material surface cause irreversibly capacity loss during processing, resulting in lower specific discharge capacities. Also, an increased pH value in the electrode paste due to the lithium proton exchange enables detrimental corrosive reactions on the current collector.
In this study it was shown, that the addition of mild acid H3PO4 in aqueously processed electrode pastes results in enhanced lithium proton exchange and capacity loss. However, cycle life of LIBs is increased due to the deposition of phosphates on the active material surface reducing the formation of additional surface impurities. In contrary, via addition of LiOH during electrode processing, less lithium proton exchange occurs yielding less irreversible capacity loss, however current collector coatings have to be utilized to prevent detrimental corrosive reactions.
Solid component homogeneity within composite electrodes was improved via surface modifications by the addition of cationic and nonionic surfactants CTAB and PVP in a second step of this study. Thereby, a homogeneous coverage of carbon black particles on the active material surface is enabled due to the reduction of repulsive forces between solid components within the electrode paste. This leads to a prolonged cycle life for LIBs with PVP-modified LiNi0.8Mn0.1Co01O2 positive electrodes.

Material effects in the production of silicon oxide/ graphite based anodes from laboratory to pilot scale

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Due to the high demand on energy storage and increased use of batteries in mobile and stationary applications, cell chemistries that provide high energy densities and potentially faster charging are required [1]. To meet this demand, silicon-based active materials were introduced due to their high theoretical capacity [1].
However, silicon oxide (SiOx)-containing electrodes suffer from prominent issues such as contact loss, cracking, and delamination of the active material from the current collector leading to limited performance and short cycle life [2].
Therefore, comprehensive insights into the interplay between binder, active material and the properties of the SiOx itself are necessary. Different approaches were reported such as using nanoparticle sized Si [3,4], fabricating composites like core/shell-particles [5], using graphite in blend electrodes with Si compounds such as SiOx [1]. Despite this, the influence of Si-based materials on the production and corresponding scalability, especially the degradation of the active materials during processing of the anode need to be fully understood [2].
This study presents the production of anodes based on SiOx/graphite via different fabrication methods ranging from laboratory to pilot and small industrial scale. Within this range, different pre-lithiated and non-lithiated SiOxmaterials, SiOx-contents (5-20 wt.-%) and binders like CMC, SBR and PAA were investigated. The electrodes were investigated with regard to their microstructure and physical as well as electrochemical properties. Testing of the electrochemical properties, e.g. the electronic conductivity, was done as well as performing cycling experiments in a cell setup with NMC-based cathodes. In addition, the effect of calendering on particle morphology and performance was investigated.

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Development of a module for inline variation of the angle of attack for existing electrode coating systems

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The global production of battery cells is currently undergoing an immense expansion in capacity, but still- or precisely because of this- faces several challenges. One major problem are the high scrap rates, which are sometimes quoted as being as high as 40 %. This represents a considerable potential for improvement from both an economic and an ecological point of view. In order to counter these problems, a concept was developed to control the coating process and produce a high-quality electrode for the subsequent processes. The control should result in both a shorter start-up time and a more robust process with higher quality in terms of the coating's shape fidelity, leading to reduced scrap.
For a low-delay and simple correction of the coating process during operation, the two parameters gap distance and angle of attack were identified, which are to be varied specifically during slot die coating. The fast reaction without impairing the productivity of the system is to be emphasized. As the angle of attack often cannot be manipulated in current coating plants, a module for integration in existing plants is presented here. Especially the available installation space in combination with the required precision is a challenge here. Finally, both the possibilities and the limitations of actively controlling the coating process by means of gap distance and angle of attack are shown.

