Technische
Universität
Braunschweig

IBPC 2024

INTERNATIONAL BATTERY PRODUCTION CONFERENCE

27 to 29 November 2024

CONFERENCE BROCHURE

WELCOME

Dear IBPC 2024 participants,

Batteries are a key driver of the global mobility revolution and the core of the energy transition. In recent years, the battery industry has seen significant progress in production capacities, technological progress regarding energy density and fast charging ability, cost reduction as well as raw material requirements. An end of the innovation pipeline 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 energy and raw material requirement as well as carbon footprint have to be decreased significantly. At the same time, the new EU battery regulation puts a special focus on circular economy of batteries. Recycling capacities for both production scrap and end-of-life materials enabling circular economy need to build up. Due to the increasing importance of resilient supply chains, the development of a European battery economy is gaining in attention.

Thrilled with the success of the last six IBPCs with each having up to 260 participants and about 50 exciting presentations on recent advancements in battery production, we are delighted to welcome you to the IBPC 2024 in Braunschweig. We will provide a platform 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 innovative electrode and cell production processes of classical lithium-ion batteries (LIBs) as well as of next-generation and solid-state batteries, cell design and safety, cell performance and diagnostics, formation and aging, sustainable and scalable production, circular economy, 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, especially also direct 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, Maschinenfabrik Gustav Eirich GmbH & Co KG, Netzsch Feinmahltechnik GmbH, NETZSCH-Gerätebau GmbH, Volkswagen AG, Retsch GmbH and our silver sponsors Buss AG, CT Systems GmbH & Co. KG, Mixaco Maschinenbau, SEEPEX GmbH, Stat Peel Ltd., Thermo Fisher Scientific, Werner Mathis AG, and Zeppelin Systems GmbH. 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

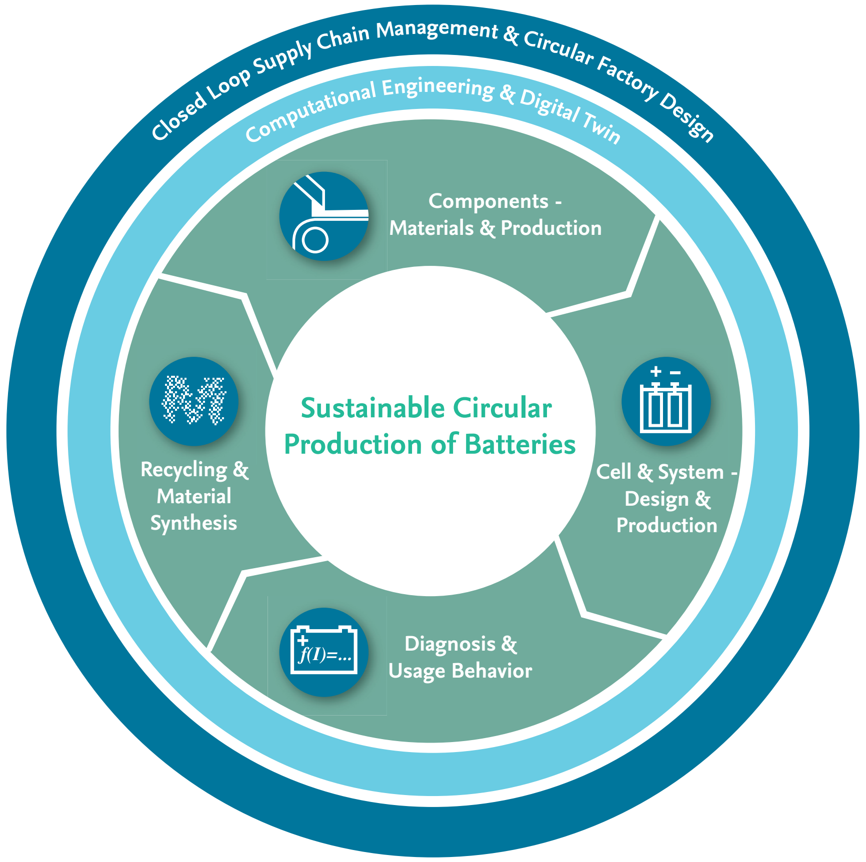
BLB+ is a regional alliance of research institutions in the Braunschweig area, uniting expertise from Technische Universität Braunschweig and local Fraunhofer partners, including the Fraunhofer Institute for Surface Engineering and Thin Films (IST) and the Fraunhofer Center for Energy Storage and Systems (ZESS). It serves as a collaborative platform to coordinate battery research, enhance visibility, and drive innovation in energy storage technologies.

Within BLB+, the Battery LabFactory Braunschweig (BLB) builds on over a decade of battery research in the region, focusing on the entire value chain- from material development and cell production to recycling and active material resynthesis from recycled raw materials. It provides a state-of-the-art environment for R&D on electrochemical storage devices, spanning laboratory to pilot plant scales. BLB's mission is to advance sustainable and circular battery cell production.

BLB+ partners collectively offer infrastructure to develop and characterize large-sized batteries, modules, and packs. This supports both fundamental and application-oriented research. Over the coming years, more than €100M will be invested in cutting-edge infrastructure across the BLB+ network, enabling exploration of advanced lithium-ion and solid-state batteries, fuel cells, and energy converters.

BLB+ Braunschweig Labfactories for Batteries and more

Sustainable circular production of battery cells



CONTENT

PARTNERS

BioLogic

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

BÜHLER

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 excellence in compounding

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/

coperion confidence through partnership

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.

Coperion supports Li-ion battery manufacturers in cost-effectively producing high-quality batteries. Our extensive range of proven first-class technology and products, spanning from single components to complete systems, coupled with expertise in designing individual machines and years of process experience, are the key factors contributing to the successful planning and building of systems in various areas of battery manufacturing.

www.coperion.com/batteries

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

CT SYSTEMS excellence in innovation

"You can never solve problems with the same way of thinking that created them" (Albert Einstein)

That's why we think differently because the world is changing:

In addition to our tried and tested core business, we have developed a new dosing system for the production of an electrode for a battery cell. It ensures temporal, spatial and, in particular, constant powder dosage and thus reduces production costs by 50%.

The CT Systems Group is a provider of cutting-edge technology for the automation of material flow in the bulk materials industry. We operate internationally.

In industrial process technology, we specialize in tailor-made solutions for current applications while also keeping an eye on future needs. Process safety is our top priority.

www.ctsystems.de

PARTNERS

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 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 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

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

SEEPEX is a worldwide specialist in advanced pump technology, offering a comprehensive portfolio of progressive cavity pumps, pump systems and Digital Solutions. Our innovative solutions are designed to handle aggressive and abrasive media with viscosities ranging from low to high, ensuring reliable performance across diverse industries.

As experts in battery slurry handling, SEEPEX provides superior contamination-free pumps essential for high-performance applications in battery manufacturing. Our pump design is perfectly suited for the automotive, electronics and semiconductor sectors, enabling smooth, efficient conveyance of battery compounds while safeguarding product integrity.

Since 2021, SEEPEX has been part of the Ingersoll Rand Group, a global supplier of mission-critical flow creation and industrial solutions across 40+ respected brands. Ingersoll Rand Inc. (NYSE: IR) driven by an entrepreneurial spirit and ownership mindset, is dedicated to helping make life better for our employees, customers and communities.

www.seepex.com

Stat Peel is a Swiss manufacturer of advanced analytical instruments designed to inspect particles in laboratory and production environments. The first Identifier system was developed to detect and quantify airborne CNTs among other carbon particles. Our fully automated Raman-spectroscopy based detection system can quantify a wide range of materials. With different system configurations you can:

- Monitor aerosol particles using wearable air sampling badges to detect cross-contamination and protect the health and safety of workers. You can quantify different nanofibers such as CNTs, or other harmful materials, among the many other aerosol particles in your lab and production environment.
- Inspect particles in liquids to quantify materials of concern in process- and wastewater.
- Use swabs to inspect potentially contaminated surfaces.
- Inspect powders and coated foils to perform quality control tasks.

With Stat Peel’s high-sensitivity Raman systems you can monitor particles in the air, liquids, powders and on coated foils for contamination, health & safety and quality control tasks. Use our sampling kit to test the capabilities of the Identifier.

www.statpeel.com

Improvements in battery technology and manufacturing lie at the heart of society’s transition to clean energy. Making affordable batteries that pack more power, last longer, charge quickly, and are safer is essential to enable the pivot towards electrified vehicles and renewable energy storage. Thermo Fisher Scientific offers global partnership, integrated analytical technology, advanced metrology, chemicals and software solutions to support and strengthen activities across the battery manufacturing lifecycle, helping battery material producers achieve greater efficiency and a smaller environmental footprint and cell manufacturers reduce waste, maximize production throughput, and improve profitability. Whatever your role in the battery supply chain and wherever you work within it, we can provide the insights you need to succeed.

www.thermofisher.com/battery-solutions

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

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 1,900 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. As an international plant engineering specialist, Zeppelin understands the specific requirements of battery mass production, regardless of whether it is a wet or dry process. With the FM high-intensity mixer a precise and efficient battery mass production is guaranteed. The mixer ensures reliable raw material handling, precise premixing, and optimal active material distribution for superior battery mass quality. We Create Solutions for our customers every day.

www.zeppelin-systems.com.

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

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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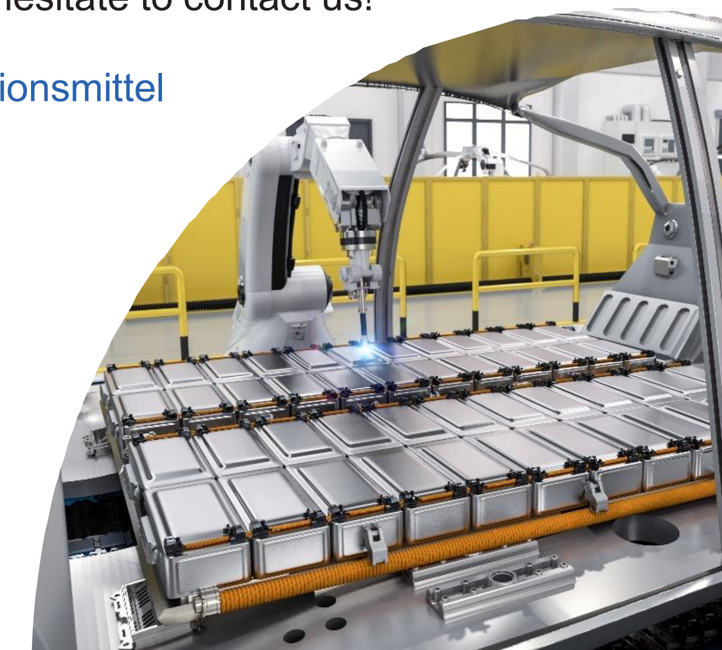

PROGRAMME

CONFERENCE DAY 1 | Nov. 27th

Seminar: Automated Electrode and Cell Production

8:30 I Seminar participants: Arrival and registration

9:00 I Introduction, material overview & electrode production
Nimes I Prof. S. Zellmer & Prof. A. Kwade

10:30 I Break

10:40 I Automated cell assembly
Nimes I D. Nguyen

11:30 I Break

11:40 I Digitalization of cell production
Nimes I Prof. C. Schilde

12:30 I Industry: digitalization solution for battery cell production
Nimes I N. Vallin, Dassault Systèmes

13:00 I Lunch

13:00 I Arrival, registration and Lunch

14:00 I Welcome Talks

14:30 I Keynote Dr. Stefan Schwarz, IBUtec
"From Niche Market to Essential Technology: Prospects for LFP Production in Europe"

15:00 I Keynote Mark Laderer, Manz und Grob
"Scaling European Battery Production"

15:30 I Break

15:50 I **Parallel Sessions**

Scaling up active material production
Room Maschinenhalle I Chair: Prof. S. Zellmer

From material development to large scale production of cathode active materials – How to close the gap
Katja Kretschmer, IBU-tec

The Glatt Pow(d)er Synthesis – Aerosol-based processes to produce battery materials
Johannes Buchheim, Glatt

Cathode Materials Pilot-Plant “Powder-Up!” – Ready for Operation
Peter Axmann, ZSW

AI-assisted battery production
Room Nimes I Chair: Prof. C. Schilde

Optimizing Battery Development and Quality Control through Data Integration and AI
Charles Jouanique, LabV Intelligent Solutions GmbH

PROTEO – Revolutionizing Battery Design with Advanced Digital Tools
Elixabete Ayerbe, CIDETEC

Artificial intelligence informed end-of-line testing in lithium-ion battery productionr
Tessa Krause, Precitec

16:35 I Discussion

16:50 I Break

17:00 I **Parallel Sessions**

Slurry processing
Room Maschinenhalle I Chair: Dr. rer. nat. M. Kandula

Challenges in Slurry Mixing Process for Li-Ion Battery Electrode Manufacturing
Tiago Charana, CeNTI

Innovative Battery Production with Eco-Friendly Water-Based Binders
Neslihan Yuca, Pomega

Transfer of the continuous production of battery slurry to different extruder scales
Juan Fernando Meza Gonzalez, KIT

Safe batteries and thermal runaway investigations
Room Nimes I Chair: Prof. D. Schröder

Battery research in the context of metrology for environmental & climate protection- quality assurance, safety, and digital product passport
Ghazaleh Esmaeelzade , PTB

Thermal Runaway Mitigation in NMC Lithium-Ion Cells: Assessing the Effectiveness of Thermal Insulation Materials
Elena Gimadieva, Otto von Guericke University Magdeburg

Thermal runaway characteristics and gas emission from sodium-ion cells – impact of state of charge level
Kofi Owusu Ansah Amano, Otto von Guericke University Magdeburg

17:45 I Discussion

18:00 I Poster Session

19:00 I Apero

PROGRAMME

CONFERENCE DAY 2 | Nov. 28th

8:45 I Morning Address by Jan Henning Behrens, Federal Ministry of Education and Research (BMBF)

9:00 I Keynote by Prof. Guido Sonnemann, Université de Bordeaux
"Carbon and water footprint of battery-grade lithium from brine and spodumene: A simulation-based LCA"

9:35 I **Parallel Sessions**

Diagnostics in electrode and battery production
Room Maschinenhalle I Chair: Prof. F. M. Wang

Porosity detection on Li-ion battery electrode using Laser Speckle Photometry
Ulana Cikalova, Fraunhofer IKTS

Non-invasive electrochemical defect identification in battery cells through quantum imaging
Gary Kendall, CDO2 Germany

Interpretation of cell-to-cell variation through process identification and statistical analysis
Tom Rüther, University of Bayreuth

Next generation (silicon-based) anode materials
Room Nimes I Chair: Prof. S. Ohsaki

Vacuum Coating Technologies for Lithium-Ion Batteries: Silicon-based Next Generation Anodes
Claus Luber, Fraunhofer FEP

Investigations of Silicon Anodes in Sulfide-Based All-Solid State-Batteries
Lukas Alexander Dold, Fraunhofer ISE

Comparison of magnetron-sputtered lithium and silicon anodes for solid-state batteries
Julian Brokmann, Fraunhofer IST

10:20 I Discussion

10:35 I Poster Session & Break

12:00 I Lunch Break

13:00 I Keynote by Henrike Schünemann, PowerCo SE "Standardization and Innovation as Enabler for Global Competiveness"

13:30 I Keynote by Prof. Paul Anderson, University of Birmingham "Elemental stewardship: its role in advancing net-zero"

14:00 I Break

14:10 I **Parallel Sessions**

Innovative drying methods for battery electrodes
Room Maschinenhalle I Chair: Dr.-Ing. M. Mund

Induction heating for accelerated drying of aqueous and solvent based electrode wet films
Max von Horstig, TU Braunschweig I iPAT

Scaling effects of fast laser drying processes in battery production
Delil Demir, Fraunhofer ILT

IR-LED Drying of Lithium-Ion Battery Anodes: Opportunities and Challenges
Larissa von Riewel, Heraeus

Processing of anorganic solid state electrolytes and batteries
Room Nimes I Chair: Prof. K. Dröder

Blue laser sintering of lithium lanthanum zirconate (LLZO)
Florian Ribbeck, Fraunhofer ILT

Enabling the Coating Process of Sulfide-Based Solid-State Battery Components for Roll-to-Roll Production in an Inert Atmosphere
Elena Jaimez-Farnham, Technical University of Munich

Influence of the Process Atmosphere on the Assembly of Sulfide Solid-State Batteries
Timon Scharmann, TU Braunschweig I IWF

14:55 I Discussion

15:10 I Break

15:25 I **Parallel Sessions**

Dry Coating
Room Maschinenhalle I Chair: Prof. A. Kwade

Impact of Particle Shape on PTFE-Fibrillation and Film Properties in Dry Coating Using Calendering for Battery Electrodes; *Marcella Horst, TU Braunschweig I iPAT*

Non-PTFE based dry coating process by Fraunhofer ISIT
Jannes Ophey, Fraunhofer ISIT

Current challenges and potential solutions for dry electrode manufacturing – will it replace wet processing completely?
Joscha Schnell, P3 automotive GmbH

Sustainability along the value chain
Room Nimes I Chair: Prof. O. S. Burheim

Using parametric life cycle assessment models for absolute absolute environmental sustainability assessments of lithium-ion batteries; *Abdur-Rahman Ali, TU Braunschweig I IWF*

Energy-saving potential in HVAC system for dry rooms in battery production
Mohammad Mehdi Salehi Dezfouli, Norwegian University

Idea Generation Workshop as a Tool for Facilitating Eco-design and Implementing a Life Cycle Perspective in Battery Production
Emanuel Bengtsson, RISE

16:10 I Discussion

16:25 I Break

16:35 I **Parallel Sessions**

Recycling of LIB: Disassembly and mechanical processing
Room Maschinenhalle I Chair: Dr.-Ing. H. Zetzener

Automated Cell Opening in Disassembly Process for Recycling of Lithium-Ion Batteries
Shubiao Wu, TU Braunschweig, IWF

Disassembly technologies for automotive batteries: automation and concepts; *Johannes Feik, FFT*

Mechanical Recycling in pilot scale: Impact and effects of dismantling level and process conditions
Steffen Fischer, Dennis Beusen; TU Braunschweig I iPAT

Discussion

Industriesession I: Dry Electrode Processing
Room Nimes I Chair: Chair: Prof. A. Kwade

Improved Solids Handling Solutions for Dry Battery Electrode Production
Hans Schneider, Zeppelin Systems GmbH

Material Feeding and Distribution for Battery Dry Coating
Urs Helfenstein, Coperion K-Tron LLC

Processing and scaling of structured dry mixes for dry battery electrodes (DBE) on a scale from 0.1 l to 500 l
Dr. Stefan Gerl, Eirich

Continuous extrusion-mixing of dry electrode masses for more cost-effective battery manufacturing
Philipp Stössel, Bühler AG

17:35 I Break/Discussion

18:05 I

Room Maschinenhalle
Conversion for dinner

Industriesession II: : Industrial characterization and simulation methods
Room Nimes I Chair: Prof. M. Kurrat

Optimized Electrodes and Separators by Particle Size Adjustment and advanced Particle- and Pore Size Analysis
Dr. Lena Weigold, Retsch GmbH

EIS and AI: Considerations to make before trusting your data to AI!
Tim Johannsen, Bio-Logic

Multi-scale characterization and elemental analysis with electron microscopy for battery manufacturing and research
Dr. Jens Greiser, Thermo Fisher Scientific

Industrial-Scale Production of Carbonnanotubes (CNTs) for Gigafactories
Maximilian Münzner, Netzsch GmbH

VW Group – Unified cell format as key for the standardization strategy
Sebastian Schoeniger, Volkswagen AG

19:35 I Break and Reception

20:00 I Gala Dinner

PROGRAMME

CONFERENCE DAY 3 | Nov. 29th

9:00 I Keynote by Fr. Grießl & Hr. Pritzl, BMW
"Road from Prototype to Pilot production: Insights into design and process of 46950 cylindrical cells"

9:30 I Keynote by Juliane Meese-Marktscheffel, H.C. Stark
"Sustainable Industrial Recycling at its Best- Challenges and Sustainable Solutions for Co, Ni and Li Recovery out of Black Mass"

10:00 I Break

10:10 I **Parallel Sessions**

Cell assembly and finalization

Room Maschinenhalle I Chair: Prof. T. Vietor

Jelly rolls for application in HV and HE battery cells with respect to design and format flexibility
Julian Grimm, Fraunhofer IPA

Mini Environments– optimized conditions for cell assembly
Nicole Neub, Exyte

Achieving Stable Cycling Performance of Pure Silicon Anode for Lithium-Ion Batteries by Scalable Electro-chemical Pre-Lithiation; *Shiho Honda, FZ Jülich*

Optimized electrode and battery performance

Room Nimes I Chair: Dr.-Ing. S. Melzig

An industry-suited production process for LIB anodes with pre-lithiated SiO-C
Alice Hoffmann, ZSW

Carbonate deprotonation on Ni-rich layered cathode: Development of a new cis-trans isomerism oligomer as an organic coverage
Fu-Ming Wang, National Taiwan University

Influence of Passive Material Distribution and Morphology on Cathode Performance: a Computational Approach
Timo Danner, DLR

10:55 I Discussion

11:10 I Break

11:25 I **Parallel Sessions**

Recycling of LIB: Hydrometallurgy and re-synthesis

Room Maschinenhalle I Chair: Dr.-Ing. H. Zetzener

Recovering Critical Raw Materials from Li-ion Batteries- Two step leaching and closed loop reagents process
Steven C. Lans, Back to Battery

Morphology and structure investigation of recycled Graphite powder after mechanical and chemical treatment process for anodic material application
Slaheddine Jabri, TU Braunschweig I IAP

Effects of different impurities on the re-synthesis of NMC particles
Markus Rojer, TU Braunschweig I iPAT

Industriesession III: Characterization methods in battery production

Room Nimes I Chair: Prof. S. Zellmer

In-line, real-time characterization of electrode slurry rheology
Fridolin Okkels, Fluidan ApS

Industrial grade solutions on gigafactory scale based on the use case of X-ray inline inspection
Markus Möller, Exacom GmbH

Development of a validated simulation model for all solid-state batteries
Roman Buchheit, Math2Market GmbH

Characterization of fibrillation in powder blends with PTFE for dry coating
Filip Francqui, Granutools

Powder rheological characterization of dry coating materials
Helena Weingrill, Anton Paar GmbH

Back to the future- 25 years of electrode extrusion
Nicolaus Rehse, Collin Lab & Pilot Solutions GmbH

12:25 I Break/Discussion

12:45 I Poster Prizes

13:00 I Lunch

13:30 I Tour to the Battery LabFactory Braunschweig

PRESENTATION ABSTRACTS

Scaling up active material production

From material development to large scale production of cathode active materials – How to close the gap

Dr. Katja Kretschmer
IBU-tec advanced materials AG

The rapid growth of LIB manufacturing capacity in Europe is leading to an increasing demand for domestically sourced cathode active material. Our presentation will provide an overview of the full spectrum of material manufacturing from initial material development to full scale production. One of the major challenges facing European manufacturers is the uncertainty associated with the intermediate scale-up process from newly developed material to full-scale production. Rigorous quality control, from raw material screening to near real-time monitoring of material properties during production, is essential to ensure the highest standard for commercial applications at any scale. The presentation will show that there is a large gap between the demand for LFP from gigafactories and the actual plans for LFP production facilities and capacity in Europe. The audience's understanding of the LFP supply chain will be complemented by insights from a major CAM manufacturer on how it is overcoming the challenges of ramping up production through clever experimental design and rapid quality control. The aim is to open the discussion for greater collaboration in the European supply chain to close the gap.
IBU-tec is the only manufacturer of LFP cathode materials in Europe with a fully operational production line and an annual capacity of 4,000 tonnes. With over 10 years of experience in producing LFP on an industrial scale, we are able to share lessons learned from past challenges and highlight current opportunities.

The Glatt Pow(d)er Synthesis – Aerosol-based processes to produce battery materials

Johannes Buchheim
Glatt Ingenieurtechnik GmbH

The development of active materials has undergone a continuous process with the aim of increasing energy density. This is being realised through the development of new, nickel-rich and cobalt-free cathode materials, the production of silicon-carbon composite materials and the development of solidstate-batteries. The increasing demand for applications within electromobility or stationary energy storage requires the implementation of innovative, sustainable and continuous manufacturing processes as well as processes for coating active materials. Aerosol-based methods based on spray drying/spray calcination and spray agglomeration are presented using selected examples. The Glatt Pow(d)er Synthesis represents a further development of spray drying [1-3]. By using an oscillating process gas stream, special thermodynamic conditions are created within a tubular reactor. The modulation in the pressure ratios caused by the pulsation as well as the freely adjustable amplitudes of the pulsation intensify the mass and heat flow by a factor of 2-5. A secondary breakdown caused by the oscillating process gas stream, the Glatt Pow(d)er Synthesis is not limited to the generation of droplets and the properties of the spray solution compared to conventional spray drying methods. The powders obtained show a high homogeneity of their properties due to the homogeneous treatment in the reactor. By using an electric heating element, powders can be produced in a continuous process under both oxidative and inert/reductive conditions. Process temperatures up to 1300°C can be applied. The liquid (solutions, suspensions) or solid starting materials are fed into the tubular reactor by injection. By abrupt cooling of the process gas at the reactor outlet, metastable phases can be generated. The Glatt Pow(d)er Synthesis is not only suitable to produce powders but also for the coating of materials. Therefore, the Glatt Pow(d)er Synthesis can be used for a wirde range of applications. In addition to the synthesis of ceramic materials, pigments, composites and catalysts active battery materials can be produced.

References:
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Cathode Materials Pilot-Plant “Powder-Up!” – Ready for Operation

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The global demand for batteries is dynamically increasing, driven by the imperative to electrify vehicles and to store renewable energy in order to reduce CO2 emissions. High performant LIB require new, high performant, cost efficient and sustainable materials. Cathode materials are the dominant component since they bring lithium in the battery cell, contain most of the costly metals and also determine key battery parameters such as energy content of battery safety. However, current speed of materials development often is not fast enough to serve marked demand. Furthermore, there is a scaling gap between laboratory- and technical-scale research, at which further transfer into industry stops: (i) New products from research institutes are usually only available in gram scale – insufficient for technical research or manufacturing of real-size battery cells. In addition, product and production related questions can only be answered with morphologically optimized materials on a scale of several kg. (ii) in general, commercial material suppliers are mostly not willing to pass on their latest product generation or even products under development to research institutions for investigations. This especially affects the supply of pilot plants for cell production, e.g. the FPL at the ZSW or the FFB but also pilot lines at automotive OEMs.. Therefore, closing this material scaling-gap is an absolutely necessary prerequisite to establish an internationally competitive battery industry research and production environment in Germany and Europe. Based on more than 25 years of experience in development of cathode materials, ZSW now goes the next step, bringing a synthesis pilot-plant called “Powder-Up!“ into operation at its Ulm, Germany site. “Powderup!” is a modern and efficient technical centre for the upscaling and synthesis of cathode materials along the 1 kg- 10 kg- up to 100 kg scale. Tailor-made cathode materials will be provided to research partners and industrial partners for cell development. The larger-scale equipment is identical to machines used in related cathode materials industry to guarantee powder production under industrially relevant conditions. Powder-up! will also allow fast scale-up and receipt development using high throughput and parallel synthesis equipment. A well-equipped analytical laboratory and small-scale electrochemical testing is rounding-up the offering. All equipment-parameters as well as analytical and electrochemical data will be tracked electronically. The presentation will give an overview on the Powder-Up! Concept, individual process steps, and the scientific and technical challenges for the development of new cathode materials. Powder-up! is supported by the BMBF under the Umbrella Concept Battery Research, Funding Programme ForBatt, and by the Ministry of Economics of State of Baden-Württemberg.

AI-assisted battery production

Optimizing Battery Development and Quality Control through Data Integration and AI

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The quality-assurance process for batteries begins in R&D and follows every step in production, from processing the raw materials to assembling the battery modules. Along each step, a precise evaluation of parameters is required that may impact battery performance, production efficiency, and waste. A range of devices and techniques exist for acquiring physical, chemical and structural data, including measurements of particle size distribution and shape in the battery slurry, elemental composition, zeta potential and thermal behavior. However, each of the analytical devices produce data along each development and manufacturing stage that is often fragmented and disconnected with other IT systems. By using practical examples, we demonstrate the positive implications of a unified, comprehensive database for serving both battery development and quality control. This allencompassing database facilitates early detection of trends like a raw material quality decline or thermal instability. Additionally, a comprehensive database is the basis for utilizing artificial intelligence (AI). AI can provide correlations and trends that would otherwise remain unknown. It can also support data-driven decision-making by providing in-depth analyses and visualizations. Finally, these data can be integrated with Smart Factory software (MES) and ERP system data to form a cohesive and AI-supported IT ecosystem from development to manufacturing.

