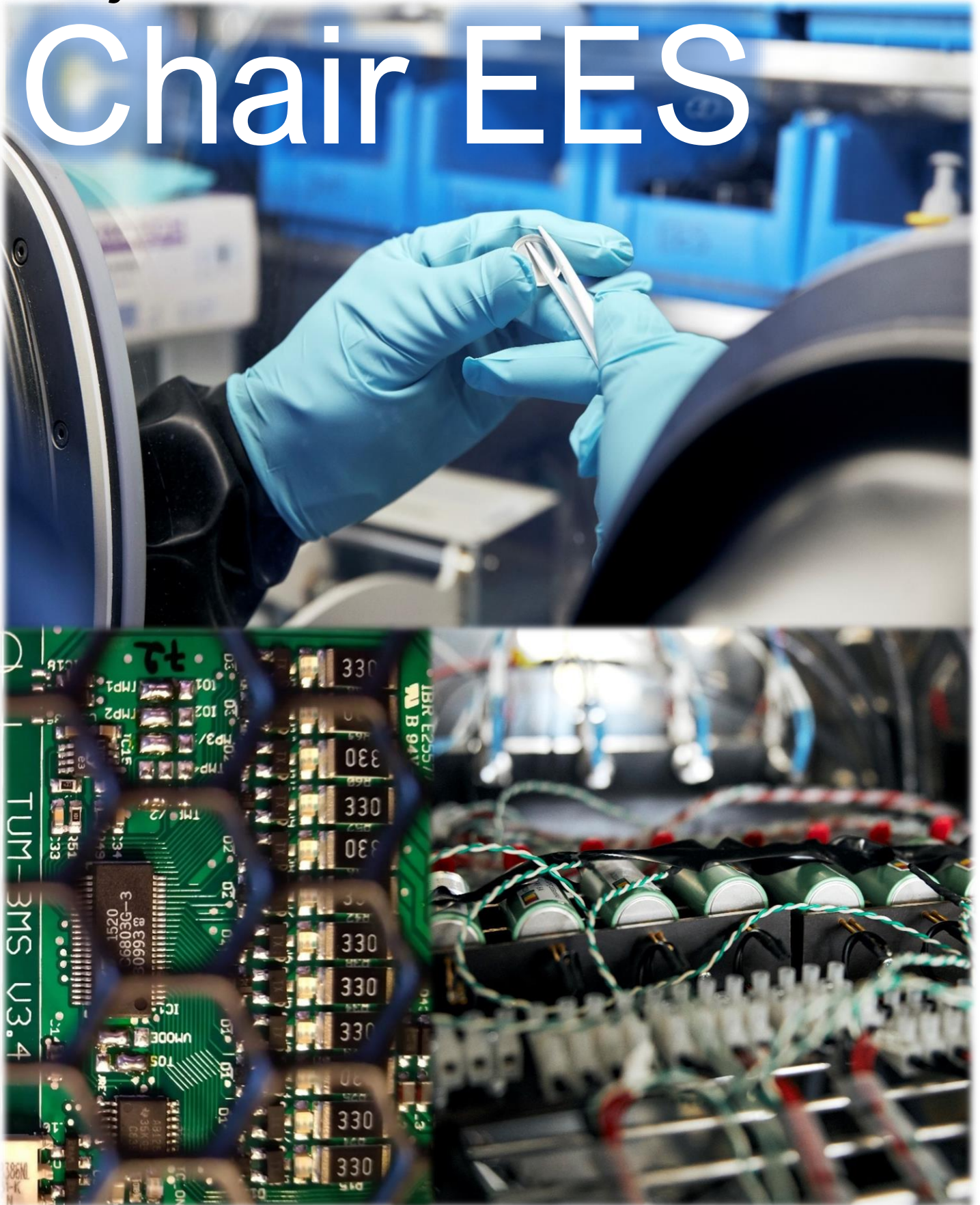


10 years of Chair EES



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Greetings from Professor Jossen

The Chair of Electrical Energy Storage Technology (EES) was founded in May 2010 to strengthen research on electric vehicles at TUM, with particular focus on battery engineering. In 2011 the chair became part of the Singaporean project TUM Create and participated in the development of the electric car "EVA". In the course of the project we developed a 150 kW fast charging regime, which in only 15 minutes could provide enough charge for a 200 km drive range. From 2013 onwards, in addition to batteries for electric vehicles, stationary energy storage systems and their applications in provision of ancillary services for grid stabilization, as well as behind-the-meter applications such as residential battery systems with photovoltaic solar have been part of our research portfolio.