Electrode, cell and module diagnostics during production

Potential of Computed Tomography Imaging for Detection of Inhomogeneities in Battery Cells

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The distribution of process parameters within the production of lithium-ion battery cells (LIB) can cause inhomogeneities and a variation of physical cell properties. As inhomogeneities are acceptable within tolerances cells of the same production batch show a distribution of performance parameters such as internal resistance and capacity. Inhomogeneities that exceed the accepted tolerances (defects) such as metal particle contamination are linked to failure of the LIB have to be avoided. In addition to electrical measurements, image-based measurement methods can be used to identify the cause of performance deviations and thus ensure the production quality and safety of LIB. While the applicability of computed tomography (CT) as an image-based measurement method for detecting defects and inhomogeneities has been proven, the limitations of this method are still unclear.
In this work a systematical analysis of the capability of CT imaging was performed. A multilayer pouch cell without electrolyte was reassembled with several inhomogeneities placed on one of the middle anodes. To investigate the boundaries of CT, inhomogeneities such as partial and complete removal of the coating, a cut and a sharp bend of the electrode and particle contaminations of various sizes and materials (aluminum, copper, steel) were chosen. By comparing the CT images of the cell with LSM images of the defective anode, it could be proven that all selected inhomogeneities except the sharp bend are detectable. This poses challenges for transferability of the method to larger commercial cells with a higher number of electrodes.

High-speed and high-resolution x-ray tomography for battery inspection

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Battery imaging is a growing field for x-ray inspection, both for high-speed inspection in production lines as well as for research and development. With recent developments in liquid metal high-power x-ray tubes, 3D battery inspection with scan times in the second range is becoming possible. Developments in nano-focus sources, further advance high-resolution imaging for industrial inspection.

Here we demonstrate 1-second CT scanning of an EV battery cell using a MetalJet E1+ with an emission power of 1 kW at 160 kV acceleration voltage and 30 µm spot size. The scans have been performed by rotating the battery cell at 360 deg/s while acquiring 2000 frames in a single second using a CdTe photon counting Thor FX20.256 detector from Direct Conversion. With the acquired scans it is possible to evaluate the cathode overhand, identify particles in the volume, etc. These measurements show that sufficient quality can be achieved in a very short time to enable in-line inspection systems.

Formation and aging

Accelerated Solid Electrolyte Interphase Formation and its Impact on the Performance of 1 Ah Lithium Ion Battery Pouch Cells

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To meet the steadily growing demand for lithium ion batteries (LIB) in the future, more cost-effective and resource-saving manufacturing approaches become increasingly crucial. One of the most timeconsuming and important process steps is the formation.[1–3]

This process step, which is usually performed conservatively in industry, involves several slow charging and discharging cycles and thus lasts several days.[2,3] During this time, an insulating layer of electrolyte decomposition products, the solid electrolyte interphase (SEI), forms on the negative electrode surface and exerts decisive influence on the performance and safety of the LIBs.[2,4] The SEI contains organic as well as inorganic species and the latter are reported to form at higher cell voltages and be the desirable key components of the SEI.[4,5]

In order to accelerate the formation and at the same time specifically influence the composition of the SEI, the cells investigated were charged faster in the lower voltage range. Both, the C-rate and the voltage range were systematically varied for these formation experiments. In addition, the selfdischarge, calendar aging, possible lithium plating, pulse resistances and long-term cycling were also investigated. For all experiments, commercial LIB pouch cells (NMC-622||graphite) with a nominal capacity of 1 Ah were used.

Acknowledgements
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Material development and production

New binder adhesion property characterization for a highquality battery production

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Binder systems are essential components of the battery itself but also in its processing, yet they are only studied with a low interest. The chemical, mechanical and electrophysical tasks of the binder are very diverse and grow with the increase of new materials and processing methods. Binders create the coating structure, forming the link between active materials and the current collector. This makes them an important component for the high-performance battery. However, the property profile of the binder is rarely adapted, even though it contributes significantly to the performance of the battery cell, since many performance problems and aging processes of the batteries are due to the weak internal electrode connection in which the binder plays a crucial role.