PROTEO – Revolutionizing Battery Design with Advanced Digital Tools

Elixabete Ayerbe
CIDETEC Basque Research and Technology Alliance

PROTEO, a battery design tool from CIDETEC Energy Storage Institute, capitalizes on over 25 years of battery development expertise to enhance every stage of the battery lifecycle, from design to operation. Employing Multiphysics models, artificial intelligence, and a dynamic database, PROTEO delivers comprehensive solutions for battery innovation.

PROTEO consists of three modules:

1. PROTEO Design: Enables users to virtually engineer and optimize battery cells from ground up, providing insights into cell design and identifying potential failure modes.

o The coupled Thermo-Electro-Mechanical Models provide detailed insights into primary electrochemical processes, heat generation, and internal stresses and displacement within battery cells

o Formation step and Degradation Models: Offers an overview of the cell's lifespan and capacity loss over time, including models for SEI layer formation, particle cracking, and lithium plating.

o Optimization Module: Integrates all models to optimize cell design, using global and local algorithms for precise parameter estimation to achieve goals like maximizing energy density or enabling fast charging.

2. PROTEO Prediction: Uses AI to predict the lifetime of a battery cell based on electrode characteristics, cell design and usage profiles

o Early Prediction: Speeds up cell research by predicting battery lifetime from a few initial cycles or from scratch, reducing the number of tests needed.

o Hybrid Lifetime Estimation and Degradation Models: Combines physics-based and data-driven approaches for accurate, flexible lifetime predictions, estimating cell status during each cycle and guiding degradation evolution.

o Extension to Electrode Manufacturing: Ensures effective manufacturing by identifying
optimal production variables, correlating them with electrode and cell properties.

3. PROTEO Data Analytics:

o Automatically gathers data from various sources for efficient management and visualization.

o Utilizes AI to identify issues and detect anomalies, enhancing data analysis and operational efficiency.

Artificial intelligence informed end-of-line testing in lithium-ion battery production

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Lithium-ion battery cells are a critical technology both in the development of modern electric vehicles and for stationary energy storage. Unfortunately, the manufacturing process of these cells is complex and prone to defects1. As such, it is essential to develop quality assurance approaches that can be used during manufacturing to identify defective cells, preventing such cells from reaching the end user. While quality assurance can be performed after each individual step in the manufacturing process, end-of-line testing is essential to assess the safety and performance of the final cell. End-ofline testing typically relies on electrical measurements, visual inspection, and/or thermal characterization to assess whether a cell should be passed on to the consumer2. In addition to standard end-of-line measurements, we introduce a measurement of cell expansion during cycling. Reversible expansion can be linked to lithium-ion intercalation into and out of the electrode materials, while irreversible expansion can be an indicator of serious issues such as lithium-plating, additional solidelectrolyte interface formation, and gas expansion3. To extract useful insights regarding cell quality from various data streams, including expansion information, we opt to employ artificial intelligence (AI) methods. AI methods have shown promise in extracting information encoded in multivariate timeseries data that can be difficult to interpret using classical methods4. The training of AI methods relies on the availability of large datasets; however, these datasets can be expensive, and time consuming to generate5. As such, we choose to pre-train the algorithms on data that is synthetically generated using first-order physical models. Since we have elected to take an unsupervised learning approach, we only need to model the behaviour of normal cells. By pre-training the network on synthetic data, we can significantly reduce the number of cells that need to be cycled to generate a data set for model training.

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Slurry processing

Challenges in Slurry Mixing Process for Li-Ion Battery Electrode Manufacturing

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The increasing global demand of lithium-ion batteries requires improvements across the entire development process to achieve batteries with a longer life span, safer, and more stable. The development chain involves several physico-chemical transformations, including slurry mixing, coating and drying, calendaring, electrolyte filling and cell assembly to obtain batteries with desired electrochemical properties.1 The critical properties of a battery, such as, specific energy, internal resistance and energy density are highly influenced by the initial stages of the process, particularly by the slurry mixing. Obtaining a stable formulation has its challenges because it depends on different factors, such as: solvents used, particle size of the powders, mass ratios, solid content, mixing order, time and speed. From all the variables mentioned above, the main challenges in achieving a homogeneous slurry are related with mass ratios and mixing time/forces involved in solid part of the electrode slurry, which are composed by active material particles and conductive additive chains. It is crucial to reduce the size of the particles in the beginning of the process and for that it is important to understand the energy involved and forces applied during this process. Solid material size reduction occurs through the application of impact, pressure and shear forces. However, these forces should not be strong enough to break the active material particles and conductive material chains, otherwise ion exchange may be compromised, leading to a decrease in the electrical conductivity of the coating.2 Therefore, in this work, the optimization procedures are presented for the development of anodes and cathodes using a planetary centrifugal ball mill and a planetary mixer. While planetary centrifugal ball mills use high velocities and energy impacts to grind the particles during mixing, planetary mixers are used for uniform mixing and kneading materials. A uniform coating is vital for battery performance and the characterization techniques used to validate the slurry mixing include oscillatory rheology, electrochemical impedance tests, coating adhesion trials and electrical conductivity measurements. In electrodes produced by a formulation fabricated in the planetary centrifugal ball mill, promising electrical conductivity values were obtained for the cathode (4x10^-4 S/cm) and for the anode (3,51x10^-3 S/cm). Also, the presented work demonstrates some of the key aspects when considering the scaleup from lab scale to pilot line, ensuring that the optimized coating procedures are compatible with the challenges of electrode cutting and z-stacking processes required at the pilot scale.

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Innovative Battery Production with Eco-Friendly Water-Based Binders

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Traditional battery manufacturing processes for Li-ion batteries heavily depend on organic solvents, which pose significant health and environmental hazards. In response, the industry is shifting towards the use of water-based binders, presenting a more sustainable and safer alternative. Water-based systems can simplify the battery assembly process, potentially reducing costs and enhancing production efficiency. However, there are some difficulties in transitioning to water-based binders. Water-based binders exhibit lower peel strength compared to solvent-based binders, leading to microcracks due to volumetric expansion in the electrodes. Additionally, the interaction and degradation of active materials with water pose significant issues when using water-based binders. The use of water-based binders in battery production can result in residual water within the battery, leading to electrolyte degradation. Problems such as gelation in the electrode slurry, localized agglomeration in the slurry, reduction in solid content, low energy density, and capacity are also encountered with current water-based binders1,2. This study focuses on modifying traditional binders like PVDF, vinylidene fluoride (VDF), and polytetrafluoroethylene (PTFE) to create hydrophilic forms that are compatible with aqueous systems. These hydrophilic modifications enhance the dispersion of active materials in the binder solution, leading to more uniform coating and improved electrode quality. Auxiliary binders, used in conjunction with primary binders, can further enhance the performance of water-based systems. These auxiliary binders also contribute to the flexibility and durability of the electrodes, enhancing their cycling stability and overall lifespan. In this study, battery production was carried out using water-based binders, and the performance of the cells was compared with those produced using traditional solvents.

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Transfer of the continuous production of battery slurry to different extruder scales

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This study addresses the critical need for efficient and scalable mixing processes in battery manufacturing, driven by the increasing demand for high-performance anode slurries. The continuous mixing approach offers significant advantages over batch processing, including improved process control, consistent product quality, and increased production efficiency. Continuous mixing also reduces downtime and labor costs associated with batch cleaning and preparation, contributing to overall operational efficiency and cost-effectiveness in large-scale battery slurry production. Even though scaling up twin-screw mixing is generally considered more straightforward than scaling up batch mixers, there is still limited common knowledge on scaling up twin-screw mixing for battery slurry production. We report on the successful scale-up of the twin-screw mixing process for anode slurries from several hundred grams per hour to over 10 kg/h while maintaining consistent dispersion quality. Particle size distribution served as a key quality parameter. Building on prior work that optimized screw configurations1, this research varied rotational screw speeds and throughputs. The results enable the translation of process parameters to larger twin-screw mixers, ensuring the maintenance of slurry quality. This advancement supports the production of high-quality battery materials at an industrial scale, meeting the growing demands of the energy storage market.

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Safe batteries and thermal runaway investigations

Battery research in the context of metrology for environmental & climate protection - quality assurance, safety, and digital product passport

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The Physikalisch-Technische Bundesanstalt (PTB) is Germany's National Metrology Institute and devoted to support industry and societal measurement tasks with metrological traceability solutions. PTB's Innovation Cluster for Environment & Climate combines all efforts and capabilities of PTB related to metrology for environmental protection and climate actions1. Electrochemical energy storage, safety2 and advanced quality measures3 of batteries are not only in PTB's focus under energy aspects. They also provide a research topic at environmental aspects as there are considerations of emission reduction, use and recycling of technology critical elements, and circular economy in general4. On safety aspects of batteries and their thermal behaviour, we will address heat generation of cells during charging and discharging processes measured by means of an isoperibolic calorimeter. By these measurements, the heat capacity of the LiFePO4 pouch cells, the spatial heat flux, the reversible and irreversible heat flow rate as a function of temperature and current rates are being investigated. Battery performance and the state of health of batteries will be discussed referring to non-destructive Electrochemical Impedance Spectroscopy and magnetic field sensors. A novel characterisation method will be showcased that facilitates measurements of the magnetic field during charging, discharging and relaxation of the cell. Here, classical fluxgates and quantum sensors, in this case SQUIDs and optically pumped magnetometers, provide spatial information of the current density in the cell during dynamic processes. The information obtained from these measurements can aid in the design and development of LFP cells, ultimately enhancing battery performance. In addition, digital transformation will benefit production, second life approaches and recycling of batteries. Here, PTB is contributing to the development of the digital product passport, which – in the form of the battery passport – is the central tool for a rational selection of appropriate RE-strategies as well as optimizing battery design and production. We provide examples of what has been PTB has developed jointly with partners of the initiative QI-Digital5 and the international quality infrastructure across all elements of the QI (Metrology, Standardization, Accreditation, Conformity Assessment, Market Surveillance).

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Thermal Runaway Mitigation in NMC Lithium-Ion Cells: Assessing the Effectiveness of Thermal Insulation Materials

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This study evaluates the effectiveness of various thermal barrier materials in preventing thermal runaway (TR) propagation in commercial Nickel Manganese Cobalt (NMC) lithium-ion cells, focusing on 2.5 Ah and 12.5 Ah capacities. The cells were arranged in a sandwich configuration incorporating different thermal barrier materials, including Phase Change Materials (PCM), Phase Change Composite Material (PCCM), Pyrobubble plates, and other composites, placed between them. Overcharge tests were conducted at 100% State of Charge (SOC) using 4C for 2.5 Ah cells and 1C for 12.5 Ah cells to induce thermal runaway. Initially, experiments were performed without any thermal insulation material. In the case of two 2.5 Ah cells, the propagation time for thermal runaway between neighboring cells was approximately 14 seconds. The TR tests utilized composite materials composed of liquid glass, fumed silica, and baking soda. These samples were produced in various thicknesses: 2 cm, 1 cm, and 0.5 cm. Notably, in the experiments with a 2 cm sample, the maximum temperature of the second battery remained at just 37°C. In subsequent experiments using a 10 mm Pyrobubble plate, the temperature of the second battery increased by an average of only 41°C. When using a plate made from phase change composite material, the maximum temperature of the second battery did not exceed 80°C. The addition of a PCM insulation layer between the cells effectively absorbed the heat generated during thermal runaway.

Thermal runaway characteristics and gas emission from sodium-ion cells – impact of state of charge level

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This work investigates the effect of the state of charge (SOC) level on the thermal runaway characteristics and gas release from 18650-type Cylindrical Sodium-ion cells of NaNi1/3Fe1/3Mn1/3O2 (NFM) cathode. A total of 10 tests are conducted by subjecting 10 cells to thermal abuse inside a reaction vessel of 10 L in volume. The SOC levels studied among the test were 0%, 25%, 50%, 75%, and 100%. Emphasis was put on the time derivative of temperature and pressure to evaluate the thermal runaway behaviour and gas production from the sodium-ion cells. The investigation revealed the occurrence of thermal runaway was more probable at SOC level ≥ 50% SOC. Thermal runaway of the Na-ion cells was observed at a rate of temperature rise greater than 1 K/s. The results demonstrated the safety in Na-ion cells varies with SOC level. As seen in Fig. 1, the high maximum pressure (3.9±0.2 bar) and peak reaction temperature (403 ± 14 0C) measured and gas production (5 ± 0.1 L; 1.1 ± 0.02 L/Wh) observed at 100% SOC indicated thermal runaway-related hazards are increased at high SOC level. The results from the gas component analysis showed the release of HF and explosible gases such as CO, HCN, CH4, C2H6, and C2H4 from Na-ion cells is inevitable.

Diagnostics in electrode and battery production

Porosity detection on Li-ion battery electrode using Laser Speckle Photometry

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The background to current research is the increasing demand for high-performance battery technologies with integrated quality assurance at all stages of production. During the production of lithium-ion battery electrodes, undesirable coating defects and porosity fluctuations can significantly reduce the battery's efficiency and lead to high follow-up costs. These issues are particularly pronounced in the calendering process, which plays a critical role in determining the final electrode quality. Calendering is a highly error-sensitive step of the cell manufacturing because defects from this step cannot be corrected in the following production and usually only reverse in the formed cell at the end of the process chain. In this process step, a certain porosity is set by post-compacting the coated and dried electrodes. The development of innovative inline measurement method for this approach will create a quality assurance platform for characterization and real-time evaluation of intermediate products during production. It is essential to monitor the porosity in this manufacturing step. This paper will present the development of such an automated optical testing technology for porosity detection in a continuous roll-to-roll calendering line. The novel method is based on the Laser Speckle Photometry (LSP) – an optical, non-contact and non-destructive method. The pre-qualified LSP laboratory demonstrator will be presented in this work. The in-situ monitoring was performed with the help of AI-based algorithms and the results were calibrated by radiographic method for porosity detection with simultaneous roughness measurement; and in addition, supported by thermal diffusivity simulation.

Non-invasive electrochemical defect identification in battery cells through quantum imaging

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The detection of defects early in the lithium-ion battery production process is key to improving efficiency and reducing material and energy requirements of battery manufacturing. It has already been shown that an array of sensitive magnetometers can be used to produce non-invasive in operando measurements of battery operation with current density imaging which are consistent with electrochemical models.1 In the current work we describe a new technique using a small number of highly sensitive quantum magnetometers (optically pumped magnetometers, OPMs) to detect, locate and quantify microscopic defects in lithium-ion battery cells. We present experimental results which demonstrate the creation and evolution of soft short circuits within pouch cells which are not externally connected. We propose a new technique for batch testing of cells after production to identify the severity and frequency of internal soft short circuits leading to capacity degradation and premature failure. This is of particular benefit to validate new manufacturing processes and will become increasingly important as energy density increases and new formulations are developed to improve battery performance.

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Interpretation of cell-to-cell variation through process identification and statistical analysis

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In the production of lithium-ion batteries, variations from manufacturing tolerances between cells impose significant challenges for their subsequent use1,2. These variations can lead to inhomogeneities within battery packs, causing accelerated and uneven aging.3,4 This presentation focuses on the impact of these variations and links them with processes within the electrode. For this purpose, 92 cells were characterized using impedance, pulse, and pseudo-open-circuit voltage measurements. Subsequently, the data is subjected to extensive postprocessing and statistical analysis. A combination of the Distribution of Relaxation Times (DRT) analysis based on the Löwner method5, the generalized DRT6, and the time domain DRT7, is introduced for a more precise and reliable process separation. To identify the processes, state of cahrge and temperature variations are carried out. The determined time constants and gains are subsequently analyzed concerning their confidence intervals and statistical distributions. The results indicate that the assumption of a normal distribution cannot be universally applied, in fact, can be excluded in certain cases. Finally, a correlation analysis is performed, which reveals a categorization of the identified processes into cell winding, electrochemical interface processes, and diffusion. The potential physicochemical causes for these variations are discussed, contributing to a deeper understanding of cell-to-cell variations. The insights gained from this study can be used for a number of future applications, including the improvement of the end of line quality control in battery production, the acquisition of a reliable understanding of the impact of production parameters on cell properties, the acceleration of factory acceptance tests, and the comprehensive modeling of cell-to-cell variations for battery module and system simulations.

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Next generation (silicon-based) anode materials

Vacuum Coating Technologies for Lithium-Ion Batteries: Silicon-based Next Generation Anodes

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The demand for high-energy-density lithium-ion batteries (LIBs) is increasing due to the growing need for portable electronic devices and electric vehicles. Silicon has been identified as a promising anode material due to its high theoretical capacity. But silicon anodes suffer from significant volume changes during cycling, leading to rapid capacity fading and reduced cycle life. To address these issues, vacuum coating technology has been employed to improve the synthesis and performance of silicon anodes. In this presentation, we will present approaches in the development of high-energy-density LIBs using vacuum technology. To meet the specific requirements of silicon anodes we start with an innovative approach for the current collector in terms of texture, surface structure and weight, including the preparation of a light-weight current collector by metallization polymer films. For the anodes, various complementary approaches based on vacuum technology are pursued:

- Functionalization of Si particles with carbon using a plasma enhanced chemical vapor deposition (PECVD) process to provide powder-based silicon anode material
- Synthesis of structured silicon thin film anodes by physical vapor deposition (PVD)
- Deposition of lithium-silicon compound layers to prepare a pre-lithiated Si anodes by PVD

From the production point of view, vacuum thin film technologies can offer process alternatives for battery anodes. This presentation aims to demonstrate the potential of vacuum technology to overcome the challenges of integrating silicon anodes into next-generation LIBs.

Investigations of Silicon Anodes in Sulfide-Based All-Solid State-Batteries

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Silicon has gained significant attention as a potential anode material for future high-energy lithium-ion batteries due to its substantial capacity advantages. However, its application has been hindered by a 280 % volume expansion during lithiation which causes severe particle pulverization and continuous solid electrolyte interphase (SEI) disruption. This results in rapid capacity loss due to the irreversible consumption of lithium and electrolyte components. Recently, the use of silicon in all-solid-state batteries (ASSBs) has shown promise, particularly due to different interfacial interactions between solid electrolytes and silicon particles 1. In our study, we compared solid-electrolyte infused silicon anodes (EIA) and solid electrolyte-free anodes (EFA) in sulfide-based ASSBs, examining their electrochemical performance through galvanostatic cycling, C-rate testing, and impedance spectroscopy. By employing cross-section scanning electron microscopy (SEM) in combination with soft X-ray emission spectroscopy (SXES) and X-ray photoelectron spectroscopy (XPS) measurements, we were able to demonstrate the lithiation of the solid-electrolyte free anode. The advantages regarding the lithium-ion diffusion in the interpenetrating solid electrolyte networks of the EIA were particularly noticeable at high C-rates of 4 C and 8 C. Nevertheless, good performance of the EFA, especially at C-rates < 4 C was observed, prompting further investigation into environmentally friendly solvent use in anode processing, demonstrating that non-toxic solvents can be used effectively under standard atmospheric conditions. This enabled the utilization of polyacrylic acid (PAA) as a binder, which is considered promising due to its ability to form strong adhesive bonds with silicon particles, particularly for silicon-dominant anodes. While an aqueous-based slurry with PAA binder led to increased impedances and reduced cycling stability due to the reaction of water with the silicon surface, the ethanol-based slurry resulted in good cycling stability with a capacity retention of more than 80 % after 300 cycles at C-rates ≥ 2 C. Overall, our findings show the potential of silicon-based anodes in ASSBs to enhance both performance and sustainability of next-generation energy storage systems, highlighting the effective use of nontoxic solvents and innovative binder technologies in anode processing.

Comparison of magnetron-sputtered lithium and silicon anodes for solid-state batteries

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Solid-state batteries (SSBs) represent a promising advancement in energy storage technology, offering enhanced safety and energy density compared to conventional liquid electrolyte batteries. Lithium, with its high theoretical capacity (3860 mAh/g) and low electrochemical potential, remains a preferred anode material. However, issues such as dendrite formation, limited cycle life, and safety concerns necessitate innovative approaches to optimize its performance in SSBs. In contrast, silicon, boasting an even higher theoretical capacity (4200 mAh/g), presents a compelling alternative due to its abundance and superior energy storage potential. Nevertheless, silicon anodes face significant challenges, including substantial volume expansion during lithiation, leading to mechanical degradation and rapid capacity fading. One focus of this work is the analysis of magnetron-sputtered lithium and silicon anodes within SSBs, aiming to presenting their respective advantages and challenges. Magnetron sputtering, a versatile physical vapor deposition technique, enables the formation of uniform, high-purity thin films crucial for next-generation anode materials. This comparative study employs magnetron sputtering to fabricate lithium and silicon anode films, followed by e.g. electrochemical testing with sulfide solid electrolytes. Key performance indicators such as cycling stability, rate capability, and interfacial resistance are analyzed to assess the viability of each anode material. The findings highlight the necessity of advanced material engineering and surface modification techniques to harness the full potential of lithium and silicon anodes in solid-state battery applications. In addition, the results emphasize the need for advanced material techniques and surface modifications to realize the full potential of lithium and silicon anodes in solid-state battery applications. Summarizing, this study provides important insights into material properties and performance metrics that can guide future research and development towards the commercialization of high-performance SSBs with optimized anode configurations.

Innovative drying methods for battery electrodes

Induction heating for accelerated drying of aqueous and solvent based electrode wet films

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The electrode drying process is particularly important during the production of lithium-ionbatteries as it accounts for about 30% of the production's energy consumption and is crucial for the particle structure and thus the quality of the electrodes. New heat introduction technologies can make the drying process more energy-efficient and increase throughput compared to conventional convective drying1. However, their impact on electrode structure and quality still needs to be evaluated. This work investigated an induction heating technology for drying LIB electrodes on a pilot scale. The inductor heats the current collector foil through eddy currents, and the heat is then transferred to the coating. Both aqueous and solvent-based wet films from electrode suspensions are dried in a convective roll-to-roll dryer. In addition to purely convective drying, induction supported drying is examined. The focus is on accelerating the initial drying phase, where high drying rates can be achieved without compromising the quality of the electrode coating. IR pyrometers assess the drying progress and determine the required dryer length. The electrodes are then analyzed for their particle structure, residual moisture, mechanical and electrochemical properties. Results and Discussion Tests on a prototype show a reduction in the dryer’s energy consumption by about 20%. Depending on the inductor power setting, comparable mechanical and electrochemical properties are achieved. If the inductor power is set too high, migration of the binder and conductive additive to the electrode surface can be observed, resulting in reduced adhesion and higher electrical resistance. Induction-assisted convective drying offers significant energy savings through more efficient energy input into the coating. However, depending on the voltage applied to the induction module, there can be reduced electrode quality and damage to the current collector foil and coating. Therefore, a knowledge-based selection of process parameters and dryer design is essential to ensure that electrode quality and performance remain at least as good as with conventional convective drying. Extensive test campaigns will follow in November and February, and the results of these studies will also be part of the presentation at the specialist group meeting.

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Scaling effects of fast laser drying processes in battery production

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The growing demand for energy storage devices, such as lithium-ion batteries (LIB), calls for fast and energy-efficient battery processing technologies. A crucial step in battery production is drying anode and cathode slurries during electrode processing. Modern factories typically use convectionbased drying ovens, primarily powered by natural gas, which occupy a considerable fraction of the facility space due to a large footprint. To make this process more energy efficient and less space consuming laser-based drying can be utilized to process water-based anode slurries in a continuous process. The approach of using highintensity laser radiation to rapidly dry electrode slurries is being investigated in a continuous roll-toroll coating and drying process. For this purpose, a laser drying module has been developed and set up in a continuous coating machine at Fraunhofer ILT, enabling drying experiments at web speeds of up to 10 m/min. This presentation explores the interaction between laser radiation and the components in the slurry. Given that high heating and evaporation rates of water up to 15 g / s · m² can be achieved, it is crucial to prevent damaging slurry components such as CMC and SBR. Various processing parameters, including drying temperature, coating speed, and film thickness, are adjusted to examine their impact on the anode. Since high evaporation rates may cause binder migration, the adhesion of the anode to the current collector foil is measured. The findings suggest that rapid drying with laser radiation can be successfully implemented under the right conditions.1

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IR-LED Drying of Lithium-Ion Battery Anodes: Opportunities and Challenges

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Along the battery manufacturing chain there are numerous steps where photonic solutions kick in. Some of them are unique in their application, some of them complement or even replace existing technologies with the objective of saving energy and costs. Considered one alternative and generally used for all kinds of heating processes, Infrared technology (IR) is already implemented in battery manufacturing for electrode drying and post-drying processes1. Although convective drying is the current predominant method, integration of IR in the process of electrode drying presents a favourable strategy for optimizing both the physical and economic facets of the drying process simultaneously.

In parallel to IR drying, laser-based drying systems appear to be an attractive, scalable, and compact solution for a cost-effective and ecological sustainable battery production, simultaneously providing a high energy input in a short amount of time and increasing the cell performance. The diode lasers are integrated in water cooled sub-modules with variable geometrical configurations offering a high degree of flexibility in designing new modular drying systems as well as in the integration into existing machines. Thus, the technology qualifies as smart solution for strip coating providing a precise and focused heating field, suitable for use in hazardous atmospheres (ATEX). Despite its benefits the lases drying faces several challenges as unproved technology involving high integration and operating costs due to water/liquid cooling. Furthermore, the implementation of such technologies in production implies complex safety considerations, legal obligations for machine builders due to safety standards. To successfully overcome the engineering challenges related to laser techniques we investigated the performance potential of IR-LED technology in the drying process of battery anode. Similar to laser diodes, IR-LEDs are semiconductor based light sources with narrow emitting band in the near IR spectral region. LEDs are energy efficient and small like their laser counterparts but typically operate at lower drive currents and are less expensive. Additionally, in the right architecture they have the capability to meet the demand for high power density output without navigating intricate safety and legal standards.

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Processing of anorganic solid state electrolytes and batteries

Blue laser sintering of lithium lanthanum zirconate (LLZO)

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As conventional Li-ion batteries approach their maximum theoretical power densities, innovative cell concepts are under investigation. To achieve the highest possible gravimetric energy density a metallic lithium anode is desired. Dendrite growth through the separator is a safety concern and major reason for decreasing battery performance. Lithium lanthanum zirconate (LLZO) is a garnetbased ceramic solid-state Li-ion conductor with chemical stability towards metallic lithium1 and a sufficiently high shear modulus to withstand penetration of Li-dendrites2. Processing of this material and implementation in an all-solid-state battery (ASSB) proved to be challenging3. Due to the formation of unwanted secondary phases during sintering and cofiring with cathode active materials (LCO, NMC) in conventional oven processes the development of novel sintering processes is required. Photonic sinter processes like rapid thermal processing (RTP)4,5, blacklight sintering6 or laser-based sintering5 are promising technologies for sintering processes with short interaction times and preservation of the desired crystal structure. Compared to the two first technologies, laser radiation has a narrow band width and therefore the wavelength can be selected according to the absorptance of the material to be processed. In this work, the laser sintering of LLZO thin films is investigated. Therefore, LLZOpowder is mixed into a paste and applied to a stainless-steel substrate via screen printing. The pure LLZO-layer shows an absorptance of around 20 % for blue laser radiation, compared to 5 % for 1 µm laser radiation. The absorptance of the layer is further adjusted using various amounts of copper oxide (CuO) as additive. The application of LLZO as the separator requires a high density and high ionic conductivity. Therefore, a laser sintering process with blue laser radiation is developed to form a dense layer on a steel substrate. Goal of this work is the investigation of the influence of process parameters on crystal structure and phase composition, the porosity, adhesion, and electrochemical properties.

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Enabling the Coating Process of Sulfide-Based Solid-State Battery Components for Roll-to-Roll Production in an Inert Atmosphere

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The sulfide-based solid-state battery has emerged as a highly promising alternative to conventional lithium-ion batteries due to its enhanced energy and power density. In addition, its production processes are comparable to those of the conventional lithium-ion battery, which facilitates its industrialization. At the iwb, the production processes of the electrodes and solidelectrolyte separator are being investigated for large-scale cell production1. This work aims to provide guidelines on the coating of the sulfide-based composite cathode and the solid-electrolyte separator on a roll-to-roll process under an inert atmosphere. Firstly, the scalability of sulfide-based solid-state battery production is addressed. Secondly, the experimental results of doctor blade coating on a pilot scale are presented. Thirdly, preliminary results regarding the drying of the coated layers are introduced. The work concludes with an outlook on further research to advance the coating and the drying process of sulfide-based solid-state battery components in order to enable industrial manufacturability.