The research topics of the chair are related to cell and system modelling and simulation, measurement technologies for Li-ion cells, battery management, charging methods, battery lifetime and safety investigations as well as topics related to the integration of stationary energy storage systems in the electric grid.

Over the last 10 years we have developed strong networks, not only inside the Electrical and Computer Engineering Department and within the TUM as a whole, but also nationally and internationally, linking with such world leading research partners as the NTU and NUS in Singapore, Imperial College London, the NREL in the USA and Tsinghua University in Beijing. Inside the TUM we are both a member and a co-founder of the TUM.Battery network, as well as a member of the Munich School of Engineering. We work closely with the departments of Mechanical Engineering, Chemistry and Physics. The majority of our funding is provided by the Federal Ministry of Education and Research, the Federal Ministry for Economic Affairs and Energy, the state of Bavaria, the European Union and industrial partners. Most projects are related to electric vehicles or stationary energy storage systems or can be placed in a more general context of battery cell development.

Another important task of the chair is the education of young engineers and scientists. The majority of both the students working on their master theses and the research associates doing their doctoral theses will move on to work in the field of battery storage systems, most typically in the automotive industry.

In the years to come, we will see a strong increase in the number of electric vehicles and the use of renewable energies worldwide. Our mission is to improve the efficiency, the performance, the safety and the reliability of energy storage systems. We aim not only to improve existing systems, but also to accelerate the development of these new technologies, and in doing so, achieve a faster transition to a more electric world.



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The First 10 Years of the Chair EES

- 2010** Appointment of Professor Jossen as head of the Chair of Electrical Energy Storage Technology (EES) at the Technical University of Munich (TUM).
- 2011** Start of TUM CREATE (Singapore), supervision of the research projects Energy Storage Engineering & Energy Storage Systems.
- 2012** Management of the newly-founded Center of Excellence for Battery Cells at the TUM, ExZellTUM.
- 2013** Management of the new interdisciplinary research project EEBatt involving thirteen research groups at the TUM as well as industry partners.
- Demonstration of the electric taxi EVA developed by TUM CREATE at the Tokyo Motor Show.
- 2015** Appointment of Professor Jossen as Editor of the journal “MDPI Batteries”.
- Organization of the 1st International Battery Safety Workshop (IBSW).
- 2016** Founding of Li.plus GmbH, the first start-up spin off from the chair as part of the EXIST program of the German Federal Ministry for Economic Affairs and Energy.
- 2017** Establishment of an additional laboratory within the TUM Research Center for Energy and Information.
- Organization of the 2nd International Battery Safety Workshop (IBSW) in Albuquerque, New Mexico, USA.
- 2018** Founding of Battery Dynamics GmbH, a second spin-off of the chair.
- 2019** Founding of crino GmbH and m-Bee (now STABL) GmbH, both spin-offs from the chair and beneficiaries of the EXIST program.
- Formation of the TUM.Battery network with the EES as one of eight founding chairs at TUM.
- 2020** Co-coordination of the competence cluster "Battery Usage Concepts" as part of the "Battery Research Factory" framework of the German Federal Ministry of Education and Research.
- Integration of the EES into the Department of Energy & Process Engineering at the TUM School of Engineering & Design.

Facts & Figures

Cumulative figures for the 10-year period from 2010 – 2020.