In this work, the physical properties of the binder systems are presented. The adhesion of the binder polymers is the decisive criterion for a functioning battery cell. The adhesion and cohesion characteristics are in the foreground of the investigations. The resulting failure modes are being interpreted and supported using imaging analysis methods. Different influencing factors on the polymer structure have an impact on the binder-material interaction itself. The rheological behavior of the battery slurry in interaction with the active materials during the coating process but also during the operation describes one of these significant influences. For example, a shear stress on the polymer structure can change the distribution and the interaction of the binder with the active materials.

In the further course, newly developed binder systems and optimized materials will be considered and investigated according to their physical properties to find out whether the standardized methods can be applied to the new binders. The investigations are performed with anode and cathode material, using various coating thicknesses and binder systems.

Study on Novel Carboxylated Binder Systems for Electrode Production

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Polymeric binders are crucial in batteries, but research on them is limited. Despite being inactive in electrochemical processes, they significantly affect the economic and ecological balance sheet. This lack of understanding creates a bottleneck in battery production and recycling. As active materials are optimized, demands for binder properties increase. They are particularly responsible for the adhesion on the current collector. Performance deficiencies, aging and the resulting shortened battery lifetime are attributed to binder properties. Understanding binder functionality is essential for sustainable and efficient battery manufacturing. Therefore, a well-founded knowledge on different levels of binder functionality must be developed. Within the scope of battery production, there are different process step requirements like mechanical stability, adhesive strength, temperature and electrolyte resistance, polarity and resistance.

Established systems with CMC (carboxymethyl cellulose) and PVDF (polyvinylidene fluoride) fail to meet growing requirements. They lack e.g. in elasticity and polarity necessary for volume expansion and adhesion. Optimizations towards active materials do not lead to desired improvements if the binder is not adapted. However, the choice of binder materials is challenging regarding the selection of different molecular weight regions and functional groups. Some binders show good adhesive properties but less elasticity or poor slurry stability. In order to optimize current state of the art systems with regard to e.g. mechanical stability, blend systems are developed and tested for battery processing. In this work, impact of different binder compositions on swelling, conductivity, adhesion, resistances and mechanical properties are highlighted. The influence on surface and deeper layers is investigated including topography and cross-section analysis.

Production of next-generation batteries

Requirements Engineering and Management for Production Technology of Solid-State Batteries

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Solid-state batteries have gained significant attention as a promising alternative to conventional lithium-ion batteries due to their potential for enhanced energy density and improved safety. However, the successful development and scale-up of solid-state battery production necessitate a systematic to approach requirements engineering and management in the early phases of the production development process (PEP).

This scientific study focuses on the crucial role of requirements engineering and management in aligning product requirements with the capabilities of production technology for solid-state batteries.

It consists of three phases: Identification of product-related requirements driven by the material properties in the early PEP, systematic matching of product requirements with the characteristics of production technology, and evaluation and gap analysis of this matching process.

Based on the analysis, actionable recommendations are provided to optimize solid-state battery production, guiding process development, equipment enhancement, and quality control measures. This framework is then validated for the specific example of the lithium metal anode and its fabrication as a representative case study within the realm of the solid-state battery.

Comparison of reaction enthalpies under solvent variation in the wet-chemical synthesis of β-Li3PS4

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All-Solid-State-Batteries are considered the next generation in battery technology due to increased energy and power density as well as freedom of design, e.g., by constructing batteries in bipolar stacks. Solid-state electrolytes offer advantages over conventional liquid electrolytes, such as greater thermal safety, because of high melting points, and high mechanical strength. One promising material group are sulfides, because they have a good intrinsic ionic conductivity. Furthermore, they can be easily processed due to their ductility and some can be synthesized wet-chemically. This offers some advantages like tailoring the particle size, working at low temperatures, short synthesis durations and the possibility of transferring the routine to a continuous process. The wet-chemical synthesis can be performed in various solvents, which can influence both the process and the product. In this work, we compare the reaction enthalpies during the synthesis process under variation of the solvent. β-Li3PS4 is synthesized by mixing lithium sulfide and phosphorus pentasulfide in an organic solvent at ambient conditions. After removing the solvent, heat treatment is used to obtain the crystalline product. We recently found that the first step of the synthesis, the mixing of the powders in the solvent, is highly exothermic and determined the reaction enthalpies for THF. With THF a temperature scarcely below the boiling point was obtained. [1] From production perspective, the replacement of THF needs to be considered to address safety and environmental issues. Therefore, solvents with more suitable chemical and physical properties are examined. Using a reaction calorimeter and differential scanning calorimetry, the reaction enthalpies of the process with ethyl acetate are determined. Furthermore, energy and environmental aspects of the solvent variation are discussed.