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Influence of the Process Atmosphere on the Assembly of Sulfide Solid-State Batteries

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Electrical energy storage systems and their continuous development are key parts of various industries, currently, they are a key part or enabling electromobility through ever-increasing energy densities and reduced manufacturing costs. All-solid-state batteries (ASSBs), representing a promising new generation of energy storage technologies, use solid electrolytes to replace conventional liquid electrolytes, offering potential benefits in safety, longevity, and energy density. Among the various types of solid electrolytes, sulfide-based materials are particularly attractive due to their high ionic conductivities. However, the high reactivity of sulfides presents significant challenges. One of the primary issues is the formation of toxic hydrogen sulfide when exposed to atmospheric moisture, which poses safety risks and negatively impacts battery performance. Addressing these challenges necessitates the development of a material-adapted, economically viable, and safe process atmosphere. To provide a suitably conditioned atmosphere for the assembly of sulfide solid-state batteries, an experimental setup is designed to efficiently and accurately replicate real conditions. This setup must be capable of maintaining dew points between-60 °C and +20 °C. Additionally, a continuous gas flow is essential to ensure consistent test conditions comparable to industrial dry room scenarios. In order to examine the effects of atmospheric exposure on hydrogen sulfide (H_2S) formation, sulfide sheets made of Li6PS5Cl were subjected to various dew points ranging from -60 °C to 0 °C. The results indicate a dew point above -20 °C being unsuitable for the assembly process, as it leads to significant H_2S formation, which can negatively impact the safety of the worker. Furthermore, the study investigated the ionic conductivity of the sulfide sheets under varying dew points and exposure times. As a result, even at a dew point of-60 °C, significant changes in performance could be observed, underscoring the sensitivity of sulfide-based materials to atmospheric conditions. These insights are a key step for the knowledge-based selection and design of dry room production atmospheres for ASSB production, a critical step towards their industrialization aimed at meeting the growing energy and power density demands of electromobility.

Dry Coating

Impact of Particle Shape on PTFE-Fibrillation and Film Properties in Dry Coating Using Calendering for Battery Electrodes

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To meet the increasing demand for lithium-ion batteries, efficient electrode production methods like solvent-free dry coating are crucial. These methods aim to enhance manufacturing economics and sustainability by reducing both the carbon footprint and energy costs [1]. In calendarbased dry coating utilizing fibrillation of a PTFE binder, the binder undergoes initial dry mixing and fibrillation in the primary process step, significantly influencing powder characteristics and the resulting properties of dry-coated electrodes. Functionalizing electrode materials through mixing to regulate powder flowability and microstructure is pivotal for subsequent processes such as powder dosing and film formation, with further fibrillation occurring during film formation. Particle shape plays a critical role in both the fibrillation process during mixing and film formation in calendering-based dry coating for battery electrodes. Different particle shapes can substantially impact the flowability and packing density of electrode materials, thereby affecting the uniformity and cohesion of the resulting film. In our research, flake-like graphite is used as the anode active material and two distinct spherical cathode materials (LFP and NCM) are blended similarly with Carbon Black and PTFE. This blending yields nearly identical particle size distributions but varying bulk densities. Spherical particles with high particle and bulk densities accelerate compaction and increase the wall friction angle. Consequently, under uniform film formation conditions, the NCM cathode forms significantly thicker free-standing films compared to graphite anode, which forms the thinnest (s. Fig. 1). Understanding these effects is essential for optimizing the dry coating process and improving the performance of lithium-ion batteries.

Non-PTFE based dry coating process by Fraunhofer ISIT

Jannes Ophey
Fraunhofer Institute for Silicon Technology

The growing interest in electric vehicles has increased the need for more efficient battery cells. To meet this demand, battery cells must be both cost effective and environmentally friendly. A significant portion of the costs and CO2 emissions in battery production are caused by the energy required for the drying step1. The dry coating process represents a technological advance as it eliminates the need for this energy-intensive drying step, resulting in significant energy and cost savings. In contrast to the current production of electrodes for lithium-ion batteries (LIB), which relies heavily on the wet coating process using the harmful and expensive solvent N-methyl-2-pyrrolidone (NMP), dry coating technology represents a more sustainable alternative. It bypasses the mixing, drying and solvent recovery required in wet processes, allowing for a drastic streamlining of production, reduced energy and equipment costs and increased efficiency. However, the application of this promising technology in battery manufacturing still needs to be further developed before it can be fully utilized. Therefore, several new dry coating technologies are currently under development, which differ significantly in terms of physics, chemistry, and maturity2. Fraunhofer ISIT has developed a dry coating process that differs from most other dry coating approaches in that it is not dependent on the fibrillization of the PTFE binder during calendering. In addition, non-fluorinated binders can be used, opening up the possibility of silicon-based anodes. ISIT's dry coating electrode technology has already been used to produce various dry coated battery electrodes, including NMC, LFP, sulphur/carbon and silicon composite electrodes. In addition, the technology enables the production of advanced cathodes and anodes in a wide range of area loadings, tailored for high capacity or high-performance electrode applications. This presentation will give you an insight into an innovative dry coating process for anodes and cathodes as an opportunity for future electrode production.

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Current challenges and potential solutions for dry electrode manufacturing – will it replace wet processing completely?

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Dry electrode manufacturing is a promising alternative to the conventional wet coating process within battery cell production: On the one hand, the elimination of the costly solvent evaporation and recovery systems leads to reduced energy consumption, floor space, and machine invest. On the other hand, thicker electrodes can be produced by dry coating since the typical binder migration issues associated with solvent evaporation are circumvented. Furthermore, the web-like binder network created by PTFE as a dry electrode binder allows for faster charging rates despite thicker electrode layers. However, the technology currently still faces significant issues with regards to industrialization and scale-up, as well as increased cost and carbon footprint. This presentation will shed light on these challenges and potential solutions from an industry perspective and give an overview of key player activities and industrialization progress within the last year to pave the way to a more sustainable and cost-efficient battery cell production.

Sustainability along the value chain

Using parametric life cycle assessment models for absolute environmental sustainability assessments of lithium-ion batteries

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In 2019, direct greenhouse gas emissions from the transport sector were 8.7 GtCO2-eq (a 74% increase from 1990) and 70% of this is due to road transport [1]. The rapid adoption of battery electric vehicles (BEVs) is an envisaged solution to mitigate emissions from road transport. To support the rapid adoption, the global lithium-ion battery (LIB) cell demand is expected to increase from 700 GWh in 2022 to 4700 GWh by 2030, a 27% increase per annum [2]. In relative environmental sustainability comparisons, BEVs have lower lifecycle greenhouse gas emissions than internal combustion engine vehicles when they are charged with low-carbon electricity [1]. However, such comparisons cannot indicate if the environmental impacts of BEVs are within the limits defined by the planetary boundaries framework or the IPCC carbon budgets [3,4]. To do so, would require taking an absolute environmental sustainability assessment (AESA) perspective [3,4]. The AESA perspective compares the environmental impacts of products against an absolute target derived based on the planetary boundaries or the IPCC carbon budgets. By providing an absolute target and comparing them with determined environmental impacts, AESA can indicate if BEVs are within the limits defined by the planetary boundaries. The environmental impacts of battery production depend on several parameters when taking a life cycle perspective, such as use of secondary raw materials and end-of-life recycling [3]. These impacts can vary due to changes in parameters such as energy consumption, the source of energy, scrap rates, the use of secondary materials, and recycling [2]. Therefore, it is important to have parametric life cycle assessment (LCA) models to estimate the changes in environmental impacts of battery production as a consequence of changes in parameters. In this study, we developed a parametric LCA model for LIB by taking a cradle-to-grave life cycle perspective. We considered parameters such as secondary material shares, scrap rates, energy efficiency improvements, raw material sourcing, and cell-to-pack ratio. Its purpose is to represent the variabilities in environmental impacts of battery production. We performed uncertainty analysis and variance-based global sensitivity analysis using Sobal indices for the development of the parametric LCA model [5]. Its purpose is to identify the important model parameters contributing to the environmental impacts. We then compared the reference model with the parametric model using descriptive statistics. Finally, we use the parametric LCA model to estimate the probabilities of meeting absolute targets.

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Energy-saving potential in HVAC system for dry rooms in battery production

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Around half of a battery factory's overall energy use is attributed to the Heating, ventilation, and air conditioning (HVAC)of the dry room1. Operational electricity costs and carbon dioxide emissions can be significantly reduced with an energy-efficient HVAC system designed for dry rooms2, with studies demonstrating energy saving potentials of 6-32% by enhancement of the HVAC system3. This study aims to determine the potential for energy savings in the air handling unit (AHU), the energy system and the control system—three essential components of the dry room. A battery production plant in Norway has been chosen as a case study. Following site measurements, the acquired data has been analysed to identify the air properties(temperature, humidity ratio, dew point, and mass flow rate) and energy flows in the dry room and HVAC system. Based on the data collected, a verified dry room and HVAC model was constructed using TRNSYS to assess the impact of different measures for improved energy efficiency. In particular, the mechanical and chemical dehumidification processes were adjusted to decrease the heating and cooling load. In order to reduce costs during periods of peak power prices, thermal energy storage was implemented in the energy system. The findings of this work indicate that the AHU and the energy system should be designed according to the local energy sources. When free or low-cost thermal energy sources, such as geothermal energy or waste heat, are available at the site, the AHU and energy system should be designed to optimize the utilization of these resources.

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Idea Generation Workshop as a Tool for Facilitating Eco-design and Implementing a Life Cycle Perspective in Battery Production

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Batteries have been pointed out as a key player in the work towards climate change mitigation, enabling electrification and zero emission vehicles, at least at the tailpipe. However, the risk of burdenshifting from tailpipe emission reductions during the use phase to emissions further upstream in the battery value chain or in the electricity generation is present, highlighted in many earlier life cycle assessments (LCAs) of batteries1. This strongly motivates the importance of taking a life cycle perspective, to keep batteries as an enabler and not a disabler for sustainable development. Via the involvement as LCA practitioners in three Horizon Europe research projects within the battery field, a methodology to facilitate eco-design and implement a life cycle perspective within the consortia was tested and evaluated. This involves conducting a screening LCA during the first year of the project, referred to as screening due to its simplified format and high level of secondary and generic data from literature and databases, although including as much project specific data as available. The screening LCA report was then used as basis for an idea generation workshop held during the month 12 meetings in all projects with all project partners2. During the workshop, the results from the screening LCA were first presented, followed by time for brainstorming and idea generation focused on generating ideas with environmental improvement potential. This resulted in between 36-61 ideas per occasion, covering a wide range of aspects such as materials, manufacturing, use phase, recycling and legislation. After categorisation of the ideas, each participant was asked to pick one idea and pitch that for the group, after which the idea together was evaluated in terms of environmental improvement potential and ease of implementation, both on a scale from one to three. The purpose with the entire workshop was to facilitate eco-design and implement a life cycle perspective among all participants in the projects, independent on their role and prior knowledge. This to help avoid sub-optimisation (burden-shifting) and increase the awareness of how environmental impacts of batteries typically are distributed and where hotspots often are located. By doing this already in the beginning of the project, the goal is that the full LCA in which the project is environmentally evaluated will show even better environmental performance, because the LCA results have been understood and used in the design work.

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Recycling of LIB: Disassembly and mechanical processing

Automated Cell Opening in Disassembly Process for Recycling of Lithium-Ion Batteries

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Current recycling processes for spent lithium-ion (LIBs) batteries involve discharging the pack and dismantling it down to module or cell level, followed by shredding and several mechanical separation processes. After obtaining the mixed powder from the shredded product, the so-called black mass, chemical processes such as pyrometallurgy and hydrometallurgy are utilized to extract the active materials. These established processes exhibit a short pretreatment chain with high processing capacities, are characterized by low material separation rates, high level of impurities, and significant material loss [1–3]. An alternative procedure is the direct recycling, where the active materials of anodes and cathodes are extracted through cell disassembly and regenerated separately. The key benefits are lower costs, reduced emissions and material losses as well as higher degrees of purity for the resulting materials [4]. However, current research in the field of direct recycling is limited to a laboratory scale due to the complex and often condition-dependent tasks of manual cell disassembly. In order to enable an upscaled direct recycling process, scalable and automatable approaches for the opening of battery cells and the disassembly of its components are required. In this study, a prototypical workstation is built and demonstrated. Various methods such as ultrasonic cutting, mechanical cutting through shear forces and cutting with circular saw are investigated. The successful experimental implementation of automated ultrasonic cutting and shear cutting for opening pouch casings is characterized by a high cutting efficiency without chipping or sparks. For further analysis, cutting process of prismatic cell casings are simulatively investigated. Using design of experiments approaches, validated experiments are performed with a circular saw. An optimization parameter combination of feed rate, rotational speed and cutting depth is obtained. With this parameter combination, the cell opening of the prismatic cell reduces the resulting chip volume, lowers process temperatures and enables a controlled cutting force. With this research, valuable insights for the automated cell opening and the further development of automated cell disassembly is generated, contributing to the establishment of an efficient process chain for the direct recycling of LIBs.

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Disassembly technologies for automotive batteries: automation and concepts

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The disassembly process is labour-intensive. Thus, automating this process makes it easier to expand recycling. The different pack architectures - cell to module, cell to pack and cell to chassis/car - force dismantling to be flexible or to focus on one architecture. However, only one type of pack architecture can then be dismantled. Ensuring high case separation of the battery pack/module allows for easier separation into the cell fractions with higher purity. This helps to fulfil the EU battery regulation.
What will be discussed?
How can batteries be disassembled automatically when there are many different designs?
How can the degree of automation and profitability be balanced?
What is the impact on the following recycling steps?

Mechanical Recycling in pilot scale: Impact and effects of dismantling level and process conditions

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In recent years, the development and promotion of electric vehicles and renewable energy technologies lead to a growing number of lithium-ion batteries (LIBs). Accordingly, the amount of spent LIBs will also increase in the near future. Currently used LIB materials are environmentally harmful and imply a safety risk. However, they present an opportunity to gain valuable resources like lithium, nickel and cobalt. Especially, the supply of the latter might be critical in future, that is why the development of independent secondary sources is mandatory. Therefore, recycling of LIBs has gain great attention in research and industry. Nowadays, the recycling focuses on the recovery of the most valuable materials of the battery, Ni, Co and Cu. More recently, approaches are shifted to a holistic recycling process combining a hydrometallurgical and pyrometallurgical part with a mechanical pre-treatment, recovering and reuse all components for a new battery. In a mechanical recycling process route, the batteries are crushed, dried and the received fractions are sieved and separated in various process steps. Each process step affects various properties, i.e. particle size, performance, purity of the fraction and have to be considered for the application of the secondary materials, since the overall performance of the battery is aimed as high as for the first life cycle. Due to many different components and primary materials of a battery, a sharp separation of the fractions is quite challenging. Dismantling of battery modules on different levels reduces the total amount of battery components and by this reduces the impurities in the recovered black mass and the effort of separation of all recyclable materials. 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 are investigated. Furthermore the influence of the dismantling level on the amount of impurities within the recycled material and the recovery efficiency of the black mass are discussed. The various disassembly depths are evaluated with regard to their possible automated disassembly process.

Industry Session I: Dry Electrode Processing

Improved Solids Handling Solutions for Dry Battery Electrode Production

Hans Schneider
Zeppelin Systems GmbH

With the growing demand for batteries in EVs and energy storage, new production lines for Lithium-Ion Batteries are essential. The dry electrode production method offers significant advantages over the conventional slurry process, such as reduced energy consumption, elimination of toxic solvents, and a smaller footprint. This has driven the industry to invest heavily in developing and industrializing the dry process.
A holistic approach is crucial for a successful dry production process, addressing both recipes and processes simultaneously due to their interaction. This involves using and continuously optimizing new types of active materials, conductive additives, and binders. These raw materials must be precisely fed in a defined sequence under specific conditions into a high-intensity mixing process, where they are converted into a homogeneous battery mass to be rolled into a film on calendaring machines. This simplified process in the lab needs a reliable scale-up for pilot and industrial production.
Zeppelin has developed and industrialized integrated solutions for the entire process, from raw material intake to post-processing, based on powder characterization and lab-to-pilot scale testing. Key steps in the process and recent achievements will be highlighted.
-Reliable Handling, Storage and Dosing of Raw Materials for the Dry Mixing Process
-Mixing and Fibrillation in High Intensity Mixers
-Postprocessing and Feeding to the Calender

Material Feeding and Distribution for Battery Dry Coating

Urs Helfenstein
Coperion K-Tron LLC

The dry coating procedure in battery production poses distinct challenges, especially in relation to material feeding into a calender gap. For most feeding applications, the setpoint and standard deviation of weight samples are relevant. However, for dry coating applications, the uniform distribution of the material across the width is crucial. This presentation will explain the variances and definitions of the involved accuracies, as well as the opportunities that enhanced accuracies present for dry coating. Upon establishing this foundation, we will provide an overview of existing feeding technologies and their limitations in meeting the demands of a dry coating process and the properties of the active materials. The flowability range can significantly vary from free flowing to bridging and rat holes, due to the mixture and processing parameters. Traditional methods to maintain material flow may prove ineffective as these mixtures are sensitive to pressure and tend to compact. The presentation will explore various new dosing concepts we tested, examining their associated challenges and potential advantages. Particular emphasis will be placed on the double-roll dosing concept, which has shown superior results in terms of simplicity, accuracy, and scalability. The proof of concept was established on a laboratory calender with NMC and LFP blends as part of the ProLIT research project. This concept has since evolved into a product, and findings from numerous feeding tests conducted with anode and cathode material blends have shown promising results, as well as certain limitations. We discovered that the initial feed factor, derived from a gravimetric calibration of the feeder, appears to be a reliable indicator for assessing flowability and the resulting accuracy. This indicator can be utilized to swiftly test new material batches for flowability, thereby accelerating process development

Processing and scaling of structured dry mixes for dry battery electrodes (DBE) on a scale from 0.1 l to 500 l

Dr. Stefan Gerl
Maschinenfabrik Gustav Eirich GmbH & Co. KG

After Eirich intensive mixers on a 1 to 50 l scale have been successfully used at many universities and research laboratories by industrial customers for several years for the development of dry electrodes (DBE), the next scaling stage was ignited at Eirich and its customers. As there have been no mixer sizes in the smaller than 1 l range for the development of dry electrodes on a coin-cell scale to date, Eirich has now turned the 0.1 l prototype developed a few years ago into a series product at the insistence of its customers. The performance and scalability for pure dry mixtures and carbon coating has already been impressively validated together with the KIT1. The coffee cup sized mixer is suitability for coating of active materials, production of segregation free dry mixes for brush or spray application to collector foils or the production of fibrillated structured dry mixes for the production of small free-standing films for coin cells, as it has been demonstrated in various customer projects. Researchers and developers now have a glovebox-compatible machine at their disposal that complements the range of Eirich mixers for dry electrodes and is particularly suitable for the development of ASSB batteries. The currently common use of planetary centrifugal mixers for homogenization with subsequent non-reproducible, manual fibrillation of the premix in a PestleMortar is now a thing of the past. Targeted studies on a coin cell scale are now possible without any problems and, above all, the development results can be scaled up to production scale. At the other end of the size scale, the first pilot plant for dry electrodes on a giga scale based on a 500l RV12 mixer went into operation in summer 2024. With filling quantities of up to 600kg per batch and an emptying system optimized in extensive tests with direct transport of the mixture to the multi-roll calender, the solution impresses with its simplicity of a one-pot process for both anode and cathode mixtures in combination with plant technology tailored to the special requirements of handling fibrillating polymers. The presentation shows the 0.1 l mixer EL 0.1 in detail as well as its scale-up capability and reports on initial experiences from pilot production at giga-scale.

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Continuous extrusion-mixing of dry electrode masses for more cost-effective battery manufacturing

Philipp Stössel
Bühler AG, Battery Solutions

The battery industry is constantly on the hunt for more cost-efficient production technologies which, in the best case, also increase battery performance. It seems this holy grail has been found in the 'Dry Battery Electrode (DBE)' approach. The technology has already demonstrated various benefits on academic and pilot level. However, the industries' expectations towards DBE are high: 10-fold reduction in footprint and energy demand for the electrode manufacturing [1] or savings of several hundred euros per EV [2]. Realizations of these expectation on an industrial scale will be the next step. Bühler's fully continuous extrusion-mixing technology, presented in (Fig. 1), effectively addresses this challenge. The extruder's small mixing volume allows for precise control of shear forces and temperature along the entire mixing zone, enabling efficient fine tuning of the complex process-structure-property interactions of different dry-coated electrode systems. The fully continuous approach ensures high and consistent product quality, eliminating the risk of batch-to-batch variations. Scaling across different extruder sizes enables seamless translation of lab findings to production scale. This presentation will focus on the transfer of concepts and results from lab to production scale, derived from internal studies as well as latest cell performance data. These studies confirm that Bühler's fully continuous dry mixing approach will represent a cornerstone in sustainable and cost-effective scale-up of next-generation battery production to meet growing demands while ensuring the highest standards of product quality.

Industry Session II: Industrial characterization and simulation methods

Optimized Electrodes and Separators by Particle Size Adjustment and advanced Particle- and Pore Size Analysis

Dr. Lena Weigold
Retsch GmbH

Particles in Battery production play an important role. These can be either graphite particles for anodes, e.g. NMC precursor and Lithium hydroxides or Lithium carbonates for cathodes or ceramic particles for separators. In solid-state batteries, for example, optimizing particle size is a balancing act that significantly affects safety, longevity and performance. For research purposes, Retsch presents several methods for adjusting particle size on a laboratory scale, including high-energy milling, cryogenic processing, and wet grinding for nanometer size distributions. With a special focus on temperature control, new electrode materials can be achieved by ball milling and mechanochemical synthesis. The porosity of anodes or separator membranes after final processing is another quality critical parameter. In order to improve battery performance and reduce production costs precise control of particle size and morphology as well as porosity and specific surface area are essential. For this Microtrac MRB offers a complete portfolio with combined Laser diffraction and image analysis for particle size and shape analysis. Oversize of electrode particles can drastically decrease the performance of batteries; this issue can literally be made visible with LD supporting image analysis. Image analysis is also a helpful tool to determine the shape of particles, see Figure 1. Further, Mercury intrusion porosimetry as mentioned in the VDI guidelines for battery production, allows the determination of meso – and macropores of electrodes and separators. Air protected gas sorption for BET specific surface area and pore size distribution on sensitive solid electrolytes as well as air protected pycnometry (density) measurements will be presented as well.

EIS and AI: Considerations to make before trusting your data to AI!

Tim Johannsen
Bio-Logic Science Instruments GmbH

Automated testing of batteries has become an important topic in the recent years – and will continue to grow in relevance. As Electrochemical Impedance Spectroscopy is an important tool in this regard: How to ensure, that the AI interprets the data given to it in a sensible way? For this, we look at the four validity criteria of impedance measurements and discuss different ways data can be misinterpreted by AI – and you will find fitting the wrong equivalent circuit may be the least of your problems.

Multi-scale characterization and elemental analysis with electron microscopy for battery manufacturing and research

Dr. Jens Greiser
Thermo Fisher Scientific

The increasing demand and rapid growth of the battery industry has highlighted the importance of analyzing and characterizing batteries at multiple scales to ensure their safety, high performance, and cost efficiency. Conventional QC techniques such as inductively coupled plasma optical emission spectroscopy (ICP OES) and optical microscopy have certain limitations when it comes to providing the necessary resolution and detail required in battery analysis. Therefore, more advanced techniques are required that can offer a higher level of resolution and elemental analysis. One significant challenge in battery manufacturing is the presence of metal impurity particles. Failure to detect and quantify these impurities can lead to various issues in the final battery product, including gradual capacity deterioration, internal short circuits, and even thermal runaway. Electron microscopy solutions play a crucial role in overcoming these challenges by providing quantified results on both particle morphology and chemical composition. This enables traceability and facilitates root cause analysis to identify the origins of impurities. By utilizing electron microscopy techniques, we can achieve a more thorough understanding of the battery's composition and detect any potential issues that may arise during manufacturing or research. This presentation will highlight comprehensive automatic particle analysis for multi-scale characterization and elemental analysis in battery manufacturing and research. By leveraging these advanced techniques, the production of safe, high-performance, and cost-efficient batteries can be ensured, while addressing the limitations of conventional QC techniques.

Industrial-Scale Production of Carbonnanotubes (CNTs) for Gigafactories

Maximilian Münzner
Netzsch GmbH

A key factor for achieving high C-rates, and thus enabling fast charging and discharging of batteries, is the cell chemistry and the use of carbon nanotubes (CNTs). Adding CNTs significantly enhances conductivity within the battery, allowing cell manufacturers to stand out with superior performance. There are different types of carbon nanotubes, such as single-wall carbon nanotubes (SWCNTs), which can cost up to $2,000 per kg, and multi-wall carbon nanotubes (MWCNTs).
To achieve the desired properties of CNT slurries, both their length and degree of dispersion are crucial. The processing of CNTs involves three key steps, typically carried out using agitator bead mills, intensive or planetary mixers, and homogenizers.
Mixing: The first step is to create a slurry by mixing dry CNTs with a solvent, such as NMP for the cathode or water for the anode. Intensive mixers are suitable for processing solid contents up to 5 wt.-%, while planetary mixers can handle higher solids, up to 10 wt.-% or more.
Grinding: The second step is grinding to control the length of the CNTs and optimize conductive contact points. This is done in an agitator bead mill, where different mill types, such as disc or pin mills, can be used depending on the specific grinding effects required.
Unbundling: The final step is the unbundling of CNTs, achieved using a high-pressure homogenizer, which generates cavitation effects with shear rates exceeding 1.5 million 1/s. Depending on the required degree of dispersion, the slurry may need to pass through the homogenizer multiple times, ranging from 2 to 15 passes.
At the end of this process, the result is a highly conductive CNT slurry. In addition to individual machines, Netzsch offers complete turn-key solutions that include powder handling, transport systems, control systems, and supporting steel structures.

VW Group – Unified cell format as key for the standardization strategy

Sebastian Schoeniger
Volkswagen AG

The Volkswagen Group has a broad-based strategy for the battery systems of the future. Within the VW Group, the Center of Excellence is the central organization for the development of battery systems and cells.

The presentation will outline the VW Group's standardization strategy for the electrification of the fleet. As part of a deep dive, the technical possibilities offered by the unified cell will be explained and how this fits into the framework of the standardization strategy.

Cell assembly and finalization

Jelly rolls for application in HV and HE battery cells with respect to design and format flexibility

Julian Grimm
Fraunhofer Institute for Manufacturing Engineering and Automation IPA

Battery cells are essential components of electric vehicle battery systems. In the automotive sector, manufacturers use three cell formats: pouch, prismatic, and cylindrical. Over the past three years, cylindrical cells have gained significant importance and popularity, mainly due to innovative designs like Tesla's tabless design. Besides the application in battery electric vehicles, cylindrical cells are used in different devices such as power tools. The heterogeneous demand implies that different specifications of the battery cells components considering materials, designs, formats, and manufacturing parameters are needed to fulfill the demand for either high performance or high voltage applications. This presentation investigates the evolving landscape of lithium-ion (Li-ion) battery cell formats. Advancements from 18650 to 4680 cells, showcasing production efficiencies, enhanced energy densities, and innovative design features like tabless designs to reduce inhomogeneities are explored and presented. Based on an examination of industrially available Li-ion cylindrical battery cells in different designs and formats, the presentation sheds light on the generic characteristics and technological advancements driving the adoption of cylindrical cells in modern applications. Design features, such as tab design, and quality parameters, like manufacturing tolerances, are displayed to provide a generic description of cylindrical cells. Current and heat transport paths as well as gravimetric and volumetric energy density, and impedance are compared and presented for basic designs and categorization. To showcase the scaling up of cylindrical cells flexible in format and flexible in design manufacturing processes for jelly rolls are described and shown. A use case for a flexible manufacturing equipment (winding machine) is shown with regard to necessary measurement system to improve the manufacturing process to raise the quality of the jelly rolls and lower production waste.

Mini Environments – optimized conditions for cell assembly

Nicole Neub
Exyte Technology GmbH

The manufacturing of Li-Ion cells involves moisture-critical processes carried out in large multifunctional dry rooms. Dehumidified air is essential to prevent potential negative quality losses due to humidity influences. De-humidification of the airflow to the required dew points is one of the most energy-intensive processes. So dry rooms play a major energy consumer role within the battery cell production.
A typical dry room in a Battery Cell Gigafactory requires 25%1 of the total energy demand, assuming average dew points and internal moisture loads. New cell chemistries may even need more stringent dew point specification, which would result in an even higher energy demand.
Energy-saving and emission reduction are top priorities for cell producers and OEMs are committed to carbon neutrality latest by 2035 to maintain sustainability.
Minienvironments are one of the technical solutions to the above-mentioned challenges. By reducing the sources of the humidity (no operator, less leakage due to lower overall volume) the minienvironments need much less air to be de-humified, resulting in lower invest costs (CAPEX) and less energy demand (OPEX).
This presentation takes up the challenges outlined above and answers the question of how a modular mini environment system must be designed to deal with them in the best possible way.