* with a cumulative funding of roughly € 13.5 m

**R&D
Projects***

41

**Battery Test
Channels**

610

**Journal
Publications**

124

**Doctoral
Dissertations**

26

Master Theses

268

Diploma Theses

40

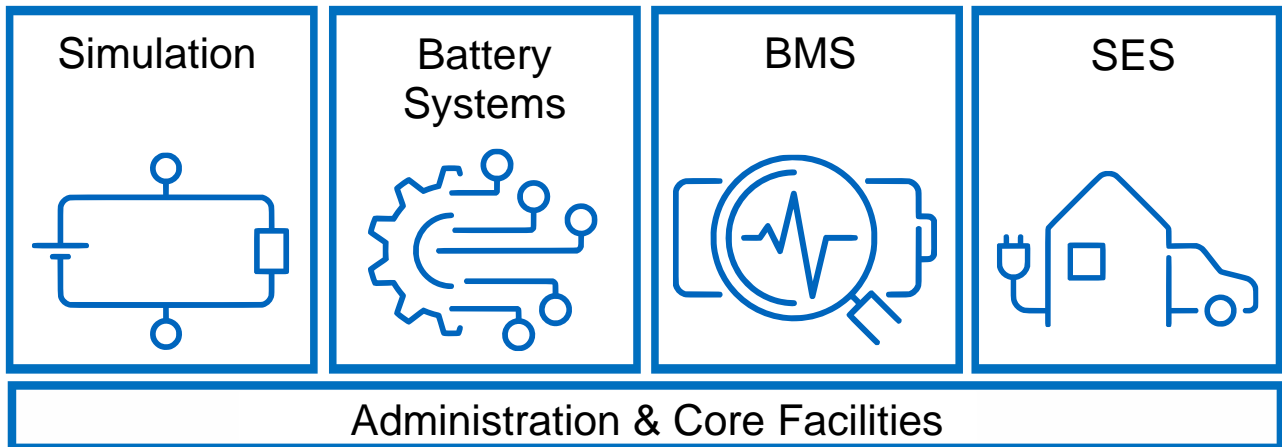
Bachelor Theses

172

Examinations

9280

Research Groups



Research at EES is conducted within four research groups focusing on broad aspects of battery research. Crucial collaboration and support from the administration, technical staff and laboratory facilities enables cutting-edge research to take place smoothly at the chair.

Simulation (SIM)

With spatially resolved and detailed physicochemical models, the electrochemical, mechanical, and thermal properties of lithium-ion batteries are investigated in order to understand, describe and optimize the underlying mechanisms. The scope of modeling and simulation typically includes experimental validation using various test setups.

Battery Systems (SYS)

The interdisciplinary team Battery Systems investigates all electrical, thermal and mechanical issues, which arise during the development and operation of modern battery systems. The scope of research covers the optimization of thermal management systems, safety behaviour, aging, cell-to-cell inhomogeneities, impact of mechanical stress and the design of cell connectors.

Battery Management Systems (BMS)

Battery management systems are an essential part of every large battery pack. The team investigates batteries on the cell level using a large range of both established and novel characterization methods. The development of advanced algorithms for battery state estimation and safety monitoring based on experimental insights is a central aim.

Stationary Energy Storage Systems (SES)

Multiple applications for stationary energy storage systems are emerging as we transition to renewable energies. The team derives models of electrochemical and chemical energy storage systems, and validates these with in-house experimental data and industrial partners. Economically and ecologically optimal sizing and operation of storage units is discussed in a variety of framework conditions.