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Direct coating of solid electrolyte on cathodes using a slot die

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Solid separators for all solid-state batteries (ASSB) are becoming more important in recent years. Due to constantly increasing energy and power densities, the trend is towards thinner separators. At the same time, solid separators should have a high mechanical strength with a certain flexibility. Furthermore, properties such as good electrochemical performance and low flammability are essential. These constantly growing requirements for solid separators increase the demand for suitable materials and their processing methods. In order to achieve these requirements, the slot die process is a suitable production method for dense and thin layers. This process is mainly controlled by three process parameters, which simplifies scaling. Further, it is already used in many production steps, e.g. for electrodes in the conventional lithium ion battery production. This offers a good opportunity to use this knowledge and adjust it for solid separator production.

Poly(ethylene oxide) (PEO) based SEs make a good model material as PEO offers many advantages, such as its good availability on the global market, high solubility in solvents like acetonitrile, and the capability to dissolve alkali salts like Lithium bis(trifluoromethanesulfonyl)imide (LiTFSI). In addition to the coating fluid materials, the substrate used becomes more important. For ASSB production, a direct coating of the separator onto the composite cathode is envisioned. Therefore, to achieve the requirements for solid separators, the effect of the substrates during producing has to be investigated.

The aim of this work is to produce solid separators and to investigate the influence of different substrate roughnesses on the coating process. The substrates are characterized prior to the coating process regarding their

surface roughness. Accordingly, the substrates are coated, and the produced solid separators are characterized with respect to coating quality, surface roughness and dry layer thickness using optical measurement methods. The results show closed and unclosed coatings of the produced separator layers as well as differences in the surface roughness of the coatings depending on the substrate. In certain coating processes, the dry layer thickness is reduced, indicating infiltration of the solid separator in the composite cathode used.

Recycling, circular economy and sustainability

Electrochemical recovery of metals from battery black mass

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A key aspect for a future closed loop economy for battery materials is a high recycling rate for the valuable metals contained. Hydrometallurgical processes are complex but are characterized by high recycling rates. A typical hydrometallurgical process is electrochemical metal recovery. With this process, metal salt solutions can be converted into metals with high purity. These metals represent the ideal starting material for the re-synthesis of high-purity battery materials.

The process is a sub-step of metal recovery from battery black mass in the "EarLiMet" project (Competence Cluster Recycling and Green Batteries). The aim is to separate, concentrate and recover the metals Li, Ni, Co, Mn and Cu. An important aspect is the combination with previous process steps. These include early separation of the lithium, chemical leaching processes, and liquid-liquid extraction processes for enrichment and separation of the metal salt solutions. For electrochemical extraction, metal salt solutions with different metal contents are available as basic material. In principle, these metal salt solutions can be completely depleted by the electrochemical process. The challenge is the correct choice of electrochemical parameters, process control, electrode material selection and electrolyte conditioning.

In this contribution, the separation and recovery of the metals mentioned is demonstrated using model and technically processed metal salt solutions. Potentiodynamic as well as potentiostatic methods coupled with the determination of the element content (ICP-OES) of electrolyte and electrodes are used. The results are supplemented by material analytical investigations.