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Achieving Stable Cycling Performance of Pure Silicon Anode for Lithium-Ion Batteries by Scalable Electrochemical Pre-Lithiation

Shiho Honda
FZ Jülich GmbH, Helmholtz Institute Münster

Silicon (Si) has considerably high theoretical capacity 3579 mAh/g. However, Si particles expand significantly during charging, making batteries difficult for long-term cycling1. For lithium (Li)-ion batteries, capacity loss occurs in the first cycle due to solid electrolyte interface (SEI) formation2. Pre-lithiation (preLi) can compensate for the Li loss and demonstrate stable capacity3. In this study, pure Si anode with a columnar structure were pre-lithiated in scalable processes. Furthermore, the ageing behaviour of Si by scanning electron microscopy (SEM, Fig. 1) and improvement with preLi over 200 cycles in pouch cells (Fig. 2) were evaluated. Compared to other preLi techniques such as using Li metal or vapour deposition, our process can be applied to mass production in a continuous way.

Optimized electrode and battery performance

An industry suited production process for LIB-anodes with pre lithiated SiO C

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

Lithium-ion batteries (LIB) are widely used for energy storage. Increasing their energy density is a persistent demand, especially for their application in electric vehicles. Much progress has been reached by introducing carbon coated SiO (SiO-C) with its high specific capacity and good cycling stability in LIB anodes, which are commonly and still mainly made from graphite as active material1. However, SiO brings about several impairments limiting its proportion in the total active material. A main issue, their still high irreversible capacity loss in the initial cycle (low ICE), can be effectively mitigated by applying pre-lithiated SiO-C particles (Li-SiO-C)2,3. However, work reported so far is mainly based on investigations in lab scale. In industrial processes, more demanding requirements occur that have to be considered to establish a stable production process. The change of the chemical environment caused by the Li-SiO-C affects different chemical and physical properties of the suspensions which have a decisive influence on processability. In this presentation, we illustrate the challenges and impairments occurring when Li-SiO-C is processed. Our work is based on highly relevant LIB electrodes containing as much as 20 % pre-lithiated SiO in the anode active material and produced in a pilot scale. Li-SiO-C particles cause strong basic slurries when applied for LIB electrode production4. As will be shown, the slurries suffer from low stability and cause filter clogging during application, defective coatings and poor adhesion. A neutralization is not feasible and would destroy the structural integrity of the slurry. As a solution, we present a customized formulation using an additive. We show its impact on the properties of the slurry and demonstrate its feasibility by results from electrode production on our pilot line. By the customized process, the stability of the slurries as well as the quality of the coatings were drastically increased. As a result, a good mechanical quality and electrochemical performance of the electrodes in full cells is demonstrated.

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Carbonate deprotonation on Ni-rich layered cathode: Development of a new cis-trans isomerism oligomer as an organic coverage

Fu-Ming Wang
Graduate Institute of Applied Science and Technology, National Taiwan University of Science and Technology

Ni-rich layered cathodes have a high practical capacity (>200 mAh·g−1) and tapped density (>3.6 mg·cm-2), thus attracting wide attention in large applications such as electric vehicles and energy storage. However, high surface reactivity of these cathodes promotes the decomposition of carbonates solvents, which contributes to the growth of the cathode–electrolyte interphase (CEI) as well as rapid fading of the battery's capacity during long-term cycle. Carbonates are favorable for deprotonation reaction by the oxygen atom in the Ni-rich layered cathode and further in the formation of the CEI. In this study, the deprotonation mechanism of cyclic and linear carbonates on a Ni-rich layered cathode was thoroughly investigated using operando Fourier-transfer infrared spectroscopy, and the reasons for cathode fading could be confirmed in terms of the carbonate structures. In addition, a new maleimide oligomer was developed and covered on a Ni-rich layered cathode to inhibit the deprotonation of the carbonates. The maleimide oligomer acts as a cis–trans isomerism that provides a bridge function for reacting with oxygen on the cathode surface by its cis formulation. Moreover, this bridge function will keep the carbonates away from the cathode surface for further decomposition during cycling. On the contrary, the battery performance exhibited a cycling ability at a high rate, and the new cis–trans isomerism maleimide oligomer helped improve the rate capability. A full-cell (>3 Ah) test containing graphite as the anode with a cis formulation of the maleimide oligomer coverage was completed.

Influence of Passive Material Distribution and Morphology on Cathode Performance: a Computational Approach

Dr. Timo Danner
German Aerospace Center (DLR)

Passive materials are an essential component of lithium-ion battery electrodes and enhance the electrical connectivity and mechanical stability within an electrode matrix. The spatial distribution of the passive materials, namely, the conductive additive and binder domain (CBD), and its internal structure, have a major effect on battery performance. However, disentangling the different transport processes in the electrodes and their impact on electrode performance is non-trivial. Combining microstructure-resolved simulations [1] with advanced imaging and electrochemical characterization techniques, provides a powerful methodology to characterize the lithium ion transport in the electrode pore space. In the standard models, the effective parameters for the transport in the CBD phase do not account for its internal nanostructure. To develop an improved model, we need to understand the properties of the CBD on the nano-scale. In the present contribution, high-resolution 3D FIB-SEM data [2] is used to obtain further geometric information on the porous networks within the CBD on the nanometer scale, shedding light on its effective ionic conductivity and its dependence on the local CBD porosity. Finally, we use a feed-forward neural network which is trained on the high-resolution FIB-SEM data to identify and assign CBD domains in the electrode microstructure with varying local porosity. More precisely, correlative microscopy is used to provide the ground truth information in the form of the high-resolution 3D FIB-SEM data that is registered with image data obtained by synchrotron tomography. In combination with the information of the high-resolution FIB-SEM data, this approach allows us to include the local porosity-dependent tortuosity in the CBD domain. We envision that this approach will enable us to transfer the methodology and information to differently processed electrodes in the future. The results highlight the importance of the CBD distribution on both, the macro- and microscale and can be employed to address future design strategies on the electrode and material level.

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Recycling of LIB: Hydrometallurgy and re-synthesis

Recovering Critical Raw Materials from Li-ion Batteries - Two step leaching and closed loop reagents process

Steven C. Lans
Back to Battery

Batteries play an important role in the energy transition. The global demand for batteries increases the dependency on critical raw materials such as lithium, cobalt, nickel, manganese and graphite. There are few concentrated sources and vulnerable supply chains. Measures have been taken at EU level to reduce this dependency, such as the Critical Raw Materials Act and the Battery Regulation. These contain clear objectives for recycling and recovery of valuable materials. It is also mandatory to use recycled critical materials in new batteries by 2031.

Back to Battery is developing a unique hydrometallurgical process for processing of black mass from shredded Li-ion batteries. The Back to Battery process provides strong technological advantages, amongst others because of two step leaching and internal recycle of reagents. It is truly zero waste. The process can be used flexibly, making the process less sensitive to the changing composition of black mass, resulting from a large variety of Li-ion battery chemistries (such as LFP, NMC, NCA, LMO, LCO). It has been successfully proven in the laboratory to make pre-cursor cathode active materials and to exceed recoveries set by the EU Battery Regulation. Back to Battery is ready for the next steps, to scale-up to a pilot plant and further roll-out.

Morphology and structure investigation of recycled Graphite powder after mechanical and chemical treatment process for anodic material application

Slaheddine Jabri
TU Braunschweig I Institute of Applied Physics

By focusing on preserving the components of Li-Ion battery material through cheaper and friendly environmental methods, recycling process could introduce scavenged impurities into resynthesized material and modify its structural and morphological properties. In this work, we compare mechanical, and chemical purified recycled Graphite-Anode material. The mechanical re-synthesized Graphite shows fast capacity fading of 80 % compared to commercial graphite in which we observed 88% after 200 cycles due to residual metallic and polymer contaminants such as a Li2CO3, CuO, CuF2 and CMC binder. However, after chemical treatment the performance of the battery cell is improved by 89 % compared to the mechanical re-synthesized. We attribute this to the high obtained graphite quality, the suppression of contaminants and removing or decreasing of the SEI layer under chemical solution. Moreover, after the treatments two main morphologies are present, rounded and planar graphite particles. The planar one contains nanochannels and pits on the basal and edge graphite plan. We suggest that these nanochannels and pits could facilitate the diffusion of Lithium ions in porous Graphite structure.

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Effects of different impurities on the re-synthesis of NMC particles

Markus Rojer
TU Braunschweig | Institute for Particle Technology (iPAT)

Lithium-ion batteries are currently widely used for applications such as electric vehicles, mobile phones or laptop computers. The recycling of all metallic components of these batteries so far however is limited due to economic aspects. One major cost factor in the hydrometallurgical recycling step is the selective extraction of individual metals prior to re-synthesis of the anode- and cathode active materials. Impurities present in the recovered metal compounds, like aluminium, iron, copper or phosphate, strongly affect the re-synthesis process and consequently, the properties and the electrochemical performance of the re-synthesized cathode active materials. The detailed mechanisms and their effect on different electrochemical properties however so far is only poorly understood. An understanding of these effects would enable a simplification of hydrometallurgical processing and thus simpler and cheaper recycling strategies. In this work, several common impurities present in the recycled metal compounds of batteries were added to the synthesis of different NMC materials. In addition to a co-precipitation route that is highly similar to industrial processes, also a sol-gel synthesis was investigated. The effects of the impurities on the properties of the re-synthesized cathode material are characterized, determining the particle shape, size, crystal structure and elemental composition. The obtained products were processed to cathodes, integrated in Li-ion coin cells and evaluated towards their electrochemical performance by cyclic voltammetry and charge-discharge cycling experiments. Recent investigations show a partially significant effect of impurities on the crystallinity and particle size. While some impurities impair the electrochemical performance, other impurities have been found to improve the crystallinity and structure of the re-synthesis product and thus, also the electrochemical performance.

Industry Session III: Characterization methods in battery production

In-line, real-time characterization of electrode slurry rheology

Fridolin Okkels
Fluidan ApS

The rheological properties of battery slurries are important in the process control for several reasons, as they influence: Coating uniformity, manufacturing efficiency, electrode performance, material distribution and cell assembly. The reason the slurry rheology is so critical is that the flow properties control how well the active materials are mixed into a homogeneous slurry and how evenly it is coated on a current collector, using e.g. a slot-die machine. Within battery production, electrode mixing and coating are rated among the most critical manufacturing processes in relation to effect on cycle life and performance1, and for the coating process: "All other process steps depend on the quality of this step."1 An improved in-line control of slurry mixing and coating will lead to a reduction of wastage in both time and materials. Traditionally, viscosity is monitored manually using off-line methods, or with in-line viscometers. Manual methods are sensitive to human errors and are time-consuming, thereby preventing any form of real-time control. Furthermore, in-line viscometers lack temperature control as well as they are unable to capture crucial rheological properties. RheoStream® is a process rheometer for real-time measurement of viscosity, degree of shearthinning, and apparent yield stress, in manufacture of viscous, non-Newtonian liquids. The instrument is fully automatic and integrates directly into production lines (at mixing tank or slot-die machine). The instrument comes in both water-based and solvent sample versions (ATEX), with automatic sampling and offering results without interrupting the manufacturing process. The instrument measures viscosities every 2 minutes, at multiple fixed shear rates ranging between 1.5 – 1000 s^{-1}. The viscosities are obtained and measured at a pre-set and constant temperature of e.g. 22 °C. Cleaning is done automatically with either water or solvent CIP liquids. Introducing in-line, real-time rheology control of electrode slurries will not only reduce both off-spec and production time, but also deliver a more fine-grained and detailed monitoring of the production that will add directly to the overall digitization of the manufacturing process.

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Industrial grade solutions on gigafactory scale based on the use case of X-ray inline inspection

Markus Möller
Exacom GmbH

Inline X-ray inspection for cell assembly has evolved as a mature and established technology in recent years. The primary focus of inspection has shifted from distinguishing good cells from bad cells to providing clients with a comprehensive understanding of the manufacturing process. This shift ultimately aids in reducing costs and improving yield, which are crucial parameters for upscaling production. Inspection systems are now highly integrated into the production process, positioning themselves as industrial solutions rather than standalone machines. This talk gives insights into optimizing X-ray inspection systems for dry rooms, establishing metrology-grade and production-ready AI pipelines, and implementing automation controls for line communication, databases, cloud solutions, and data storage concepts and handlings system integration. We will address the challenges of operating in a rapidly growing and constantly evolving industry and the organizational measures required to meet stringent demands. As traditional supplier and customer roles shift towards partnerships, close communication and collaboration become paramount for success, particularly under tight timelines.

Development of a validated simulation model for all solid-state batteries

Roman Buchheit
Math2Market GmbH

The development of all-solid-state batteries (ASSBs) presents both challenges and opportunities for battery manufacturers worldwide. Numerical simulations have already proven to be invaluable in conventional lithium battery R&D within the simulation framework of the GeoDict software. Here, we adapt and apply them to ASSBs. Adapting and validating GeoDict for ASSB research poses various challenges. These are addressed in the publicly funded DELFIN project, in which Math2Market collaborates with leading academic institutions and industry partners. We cover the entire process:

1. Modeling the microstructure of ASSB electrodes from µCT scans is a challenge due to the lack of contrast between active materials and solid sulfuric electrolytes. We enhance contrast and resolution using multi-channel segmentation and AI algorithms in GeoDict.
2. Accurate microstructure modeling forms the basis for modeling a digital twin with the same microstructural properties as the original ASSB electrode material.
3. For precise electrochemical simulations, GeoDict is adapted to account for the absence of a concentration gradient and determining Butler-Volmer rates, based on experimental exchange rate constants.
4. The Justus-Liebig-Universität Gießen provides the experimental data to validate the material parameters used in GeoDict simulations, culminating in a validated ASSB model.

The result of the DELFIN project are summarized in regard to their potential impact on industrial battery manufacturing R&D.

Characterization of fibrillation in powder blends with PTFE for dry coating

Filip Francqui
Granutools

Dry coating is gaining popularity for electrode production. The raw materials (active material, conductive additive and binder) directly handled in powder form are coated on a current collector with new techniques that do not need a solvent. Polytetrafluoroethylene (PTFE) is a good candidate for dry coating due to its plasticizing properties, allowing to produce from a dry powder blend of active material, conductive additive and PTFE a soft film that can be coated directly on a conductive sheet and calendered to produce an electrode. The plasticizing behaviour is due to the long chains of polymer of PTFE creating an entangled network with the active material and the conductive additive. The powder blend must be first fibrillated to activate this plasticizing behaviour, i.e. elongating the agglomerated PTFE chain via a high share rate to obtain long fibrils. The length and the quantity of these PTFE fibrils influence the entangled network and thus the mechanical properties of the produced film. In addition, it also influences the flowing behaviour of the powder blend before calendering which influences the processability of the powder blend. Therefore, the degree of fibrillation of the powder blend must be perfectly controlled to reach the optimal quality which requires accurate and reliable characterization methods. In this work, we present a study on powder blends of Lithium Iron Phosphate (LFP), PTFE, and carbon black that were fibrillated with different times of fibrillation, resulting in different degrees of fibrillation between the blends. The powders were characterized with an improved tapped density method (GranuPack, Granutools, Belgium). The packing dynamic was observed to be correlated with the degree of fibrillation of the powder. Consequently, the packing dynamic analysis with a high resolution tapped density measurement gives an interesting metric to quantify the degree of fibrillation of a powder blend containing PTFE. Furthermore, since the powder material is generally fibrillated and handled in hot conditions (from room to 180°C), measurements were performed at high temperature to investigate the effect of the heating on the powder behaviour and characterize the material close to the conditions of the process. We will show how such methods, integrating temperature, can pave the way for fibrillation characterization for dry coating improvement.

Powder rheological characterization of dry coating materials

Helena Weingrill
Anton Paar GmbH

The dry coating process has several advantages compared to traditional solvent-based coating procedures, like energy savings, environmental advantages, reduced costs and coating uniformity. In the process, the active material, conductive additive, and polytetrafluoroethylene (PTFE) binder transition from fine powder to agglomerates under shear, facilitated by PTFE fibrillation. This transformation is critical for battery performance, requiring a homogeneous mixture with the appropriate fibrillation before calendering1. Powder rheology enables the characterization of particulate-solid transformations via time consolidation measurements. The aim of the present study was to find suitable testing parameters to investigate the fibrillation process in detail and relate properties of the final coating to the rheological characteristics of the base particulate material. For this purpose, anode materials (graphite, carbon black, and PTFE) were characterized both before fibrillation (as premixes) and after fibrillation (as aggregates) with varying binder contents of 1 wt.-%, 3 wt.-%, and 5 wt.-%. At temperatures exceeding PTFE's crystalline transitions (between approx. 20 °C and 30 °C)2, time consolidation measurements revealed that normal and shear stresses significantly impact the fibrillation process, evidenced by a pronounced decrease in flowability with increasing levels of both types of stresses. The second phase of the study investigated the influence of varying mixing conditions, specifically the degree of fibrillation, on the mechanical properties of aggregates at a constant binder content. This analysis was conducted using two primary methods: powder rheological characterization of aggregates and dynamic mechanical analysis (DMA) of the films. These methodologies allowed for a detailed differentiation of the samples and will be further implemented for maximizing the mechanical properties of dry electrode films.

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Back to the future - 25 years of electrode extrusion

Dr. Nicolaus Rehse
Collin Lab & Pilot Solutions GmbH

COLLIN has built its first electrode extrusion line 25 years ago. Since then, we have improved our machines in many ways to deliver a complete solution to produce electrodes with less or even no solvent. State-of-the-art processes for electrode production involve large amounts of hazardous solvents and have a high demand for energy (drying, solvent recovery). Processes well established in the polymer industry could help to improve the carbon fooibptprint of battery cell production. The mixing of the electrode material can be performed by continuous compounding of the base ingredients in a twin-screw extruder. Due to controlled shearing and individual screw design a good dispersion of all materials is possible. This electrode material can be extruded directly as a free-standing electrode and subsequently laminated with the current collector. Or it can be applied via extrusion coating onto the metal foil. Since 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 drying and therefore a solvent recovery is not necessary in this electrode coating process.

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
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Homogeneous powder and structured dry mixes
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High-performance batteries
Mixing technology for highly reproducible processes

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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
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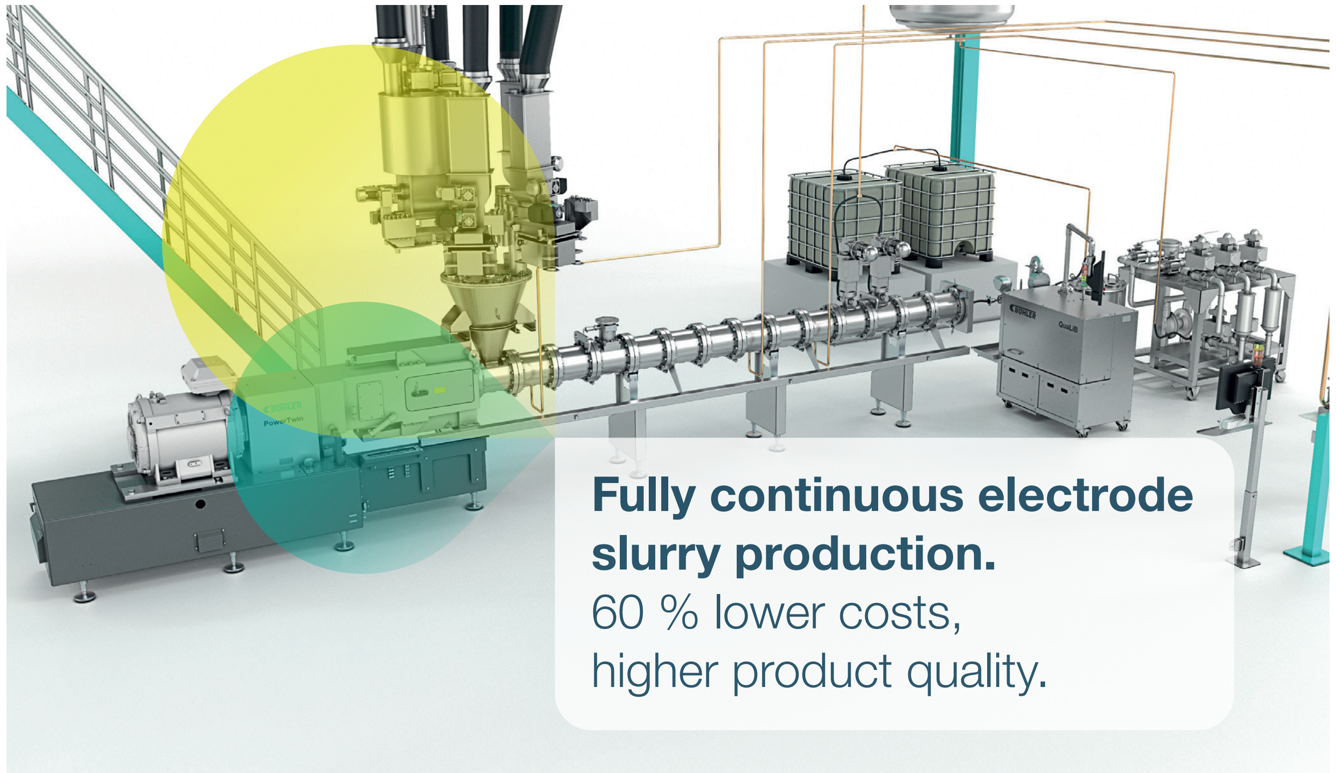
Unique mixing technology



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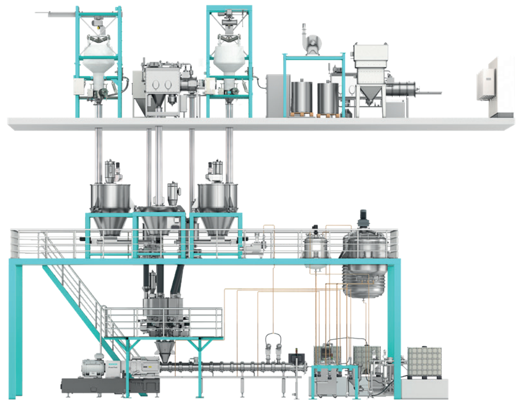

- > 10 years of process know-how in the LIB industry and > 70 continuous LIB mixing lines in operation from lab to giga factory scale
- Proven for the conventional slurry process and ready for future manufacturing technologies such as the dry electrode process

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BÜHLER

POSTER SESSION I Day 1

Electrode and cell production: Slurry processing

SP_1.1 Effects on Gr/SiOx blend electrodes based on batch and continuous processing
Anna Gerlitz, University of Münster I MEET

SP_1.2 Validation of different process routes for Si-based anodes using nature inspired polydopamine
Jingyu Xie, Landshut University of Applied Sciences I TZ

Electrode and cell production: Coating and drying

CAD_1.1 Prediction of coating defects in simultaneous two-layer slot-die coating by numerical and empirical models
Alexander Hoffmann, KIT I TFT

CAD_1.2 Quantitative Analysis of Energy Saving Potential of Induction Drying for Lithium-Ion Battery Cell Production
Chao Zhang, TU Braunschweig I IWF

CAD_1.3 Developing Eco-Friendly Binder Materials for Cathodes of Li-Sulfur Batteries
Felix Hahnewald, Kiel University I Functional Nanomaterials

CAD_1.4 Continuous extrusion coating of battery electrodes: Advances in process development and pilot-scale scaling
Granit Jashari, Fraunhofer IKTS

CAD_1.5 Towards an energy- and cost-efficient battery electrode production – Experimental insights to the drying behavior of solvent-reduced granule-based systems
Kevin Ly, KIT I TFT

CAD_1.6 Calendering Study for Optimized Energy Consumption
Luca Schneider, Leclanché GmbH

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Annika Völp, Thermo Fisher Scientific

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Oliver Fitz, Fraunhofer ISE

DC_1.3 Strategic evaluation, general principles and process advantages of semi-dry electrode production
Finn Reinkensmeyer, TU Braunschweig I iPAT

DC_1.4 The influence of different types of graphite on dry processed lithium-ion battery anodes
Franziska Beverborg, TU Braunschweig I iPAT

DC_1.5 Effect of stress variation on dry processed granules via extrusion: Impact on powder properties and film formation characteristics
Julius Gerk, TU Braunschweig I iPAT

DC_1.6 Dry transfer electrode coating- DRYtraec® R&D platform and innovation module for preparing the transfer into industrial scale
Christian Girsule, Fraunhofer IWS

Electrode and cell production: Cell assembly

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Fatjon Maxharraj, Fraunhofer IKTS

Electrode, cells and systems analytics and applications: Diagnostics during production- and use-phase

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Alexandra Burger, Fraunhofer ISIT

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Michael Stalder, Berner Fachhochschule I I3S

DDP_1.3 Impact of Sodium Carboxymethylcellulose Binder on the Performance of Lithium-Ion-Batteries
Noah Keim, KIT I IAM-ESS

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Julia Gandert, KIT I TVT

Electrode, cells and systems analytics and applications: Battery production 4.0, modelling, simulation and digital twin

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Aleksandra Naumann, TU Braunschweig I IWF

BPM_1.2 Fast Predictive Modeling of Lithium-Ion Electrode Wetting Using a Cellular Automaton Approach
Benjamin Schumann, TU Braunschweig I IWF

BPM_1.3 Methodologies for scaling machine parameters to simulate SSB production lines
Felix Buck, Fraunhofer IST

BPM_1.4 Macroscopic Simulation of Electrolyte Wetting in Prismatic Lithium-Ion Batteries
Michael Hinkers, Fraunhofer FFB

BPM_1.5 Traceability in Continuous Mixing Process in Battery Cell Production
Simon Otte, KIT

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Sylvain Gouttebroze, SINTEF Industry

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Marc Kissling, Fraunhofer ISE

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Benedict Ingendoh, RWTH Aachen University I PEM

MDP_1.2 Investigation of Polyacrylonitrile-Derived Multiple Carbon Shell Composites for Silicon-Based Anodes in Lithium-Ion Batteries
Chinmay Bapat, Fraunhofer ISE

MDP_1.3 A Scalable Approach to Prelithiation of Silicon Anodes: Continuous Process and In-Line Quality Control via Spectroscopic Analysis
Hyunsang Joo, Helmholtz-Institute Münster

POSTER SESSION I Day 1

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Svenja Weber, Fraunhofer IST

Development and production of innovative and next-generation batteries: Solid state electrolytes and batteries

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Andreas Twyhues, Fraunhofer IST

SSB_1.2 Experimental analysis of the stacking behavior of PEO-based composite cathode sheets
Sebastian Schabel, KIT

SSB_1.3 Experimental study on jet-based direct mixing method for the production of solid-state battery cathodes
Joscha Witte, University of Wuppertal I Institute of Particle Technology

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Anja Rajic, TU Braunschweig I ifs

Recycling & Sustainability: (Direct) recycling and resynthesis

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Felix Frobart, TU Braunschweig I iPAT

DRR_1.2 Investigation on cutting techniques for the automated dismantling of battery systems
Malte Mund, TU Braunschweig I ifs

DRR_1.3 Mechanical Characterization of End-of-Life Battery Cell Electrodes by Means of a Modular Disassembly Setup
Sebastian Henschel, KIT

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Sandra Boekhoff, TU Braunschweig I iPAT

Recycling & Sustainability: Circular economy, battery supply chains and factory designs

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Engin Alkan, Pomega Enerji Depolama Teknolojileri A.S.

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Rebekka Tien, University of Münster I MEET

SP_2.2 Influence of different blending procedures for cathode slurry preparation on the performance of lithium-sulfur pouch cells
Ralf Schmidt, Fraunhofer IWS

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Vinzenz Göken, University of Münster I MEET

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Florian Hermann, Precitec GmbH & Co. KG

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Johannes Dörr, KIT

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June Blanco, CIC energiGUNE

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Pirmin Koch, KIT

DC_2.3 Influence of electrode density on the characteristics and electrochemical performance of dry-coated NMC811 cathodes
Svenja Schreiber, TU Braunschweig I iPAT

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Volker Lewandowski, Fraunhofer FFB

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Electrode, cells and systems analytics and applications: Diagnostics during production- and use-phase

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DDP_2.2 Estimation of cell aging through spatially resolved irreversible expansion measurement at high charging rates
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DDP_2.3 On the effect of calendering pressure on morphological properties of graphite anode samples
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POSTER SESSION I Day 2

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Xukuan Xu, Aschaffenburg University of Applied Sciences

BPM_2.2 Digital shadowing in industrial electrode coating: Preparing process parameter prediction
David Becker-Koch, Center for Solar Energy and Hydrogen Research Baden-Württemberg

BPM_2.3 Simulation of the electrolyte wetting process: physical model and parametrization approach
Jochen Zausch, Fraunhofer ITWM

BPM_2.4 Prediction of cell life and failure analysis in virtual environment
Luke Hu, Electroder GmbH

BPM_2.5 In-line Electrode Homogeneity Assurance-Insights from HighPrecision Edge Monitoring in LIB Manufacturing
Muhammad Momotazul Islam, Fraunhofer IKTS

BPM_2.6 Rethinking Equipment Assessment: Leveraging TCO Analysis for Cost-Effective and Sustainable Battery Manufacturing to Reduce Production Costs
Noah Rieple, P3 automotive GmbH

Electrode, cells and systems analytics and applications: Battery safety

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Sicong Deng, RWTH Aachen University I PEM

Development and production of innovative and next-generation batteries: Material development and usage of innovative materials

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Franziska Jach, Fraunhofer IISB

MDP_2.2 Green method for the synthesis of biobased carbon from miscanthus X gigantheus for Lithium ion batteries
Fabisch Mutinda Kilonzi, TU Braunschweig, iPAT

MDP_2.3 Sodium ion Battery as Next Generation Battery Technology: Investigation of Slurry and Manufacturing characteristics of NMO as a Promising Cathode Material
Kriss Kevin Kasten, TU Braunschweig I iPAT

MDP_2.4 Scalable anodes for sulphide-based solid-state batteries
Daniel Gundlach, TU Braunschweig I iPAT

MDP_2.5 High-energy-density batteries enabled by high mass loading of cathodes via UCC and electrode architecture engineering
Aldo Girimonte, CTO Novac S.r.l.

Development and production of innovative and next-generation batteries: Solid state electrolytes and batteries

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Santiago Navarro, TUM School of Engineering and Design

SSB_2.2 Hybrid electrolytes for solid-state lithium-sulfur batteries
Sharif Haidar, TU Braunschweig I iPAT

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Frederieke Langer, Fraunhofer IFAM

SSB_2.4 Mechanical modeling of halide electrolyte-based battery components for AL-solid-state batteries using DEM
Cerun Alex Varkey, Fraunhofer IST

SSB_2.5 Electrode Manufacturing Processes for Solid-State Batteries with Sulfidic Electrolytes
Lajos Groffmann, Fraunhofer IST

Recycling & Sustainability: Material mining and synthesis

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Maximilian Rolinck, TU Braunschweig IIWF

Recycling & Sustainability: (Direct) recycling and resynthesis

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Sebastian Melzig, Fraunhofer IST

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Farzaneh Alipour, Fraunhofer IKTS

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Jannik Born, TU Braunschweig I iPAT

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Nora Schelte, Fraunhofer IPT

BSC_2.2 Sustainable Battery Recycling and Lifecycle Management: Insights from the greenBatt Cluster
Edith Uhlig, TU Braunschweig I IWF

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LABORATORY MILLS TO PREPARE SAMPLES OF BATTERY RECYCLING FRACTIONS

In a battery recycling process, the exhausted batteries are separated into different material fractions. To evaluate the efficiency of a recycling process and to investigate the purity of each fraction, samples are homogenized and analyzed. The market value of the black mass, for example, depends on its content of valuable metals, like lithium or cobalt. Black mass can be homogenized in a ball mill. To avoid cross contamination, metallic or ceramic grinding tools should be chosen, respectively. The polymeric material fraction and metallic foils are first pre-cut with a cutting mill and then pulverized, usually at cryogenic temperatures, for example with RETSCH's CryoMill.

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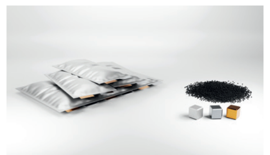


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POSTER ABSTRACTS I Day 1

Electrode and cell production: Slurry processing

Effects on Gr/SiOx blend electrodes based on batch and continuous processing

Anna Gerlitz
University of Münster I MEET

To meet the demand of high energy storage cell chemistries not only the use of high voltage cathode active materials has increased but also the use of anode active materials or composites with greater specific capacities has intensified. Especially silicon-based active materials can be used to realize increased specific capacities for negative electrodes.1 However, with the implementation of Si or Si-oxides (SiOx) issues such as contact loss, cracking, and delamination of the active material from the current collector due to volume changes during (de)lithiation can lead to limited performance and short cycle life as well as undesirable reactions of the Si composite leading to gassing.2,3 To circumvent this, a deeper look into the engineering and processing of these electrodes is necessary. Measures such as using nanoparticle sized Si, fabricating composites like core/shell-particles, using graphite in blend electrodes with Si compounds such as SiOx have been reported.1,4 For a thorough understanding, it is important to study the influence and behavior of Si-based materials on the production process on different scales. From beneficial Si amounts to degradation of the active materials during processing, many factors have to be further investigated. The presented work focusses on methods of processing Si-based negative electrodes to obtain a high energy setup. The study includes production from a laboratory batch scale to small industrial continuous scale and comparative testing of the fabricated electrodes. By doing so, extensive insight

Validation of different process routes for Si-based anodes using nature inspired polydopamine

Jingyu Xie
Landshut University of Applied Sciences

A novel idea for the manufacturing of silicon (Si)-based electrodes is inspired by polydopamine (PDA), a natural material which is found in mussel adhesive protein. PDA as binder additive in electrodes has proven a higher adhesion and led to the improvement of the electrochemical performance. [1-2] Moreover, PDA carbonisation has succeeded in obtaining a high electrical conductivity up to 1.2 x 10 5 S/m. [3] Thus, the concept of combining these two inherent advantages of PDA with Si-based anodes is not only interesting, but also beneficial. Previous investigations have shown that it is possible to manufacture functional Si-PDA electrode in a controlled fashion. In particular, with only partial carbonisation at 300°C, 500°C and 800°C after electrode coating, one part of the PDA maintains its characteristics as binder. Simultaneously, another part of the PDA reduces to carbonaceous material to improve the electrical conductivity in the electrode. The lithiation capacity in the first cycle reached the theoretical capacity (above 3000 mAh/g). Moreover, the residual capacity after 100 cycles at 0.1C was up to 2300 mAh/g. In the actual state, the produced electrodes still have some drawbacks related to their manufacturing, which limit the cell reproducibility, and there is still potential for improving the electrochemical performance. Since the polymerisation parameters have strong influence on the polymer structures and properties, the electrode manufacturing procedure can be done in different paths. One path is finishing the polymerisation first before adding Si active materials. The second path is mixing Si active material before the self-polymerisation step, and control the further process from there. With this route, the particle distribution of PDA and Si may be more homogeneous. The third path combines the above two concepts. The pre-polymerised PDA possess a more complex structure and higher molecular weight, while the post-polymerised PDA exhibit a simpler structure and lower molecular weight. The produced electrodes based on above paths have different structures, and hence exhibit different electrochemical characteristics after carbonisation.

Electrode and cell production: Coating and drying

Prediction of coating defects in simultaneous two-layer slot-die coating by numerical and empirical models

Alexander Hoffmann
Karlsruhe Institute of Technology (KIT) I Thin Film Technology (TFT)

Simultaneous multilayer slot-die deposition has significant potential for improving battery electrode 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. 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 to an unstable coating bead, fluid-fluid interactions and vortices, that can lead to intermixing or wetting issues, are investigated systematically. The investigation also 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.

Quantitative Analysis of Energy Saving Potential of Induction Drying for Lithium-Ion Battery Cell Production

Chao Zhang
TU Braunschweig | Institute of Machine Tools and Production Technology (IWF)

Lithium-ion batteries are a leading energy storage technology due to their high energy density and long cycle life. However, battery cell production involves energy-intensive processes, with electrode coating and drying being significant energy hotspots. Traditional methods such as convective or infrared drying consume significant energy and produce high greenhouse gas emissions, highlighting the need for innovative drying techniques. Induction drying has recently attracted attention for its efficient heat generation, showing potential to reduce energy use and environmental impact. This poster reviews the latest advances in induction drying technology and presents a case study from CircularLab Braunschweig (CLB) to quantify its energy-saving potential. By analyzing temperature curves of the electrode surface along the dryer section, the study compares the power demand of induction drying with conventional convective drying. Results indicate theoretical energy and CO2 savings per cell of 13.14% for induction drying compared to pure convective drying, reducing energy consumption from 24.19 to 21 Wh and CO2 emissions from 10.5 to 9.1 g CO2-eq. However, when accounting for the energy consumed by the induction cooling unit, energy consumption per cell increases by 12.30% to 27.16 Wh, and CO2 emissions rise to 11.8 g CO2-eq. Based on these results, this work discusses the challenges, research gaps, and future prospects of induction drying, suggesting that addressing these issues could improve production efficiency and reduce the environmental footprint of lithium-ion batteries.

Developing Eco-Friendly Binder Materials for Cathodes of Li-Sulfur Batteries

Felix Hahnewald
Kiel University I Functional Nanomaterials

Sulfur cathodes are known for their high theoretical energy density, however, challenges such as polysulfide dissolution and poor mechanical stability of electrodes hinder their practical application. The utilization of binders as a controlling parameter is crucial in achieving high-performance batteries through electrode adhesion and microstructure design. This study investigates the fabrication and characterization of various carbon-sulfur (50 wt.% sulfur) cathodes with different binder materials, including: carboxymethyl cellulose in combination with styrene-butadiene rubber (CMC+SBR), lithium polyacrylate (LiPAA), acrylic acid modified cellulose (AAMC), polyvinylidene fluoride (PVDF), polyethylene oxide (PEO), paired with surface-treated aluminum (Al) foils as a current collector (CC) to improve the mechanical stability (adhesion), polysulfide immobilization and electrochemical performance of eco-friendly sulfur cathodes with enhanced sulfur loading. The structured Al CCs improved adhesion between the mass load and the Al surface, resulting in overall higher electrode stability. Additionally, creating finer crack structures, enhanced cycling stability, and rate capability of battery cells due to better electrolyte diffusion. Various binder materials, including water-soluble polymers, were tested for their ability to maintain electrode cohesion/adhesion and improve the battery performance. Employing different binders resulted in different mixing behaviors and required different solvent/solid contents for making pastes. The cathodes using binders with high mechanical stability, such as CMC+SBR and LiPAA, showed superior performance in terms of mechanical and electrochemical characterization. Using water-soluble binders in combination with structured Al foils allowed capacities over 1000 mAh g-1 and up to 30 % more capacity retention after 250 cycles and up to 60 % more capacity retention at elevated C-rates from 0.1 C to 2 C than for electrodes made with PVDF as a binder. The possibility of using water-soluble binders as an alternative to the commonly used toxic NMP solvent-based binders was demonstrated. All in all, the mechanical interlocking of the surface structured Al foils together with using water-based binders enables the fabrication of electrodes with high mass loading containing many cracks which can be used for making high-performance electrodes for Li- and Na-ion batteries.

Continuous extrusion coating of battery electrodes: Advances in process development and pilot-scale scaling

Granit Jashari
Fraunhofer Institute for Ceramic Technologies and Systems IKTS

Lithium-ion batteries (LIBs) are the predominant battery type in the consumer sector and are increasingly being used in motor vehicles and stationary storage applications. To further penetrate these markets, cell costs must be further reduced, which requires the development of new processes and cell concepts. Drying processes consume significant amounts of energy, which is associated with considerable costs and environmental impact. An effective strategy to mitigate these problems is to increase the solids content of the materials to be dried, thereby reducing energy consumption. The development of processes for continuous direct extrusion coating of battery electrodes with high solids content and their scaling up to pilot production are therefore important steps to advance the production of high-performance batteries1-2. Our recent research has successfully demonstrated the production of directly extruded electrodes, reducing the solvent content in cathode and anode production by up to 10 % and 30 % respectively compared to conventional wet film casting processes3. This reduction in solvent content leads to lower energy consumption during the drying process. In this study, we investigated the coating of cathode and anode paste formulations with high solids content, specifically above 80 wt% for cathodes and 65 wt% for anodes, using a twin-screw extruder. Different binder materials were investigated to achieve an even distribution of the binder in the paste and to improve the adhesion strength of the coating. For anode production, we investigated carboxymethyl cellulose with different molecular weights and polyacrylic acid. For cathode production, we investigated a mixed binder system of PVDF/additive in NMP with different ratios as well as water-based binders. Based on the different formulations used, rate capability tests of the produced electrodes with different area capacities were performed in stamping cells and the results are discussed in detail. Overall, this low-solvent process combines several steps of electrode production, including mixing, coating and drying. This streamlined process not only reduces complexity, but also leads to significant cost savings in machine investment and energy consumption.

Towards an energy- and cost-efficient battery electrode production – Experimental insights to the drying behavior of solvent-reduced granule-based systems

Kevin Ly
Karlsruhe Institute of Technology (KIT) I Thin Film Technology (TFT)

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. 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.

Calendering Study for Optimized Energy Consumption

Luca Schneider
Leclanché GmbH

The content of this poster is one of the results from the EU-founded project called BATMACHINE. The core vision of the BATMACHINE project is centered on strengthening Europe’s battery cell industrial manufacturing value chain by developing new battery cell manufacturing machinery. This is done whilst giving priority to minimizing the energy for cells production, enhancing plant efficiency rates and integrating intelligent control processes to reduce scrap. BATMACHINE will develop and implement an optimized and energy-efficient process chain considering slurry mixing, coating, drying and calendering. The calender developed in the BATMACHINE will be used at Leclanché's site in Germany to study the influence of machine parameters on the novel electrode, the electrochemical performance and the impact on the energy consumption of the calender machine.

Electrode and cell production: Dry coating

Continuous dry processing of NMC cathodes with PFAS-free binder and characterization of its visco-elasticity and adhesion

Annika Völp
Thermo Fisher Scientific

The growing global demand for affordable electromobility requires further optimization of the battery technology used, as this is still one of the main cost factors in the production of an electric car. One approach is the solvent-free production of cathode materials in order to eliminate the energy-intensive drying step during production. The use of the established binders polyvinylidene fluoride (PVDF) and polytetrafluoroethylene (PTFE) for dry processing is being called into question by a planned EU restriction on per- and polyfluoroalkyl substances (PFAS). Polypropylene carbonate (PPC) has recently been tested as a PFAS-free binder alternative for LFP cathodes mixed in small batches.1 PPC acts as an amorphous adhesive with a low glass transition temperature of about 40 °C, is considered environmentally friendly due to its fast decomposition and has a higher lithium-ion conductivity than PVDF. We tested the suitability of PPC for continuous, solvent-free processing of NMC cathodes using a laboratory twin-screw extruder as a continuous mixer. The cathode mixtures were formed into free-standing cathode foils and laminated onto the current collector using a calender. The process parameters and the screw configuration of the twin-screw extruder must be adapted to the respective binder system in order to achieve a homogeneous distribution of the binder, as can be seen in the SEM images. The mechanical performance of the cathode films was tested using oscillatory rheology to characterize viscoelasticity and peel testing to evaluate adhesion to the current collector. The results are compared with those of dry-processed cathodes with state-of-the-art PVDF and PTFE grades.

PROCESSING OF ACTIVE MATERIAL FOR THICK ELECTRODES IN SODIUM-ION BATTERIES FOR STATIONARY APPLICATIONS

Dr. Oliver Fitz

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Sodium-ion batteries (SIBs) have recently attracted rising attention due to the use of highly available and globally evenly distributed raw materials, potential low cost, similarity to Lithium-ion-battery (LIB) chemistries, and convincing performance.[1] The optimization of the manufacturing process of SIBs can further increase economic and environmental competitiveness with modern LiFePO4-based batteries, e.g., by transitioning to low solvent or solvent-free processes. Additionally, the possibility of such processes to obtain an increase of the electrode thickness can be an important opportunity for increased energy densities of SIBs, reducing the share of components that do not directly contribute to the charge storage process. The areal loading of most commercial cells does typically not exceed 3.5 mAh·cm-2, which is usually well below 20 mg·cm-2, even for NMC-based cathode materials. This is due to the rising mechanical stress of high areal loadings obtained in slurry processes upon drying of the wet film.[2] Especially for stationary battery applications the use of thicker electrodes is very suitable, as diffusion-limited power performance is not necessarily an issue at such scale (or can be addressed by combining SIBs with power sources such as super caps). This poster provides insights into the feasibility of using (semi)-dry-processed thick electrodes in SIBs. The resulting electrode material is hot-pressed, resulting in designable electrode structures on a millimeter scale, with high porosity, good structural stability, ultra-high areal loadings and energy density, and good contact with the current collector foil. The electrode thickness is systematically varied up to 1000 µm and compared with slurry-based reference electrodes. For electrochemical, optical, and structural characterization, the electrodes are characterized in full-cell setups based on Nickel-free layered transition metal oxides and hard carbons as cathode and anode materials, respectively. Based on a careful investigation of the influence of the thickness and calendaring pressure on the rate capability, the results show that such thick electrodes with very high areal capacity und good performance can be successfully produced using a hot-pressing process.

Strategic evaluation, general principles and process advantages of semi-dry electrode production

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The reduction of solvent content in lithium-ion battery processing is a key factor for lowering both the costs and the environmental impact of cell production. Therefore, various methods, ranging from completely solvent-free to semi-dry processing of battery electrodes, have been developed in recent years. A broad application of these methods is rather challenging because many approaches rely on complex and discontinuous processes that are often only applicable to a very specific set of parameters and materials. In contrast, the developed semi-dry method as illustrated in Figure 1 has been established as a continuous, scalable process suitable for a wide range of applications in anode and cathode production. Furthermore, this approach enables the integration of the coating, drying and calendering steps from the conventional wet coating process into single production step, thereby reducing the footprint of the production plant. This also contributes to the high energy efficiency of the process shown in Figure 2, where a significant reduction in overall energy consumption can be observed compared to the conventional wet coating process. Moreover, the low solvent content prevents the segregation of inactive materials of the electrode during drying. In the development of the semi-dry process for electrode production, comprehensive study of process parameters in the extrusion and calendering steps has been conducted, revealing direct correlations to electrode quality. In particular, from these studies, a saturation degree for granules has been defined to quantify the processability of different material systems for future applications.

The influence of different types of graphite on dry processed lithium-ion battery anodes

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In terms of increasing depletion of fossil fuels and of global climate change, power generation is shifting to renewable energy sources. The established manufacturing process of wet film coating for lithium- ion batteries includes a drying step that requires a high energy input for solvent recovery and drying. Dry coating is an excellent way to avoid the use of solvents and the drying step and to improve the energy saving potential. The dry mixing of powdered electrode components (active material, conductive additive, PTFE binder) represents the first step in this coating process. A uniform distribution, arrangement and first fibrillation of the binder among the active materials and conductive additives, as well as an ideal powder flowability for precise dosing and film formation is the aim of the first step. In the following step, the film formation by calendering, the shear forces in the calender gap cause further fibrillation of the binder and thus increase the cohesion to form a stable film. In order to investigate the influence of different graphite materials on the process-structure-property relationship, different types of graphite based mixtures for dry coating were produced in a batch mixing process with similar process parameters. At the same time, the influence of mixing temperature in the processing of the fibrillated powders were determined. The resulting process-structure-property relationships between the batch mixing process and the film formation process by calendering were evaluated using various powder characterization methods. The results showed that different graphite types in the same batch process affect the particle size distribution and flow coefficient (Fig. 1). Flake-shaped graphite led to thicker films under the same calendering process, which significantly affects the resulting electrochemical performance. Furthermore, the discussion will delve deeper into how different graphite structures influence powder properties, electrode characteristics and electrochemical cell performance.

Effect of stress variation on dry processed granules via extrusion: Impact on powder properties and film formation characteristics

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The Lithium-ion batteries are a key component of technological progress and the green transition of the future. With the constantly increasing demand of batteries, a variety of challenges arises regarding sustainable and economical production. The conventional electrode production relies on volatile organic solvents, the elimination of which can improve economic efficiency, sustainability, and reduce the carbon footprint of battery manufacturing. Solvent-free production of battery electrodes offers a pathway to achieve these goals, with the calender-based dry coating process emerging as one of the most promising methods. The dry coating process simplifies electrode production to dry mixing of the electrode components, film formation and lamination. As the dry mixing is at the beginning of the process chain, it has a significant impact on the performance of the resulting dry battery electrodes. However, mixing not only influences electrode performance but also can alter the processability of film formation due to different powder properties. Therefore, it is essential to control the macroscopic and microscopic powder properties as required. To modify the macro- and microscopic structure of the powder, raw materials are stressed with different levels of mechanical and thermal stress. Specially, variations in mechanical stress can significantly influence the distribution and structure of the binder, which holds together the active material and conductive additive in the electrode. The powder structures resulting from the varied continuous mixing process via twin-screw extrusion are assessed using diverse powder characterization methods (e.g. flow coefficient, powder conductivity, compressibility and particle size distribution). Sieving is employed to achieve the fragmentation of the granules into specific particle size distributions. Subsequently, studies are conducted using the different sieve fractions to investigate their influence on calender feeding and film formation. The results show a small homogeneous particle size distribution leads to films with less edge chipping of the calendared films. Apart from that, a bigger particle size results in thinner films.

Dry transfer electrode coating - DRYtraec® R&D platform and innovation module for preparing the transfer into industrial scale

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Fraunhofer IWS

In the quest for advanced energy storage solutions, dry electrode manufacturing has emerged as a promising technology for lithium-ion and solid-state batteries. This innovative approach addresses the environmental and economic drawbacks of traditional wet-chemical methods, which rely on toxic solvents and energy-intensive drying processes. The DRYtraec® process of the IWS can be used to approach this question. The Fraunhofer IWS and the Fraunhofer FFB are cooperating to further develop the technological readiness level of the process for Lithium-ion cathode and anode. The path of scaling-up, results of a coating campaign with speeds of up to 10 m/min are presented and results from half-cell tests are shown.

Electrode and cell production: Cell assembly

Multilayer Electrodes with Graded Design for Enhanced Energy and Power Density in LIB-s

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Multilayer electrodes (electrodes composed of 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 electrodes is their ability to mitigate the specific limitations that typically occur in singlelayer cathodes. Using multilayer electrodes with graded design both energy and power density can be enhanced. To improve the power density, it is beneficial to have a higher porosity near the separator which enhances transport rate, while maintaining a greater amount of active material towards the current collector will help retain a higher energy capability.[2] Here in we report manufacturing of bilayer cathodes with graded porosity (Fig. 1.) and its impact on electrode properties. Electrodes with different mass loadings are manufactured while keeping constant parameters such mass ratio between the first and second layer and overall porosity. To evaluate the effect of a bi-layer cathode featuring a graded porosity design, a single-layer cathode with identical overall parameters (porosity, thickness, and mass loading) is also produced for comparative analysis. As cathode material NCM622 with PVDF binder is used. Processed bi-layer electrodes had a porosity of 20% for the bottom layer and 40% for the top layer, with an overall porosity of 30%. Electrodes with different areal capacities 4 mAh/cm2, 7 mAh/cm2 and 10 mAh/cm2 are investigated. For electrode characterization, methods such as electrochemical impedance spectroscopy (EIS) for ionic resistance, galvanostatic techniques for rate tests, and electronic conductivity tests are utilized. From these measurements, we observed a significant impact on electrode properties resulting from the grading. The bi-layer electrodes exhibited lower tortuosity and enhanced rate capability when compared to single layer electrodes. Using Ragone calculations, we found that at high power densities (600 W/kg), an increase of approximately 35% in energy density from 110 Wh/kg to 154 Wh/kg can be achieved only by using graded electrodes, as illustrated in Fig. 2

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Electrode, cells and systems analytics and applications: Diagnostics during production- and use-phase

Smart Battery Cells – In-Operando Monitoring of LIB by Integrated Sensors

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Lithium-ion batteries (LIB) are widely used due to their high energy and power density. Ensuring their safety and continuous performance under various conditions is crucial. In-operando monitoring of internal parameters such as temperature, state of charge (SOC), and state of health (SOH) is essential, but typical battery management systems focus on external parameters while neglecting internal changes. Our work addresses this gap by integrating sensors directly into LIBs to monitor internal parameters. In particular, we focus on internal temperature changes using integrated glass fibres or temperature sensors, and on individual electrode potentials using reference electrodes. Both internal temperature and electrode potentials are critical for battery safety and health. Monitoring internal temperature includes both average values and distribution within the cell, which is achieved by placing sensors at specific positions. This allows for direct observation of temperature changes during operation. Additionally, monitoring of individual electrode potentials provides insights into safety-critical phenomena that cannot be detected by measuring only the voltage difference between the anode and cathode. For instance, reference electrodes can detect Li-plating at an early stage. Our sensor integration approach enables real-time monitoring of temperature and electrode potentials, significantly enhancing the ability to detect safety-critical states and improving the safety of LIBs. This contribution will provide insight into some of ISIT's technological approaches to in-operando monitoring of LIBs.

Sub-pixel particle detection on electrode surfaces

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In this contribution we propose a method to detect small particles on electrode surfaces. The method uses a state-of-the-art line scan camera, and by appropriate lighting the particles can be made to appear larger on the camera image than their physical size. The approach is capable of detecting particles as small as 5 m with an image resolution of about 6.5 m/pixel. With our experimental setup we have demonstrated that particles in the range of 5 m can be detected on a 10 cm wide electrode using a 16k pixel line scan camera. Further we show that the particles can be reliably located and measured by the image processing algorithms. Using the color information of the camera even the particle material can be identified, which can be an important information to assess the harmfulness of a particle.

Impact of Sodium Carboxymethylcellulose Binder on the Performance of Lithium-Ion-Batteries

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To change the solvent in LIB electrodes to water, a water-based polymer binder has to replace the current PVdF binder. This led to Sodium Carboxymethylcellulose (NaCMC) being introduced as a water-soluble binder for LIBs. Due to NaCMC creating a weak connection with the current collector, usually, another additive like SBR rubber is usually added to increase adhesion. Nevertheless, NaCMC dominates the properties of the slurry and influences the structure of the final electrode decisively. Combining the multitude of functionalities of the NaCMC with it being produced from the most abundant polymer in the world, it creates a highly attractive binder, also from an industrial point of view. However, despite widespread use, there is only limited knowledge on how the NaCMC influences key battery properties and battery performance.1 The objective of this research is to provide valuable insights into optimizing the composition of lithium-ion battery electrodes for enhanced energy storage and cycling stability, based on a better understanding of the influence of NaCMC. Especially, the influence of varying properties of the NaCMC, like degree of substitution and molecular weight are explained in more detail, which were analysed via adhesion strength testing, Karl-Fischer titration, electrical resistance and potentiostatic cycling. Finally, the influence of the varying NaCMC properties on the battery performance and SEI formation was investigated with post-mortem liquid NMR.

Comparison of Measurement Techniques for the Determination of the Effective Thermal Conductivity of Battery Electrodes

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Several researchers have recently reported that the temperature level and thermal gradients within lithium-ion batteries have a major impact on the performance and aging. To model the thermal behavior and predict the temperature distribution within these cells, it is crucial to have reliable data for the thermal transport properties. For an optimization of these properties, it is of advantage to evaluate them already during the production stage. While the density and specific heat capacity are relatively easy to determine via differential scanning calorimetry and gas pycnometry, respectively, and only vary with the composition of the electrodes, the determination of the thermal conductivity poses challenges. Commonly used methods are the laser flash analysis (LFA) and guarded hot plate method (GHP) which, however, showed large deviations from each other for the electrodes investigated in literature. For a more detailed quantification and understanding of the differences between the two methods (LFA and GHP), we conducted measurements on the same batch of single-sided coated electrode samples with both methods. Our results confirm the significantly higher values in thermal conductivity obtained by the laser flash analysis. While the values obtained by the GHP method can be impaired by contact resistances within the measurement rig, the evaluation of LFA measurements is complex and factors potentially contributing to errors are not yet understood. Still, the LFA is a popular method for rapid estimations due to its seemingly easy application and the commercial availability of measuring devices. Moreover, concepts have emerged to use LFA or similar approaches like the front face technique or infra-red thermography for in-line diagnostics and the detection of inhomogeneities and defects. Thus, it would be beneficial to gain understanding of the limitations for the further application.
In this context, we extended our study with numerical simulations of the LFA measurements. This way, we could quantify the weight of different boundary conditions for the thermal conductivity resulting from the experiment and determine how they contribute to the high thermal conductivity values in the measurements. Furthermore, there are different evaluation methods for laser flash experiments. We considered different fitting approaches and assessed their applicability, keeping in mind the highly anisotropic character of the electrode samples due to the constitution of different layers and the porous coating with a considerable surface roughness.