Enhancing Battery Sustainability: A Novel Sustainability Modelling Platform for Battery Production

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Batteries are vital for various applications, but have significant environmental and economic costs. Enhancing their sustainability requires innovative battery designs and production processes across the value chain. Life cycle assessments (LCAs) and cost estimations are valuable tools to evaluate these innovations and facilitate sustainable decisions. However, existing assessments do not sufficiently capture the technical details involved in battery production for adequate engineering decision-making, and can also be time-consuming to establish. This necessitates advanced models that enable efficient, automated assessments while enhancing their relevance to engineering decision-making. This presentation introduces a novel modelling platform for the environmental and techno-economic assessment of batteries. It incorporates detailed models for products and processes, simulates material and energy flows, and links these to LCAs and cost evaluations. The platform's flexible and modular structure enables an extensive analysis of the complexities of novel battery technologies. Its capabilities are demonstrated through a case study comparing conventional and a novel cell production route. The case study exemplifies how the platform enhances the engineering applicability of LCAs and cost estimations, while significantly reducing effort for practioners. The platform thus stands as a valuable tool for enabling sustainable decision-making in future battery research.

Feasibility analysis of the automated dismantling process for the automotive traction batteries, including a comparative economic analysis

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The growing importance of electromobility and the resulting variety of battery models are driven by a strong focus on competitiveness and cost-effective solutions for automotive manufacturers. However, the end-of-life phase of batteries poses a challenge as efficient and environmentally friendly dismantling is necessary to recover valuable resources and minimize potential environmental impacts. In this context, this study aims to analyze the feasibility of automated dismantling processes for electric vehicle (EV) batteries and consider economic aspects to provide recommendations for potential implementation.
The focus lies on evaluating different scenarios using a morphological box and an evaluation matrix incorporating selected criteria. By using advanced robotics and automation technologies, along with the expertise of the plant engineering company FFT Produktionssysteme GmbH & Co. KG, which operates in body construction and battery assembly, can provide concrete action recommendations for the dismantling process. To assess the economic viability of this approach, factors such as investment costs, operating costs, scalability, and potential cost savings compared to manual dismantling are taken into account.
The feasibility analysis reveals that entering the market for automated dismantling is advisable, and a hybrid dismantling approach proves to be cost-effective, contributing to the transition towards a circular economy and promoting sustainable electromobility. The results of this study offer valuable insights for companies and decision-makers which involved in EV battery dismantling.

Modelling and Flow Sheet Simulation of Mechanical Recycling Processes for Li-Ion Batteries

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The recycling of Li-ion batteries gets increasingly important due to the rising demand of electric cars and the request for more independence from raw material markets. One way of recycling Li-ion batteries is the mechanical process route, e.g. a combination of several crushing (e.g. shredder, cutting mill) and separation steps (e.g. screen, zig-zag-sifter) [1]. In order to optimize this process chain, a deep understanding of the processes and a large database are crucial. Therefore, dynamic flowsheet simulations of sub-processes and process chains are beneficial to investigate the influence of numerous operating parameters. For these simulations, models of the individual processes, such as cutting mill (used for second comminution) and zig-zag-sifter (either used for the separation of heavy e.g. casing parts or light separator foils), have to be developed and adapted to the material system. The model of the cutting mill, for example, has to calculate the product particle size distributions of the respective fractions after comminution, as these have a decisive influence on the subsequent separation processes (e.g. zig-zag-sifter). Based on these product particle size distributions as well as further material and process parameters, the model of the zig-zag-sifter can then calculate the separation curves for the respective materials.
These and further process models can finally be used for flow sheet simulations of individual processes and interconnected process chains. This enables the simulation of the influence of parameter variations of an individual process on subsequent processes, as well as the resulting effects on mass recovery and energy consumption.