Electrode, cells and systems analytics and applications: Battery production 4.0, modelling, simulation and digital twin

Data-driven Control System for Circular Production of Battery Cells

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One of the major challenges in battery production is the high scrap rate between 5 and 30%, depending on the scale of production, and the associated high demand for material and energy. Considering future-oriented trends such as circulation factories, it is evident that recycling processes play an important role in increasing production efficiency. Consequently, recycling must be considered in production and the combination of both aspects within one circulation factory would facilitate the sharing of resources from material and energy to expert knowledge. This might lead to a higher resource effectiveness and a better overview as well as control of material flows. From a control perspective, a combined approach that offers more transparency in both process chains and their interaction with each other can offer new opportunities such as a data-driven feedforward control approach using the process parameters and intermediate product features to predict the quality of the cell enabling an early detection of rejected parts or adaption of process parameters to prevent those. Aside from the chances, different challenges need to be considered. The scrap from production is variable in its amount and potentially its composition (e.g., contamination or material degradation over multiple loops). This means there is a need for evaluation of the remaining quality of the scrap material as well as an investigation of what happens when the amount and quality of secondary material fluctuates. This work proposes a cyber-physical control system to address the challenges but also the chances provided by a combined approach for both production and recycling. Boundaries and limitations depending on the scale of the factory are shown highlighting the main decision points of such an approach

Fast Predictive Modeling of Lithium-Ion Electrode Wetting Using a Cellular Automaton Approach

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In response to the increasing demand due to the electrification of the mobility sector, scaling up production for lithium-ion batteries is essential. In this context, given the high proportion of material costs in production costs, developing a process chain with minimal reject rates is considered a key objective. One approach for avoiding rejects is to enable process chains to compensate for quality defects during previous processes. As the final process before for- mation, with dependencies on geometric and material parameters, the electrolyte filling process has the potential to compensate for quality defects from upstream processes such as electrode production, stacking, and housing. To achieve this, it is necessary to make predictions about the spatial wetting behavior of individual battery cells in inline-capable simulations. Common models for spatial descriptions of wetting behavior, such as Lattice-Boltzmann models, cannot meet the required runtime limitations when simulating entire electrodes. While machine learning models can be used for faster simulations, they rely on the time-consuming and costly creation of a database. However, for one-dimensional considerations, analytical models such as the Lucas-Washburn equation are sufficiently performant and do not rely on extensive data collection efforts. To enable the spatial wetting predictions using these models, a modeling framework was developed. This framework allows one-dimensional descriptions of wetting behavior to be applied to discrete voxels in a cellular automaton. The flow term of the one-dimensional (Lucas-Washburn) equation is divided into several direction-dependent components. Runtime is reduced without loss of information through a step-size control maintaining a constant propagation speed. The model is fine-tuned using real data by simulating conditions during wetting tests in a tensiometer. The resulting model, which implements the Lucas-Washburn equation for a two-dimensional representation of an NMC611 cathode, achieves runtimes under one minute and provides insights into wetting duration as a function of electrode geometry.

Methodologies for scaling machine parameters to simulate SSB production lines

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The aim of this work is to create a better data basis for simulating scalable solid-state battery (SSB) production lines. For this purpose, scale-up methodologies are identified and classified in order to select the most promising method in the context of data availability. The topic is particularly relevant as the simulation of the production of modern energy storage systems, such as solid-state batteries, requires a high degree of agility and flexibility in the planning of new or the expansion of existing production facilities due to the complex and dynamic research environment. In this context, discrete event simulation is an established tool to support planners and decision-makers in their respective considerations by quickly comparing different variants of possible production scenarios. However, a realistic simulation requires sufficient machine performance data in terms of completeness and accuracy for the respective scaling. This is currently a major challenge, as data sets are often incomplete or only available for systems on a laboratory scale due to e.g. reasons of confidentiality towards external parties. For this reason, data is often estimated based on the performance data for laboratory-scale systems using different scaling approaches without adequately considering the accuracy. In order to contribute to better data quality for simulation, the terminology of scaling is explained in the context of battery production. Further, possible methodologies are identified and classified according to data requirements and accuracy. Building up on this, the influence of the chosen methodology on the resulting machine parameters is demonstrated onto a SSB production process chain. One of the resulting findings is that in comparison to more complex calculation approaches, simple scale-up methodologies tend to overestimate the results to varying degrees depending on the specific parameter.

Macroscopic Simulation of Electrolyte Wetting in Prismatic Lithium-Ion Batteries

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In battery cell production, electrolyte filling is one of the most time-consuming steps, thus limiting the over-all throughput of cells being manufactured1. The process of electrolyte filling operatively comprises two subprocesses, particularly filling and wetting. While filling takes only between a few seconds and an hour depending on the cell format, wetting takes up to 24 hours. The long process time is needed to ensure complete and homogeneous wetting of all the pores in the separator and in the electrode structure, which is crucial for the performance and safety of the cell2. Taking into account the current development trends of producing larger battery cells formats particularly in the automotive sector the limitation in production capacity represented by electrolyte filling becomes even more critical due to the increase in wetting time3. Since electrolyte filling takes place in an opaque cell enclosure, analysis of the processes and corresponding mechanisms requires hugh experimental effort such as the use of ultrasound or X-ray measuring devices. As a result, the cause-effect relationships between process parameters or material choice and wetting duration are poorly understood4. Thus, simulative observation of electrolyte filling is a promising and powerful method that allows to gain insights in this hardly accessible process. Therefore, in this study the wetting process for large prismatic battery cells (300*100*30 mm) was studied in a simulation environment using the software "FLUID" provided by the Fraunhofer ITWM. To parameterize the simulation for the relevant materials (AL2O3-coated PE separator, graphite anode, NMC622 cathode, LP572 electrolyte), capillary rise experiments were carried out on a laboratory scale. Afterwards, a model was set up in "FLUID" to investigate the effect of crucial process parameters, for example pressure and pressure cycles, on the wetting behavior and duration. In addition to the material-specific simulation, this study also allows the derivation of a general methodology.

Traceability in Continuous Mixing Process in Battery Cell Production

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Karlsruhe Institute of Technology (KIT)

This study addresses the critical issue of traceability within the continuous mixing process, which is essential to maintain quality and ensure product consistency in battery manufacturing. Our research involved an extensive analysis of existing literature to identify key parameters and their interdependencies. A Design Structure Matrix (DSM) was constructed to analyze the influence of these parameters within the continuous mixing process, followed by a Pareto analysis to identify the parameters with the most significant influence. Key findings indicate that parameters such as solids content, agitator speed and specific energy input have a strong influence on the mixing process. In addition, parameters such as dynamic viscosity, sedimentation rate, and slurry homogeneity are influenced by multiple factors.

Semantic dataspace for battery production equipment

Dr. Sylvain Gouttebroze
SINTEF Industry

The digitalization of battery production in Europe is a critical advancement to establish a competitive industry value chain. As the demand for sustainable energy solutions grows, new materials, processes, and equipment are developed that requires fast optimization and production ramp-up. The integration of smart equipment and data space solutions is the key to unlock the potential of AI and big data analytics. BATMACHINE project is a Horizon Europe-funded initiative that aims to boost Europe's sustainable industrial battery cell manufacturing value chain by developing an optimised machinery with intelligent control processes to minimise costs, waste and energy consumption. To achieve that ambitious goal, a framework has been developed that integrates logger, controller, and a semantic dataspace. We will present the technical solution under development and compare with similar approaches developed in parallel [1,2]. The discussion will be mainly focused on the integration of semantic and how it is exploited to support multi-step process optimization.

Electrode, cells and systems analytics and applications: Cell Types, module and pack design and production

High Performance Cooling Concept for Battery Pouch Cells –Pouch Heat Pipes

Marc Kissling
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The use of heat pipes for the thermal management of batteries is being investigated in recent research [1-2] as a compromise between thermally less effective heat-conducting elements (such as compressible nonwovens) and cost- and weight-intensive direct liquid cooling. The idea presented here is to realize the cooling of pouch cells with the help of foil-pouch heat pipes, which are made of the same foil material. Fig.1. Pouch Heat Pipe (left), Battery Pouch Cell (right) The evaporation/condensation cycle of a heat pipe can achieve a better cooling performance than is possible with pure heat conduction (for example with a copper plate). The mechanically flexible foil container of the heat pipe is intended to provide the flexibility required for the thermal bonding of the pouch cell surfaces. Due to the presence of a vapor barrier (aluminum core) in pouch cell films, the same film material can be used for the heat pipe as is used for pouch cells and the chance of thermal stability is increased. The material redundancy offers cost reduction potential in production (e.g. use of the same tools for the deep-drawing process of the pouch cell and pouch heat pipe) and opens up the possibility of completely new cooling concepts (see Fig. 2). The planar shape of the pouch heat pipe promises more even cooling of the battery cells, which avoids hot spots and increases the service life of the cell. In addition, the film material as rolled goods and the closure of the film pouches via thermal sealing offer a high degree of freedom of shape, which allows easy adaptation to different cell geometries. Finally, there is potential for weight and cost reductions compared to conventional heat pipes that use metal as the container material.

Development and production of innovative and next-generation batteries: Material development and usage of innovative materials

Production of lithium-ion batteries with fabric-based current collectors

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Electrical energy storage systems play a decisive role in the success of the global energy transition. On the one hand, they are indispensable stationary storage systems in combination with renewable energies and, on the other, they are a basic prerequisite for the acceptance of electromobility. The driving goals in battery development include increasing the range of electric vehicles and reducing the cost of energy storage systems. This goes hand in hand with increasing the storage density and improving the service life and cycle stability of batteries. At the same time, it is very important to minimize the consumption of scarce or expensive materials and production costs. In line with these objectives, all battery components and production processes need to be further developed. Currently, copper and aluminum foils are used as current collectors in battery production. A promising approach to improving the quality and efficiency of batteries is the use of fabric-based current collectors. The substitution of metal foils with metallized fabrics leads to a considerable reduction in weight and thus to an increase in gravimetric energy density. The use of metallized fabrics instead of metal foils also enables a significant reduction in metal consumption. This study focuses on a critical process step for the production of fabric-based current collectors, the contacting process. The most relevant results are presented and discussed to derive conclusions for the production process of electrodes with a fabric-based current collector.

Investigation of Polyacrylonitrile-Derived Multiple Carbon Shell Composites for Silicon-Based Anodes in Lithium-Ion Batteries

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Silicon-based anodes are emerging as the most promising candidates for the next generation anode materials for lithium-ion batteries due to the nearly ten times larger theoretical specific capacity of silicon 3578 mAh·g-1 (for Li15Si4) compared to graphite (372 mAh·g-1) and a low working potential of 0.2–0.4 V vs. Li/Li+ 1,2. The challenges with silicon are the huge volume change during (de-)lithiation leading to particle pulverization, electrochemical milling, excessive SEI formation, and the associated phenomena ultimately resulting in a rapid capacity fade. This poster is based on our research that focuses on the processing and in-depth analysis of silicon-carbon (Si/C) composites with single and multiple carbon shells for use in lithium-ion battery anodes1. The primary objective was to enhance the electrical conductivity and cycling stability of these composites by embedding silicon particles within carbon shells, thereby minimizing direct solid electrolyte interphase (SEI) formation on the silicon surfaces. The composites were produced through a simple and scalable method involving the carbonization of polyacrylonitrile. We thoroughly examined the carbonization process and assessed the structural, physical, and electrochemical properties of the resulting Si/C composites. The comparison between single carbon shell (SCS) and multiple carbon shell (MCS) composites formed the core of this research. The MCS composites, which undergo a second thermal treatment and contain a higher carbon fraction, demonstrate a substantial increase in electrical conductivity—up to ten times that of SCS composites. This enhancement is attributed to both an increased carbon content and a second thermal process step1. A novel NaOH etching approach was implemented to elucidate the coverage of silicon surfaces by the carbon shells followed by elemental analysis. This allows for the estimation of the surface coverage of silicon particles in Si/C composites, to determine the initial fraction of silicon accessible to the electrolyte, a critical factor in the formation of unstable SEI and impedance growth. Scanning electron microscope images before and after etching revealed spherical holes where silicon was etched in the composites. These findings were complemented by BET surface area measurements wherein the best performing MCS composite with 30 wt.% silicon showed a specific surface area of 6.51 m2·g-1. The results indicate that MCS composites provide a more effective encapsulation of silicon particles, significantly reducing the exposed silicon surface area and thereby enhancing the structural integrity and electrochemical performance of the composites. The MCS composite with 30 wt.% silicon exhibited superior cycling performance in half-cells at 0.5 C, achieving an initial capacity of 776 mAh·g-1 and maintaining 83.0% capacity retention after 100 cycles. In conclusion, we found that the formulation and manufacturing processes of Si/C composites have a crucial impact on their structural and electrochemical properties. These findings can be a basis for development of more efficient and durable lithium-ion batteries

A Scalable Approach to Prelithiation of Silicon Anodes: Continuous Process and In-Line Quality Control via Spectroscopic Analysis

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The transition to e-mobility is becoming urgent as one of the most realistic and effective ways to achieve global carbon neutrality. The key to ushering in the era of e-mobility lies in the development of advanced energy storage devices. Lithium-ion batteries are currently the most viable option for mobility purposes due to their superior power and energy density. Among the various strategies for enhancing battery performance, adopting silicon as an anode active material is expected to extend the driving range substantially. However, the lifespan of silicon-based anodes still lags behind that of commercialized graphite despite extensive research. Prelithiation is gaining attention as a method to mitigate the rapid deterioration of silicon anodes 1-3. Our research has focused on proving a scalable prelithiation process. This presentation will demonstrate our concept and how it can be applied to the production process. Furthermore, even with a mass-producible prelithiation technology, ensuring process uniformity and quality evaluation is crucial. Without these measures, the technology will be less viable for commercial use. This presentation will explore the potential for evaluating the prelithiation process using spectrometry with light in the ultraviolet to near-infrared wavelength bands. We observed that light reflectance decreases across all wavelength bands in this region according to the degree of silicon lithiation, with more noticeable changes occurring in the 700-800 nm range under our measurement conditions. A method for determining the degree of lithiation over large areas of silicon anodes in a continuous process has not been proposed until now. If this evaluation result can be utilized for process control through a closed-loop system, it will enable monitoring the uniformity of prelithiation dosage and significantly enhance production quality.

No PFAS, No Problem? – Investigating Bio-Based Alternatives for Lithium-Ion Batteries

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Lithium-ion batteries are a well-established technology with growing demand across various applications. This surge in demand necessitates the development of high-quality, cost-effective, and environmentally compatible materials. The current polymer binders in lithium-ion batteries pose challenges with regard to recycling and safety. Furthermore, particularly toxic solvents on the cathode side are a concern. Upcoming regulatory changes in view of the potential prohibition on PFAS-based materials are further boosting research into promising alternatives, including bio-based variants. Early integration of these new materials into environmental life cycle assessments is crucial to evaluate their impact and guide decision-making for sustainable production methods. The focus of this work is to bring together the potential regulatory developments regarding fluorinated binders with current research work on alternative material systems. To demonstrate this, a classification and assessment of environmental impacts and identification of key hotspots of potentially used alternative material systems for the cathode production of lithium-ion-battery cells has been per- formed. This assessment incorporates expert opinions on the processes, laboratory-scale energy meas- urements, and background data. To quantify and interpret the results, they are set in relation to a reference material system. The replacement of conventional high-risk battery materials may become indispensable in the future. The accompanying evaluation of promising alternative materials enables the derivation of measures to conserve resources and contribute to the sustainable-oriented design of electrochemical storage systems

Development and production of innovative and next-generation batteries: Solid state electrolytes and batteries

Preparation of Lithium Metal Particles and preparation of particle-based Anodes for Solid-State-Batteries

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The need for energy storage is growing rapidly in today's society. Lithium-ion batteries (LIBs) play in important role as storage systems for mobile applications like smartphones and notebooks but also for electric cars. One important characteristic of the LIB is the gravimetric and volumetric energy density. By using different electrode materials like lithium metal for the anode side the energy density can be increased. However, bare lithium metal is incompatible with liquid electrolytes which are used in most of today's LIBs. Therefore, lithium metal anodes are used in all solid-state batteries (ASSB) in which the liquid electrolyte is replaced by a solid one. Nevertheless, there are also some challenges that need to be overcome with lithium metal electrodes. Electro dissolution and deposition often occur at the same spots, resulting in high surface area lithium (HSAL), especially at high current densities. An approach to overcome this challenge is the use of lithium metal particles. By using lithium particles the surface area is drastically increased which leads to a decreased current density and thus formation of HSAL. In this work the preparation of Lithium particles and the tailoring of the particle properties is shown. Therefore, the so-called Droplet Emulsion Techniqus (DET) and milling technologies are applied [1]. In order to be able to provide sufficient amounts of the lithium metal particles, this process is performed outside of a glovebox or a dry room in a scalable reactor. Furthermore, the particle characteristics are examined via different methods like scanning electron microscopy (SEM) or particle size distribution. Additionally, the lithium particles were used to fabricate lithium anodes. With these Anodes, battery cells with a sulfidic solid-state electrolyte and composite cathodes have been assembled and tested with various electrochemical tests like potentiostatic impedance spectroscopy (PEIS) and constant current cycling (CCC).

Experimental analysis of the stacking behavior of PEO-based composite cathode sheets

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Recent advancements in battery technology have been substantial, yet the increasing demand for electric mobility emphasizes the limitations of conventional lithium-ion batteries (LIBs), such as limited range, fast charging capability, and safety issues. Among alternative technologies, solid-state batteries show great promise for enhanced safety and higher energy densities. By utilizing non- flammable solid electrolytes instead of liquid ones, the risk of fire is significantly reduced. Additionally, replacing the graphite anode with a lithium metal anode greatly increases energy density.1-3 Besides that, there is also a trend to producing application-specific cell geometries. Therefore, the approach of agile cell production for conventional lithium-ion batteries is currently being investigated at wbk Institute of Production Science.4 In order to expand the application of this material- and format-flexible approach, manufacturing processes for solid-state batteries (SSBs) are examined. This work presents a semi-automated test-rig for the evaluation of the gripping, moving and placing of PEO-based composite cathode single sheets and thus stacking on pre-defined platforms. A camera system with an image processing tool is used to monitor and quantify the process quality.5 This work shows the results of the first stacking tests with regard to positioning and orientation accuracy.

Experimental study on jet-based direct mixing method for the production of solid-state battery cathodes

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An innovative jet-based direct mixing process in the gas phase was developed and implemented to optimize the homogeneity and electrochemical properties of cathode materials for solid-state batteries (SSB). SSB are seen as a promising technology for future energy storage, as they can offer higher energy density, improved safety and longer life compared to conventional lithium-ion batteries. The proposed process enables the mixing, coating, and agglomeration of lithium iron phosphate (LFP), carbon black (CB), and lithium halide (LIC) in the gas phase. After dispersion, the materials are brought together as particle-laden aerosol jets in a turbulent mixing zone to form hetero- agglomerates through interactions of the different primary particles. The heterogeneous composites formed can be removed in situ from the process with a sample holder for SEM analysis (SEM stub) or with a cascade impactor, which performs size fractionation by inertial separation. On the other hand, the entire sample can be deposited ex-situ on a filter for electrochemical analysis, for example. The particle size distribution (PSD) of the feed jets before they enter the mixing zone is first analyzed using laser light diffraction, whereas the PSD of the composites formed in the mixing process is examined using the cascade impactor. The resulting microstructures are analyzed using SEM in combination with focused ion beam (FIB). The electrochemical properties, such as electronic and ionic conductivity as well as specific capacity, are measured to characterize the material functionality. To complement the experimental data, the gas phase process is investigated by numerical simulations using a Lagrangian particle tracking approach to gain detailed insights into the process dynamics that are not accessible experimentally. Experimental studies focus on investigating the influence of different process parameters on the mixing and structuring of the SSB cathodes in order to improve the process efficiency and the quality of the produced composites. In addition to optimizing the existing process, the ultimate goal is to correlate the investigated process parameters with the resulting microstructures and functional properties (electron and ion transport) in order to further improve the performance of the battery materials.

Recycling & Sustainability: Material mining and synthesis

Investigation of different separation techiques at electrode level for the battery recycling process

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The increasing interest in batteries and legal requirements demand adequate recyclingprocesses. Since the current recycling process may not be the most efficient, as many of the materials used for module components, battery cells and housings are mixed with valuable active materials, an alternative approach may lead to a more sustainable process. By disassembling individual battery components and extracting the active components from the cells before shredding, a high degree of material separation can be achieved even before the recovery of the active materials begins. There are several possible techniques for separating the active material from the current collector. In this investigation the thermal, chemical and mechanical separation processes are presented: By treating the electrodes in an ultrasonic waves and efficient separation can be achieved. By using various solvents the process can be optimized depending on the electrode material. Further different factors such as a thermal influence on the ultrasonic bath are being investigated. The process of the laser ablation, in which the electrode coating is removed and collected, is presented. Finally, the thermal separation process is introduced, involving the dissolving of the coating by heating the electrodes. Various temperatures influence anode and cathode differently, challenging the separation and recovery of the active materials. Depending on the separation technique the reusability of the active materials is introduced. Using imaging analysis methods, the structure of the particles and its recovery is investigated. The comparison of the separation processes will be carried out by testing the adhesion strength, that plays a decisive role in the separation of the coating from the current collector. Further, the adhesive bonding of the electrodes is significantly influenced by the binder. Binders create the coating structure, forming the link between active materials and the current collector. The influence of the thermal and mechanical separation techniques on the binder and on the adhesion strength will be carried out in this work. The investigations are performed with anode and cathode material, using various binder systems.

Recycling & Sustainability: (Direct) recycling and resynthesis

Reconditioning of Spent Graphite from End-of-Life Lithium-ion Batteries through Thermal Treatment

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As the market for lithium-ion batteries (LIB) continues to expand, so too does the demand for battery resources (e.g. cobalt, nickel, lithium and graphite), as well as the number of spent batteries.[1,2] To prevent material shortages and the waste of valuable resources, recycling spent batteries represents a sustainable approach. Previous research has focused on cathode materials, while graphite is often discarded. However, as the most commonly used anode material, graphite is vital to the battery industry. [3,4] In order to reduce dependence on foreign resources and meet recycling targets, graphite recycling becomes mandatory. The objective of this research is to close the loop for graphite recycling in the context of LIB via thermal treatment processes. Furthermore, the performance of electrodes manufactured from recycled graphite will be assessed. The spent graphite used in this study was obtained from aged battery cells via mechanical processing and leaching steps with sulphuric acid. However, it still exhibits impurities (up to 4 wt.%, mainly aluminium oxide) and structural or morphological defects such as an increased specific surface area. The presence of impurities in the spent graphite results in a decrease in specific discharge capacity during cycling when compared to commercially available graphite. To reverse the aforementioned changes, the graphite is subjected to thermal treatment at temperatures of up to 3000 °C under an argon atmosphere. This high-temperature treatment increases the crystallite sizes, effectively removes residual impurities (less than 0.5 wt.%) and thereby decreases the specific surface area. It is essential to ensure the complete removal of impurities for optimum anode performance, as observed in high-temperature treated graphite. Further results regarding the electrochemical performance of high-temperature treated graphite will be presented as the research progresses.

Investigation on cutting techniques for the automated dismantling of battery systems

Malte Mund
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Investigation on cutting techniques for the automated dismantling of battery systems Since simple dismantling is not possible in most cases, the current practice is to shred the modules as a whole and then sort the individual materials in subsequent processes. On the one hand, this means that individual components cannot be reused and, on the other, that complex sorting and treatment processes are required to separate and recycle the individual materials. In order to reduce the effort involved in recycling, one approach is to use cutting processes for dismantling in order to achieve the purest possible separation of materials so that the sorting and preparation processes can be organised more efficiently. The basis for automated and variant-flexible disassembly is the characterisation of the possible cutting processes so that the most suitable cutting process can be used for the specific application. In this work, various separation techniques for cutting typical materials used in battery systems are evaluated. These include laser-based cutting processes, water jet cutting and mechanical separation processes. In addition to the cutting quality, the evaluation of the processes takes into account both the process properties (e.g. cutting speed) and the effects of the cutting processes on the materials to be cut (e.g. thermal and mechanical stress) in order to lay the foundation for selecting suitable cutting processes for battery module disassembly. The results show that laser beam cutting in particular has great potential for disassembly. Due to the low contamination and high cutting speeds, the process offers excellent conditions for use in battery module disassembly.

Mechanical Characterization of End-of-Life Battery Cell Electrodes by Means of a Modular Disassembly Setup

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Due to the current spike in demand for lithium-ion-batteries as well as several new regulatory frameworks, the recycling of batteries and reuse of their components is of growing importance. Especially the direct recycling approach is promising substantial improvements over current state of the art approaches involving pyro- or hydrometallurgical processes1-2. In order to foster from the advantages of lower energy and chemical consumption, the precise separation of anode and cathode active material is required. However, a current challenge is the disassembly of the individual cells in order to retrieve individual anodes and cathodes from the stack and allow for further processing3-5. To better understand the mechanical condition, in which cells and their components are returned to the recycler at the end of their life cycle, this paper presents a modular disassembly setup with an integrated force-torque sensor. This allows for the precise mechanical characterization of the individual cell components. Data, such as the Youngs modulus of the used electrode sheets can be collected this way. In addition, the analysis of process forces becomes possible. These may include the force necessary to peel of a single electrode sheet from the separator in a single stacked cell for example. By collecting and analyzing these forces in different setups and with different cell materials, a better understanding of the disassembly process of individual lithium-ion-cells can be achieved. In a next step, this understanding can then be used to create an automated setup for the cell disassembly. This research presents the setup for the mechanical characterization of the cell components, based on a modular approach using an industrial robot with an attached force-torque sensor, as well as first results from the disassembly process of different end-of-life cells.

Recycling & Sustainability: Second use, repurpose and remanufacturing

Crushing of polymer-metal composite parts from the battery environment

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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. 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 polymers 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 different components taken from an electric vehicle are crushed, while the energy consumption and the crushing time is measured. The use of liquid nitrogen to cool down the components additionally changes the crushing result. Furthermore the influence of the joining process of metal and polymer is analyzed using a demonstrator component in a crushing mill with two different rotors. The aim is to determine a correlation between the joining process and the crushing results and find ideal parameters for crushing industrial components

Recycling & Sustainability: Circular economy, battery supply chains and factory designs

Cost Analysis of Giga-scaled Lithium-ion Battery Production Line with Advanced Production Methods and Integration of Renewable Energy Source

Engin Alkan
Pomega Enerji Depolama Teknolojileri A.S.

Lithium-ion batteries have a very important place in terms of meeting the increasing energy needs and expanding renewable energy sources. In addition to increasing product quality, the positive effects of new generation production technologies on unit cell cost have also been investigated. Modeling of lithium iron phosphate-based prismatic cell production, which is widely used especially in energy storage systems (ESS), has been searched based on the literature. The battery material demand assessment and the battery cost projections suggested in this study are based on technological developments and innovations in lithium-ion batteries that do not require fundamental technological variations of battery module and pack design. Battery production line should be able to accommodate increased number of battery cells in a pack and modules for the energy storage system. Across scenarios, battery production plant located in Türkiye are shown to exhibit cost advantages mainly driven by lower labor cost and evaluated for 1 GWh ESS production annually. However, cost differences between production methods and machinery system are presented to significantly reduce by using highly automated machines rather than manual ones. In this study, each step of the current manufacturing process has been evaluated and compared their contributions in manufacturing cost, operating cost, labor cost, energy consumption, and throughput impact for the entire ESS installation combined with renewable energy sources.

POSTER ABSTRACTS I Day 2

Electrode and cell production: Slurry processing

Effects during aqueous processing of lithium iron phosphate (LFP)-based positive electrodes

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To this day, N-methyl-2-pyrrolidone (NMP) is the solvent of choice when it comes to manufacturing pastes for the production of positive electrodes for lithium-ion batteries1. Although NMP is very suitable for producing pastes with high dispersibility, the solvent has been criticized for its toxicity and environmental damage2. Water-based processing has already been established for the production of negative electrodes1. Efforts to process positive electrodes aqueously are in research focus due to the lower toxicity, the higher environmental friendliness, the avoidance of fluorinated binders and the significantly lower costs2,3. The aqueous processing of cathode pastes poses a number of challenges, such as ageing effects of the active material and possible reactions with the binder2. In addition, a lithium-proton exchange can lead to an increase in the pH value, which can result in corrosion of the current collector4. Furthermore, it has been shown that aqueous cathode pastes can exhibit gelation effects that impair further processing5. This study shows the investigation of aqueous processing of cathode active materials, focusing on lithium iron phosphate (LFP). Various material compositions for the production of electrodes were tested and different processing methods were compared. Effects like the lithium-proton exchange, that occur during the processing of LFP in water, were analyzed. A better understanding of the effects enables the optimization of process times and conditions

Influence of different blending procedures for cathode slurry preparation on the performance of lithium-sulfur pouch cells

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The lithium sulfur (Li-S) cell chemistry is promising due to the high specific capacity of its active materials resulting in high specific energy cells[1,2]. Consequently, this battery type is notably suitable for lightweight applications such as aviation[3]. In the past years, the number of publications on practical prototype cells have increased, already reporting high specific energies (> 460 Wh kg-1) with low electrolyte-to-sulfur ratios (E:S < 3.0 µl mg(S)-1)[4,5]. To enable the complex conversion chemistry at low E:S ratios, the cathode porosity adaption is crucial and strongly depends on suspension blending procedure[6]. In general, there are several methods and devices to prepare suspensions for battery electrodes, e.g. dissolver and planetary mixers. After pre-evaluation, a simple laboratory blender with low shear forces (Eirich, EL1) and a high shear mixer (HSM) are compared for preparing carbon-sulfur dispersions in a relevant scale. In this study, the influence of the slurry preparation on the final performance is investigated by coating via slot die on a roll-to-roll device to produce carbon-sulfurcathodes. The as-prepared electrodes are characterized via optical and mechanical measurements. Electrochemical analyzation is conducted using coin cells for pre-evaluation as well as multilayer pouch cells with reduced electrolyte volume (3.0 µl mg(S)-1). It could be shown that the HSM enables increased binder dispersion and less porous cathodes leading to improved cycle life.
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Electrode and cell production: Coating and drying

Enabling High-speed Laser Drying of Aqueously Processed Lithium-Ion Battery Electrodes

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In this study differnt polmeric CMC binders were investigated on the impact of binder migration during electrode dying. While for conventional oven drying no impact can be obtained due to the slow drying process, different polymer sizes of the binder CMC have an impact during highspeed laser drying of LIB anodes

Increasing the OEE along the battery production chain by advanced sensors

Florian Hermann
Precitec GmbH & Co. KG

Precitec stands for the passion for light, which we make use of in the fields of optical measurement, laser cutting and laser welding. In this contribution, we invite you on a journey along the battery production chain- starting with (i) electrode via (ii) cell up to (iii) module production. Various photonic technologies are used during production and some of them even interact with each other, enabling closed-loops or a roll-to-roll repair. Example#1: After coating, the edge profile can be measured by chromatic confocal means and the superelevation can be removed by laser ablation. Example#2: Residual moisture during drying can be determined by lock-in thermography and the laser drying process can be adapted accordingly. Or, example#3: Thickness of insulation layer (stripe of Al2O3 on cathode) can be measured by interferometric means and the subsequent laser notching process can spare out regions of damaged insulation. The presentation concludes with an example showing a Machine Learning approach applied to advanced sensor data that greatly simplifies the operator's life and significantly increases throughput.

Post-drying of battery electrodes: micro- and macroscale mass transport mechanisms

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Energy savings in cell production are essential for competitive battery cells. A significant cost factor in the manufacturing process of lithium-ion batteries is moisture management and post-drying. In the post-drying process, the moisture adsorbed from the air and residual solvent is removed from the battery compounds by a high energy input. Otherwise, moisture will react with the electrolyte during operation of the battery, leading to its degradation. In order to remove the moisture from the battery compounds cost-effectively, this process step must be thoroughly understood. Therefore, a precise and comprehensive simulation, together with knowledge of the water sorption equilibrium and the kinetics of mass transfer, reveals the potential for optimizing 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, geometries and pressures. In addition, sorption equilibria of the compounds of a Li-ion battery have been determined 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. Depending on the geometry of the electrode (free standing, coil or stack) different transport mechanism may limit the post-drying process. The micro-scale resistance e.g., the mass transport through a hydrophilic, polymeric binders and the macro-scale resistance e.g., the mass transport through 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 at an industrial scale.

Innovative metrology methods create opportunities for improving yield in battery cell production

Christopher Burnett,
Thermo Fisher Scientific

Electrode line operators and gigafactory managers are responsible for producing large volumes of cells every day while maintaining high standards for cell quality. Inline metrology tools are regularly employed to provide accurate and reliable measurement data across a variety of process parameters. These sensors assure that batteries used in electric vehicles meet design parameters related to charge density, recharge time, cycle time and safety. Tight tolerances for composition, loading and final battery cell size established by battery design teams assure those requirements are met. Cells that fail to meet these requirements must be diverted from the manufacturing stream to be recycled or scrapped. This presentation will discuss an innovative technology that has recently been developed to help solve production issues through use of previously unavailable metrology data. With high-resolution, highspeed electrode loading data, line operators and managers are able to understand and control their production. Specifically, allowing to address critical quality issues, such as the anode to cathode (A/C) ratio which directly impact final cell safety and performance.

Improving battery performance through surface structuring of collectors and electrode crack formation

Jakob Offermann
Christian-Albrechts-University

The ever-increasing demand for high-performance batteries poses major challenges for existing energy storage systems. High charging speeds are no longer only required for special applications, but for example, also in the sector of individual mobility. Unfortunately, a frequent problematic consequence is the related delamination of the active mass loading from the current collector (CC). In this study, a surface structuring of aluminum (Al) foils (as a current collector) is developed to overcome the above-mentioned delamination process for sulfur (S)/carbon composite cathodes of Li-S batteries (LSBs). The structuring process creates a mechanical connection between the components, increasing the electrode adhesion to the CC. In order to enable improved electrolyte wetting in deeper layers, cracks are created in the layer, which leads to enhanced ion transport and utilization of the active mass even with elevated surface loading. Moreover, the surface structuring improves the wettability of water-based pastes without the need for additional primer coatings. Compared to cells produced with untreated CC, the cells fabricated with structured CC have significantly improved rate capability and cycling stability with a capacity of over 1000 mAh g–1. The concept of mechanical interlocking also offers the potential to be applied to other energy storage electrodes

Electrode and cell production: Dry coating

JSolvent-free cathode manufacturing process for solid-state batteries

June Blanco
CIC energiGUNE

The electric vehicle (EV) market is of utmost importance nowadays, and solid-state batteries (SSBs) are expected to be the next-generation battery systems to power them. 1 Currently, Li-ion batteries based on wet coated electrodes are the most preferred choice. However, this fabrication methodology, used in mass production, has some disadvantages such as high energy consumption, costs and contamination due to the use of normally organic solvents. As an alternative, solvent-free processes are gaining major attention. Moreover, SSBs are expected to improve energy density and electrochemical performance of Li-ion batteries. As a result, a reduction of the cost and environmental impact of Li-ion battery manufacturing is foreseeable.2 The aim of this study is to compare the effect of the processing parameters on the electrochemical performance when the LFP-based positive electrode of a SSB is prepared using different compositions and dry processing parameters. The change from solution casting to a solvent free process for electrode preparation is extremely challenging owing to the high amount of active material required within the product. In this work, a two-step process has been developed for the fabrication of the electrodes. In the first stage, the materials are mixed in a torque mixer, while in the second stage, the electrodes are laminated by means of a calender. The use of this small torque mixer allows the evaluation of different electrode recipes and process parameters without the need of using large quantities of material.

Influence of selected binder/additive for roll milled dry-processed electrode manufacturing

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There is still a demand to improve the homogeneity of dry-processed electrodes before they can be used in large-scale production. Inhomogeneity of the material distribution in the powder mixture affects the electrochemical performance of the electrode while also resulting in inadequate mechanical and flow properties. This complicates the dry powder processing and results in electrodes with diminished performance. The work presented here addresses these challenges by further developing the process chain beginning from material selection up to electrode formation focusing on the flow properties of all material components and their influence on material processibility and thus, the resulting electrode homogeneity. The primary function of electrode additives is to provide mechanical strength and to improve electrochemical performance. For dry processing, additives can help improve the flow properties of the dry powder [1]. Important key parameters are the plasticity and viscosity of the polymer binder at elevated temperatures and the friction properties of the carbons at high normal and shear stresses. Both will be investigated with regards to the optimization of the mixing and molding process and with a view to fluorine-free binders. The resulting material systems will be analyzed to determine differences in additive properties and powder blend homogeneity.

Influence of electrode density on the characteristics and electrochemical performance of dry-coated NMC811 cathodes

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The successful transition to renewable energies and the associated switch to electric mobility require high-energy batteries and their production in energy- and resource-saving processes. The solvent-free production of battery electrodes using a dry coating process eliminates the need for a drying step and therefore offers considerable potential for improving both the cost efficiency and sustainability of the process. In addition, this method enables the production of electrodes with a high area weight without causing the well-known problem of binder migration that often occurs producing wet-coated electrodes. This work investigates a solvent-free processing method involving two main steps. First, the active material (NMC811), carbon black, and PTFE binder are dry-mixed in a twin-screw extruder. Next, the granules are fed into a two-roll calender to produce freestanding films and laminated electrodes. To achieve cathodes with specific areal capacities, it is essential to coordinate the parameters of the calender-based dry coating process, including line load, roller speed, and friction. Adjusting these parameters affects the electrode properties such as density, mass loading, and pore structure as well as the electrochemical performance. While higher electrode densities allow for high energy densities, excessive calendering can lead to particle breakage or pore network impairment, thus compromising electrochemical performance. By increasing the friction, thinner films can be produced, while at the same time the material infeed into the calender gap becomes more challenging. Inconsistent material intake can result in unevenly densified areas, which appear in the form of periodically continuing ridges. In order to determine the process-structure-property relationships, cathodes with different electrode densities were produced. The resulting cathodes are examined using SEM/EDX images, adhesive strength, and porosity. Finally, the electrochemical properties of the cells are evaluated in coin cells.

LCA of Industrial PTFE synthesis and its CO2 Impact on DRY processing

Volker Lewandowski
Fraunhofer research institution for Battery Cell Production FFB

Lithium-Ion battery (LIB) cell manufacturers, especially in Europe, currently face high energy costs depending on the country of production. In general, the energy consumption within cell production separates to ~ 17% for the drying process, 28% for the formation, ~30% for the use of dry rooms and ~ 25% for others. [1] In this regard, eliminating the cost and energy intensive drying process step of the electrode production is one key to decrease the process costs and potentially lower the investment costs.[2] Additionally, cathode production conventionally uses the toxic solvent NMP, which can be harmful for people and environment and need to be recycled. [3] Thus, omitting the use of toxic solvents for mixing and coating can add up to the sustainability of LIBs by lowering the Green House Gas (GHG) emissions of battery production. [1] Eliminating these points for the LIB production is one goal of the Fraunhofer FFB within the innovative module of DRY processing. This innovative technology includes two process steps, DRY mixing and coating. Firstly, the active material, conductive additive and binder are mixed without the use of any solvent. [4] The second process step creates an electrode film, by applying the powderous mixture onto a multi-roll calender and subsequently laminating the film onto the current collector. [4] The following process steps are the same as for the conventional LIB electrode production. Up to date some of the most promising DRY processing technologies rely on PTFE as a binder. [4] Thus, changing the binder and eliminating the solvent for the electrode production can change the production costs and cause a different carbon footprint of the cell production. Therefore, the Fraunhofer FFB carried out an LCA of PTFE synthesis and put it into perspective with a dry electrode production. Thereby, the calculations were carried out with estimated material and plant requirements for a pilot-scale production and then scaled to an industrial production with 10 GWh/a outcome. These calculations can help to further estimate the costs and the carbon footprint of a future dry electrode production.

Non-PTFE based dry coating process by Fraunhofer ISIT

Jannes Ophey
Fraunhofer Institute for Silicon Technology ISIT

The growing interest in electric vehicles has increased the need for more efficient battery cells. To meet this demand, battery cells must be both cost effective and environmentally friendly. A significant portion of the costs and CO2 emissions in battery production are caused by the energy required for the drying step1. The dry coating process represents a technological advance as it eliminates the need for this energy-intensive drying step, resulting in significant energy and cost savings. In contrast to the current production of electrodes for lithium-ion batteries (LIB), which relies heavily on the wet coating process using the harmful and expensive solvent N-methyl-2-pyrrolidone (NMP), dry coating technology represents a more sustainable alternative. It bypasses the mixing, drying and solvent recovery required in wet processes, allowing for a drastic streamlining of production, reduced energy and equipment costs and increased efficiency. However, the application of this promising technology in battery manufacturing still needs to be further developed before it can be fully utilized. Therefore, several new dry coating technologies are currently under development, which differ significantly in terms of physics, chemistry, and maturity2. Fraunhofer ISIT has developed a dry coating process that differs from most other dry coating approaches in that it is not dependent on the fibrillization of the PTFE binder during calendering. In addition, non-fluorinated binders can be used, opening up the possibility of silicon-based anodes. ISIT's dry coating electrode technology has already been used to produce various dry coated battery electrodes, including NMC, LFP, sulphur/carbon and silicon composite electrodes. In addition, the technology enables the production of advanced cathodes and anodes in a wide range of area loadings, tailored for high capacity or high-performance electrode applications. This presentation will give you an insight into an innovative dry coating process for anodes and cathodes as an opportunity for future electrode production.

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Electrode, cells and systems analytics and applications: Diagnostics during production- and use-phase

Inspection system for defect detection in Li-ion electrode production

Dr. Peter Malik
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The Li-ion battery production includes three processes: electrode production, cell assembly and formation. To reduce the wastage, all of these processes should be monitored with modern technologies in inline setup in real- time. Modern technologies allow to detect the defects immediately during the production and to recycle defected components so the wastage is significantly reduced. This paper presents an inline inspection system of the Li-ion battery electrodes that specializes in defect detection. It is an intelligent system based on deep artificial neural networks. It is a contactless system which uses optical measurements as inputs. The optical measurements are produced by the Laser Speckle Photometry (LSP) technology. The system learns to predict flawless shapes of the samples under inspection. This characteristic results in the system with very high sensitivity to detect unknown defects, which is one of its main advantages. The predictions are compared with the measured data and the defects are detected. This is all done as an unsupervised process with the ability to use unlabeled data for training the system as another benefit. The detected defects are classified into defined types using a supervised process at the end. The current version, while still a prototype in development, reaches an 87 % detection accuracy. The presented system is complementary to other defect detection systems based primarily on AI defect detectors such as YOLO or R-CNNs.

Estimation of cell aging through spatially resolved irreversible expansion measurement at high charging rates

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Electromobility is one of the most important factors in achieving the climate targets within the transport sector. A transformation of the transportation sector towards battery-powered vehicles requires large amounts of resources for the battery cell production. With that in mind, it is necessary to maximize the lifetime of battery cells in order to achieve a resource-saving mobility.1 Over the lifetime of a lithium-ion battery cell, the cell generally expands during the charging cycle and contracts during the discharging cycle. The (de-)intercalation of lithium ions into the active material of the electrode layers causes reversible expansion behavior.2 Irreversible expansion can occur due to ageing processes and excessive stress during charging and discharging cycles.3 Measuring this irreversible expansion behavior can provide information about the state-of-health (SoH) and thus information about extending the lifetime of the battery cell.4 The expansion measurements of compressed battery cells are performed here with various electrical parameters such as different charging rates (C-rates) including the maximum discharge rates and various external influences (e.g. the variation of the pressure applied on the battery cells surface). Chromatic confocal distance sensors are used to measure the expansion behavior during charging and discharging cycles. In addition, a pressure sensor matrix is placed on the battery cells surface in order to measure spatially resolved in-operando expansion. The measurements are performed with battery cells containing NMC622-graphite electrode material and a cell capacity of 1 Ah. Degradation products caused by the high electrical loads and low tension on the battery cell surface can be visualized using SEM images. With the help of in- operando expansion measurements, it is possible to obtain additionally information about the aging of the battery cells by different C-rates.

On the effect of calendering pressure on morphological properties of graphite anode samples

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During the production process of copper-coated graphite anodes the calendering pressure is adjusted in order to provide specified layer thicknesses. This adjustment also affects the surface roughness, density and pore-space properties of the graphite layer and, hence, the efficiency of Li-ion batteries. In this study, various copper-coated graphite anode samples with graphite layer thicknesses from 65 to 115 µm and porosities from 20 to 60 % were investigated, employing methods tailored to the challenges posed by the small size of morphological features of graphite layers, such as pores. Layer thickness and pore-space properties were determined using ultrahigh-resolution field emission scanning electron microscopy, pycnometer measurements, and 3D X-ray imaging. Furthermore, the surface roughness of the graphite layers was analysed by infinite focus microscopy. The obtained results provide access to correlations between calendering pressure, layer thickness, density as well as surface roughness and pore-space parameters. These correlations may serve as basis for the goal-oriented adaptation of process parameters in the calendering process. Moreover, the correlation between surface roughness and porosity may allow the determination of the porosity of graphite layers from non-invasive surface measurement procedures, such as Laser Speckle Photometry (LSP)- based methods. Finally, insight into the bulk morphology of the graphite layers provides access to input data for micromechanical models and, hence, the effective material (mechanical, thermal) properties of graphite layers. These properties- when used in proper analysis models- shall enhance monitoring systems exploiting the material's response in consequence of mechanical/thermal excitation. Accordingly, unknown parameters such as the porosity of graphite layers may be obtained by backanalysis.

Electrode, cells and systems analytics and applications: Battery production 4.0, modelling, simulation and digital twin

ML-based quality control for LIB cell production: an implementation on a pilot production line in KIproBatt

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The production of lithium-ion battery cells involves multiple steps and is plagued by significant scrap rates. Machine learning (ML) based process monitoring provides solutions to mitigate the impact of substantial scrap rates by repeated multifactorial quality predictions (virtual quality gates) along the process line. By identifying and rejecting battery cells that are unlikely to meet the required specifications early in the process, this approach prevents further resource waste in subsequent production stages and facilitates easier recycling of rejected cells. A hierarchical architecture is implemented to utilize ML algorithms for process-specific feature extraction, which is informed by prior knowledge of common production anomalies. The focus of building a predictive model using these process features is to maximize the generalizability of the model given the constrained amount of data. In the context of flexible production, the resulting predictions may trigger adjustments of later process steps to compensate for detected deficiencies. An implementation is illustrated with data acquired from a pilot battery cell assembly line.

Digital shadowing in industrial electrode coating: Preparing process parameter prediction

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A promise, often mentioned in the discussions about digitalization, is the reduction of scrape in production through prediction of the machine parameters for a desired product property. 1 A way to achieve this, is to build a model of the process and let it predict the machine parameters before the begin of production. Thereby the material in starting the process can be reduced by a better first set of machine parameters. A variant of this approach is tested at the research production line (RPL) at the ZSW in Ulm. For the electrode coater a digital shadow was implemented. This involved the development of a track and trace system for the sheet sections on the electrode coil. The data aggregated in each section was used to train a machine learning model to predict the grammage. The model can be attached to the process for live prediction with a delay of a few seconds. In the actual coater at the RPL the measurement frame for the grammage is at the end of the coater after a drying track. The difference between the slit and the measurement frame is therefore around 50 m. For the machine operator this means a delay in his abbility to react to a change in grammage. Accordingly, a large portion of the electrode can be slightly diminished in quality, if a sudden change in slurry or machine properties arises. The built digital shadow can be used to reduce this the delay by predicting the grammage before it is measured. In this way the overall quality settings can be better and faster controlled.

Simulation of the electrolyte wetting process: physical model and parametrization approach

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Driven by electromobility, the demand for lithium-ion batteries is strongly rising. Hence, it is imperative to increase the production capacities by optimizing production processes. After cell assembly, an important but time-consuming step is the addition of the liquid electrolyte. It is supposed to fill the electrode and separator pores homogenously. Driven by capillary forces and external pressure, the wetting process may take several hours. Moreover, since there is no inline characterization of the wetting state yet, duration and process control are often based on experience or trial and error. We propose to improve process design by supporting numerical simulations of the wetting process. The developed model describes macroscopically the dynamics of the electrolyte penetration into the porous sheet stack within the cell. It allows to predict the wetting timescale and the resulting electrolyte distribution. It is based on extended Navier-Stokes-Brinkman equations considering capillary forces as major driving force [1]. Furthermore, the model does not only account for the effective electrolyte flow through the porous media, but also for the residual gas-phase inside the pores and the applied external pressure. This approach was implemented in ITWM's software framework CoRheoS FLUID enabling the computation of time and space evolution of the electrolyte distribution. In this contribution we present the details of the model and compare it to a simplified formulation based on the Richards Equation that cannot account for gas pressure effects. However, due to its efficiency, the latter plays an important role for the development of the proposed parametrization workflow: First, effectively one-dimensional capillary-rise experiments were carried out at FFB on single sheets. Subsequently, this data was used to identify the relevant input parameters for the simulations. This approach will be described in detail and demonstrated on FFB materials.

Prediction of cell life and failure analysis in virtual environment

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A lithium-ion battery cell is at the forefront of technological advancements for electric mobility and energy storage solutions. As we transition towards more sustainable energy sources and consumption methods, these cells emerge as foundational elements in various systems and applications. One of the primary considerations when incorporating these cells in the development process is their cycle life, which constitutes a significant impact to the system cost and duration. Investors and business stakeholders scrutinize this factor closely, as the cost of the battery cell directly impacts the Return on Investment (ROI) in energy storage projects. This makes the efficiency, durability, and performance of the battery cell paramount to the overall success. Yet, one of the major challenges faced by researchers and developers in this field today is the process of testing the lifespan of these battery cells. The life testing of cells is not a swift procedure. In fact, it's quite the opposite. This process is characterized by its intensive duration, often stretching over several months. Such lengthy durations pose a dilemma: by the time the testing results are available, they might no longer be relevant for designs or systems that are already in the early or middle stages of development. Consequently, decisions made in the initial design phase may not fully consider the lateracquired knowledge about the battery's performance, lifespan, or other critical parameters. Beyond the temporal challenges, cell life testing also brings with it substantial financial and environmental implications. The resources, both in terms of money and energy, that are poured into these tests are considerable. The infrastructure, equipment, and continuous monitoring required for these tests are expensive. Moreover, the energy consumed during these tests is significant. Improving the use of this kind of resources on high probability designs can be helpful to considerable carbon emissions reduction. The capability for virtual design and evaluation is one essential solution. Over the years of our cell design experience, we've developed some standard methodology and virtual technologies to predict cell life and build it into the process of evaluating different cell design options. Thus, the cycling performance can be simulated early and frequently in a relatively short period of time. It is also worth to note that the working conditions (e.g., different temperature) can be quite diverse and customized so variety of applications can benefit from the highly relevant analysis. In this study, we summarized the method and the tool we used to conduct such studies, including several real application cases to demonstrate its effectiveness.

In-line Electrode Homogeneity Assurance-Insights from HighPrecision Edge Monitoring in LIB Manufacturing

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The surge in energy storage demand, driven by electric mobility, propels lithium-ion battery (LIB) manufacturing. Forecasts predict 6 TWh annual capacity by 20501, a significant increase with scrap rates between 5-30% 2,3 which represent considerable material and environmental costs that must be mitigated through efficient quality assurance. One type of coating defect in conventional electrode manufacturing is edge elevation. Despite this being extensively reported on in the scientific literature4. The presentation showcases a confocal line sensor implemented for precise edge detection during the coating process, along with automated data analysis and interpretation. Additionally, it details correlation studies of the coating process to identify geometric features of the wet electrode edge using the acquired data. The final section of the presentation explores various simulated results of cells, highlighting evaluations conducted through cell characterization to investigate thickness inhomogeneity occurring in the coating process.

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Rethinking Equipment Assessment: Leveraging TCO Analysis for Cost-Effective and Sustainable Battery Manufacturing to Reduce Production Costs

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In the rapidly evolving field of battery production, the focus on low CAPEX values when purchasing new production equipment often overlooks the broader financial implications associated with Total Cost of Ownership (TCO). This presentation highlights the critical importance of TCO analysis by showing that while CAPEX and OPEX are significant, the majority of costs arise from scrap and waste during production.

Our analysis shows that traditional procurement practices lead to misguided developments and misplaced incentives, causing manufacturers to prioritize initial cost savings over long-term efficiency and sustainability. By integrating TCO analysis from the outset, manufacturers can shift their focus towards minimizing scrap and waste, enhancing the overall cost-effectiveness. This approach promises significant cost savings for cell manufacturers and fosters more sustainable manufacturing practices. The broader implications extend to the automotive industry, particularly in Europe, where reduced production costs can make electric vehicles more affordable and accessible. Furthermore, the importance of recycling and sustainability will be addressed. By adopting TCO analysis, equipment manufacturers can move beyond price optimization towards creating more efficient, cost-effective, and sustainable equipment. This shift is essential for the future of the battery industry, ensuring that economic and environmental benefits are realized across the entire value chain.

Electrode, cells and systems analytics and applications: Battery safety

Estimation of locally generated Joule Heat during Thermal Runaway using DEM and simplified Full-Cell Simulations

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The continuously increasing energy density of modern lithium-ion batteries makes battery safety an increasingly relevant topic. In the event of an electrical vehicle accident, the mechanical stress on the battery can lead to a short circuit. In the worst case, this can result in an uncontrolled thermal runaway, where more and more energy is released as capacity and energy density increase. Therefore, during the development process, the battery cell must be optimized for safety to minimize the probability of a thermal runaway. To perform 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 to these simulations of the thermal runaway is the heat generated at the location of the short circuit. Here, a workflow will be presented that allows the estimation of 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 abuse is simulated using DEM models. Prior to this, the electrodes and the separator are calibrated individually with regard to their mechanical behavior using calendaring studies, tensile tests, and other experimental methods. The electrodes and separator are then stacked to form a unit cell, on which the abuse simulation is performed. With the help of continuum methods, it is possible to derive electrochemical properties from the resulting microstructure. This approach enables the determination of the change in resistance of the unit cell due to mechanical stress. Finally, this information is utilized in a simplified full-cell simulation to permit an estimation of the current density at of the short circuit location and thereby enabling the calculation of the generated heat. The simulation results are then compared with voltage and temperature curves from nail penetration tests using multilayer pouch cells.

Electrode and cell production: Formation and aging

Evaluation of cell finishing production line concepts under consideration of flexibility requirements

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Due to the increasing demand for traction batteries in electric vehicles, the importance of large-scale battery production is growing to guarantee the required capacities. In the planning of battery cell production, the cell finishing is considered time-consuming and cost-intensive depending on the selection of measurement technologies. In addition, the design and process parameters can change during the production planning process, resulting in high uncertainties and continuous updates of the cell finishing planning. In the context of the current research work, which aims to demonstrate the large-scale production for research purposes, the so-called flexibility corridor needs to be considered, including further research-relevant requirements beyond the standard production line. Therefore, a thorough understanding of correlations between cell design, production process and measurement technology is fundamental to efficiently evaluate requiring line concepts. This work provides an overview of measurement technologies and evaluates their potential of application in cell finishing. Restricted by the production requirements, two benchmark lines are identified in this work with the respective focus on large-scale production and future research requirements. With further optimization criteria such as process stability and cost efficiency, cell finishing line concepts can be derived from the flexibility requirements for large-scale battery cell production and research.

Development and production of innovative and next-generation batteries: Material development and usage of innovative materials

Aluminium-Graphite Dual-Ion Batteries: Progress and Challenges towards Application

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Lithium-free Al-graphite-dual-ion batteries (AGDIB) have gained much attention due to their low-cost and sustainability. Commercial Al-foils and natural graphite are employed as electrode materials, ionic liquids e. g. AlCl3/[EMIm]Cl as anolyte. Al2Cl7– and AlCl4– within the anolyte are responsible for Al dissolution and plating, whereas AlCl4– is (de)intercalated between layers of graphite1. Given the high power density (up to 9 kW/kgGraphite)1 and the long cycle life of >25,000 cycles in lab test cells, AGDIBs represent a promising, cost-effective and powerful energy storage system and can, for example, meet the highly dynamic requirements necessary for grid stabilisation, as revealed by chronoamperometry experiments. AGDIBs as high-power batteries fill the gap between supercapacitors and established (high-energy) battery types. With the aim of moving towards battery application, several challenges have to be met: Regarding a long-term stable pouch cell design, the electrolyte's corrosivity and its sensitivity towards moisture are the biggest challenges. Carefully choosing suitable casing materials and significantly reducing moisture sources inside the cells allowed for long-term stable (single-layered) pouch cells achieving a high rate stability with stable capacities up to 10 C and a lifetime of >1200 cycles2. In first double-layered cells, the capacity could be raised to 42 mAh and the internal resistance reduced to 100 mΩ. In addition, electrode manufacturing was optimized, e.g. with respect to binder materials and conductive additives of the water based slurries. Post-mortem microscopic and spectroscopic methods were employed to analyse material stability of active and passive components upon cycling. The thus revealed causes for battery failure such as dendrite formation will allow for further optimization of AGDIB pouch cells. The AGDIB's poor shelf life is a significant drawback for application. In a systematic selfdischarge study, several independent influence factors for self-discharge processes were identified allowing to significantly reduce self-discharge capacity losses from 10% to 3% in 24h3. It can be anticipated that these insights will enable a further reduction of self-discharge, enhancing the overall stability and longevity of these batteries and reducing operational costs.