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Towards a harmonized approach for prospective environmental and economic assessments of battery innovations

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Innovations to improve the technical performance of battery technologies are being developed rapidly. To identify whether such new technologies are worth pursuing from a sustainability perspective, prospective assessments are increasingly promoted to support decision-making in the early stage of technology development. However, these prospective assessments face challenges in terms of data quality, availability, comparability and uncertainty. At the same time, current guidance frameworks for practitioners are underdeveloped compared to those for retrospective assessments. Therefore, with increasing research on new battery technologies towards a consistent resources and energy transition pathway, structured and harmonized approaches are essential to guide practitioners in life cycle assessment and cost estimation of new battery technologies.
This work introduces a harmonized framework to address the research gap in conducting prospective economic and environmental assessments of emerging battery technologies at different technology readiness levels (TRLs). The framework serves as a practical tool, providing guidance at different stages, such as goal and scope definition, generating inventory data for production including upscaling as well as future impact assessment consideration, and uncertainty analysis for emerging battery components based on specific TRLs. The value of this framework is demonstrated through a case study on all-solidstate batteries, highlighting its ability to streamline the assessment process and provide comparable results, while enhancing decision-making in battery technology development.

How to quantify recyclability improving design decisions?

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In the European Union (EU) a new regulation will come into effect in the EU this year with the update of the EU Directive 2006/66/EC (on batteries and accumulators), that will mandate among other things strict recycling quotas for essential materials [1]. In this context, significant importance is attributed to the batteries' design, as the structure and composition of products have a substantial influence on their recycling possibilities [2]. Therefore, it is necessary to closely examine the impact of a product's design on its recyclability, preferably in an early stage in the development process already. From the perspective of battery development, the question arises regarding the specific criteria by which different design options can be compared in terms of their recyclability. Already existing approaches for other products can be classified into qualitative [3], indirect-quantitative [4] and direct-quantitative methods, with the complexity but also usefulness typically increasing in the same order. Possibly, the most favourable but also complex would be a method that directly quantifies the design-dependant environmental impact, so that, for example, the benefits of certain design decisions on the product's or even an entire organization's future carbon footprint could be estimated. As most companies have strict carbon footprint targets, the overall importance of circular product design could thereby be greatly enhanced if a link between the two topics could be achieved. In the framework of this contribution, we would like to examine the possibilities of establishing such a quantifying method in the context of lithium-ion batteries, as this issue raises a number of questions regarding achievable accuracy, necessary pre-conditions and the overall feasibility. We would like to discuss our approach to the topic that we apply to the concept demonstrator, developed within the greenBatt ReDesign project. The overall goal is to quantify the exact benefits, that the ReDesign demonstrator would have in comparison to a state of the art battery which in turn could motivate the implementation a selection of its recyclability-enhancing design characteristics into industry.

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Environmental aspects linked to life cycle phases of solid-state-batteries

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With perspective of higher energy capacity and safety, solid-state-batteries (SSBs) are being developed not only in laboratories but also by bigger battery manufacturers [1,2,3]. In 2021, however, their production did not overreach 2 Wh of storage capacity produced globally compared to 400 Wh for conventional lithium-ion-batteries (LIBs) [4]. This is explained by further need for optimization of material composition for better performance and cost reduction.
There are three main types of SSBs depending on the solid electrolyte: oxid-, polymer- and sulfide-based SSBs. Further type is hybrid SSBs, in which through combination of different electrolytes, their weaknesses can be reduced and strengths increased to receive a more stable battery. While polymer SSBs are the only currently commercially produced type of solid-state batteries, recently the focus has shifted more towards oxide-based and sulphide-based electrolytes which are expected to achieve a higher potential for future development [4]. With these tendencies the following question arises: Which challenges in terms of environmental impacts are expected, if SSB production increases?
This poster reflects on possible changes expected to occur in different life cycle stages of SSBs compared to conventional LIBs: Raw materials Extraction, Production, Use and End-of-Life phases. Qualitative changes within process chains are indicated and potential challenges are discussed.