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Green method for the synthesis of biobased carbon from miscanthus X gigantheus for Lithium ion batteries

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Due to its excellent cycle stability, high electrical conductivity, low density and good availability, graphite is the most commonly used anode material in lithium-ion batteries (LIBs). However, it has a limited capacity of 372 mA h g-1 and reacts easily with the electrolyte solution. Nanostructured carbon materials, including carbon nanotubes, graphene, and mesoporous carbon, promise significantly higher capacity due to their unique ability to hold large quantities of lithium ions per unit mass. This is attributed to their short, interconnected porous structures, comprising mesopores and macropores that function as channels for rapid electrolyte transport and provide brief, stable pathways for ion diffusion, along with a modified storage mechanism. Of particular interest are bio-based mesoporous carbons, which are sustainable materials. A wide variety of carbon-rich biological materials are being investigated as starting materials in the research literature. However, only materials that are available in large quantities and of defined quality are realistic candidates for subsequent industrial implementation. In this work, Miscanthus X giganteus (MG), the giant china reed, which is considered one of the fastest growing energy crops, was used for the synthesis of biobased carbon for LIBs using a cascaded hydrothermal carbonization followed by calcination. The popular synthesis method for mesoporous carbon from biomass involves pyrolysis followed by chemical activation, which generates chemical waste challenging the environmental friendliness of the process, and is also energy-intensive (costly) and time-consuming. In this contribution, we have established hydrothermal carbonization followed by calcination as green synthesis route avoiding the use of harmful chemicals. After optimization of the hydrothermal synthesis step particularly regarding reaction temperature, calcined hydrochar products with specific surface areas of above 450 m2 g-1 and very good discharge capacities of 1000 mA h g-1 at 0.5 C were obtained, which surpass commercial graphite as well as chemically activated carbons from comparable biomass sources.

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Sodium ion Battery as Next Generation Battery Technology: Investigation of Slurry and Manufacturing characteristics of NMO as a Promising Cathode Material

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Lithium-ion batteries (LIBs) presently reign supreme in the energy storage market, delivering exceptional performance. However, in order to counteract the steadily increasing demand, especially for potentially resource-critical elements such as lithium or cobalt, new material compounds and systems need to be investigated and developed. As one of those next-generation batteries, sodium-ion technology is currently intensively studied. Nevertheless, there are currently large numbers of possible sodium active materials and still some challenges in the processing- e.g. the stability of active materials under normal atmosphere, the basicity or the spring back effect of the hard carbon [1, 2]. Comprehensive characterization of material properties and optimal formulation establishment are crucial. Our research focuses on Na0.44MnO2 because of its layered oxide structure with a theoretical capacity of 105 mAh/g [3]. Unlike conventionally spherical LIB active materials, e.g. NMC, it exhibits a characteristic rod-like particle shape. The particle morphology and the interactions in water-based systems necessitate an adaption of processes specific to the material. This requires systematic investigations on the mechanical, rheological, electrical and electrochemical properties before scaling-up the active material cathode slurry for battery production. The poster shows a formulation and characterization study of the processing of an water-based sodium-ion suspension in a batch process. A systematic investigation of the cathode active material was carried out to characterize the influence of the buffer and the pH value by means of zeta potential on the stability of the suspension. Further investigations show the impact of formulation and processing as well as calendering on the mechanical, electrical and electrochemical properties of the cathodes. In order to be able to better classify the results, these are compared to conventional LIB technologies.

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Scalable anodes for sulphide-based solid-state batteries

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The development of next-generation lithium-ion batteries has demonstrated the potential of all-solid-state batteries (ASSBs) to enhance energy density, safety, and longevity. The use of graphite-silicon composite anodes represents a balanced approach that leverages the high specific capacity of silicon (~3579 mAh/g) and the stability of graphite (~372 mAh/g). The composite structure is capable of mitigating the significant volume expansion (~300%) that pure silicon undergoes during lithiation. Such expansion would otherwise lead to structural degradation and capacity fade. Furthermore, silicon-graphite composites demonstrate enhanced cycle stability in comparison to pure silicon anodes, while simultaneously offering a higher energy density than graphite alone [1].

One of the primary challenges in developing ASSBs with Si-graphite anodes and lithium phosphorus sulfide chloride (LPSCl) is maintaining a stable interface and mitigating the mechanical stress caused by silicon expansion. The binder is of great importance in maintaining the structural integrity of the composite anode, enhancing adhesion between particles and ensuring good contact with the electrolyte. Conventional binders are not ideal due to their incompatibility with sulphide electrolytes and/or the solvent needed to process such, which has led to the exploration of novel binder chemistries that can endure the mechanical and electrochemical demands of these systems.

The forthcoming poster will present research on wet coated graphite-silicon (Si-C) composite anodes with the ionically highly conductive LPSCl, with the aim of addressing critical challenges in solid-state battery technology. Here, we will provide a comprehensive evaluation of the formulation, electrochemical performance, structural stability, and material properties of Si-graphite anodes in LPSCl-based all-solid-state half-cells. The key findings will include data on porosity, cycling capability and, consequently, proof of their viability for high-energy-density applications. Insights into ionic conductivity and interface resistances will be provided by impedance spectroscopy, while Raman spectroscopy will identify inert by-products during cyclisation. SEM will reveal microstructural evolution during the cyclisation. These results contribute to the optimisation of Si-graphite anodes and LPSCl electrolytes for next-generation solid-state batteries.

High-energy-density batteries enabled by high mass loading of cathodes via UCC and electrode architecture engineering

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The growing requests for high-energy-density batteries have highlighted the need of achieving high mass loading in battery electrodes, as it directly enhances the energy density of the cells thanks to a better exploitation of Cathode Active Materials (CAMs). Furthermore, higher mass loadings contribute to increased energy density in batteries by minimizing the relative weight of inactive components such as current collectors, allowing for a higher proportion of active material in the device. Conventional electrode fabrication techniques often struggle to maintain stability and performance at elevated mass loadings. Universal Current Collector (UCC) technology represents a novel substrate that strengthens electrode structure and optimizes CAMs exploitation. It is engineered by coupling a conductive carbon fibre with an aluminium metal foil, allowing for higher mass loading without sacrificing mechanical stability or electrochemical performance, since it gives the possibility to enhance both conductivity and structural integrity. The structural and electrochemical properties of UCC electrodes are presented, showing improvements in energy density compared to those manufactured by conventional methods. Electrochemical properties were assessed using Electrochemical Impedance Spectroscopy (EIS), Cyclic Voltammetry (CV), and Galvanostatic Charge-Discharge (GCD) techniques. Mechanical stability was evaluated through bending tests and ultrasonic wave stress tests, comparing the maximum loading capacity achievable on UCC with that of a standard aluminium foil benchmark. These results of this characterization highlight UCC technology potential compared to currently available solution, with the aim to provide next-generation batteries with increased energy density, effectively meeting market demands of energy storage solutions.

Development and production of innovative and next-generation batteries: Solid state electrolytes and batteries

Milestones Towards the Production of Sulfidic Cylindrical All-Solid-State-Battery (ASSB)

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When aiming for increased energy density and safety for future batteries, ASSBs are believed to be a promising technology. However, ASSBs face substantial challenges, particularly in terms of cost and technology hurdles [1]. To ensure ionic conductivity, among others homogeneous and constant con- tact between the ASSB sulfidic composite electrodes (SCE) and the sulfidic solid-state electrolyte (LPSCI) is essential. This results in challenges, as high pressures are required during production and operation [2]. Different cell housing designs, such as cylindrical cans are investigated to ensure the mechanical stability to withstand significant operating pressures. In this work we describe the effect of single bent SCEs on the macro and microstructure. A design of experiments is used to investigate deformation properties of SCEs as a function of the mandrel diameter. The samples are analysed with scanning electron microscopy (SEM) giving data on surface topography. A bent single layer full cell is then object to an electrochemical characterization. The gained data is compared with electrochemo- mechanical data from wound electrodes used in conventional cylindrical lithium-ion batteries (LIB) [3] pointing out the challenges of a cylindrical ASSB. These investigations will be an important contribution to future studies to define the winding operation window of SCE.

Hybrid electrolytes for solid-state lithium-sulfur batteries

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In this contribution, novel concepts and investigations on SSLSBs are presented. On the one hand, the effects of different types of filler particles, passive ZrO2 and active Li7La3Zr2O12 (LLZO), are compared. The surface of the filler particles is functionalized with a silane ligand prior to their integration into the PEO matrix. This modifies the interfacial properties between the polymer and the filler particles, hence influencing the ionic conductivity. The functionalized ZrO2 fillers enhance the ionic conductivity of the HSEs by reducing the crystallinity of PEO, reaching an ionic conductivity of up to 6.66·10-4 S cm-1 at 20 °C. Additionally, the use of the silane ligand without the introduction of filler particles also improved the ionic conductivity, while the incorporation of functionalized LLZO fillers does not, which is attributed to a LiCO3 passivation layer. The results suggest a viable strategy for the optimization of HSEs for practical applications

Determination of thermo-mechanical properties and tortuosity of polymer-based composite cathode produced by solvent-free extrusion

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All-Solid-State Battery (ASSB) is the next generation technology that promises to replace the conventional Lithium-Ion Battery (LIB) in future. Replacing the flammable and volatile organic liquid electrolyte with an ion-conducting solid, e.g., by polymers, sulfidic or oxidic materials, improves the safety of such a battery cell. Further, these solids enable the use of metallic Lithium as anode for high energy density ASSBs. From a materials perspective, the current challenge is the interfacial connection between the solid electrolyte and the cathode. A promising solution to provide good interfacial contact between these two components is the use of a composite cathode consisting of conventional cathode materials and a solid electrolyte as catholyte. From a production perspective, the current challenge is to scale up the individual manufacturing processes of each battery components, such as the solid electrolyte (SE) and composite cathode. Due to the malleable nature of polymeric materials and their operation at low pressure, the focus of research shifts more on scaling up the processing. Thus, we are investigating the solvent-free and dry process route of polymer-based solid-state batteries using extrusion. To better understand the process and the relationship between process parameters and product quality, we have developed an experimental setup ranging from measuring of small quantities through kneading experiments1 to producing larger quantities through extrusion experiments2. In this work the polymer-based SEs and composite cathodes are produced using a twin-screw extruder. The produced battery components are optically and mechanically characterized by optical microscopy, SEM and DMA, respectively. Electrochemically, the ionic conductivity of the SEs and the tortuosity of the composite cathode are determined by EIS. Furthermore, their performance in a ASSB full cell with a Li metal anode is tested in a 30 x30 mm pouch format.

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Mechanical modeling of halide electrolyte-based battery components for AL-solid-state batteries using DEM

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Currently, halide materials are gaining popularity as a potential electrolyte for ASSB due to its ability to bring the best of both worlds from Oxides and Sulfides, considering their moderately high ionic conductivity at RT (>2mS/cm) and safe processibility. The microstructural behavior of the particles plays a key role in the deep understanding of the mechanical properties of the particles during cycling as well as its ionic and electronic transport properties and is best deduced using the Discrete Element

Method (DEM). Herein, we propose a contact model that calculates the normal forces considering the elastic-plastic behavior [1] and by simultaneously contemplating all the contacts of a Halide particle [2]. The influence of volume change of the active material (AM) particles during the charge/discharge cycling of the battery on the contact parameters such as contact area, reaction force is evaluated. The contact properties retrieved is used to determine the grain boundary conductivity, which is experimentally tedious to evaluate. This work provides a realistic approach to the calculation of contact forces and estimate significant yet experimentally challenging material properties. The authors gratefully thank European Union for providing financial support within the Horizon Europe program for research and innovation (Project: HELENA; Grant agreement No. 101069681).

Electrode Manufacturing Processes for Solid-State Batteries with Sulfidic Electrolytes

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Solid-state batteries offer the possibility to combine increased energy densities, high voltages, thermal stability, and safe operation. Furthermore, the category of sulfidic solid electrolytes in particular, due to their high ionic conductivity, possesses enormous potential to fully exploit the aforementioned ad-vantages. However, the performance of the battery is often limited by the positive electrode, necessi-tating an optimized cathode design.

Within this work, different formulation strategies to increase the cathode and separator properties were investigated. For this purpose, cathodes and separators are manufactured on a laboratory scale in different devices (mixer, dissolver, extruder). The components produced were then tested in coin cell format against indium and lithium anodes in terms of their specific capacities during the initial cycling. The most promising manufacturing method was subsequently used for a cathode-side formu-lation study, where the specific capacities of the different formulations were compared at the pouch cell level. These were assembled against metallic lithium and then cycled. The electrochemical results, including electrochemical impedance spectroscopy, specific capacity, and the achievement of the end-of-charge voltage, were used as evaluation criteria.

Recycling & Sustainability: Material mining and synthesis

Handling information flows in the upstream battery value chain to meet new regulatory requirements

Maximilian Rolinck
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The energy transition and the development towards electrified mobility are leading to a growing demand for batteries and energy storage systems. Electrification has the potential to reduce greenhouse gases, but at the same time leads to a shift of environmental burdens. In particular, the upstream value chain of battery production leads to considerable environmental impacts. The European Union (EU) Battery Regulation aims to enhance the circular economy, improve resource use and efficiency, and extend the life cycle of batteries to promote sustainability. Economic operators, placing batteries on the EU market, are therefore required to make information about their upstream value chain transparent. This includes the reporting of e.g. recycling content shares and the product carbon footprint of batteries in a so called battery passport. In order to make this information available, the challenge is to create transparency across the value chain, including the consistent collection and processing of data and the reliable exchange of information across organizational boundaries. Based on the results of the BMBF funded project SUSTRAB, we propose a blockchain-based transparency platform to enhance the cross-organizational data exchange. An LCA query mask, which facilitates the reporting of material and energy flows and the automatic generation of Life Cycle Inventories, is presented. These inventories serve as a basis for further calculations and are linked to digital assets. So called smart contracts facilitate the processing and aggregation of inventories, by executing automated transactions against the blockchain. A user interface provides an overview of relevant information and facilitates organizations in the network to compare materials and cells of different provenance. Advanced functionalities for decision support based on the transparency platform enable organizations to make their value chain more sustainable and meet increasingly demanding regulatory thresholds.

Recycling & Sustainability: (Direct) recycling and resynthesis

Synthesis of nickel-rich layered oxide cathode active materials using recycled materials

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The ongoing transition to more sustainable mobility solutions is increasing the importance of closing material cycles in battery production. With the rising demand for electric vehicles and energy storage systems, the recycling and recovery of valuable materials from spend batteries have become crucial. This is especially true for cathode active material, given the limited availability of valuable metals re- quired for the production. The significance of recycling is further emphasized by the upcoming EU regulations on recycling rates. Nickel-rich layered oxides, among other materials, have garnered sig- nificant attention as cathode active material due to their high usable capacity. However, their poten- tial negative environmental impact requires the development of efficient recycling and resynthesis strategies. The aim is to convert cathode active materials from spent batteries into metal salts, such as nickel sulfate. This allows for the resynthesis of cathode active materials with electrochemical per- formance similar to that of commercially available materials. It ensures sustainable and reliable sup- ply chains in the battery industry. In this study, nickel-rich cathode active materials (NCM) have been synthesized on a laboratory scale. A two-step hydroxide coprecipitation was used as the synthesis method. As educts primary materials or recycled materials from hydrometallurgical processes were used (e.g., nickel sulphate, cobalt sul- phate, lithium hydroxide and lithium carbonate). This enabled the analysis of the influence of primary and recycled materials on the synthesis process of the precursor (pCAM) and the product properties. In particular, the influence of impurities resulting from the recycling process were considered. The influence of different reaction systems on the pCAM synthesis were investigated. As well es a variation of key process parameters (e.g., temperature, pH, reaction and aging duration) and formulation parameters (e.g., educt concentration). After the pCAM synthesis a controlled drying process and a two-step calcination followed. The starting materials, intermediates and final products were analysed to determine their particle size distribution (laser diffraction), morphology (SEM) and chemical composition (ICP-MS / ICP-OES, EDX). Furthermore, the crystal structure (XRD) and electrochemical properties of the products were evaluated.

Lithium iron phosphate battery recycling by using a direct approach

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As the demand for lithium-ion-batteries (LIBs) increases sharply due to their key role in electric vehicles and renewable energy storage, the need of sustainable end-of-life solutions is essential to contribute to a circular economy. However, the limited lifetime of LIBs leads to an increasing quantity of spent batteries and battery waste. Among various technologies, the lithium iron phosphate (LFP) battery has been becoming remarkably important due to their safety, longevity, and cost efficiency. Therefore, efficient recycling techniques will be required to close material loops, especially for such batteries, and to reduce costs as well as environmental impact throughout the product life cycle.1 A promising alternative recycling strategy is the direct recycling approach, since it aligns with the green deal principles by developing sustainable industry and reducing the consumption of battery materials with high processing. In this process, the electrode materials are mechanically separated including disassembly and physical separation of components as well as reprocessed without destroying their chemical structure. By applying direct recycling for LFP batteries, the crystalline structure of the cathode material can be preserved which leads to its almost original performance with minimal energy input and reduced chemical treatments. Current research focuses on the further development of these processes for scalability and integration with existing battery manufacturing infrastructure. Overcoming challenges such as the standardization of disassembly procedures and the purity of recovered materials will be crucial for the widespread introduction of direct recycling.2 This study focuses on the investigation of the delamination behavior of LFP cathodes by using different solvents for the cathode active material (CAM) recovery. Considering the cathode composition, water or organic solvents (e.g., N-Methyl-2-pyrrolidone-NMP) are examined to strip the LFP material from the aluminum current collector. Hence, different process parameters (e.g., reaction time, temperature, solvent-liquid-ratio, pH value) and the recovered active material is investigated to get more insights into the delamination as well as extraction process.

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Low volatile electrolyte components and conductive salt recovery using solvents

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In recent years, the surge of electric vehicles and renewable energy technologies has result-ed in a significant increase in the production and use of lithium-ion batteries (LIBs). Conse-quently, the number of spent LIBs is expected to rise significantly in the near future. The ma-terials currently used in LIBs pose environmental hazards and safety risks. However, they also contain valuable resources, such as lithium, nickel, and cobalt, which must be recov-ered for the sake of economy and due to EU regulations. Given the potential future scar-city of these critical materials, particularly cobalt, developing independent secondary sources through recycling is essential. This urgency has driven considerable interest and re-search in LIB recycling within both academic and industrial sectors.
To improve sustainability, the recycling rate for end-of-life (EoL) batteries aims to surpass 70% by 2030. This push for higher recycling efficiency is not limited to just the core compo-nents of batteries; it extends to recovering other vital materials as well. For instance, specif-ic processes can now reclaim electrolyte components that are typically lost during current recycling methods due to thermal decomposition.
Conducting salt, binder and low volatile electrolyte components are thermally decomposed in most conventional processes and cannot be recovered. In the ElRec (Electrolyte Recovery) project, these are to be washed out of the black mass produced with the aid of suitable sol-vents. For this purpose, the LIB shredded material produced is mixed with a solvent that can dissolve the conductive salt and the remaining carbonates, allowing them to be extracted. In a second process step, the binder components are then removed with a further solvent.
The aim is to produce a purer electrolyte and binder-free black mass for easier hydrometal-lurgical processing. In addition, the removed components can also be processed and recycled.

Recycling & Sustainability: Circular economy, battery supply chains and factory designs

Identification of Sustainability-Related Use Cases for Digital Twins and Traceability Systems in Battery Production

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While batteries generate no direct emissions, their production and end-of-life have significant environmental impacts.1,2 Continuous monitoring and exchange of data on batteries, materials, and processes within and between life cycle phases is considered essential to enhance sustainability in the battery industry2–4 and to comply with regulations like the EU battery regulation5. Solutions such as digital twins or traceability systems could support life cycle analysis, production optimization, or endof-use decisions, reducing energy demand, scrap rates, or CO2 footprint.2,3 Despite demonstrated benefits in case studies, the broader potential of traceability and digital twins for sustainable battery production is not systematically explored. Moreover, the adoption of these “sustainability use cases” remains limited due to complexity, data requirements, and costs, compounded by uncertain economic and ecological benefits.3 This presentation will introduce a decision support tool designed to help stakeholders identify suitable use cases for traceability systems and digital twins in battery production with environmental benefits. We combined a systematic literature review and interviews with industry experts to define relevant environmental targets in the battery industry, use cases addressing these targets, and barriers hindering their implementation. The use cases were systematized in the form of a taxonomy considering their relevance for different life cycle phases and environmental targets, the required data points, and technical options for implementation. The taxonomy was further developed and validated in case studies with experts from different steps of the battery value chain. The resulting use case database serves as the foundation for the decision support tool. The tool matches the stakeholder's information on relevant life cycle phases, environmental targets, and available data with the database of use cases. In this way, the stakeholder receives an individualized, comprehensive list of use cases with information on the benefits and next steps for implementation.

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Sustainable Battery Recycling and Lifecycle Management: Insights from the greenBatt Cluster

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Effective end-of-life (EoL) management of lithium-ion batteries (LIB) is crucial for the sustainability and environmental impact of the battery landscape in Germany and Europe. Proper EoL strategies ensure the conservation of valuable resources and the minimization of ecological footprints, playing a vital role in the transition to a circular economy, especially within the mobility sector.
The cluster “Recycling and Green battery”(greenBatt) focuses within their cluster projects on establishing fundamental foundations for the sustainable recycling of LIB and closing material cycles in the battery lifecycle. The clusters accompanying project evaluated, over the cluster duration, the ecological and economic advantages of EoL phases, such as the recycling of batteries. Furthermore, these projects conducted comprehensive system analysis and assessment, analysing and evaluating the entire battery lifecycle with various EoL pathways and reuse scenarios. Based on that, recommendations regarding the handling the EoL of LIB for policymakers and industry were derived. Another key result was the development of an open-source tool for evaluating second-life and recycling options. This tool is based on a comprehensive system analysis and assessment using scenarios, reference process chains and developed models. The reference chain for the recycling of the LIB were compared to pre-existing recycling routes. The developed tool enables a thorough economic and ecological assessment of various reuse and recycling options.
This work discusses the insights and tools collected and developed in the greenBatt Cluster over the past three years. The results significantly contribute to promoting a sustainable battery economy and offer practical solutions to the challenges of battery recycling and circular economy. All tools and recommendations can be further used by industry, academia, and policymakers to facilitate informed decision-making for optimal battery reuse and recycling strategies.

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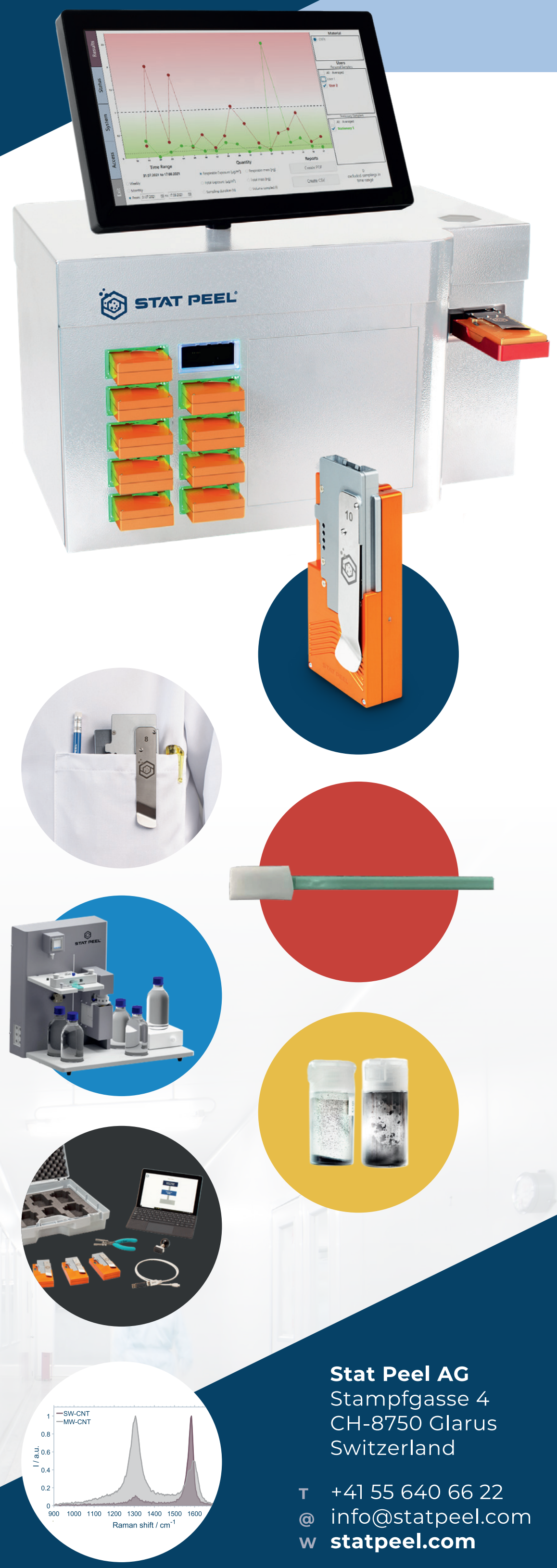

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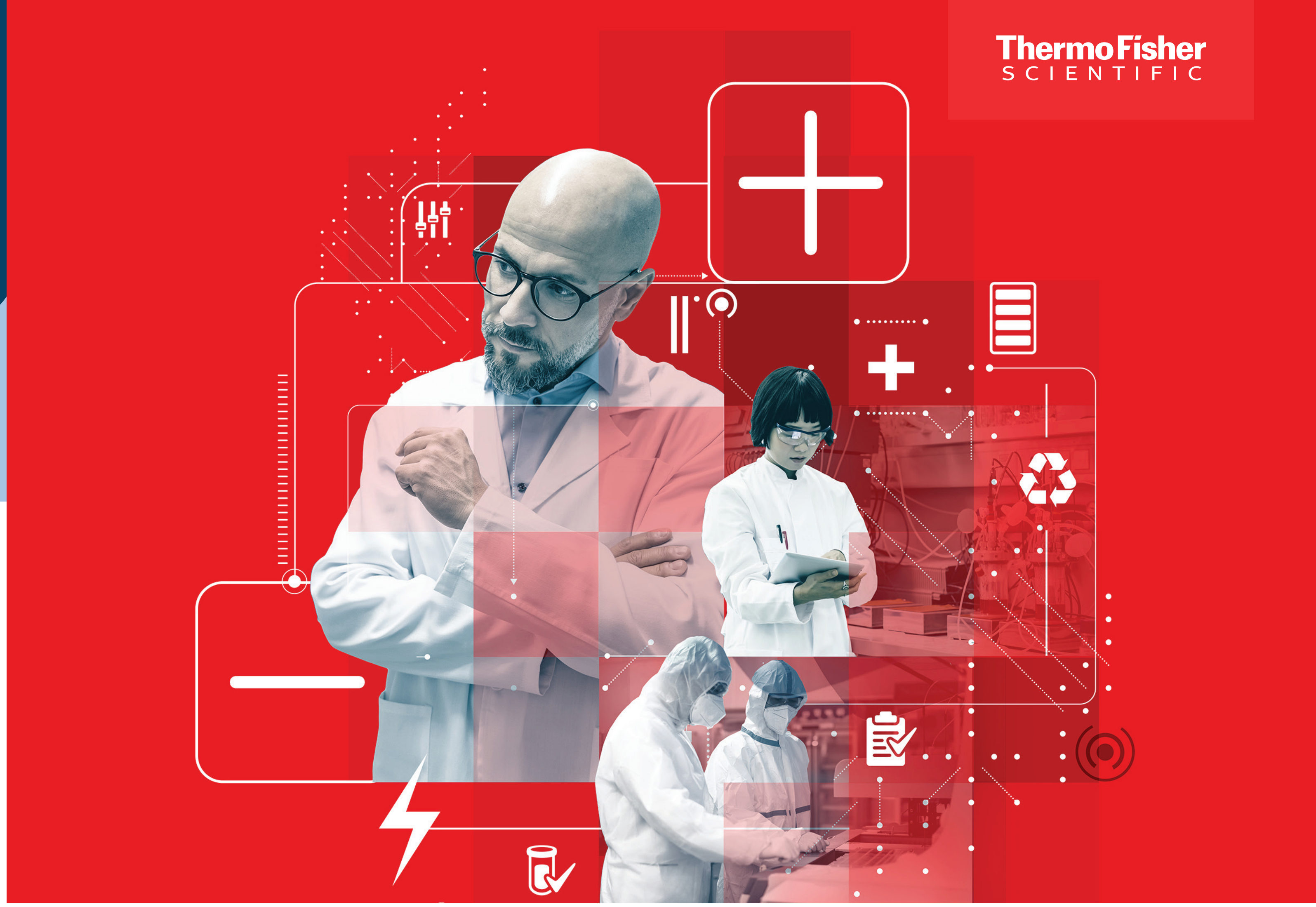

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