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Effects of different impurities on synthesized NMC particles

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Lithium ion batteries are the state-of-the-art energy storage devices for a multitude of applications. However, lithium nickel manganese cobalt oxide (NMC) as the most common cathode active material for automotive applications consists of critical materials like cobalt, nickel and lithium. Hence, recycling of batteries reduces dependence on unsafe and ethically critical resource supplies. Thereby, the resynthesis, i.e. the synthesis from recycled materials, is crucial, however so far, the influence of possible impurities resulting from the hydrometallurgical regeneration step is largely unknown. In the project EVanBatter, this influence is systematically investigated and a contamination-resistant resynthesis route of active materials for lithium-ion batteries is developed.
Thereby, the synthesis is performed from commercial precursors in the presence of defined amounts of further compounds as impurities. A two-step synthesis, consisting of precursor precipitation and calcination, was established and four different cationic impurities of Cu2+, Al3+, Fe2+ and Ca2+ as well as one anionic impurity of PO4 3- were applied. The morphology of resynthesized NMC particles was analyzed with SEM. To confirm the composition of the resynthesized NMC particles, XRD and ICP-OES were conducted. In addition, their thermal properties are analyzed with TGA and a laser granulometry was used to analyze the particle size of formed particles. The results show that the cationic impurities with different charge states led to a change in morphology and particle size distribution of NMC particles. The characterized materials were incorporated in Li-ion coin cells and extensively tested.

Cell Types, module and pack design and production

Identifying the impact of the positive active material on the cell design and battery cell production capacity

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The most favorable advanced electrochemical energy storage technology regarding performance and costs are lithium ion batteries [1].
In addition, the demand for higher driving range of electric vehicles (EV) is steadily increasing, while the space for the assembled battery pack is limited [2]. One way to realize increased energy density on cell level is the adaption of the active material. Due to high demands in EV application regarding safety, environmentally friendliness, abundance and recyclable of raw materials, olivine-based active materials are an appropriate choice. However, these co-free alternatives with increased safety properties provide less deliverable capacity, which can affect the energy density on cell level and thus the cell production capacity. Therefore, the composite positive electrode is the bottle neck for battery cell production capacities of giga factories.
Especially for EV manufacturers, the consideration for an in-house cell production is getting more attractive as the battery represents the largest cost factor for EVs. Furthermore, the battery cell production capacity must be adapted to the production capacity of the EVs to remain profitable.
Therefore, this work presents various considerations comparing layered-oxide and olivine based active materials on the resulting battery cell production capacity per GWh for identical prismatic battery cell dimension.

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Towards Multi-Disciplinary Design Automation of Circular Battery Modules – Framework, Potentials, and Future Research

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The design of circular batteries is an emphasis of research towards more sustainability of battery production and use. It involves enabling reuse, repair, refurbishing, remanufacturing, and upgrading of cells or modules. Following the concept of Design for X (DfX), in most current research works proposed guidelines to enable a specific R-strategy (Mesa, 2023). However, in addition to circularity, properties like cost, durability or electric and thermal performance have to be considered in module design. The different design goals and requirements result in a multiobjective design problem. Conventional approaches separate the engineering disciplines (mechanical, electrical, thermal, economics, and manufacturing) and make design decisions based on analysis in a sequential manner, resulting in lengthy iterations cycles within the design process. In order to overcome these challenges, different authors proposed design automation approaches. In general design automation (DA) can be understood as computer based engineering support, that implements information and knowledge in solutions, tools or systems to support the progress of the design process through automation (Cederfeldt and Elgh 2005). Since battery modules are multidisciplinary systems, in this contribution the concept of DA is extended to multidisciplinary design automation (MDDA) to point out the multiple domains involved in design automation. Based on a structured review, following the PRISMA approach in the contribution current applications and potentials of DA and MDDA are analyzed. This review points out the following aspects of DA, c.f. (Rigger 2019) in battery module design:

- Inputs, outputs and goals of the design automation task, e.g. with regard to the module's input geometry
- Knowledge representation and reasoning methods, e.g. shape based representations and procedural rules for knowledge representation or evolutionary algorithms and multi-objective optimization algorithms for reasoning
- Considered domains in the design automation task as well as the coupling of the domains.

Based on the review results a framework for MDDA in battery module design is proposed pointing out the potentials and future fields of research. Here a particular focus is on circularity of battery modules.

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