Members of the Chair



Head of the Chair

Prof. Dr.-Ing Andreas Jossen

Dr.rer.nat. Holger Hesse

Research Management

Dr.rer.nat. Gudrun Rahn-Koltermann

Administrative Staff

Carolin Nierwetberg

Anne Diehl

Stefanie Käfer

Technical Staff

Jens Dietrich

Korbinian Schmidt

Research Staff

Andreas Aufschläger

Felix Bauer

Nils Collath

Axel Durdel

Stefan Englberger

Alexander Frank

Sven Friedrich

Elisabeth Gillich

Thomas Heil

Philipp Jocher

Ludwig Kraft

Daniel Kucevic

Alexander Kunz

Sebastian Ludwig

Marc Möller

Erfan Moyassari Sardahaei

Andreas Noel

Andreas Oberbauer

Anupam Parlikar

Thomas Roth

Maximilian Scheller

Markus Schindler

Julius Schmitt

Jonas Soellner

Franz Spingler

Marco Steinhardt

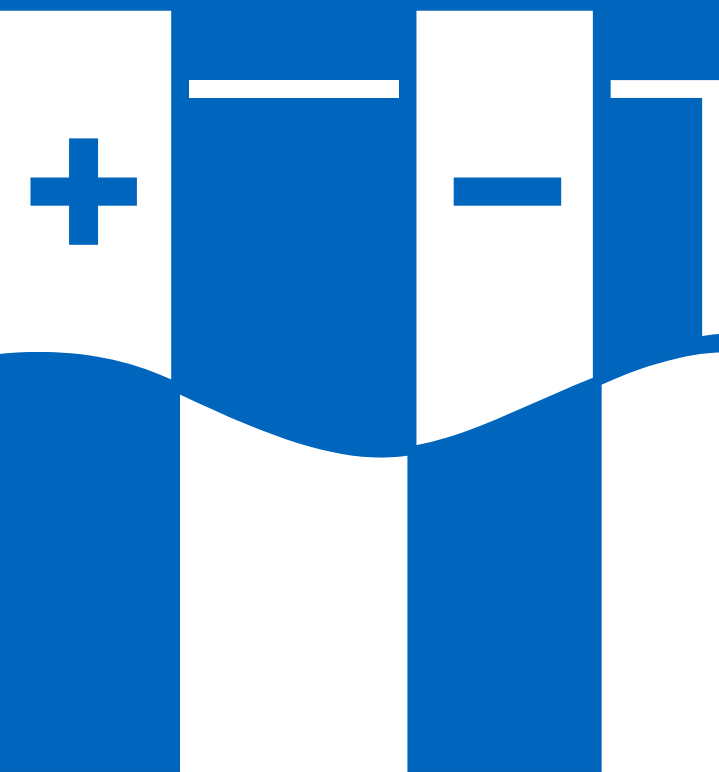
Luiza Streck

Johannes Sturm

Benedikt Tepe

Yulong Zhao

Ilya Zilbermann



Research Activities

Experimental research activities are conducted in laboratories operated by the EES and by partner institutes. The laboratories are located at three locations – at the main EES premises (Karlstr. 45 in Munich, Germany), at the TUM main campus (Arcisstr. 21 in Munich, Germany), and at the Research Centre for Energy and Information (Lichtenbergstr. 4a in Garching, Germany). The four research groups at EES engage in highly collaborative research across the entire chain in battery research.



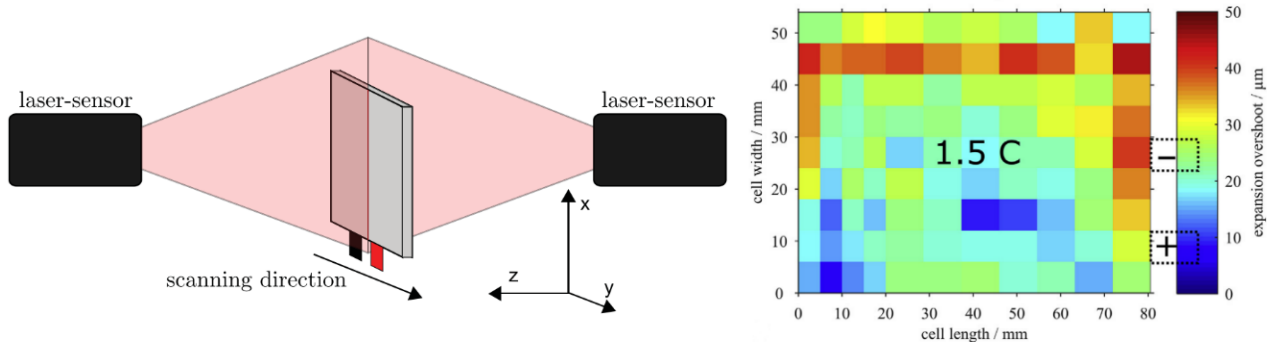
Research associates at the Research Centre for Energy and Information.



Electrochemical Impedance Spectroscopy (EIS) measurements being carried out within a temperature-controlled environment.

Modeling, Simulation and Validation

Mechanical Aspects of Battery Performance



Schematic of 2D Laser-Scanning setup for the measurement of local cell expansion during operation (left) and local expansion overshoot of a pouch cell during high-current charging (right).

Researchers

Andreas Aufschläger
Sven Friedrich
Erfan Moyassari
Maximilian Scheller
Franz Spingler
Johannes Sturm

Publications

Y. Zhao, F. Spingler et al., Localized Swelling Inhomogeneity Detection in Lithium-Ion Cells Using Multi-Dimensional Laser Scanning, J. Electrochem. Soc., 2019.

F. Spingler et al., Optimum Fast Charging of Lithium-Ion Pouch Cells Based on Local Volume Expansion Criteria, J. of Power Sources, 2018.

J. Sturm et al., Non-Destructive Detection of Local Aging in Lithium-Ion Pouch Cells by Multi-Directional Laser Scanning, J. Electrochem. Soc., 2017.

B. Rieger et al., A New Method to Model the Thickness Change of a Commercial Pouch Cell during Discharge, J. Electrochem. Soc., 2016.

B. Rieger et al., Strain Propagation in Lithium-Ion Batteries from the Crystal Structure to the Electrode Level, J. Electrochem. Soc., 2016.

Mechanical Characterization from Particle to Cell Level

Intercalation electrodes used in lithium-ion cells expand and contract upon charging and discharging. This creates mechanical stress as cells are confined by their individual cell casings, and typically embedded in modules. Depending on the electrode material, the magnitude of the reversible volume change varies considerably.

One important objective is to understand the implications of electrode volume change and mechanical stress on the performance, safety and lifetime of batteries.

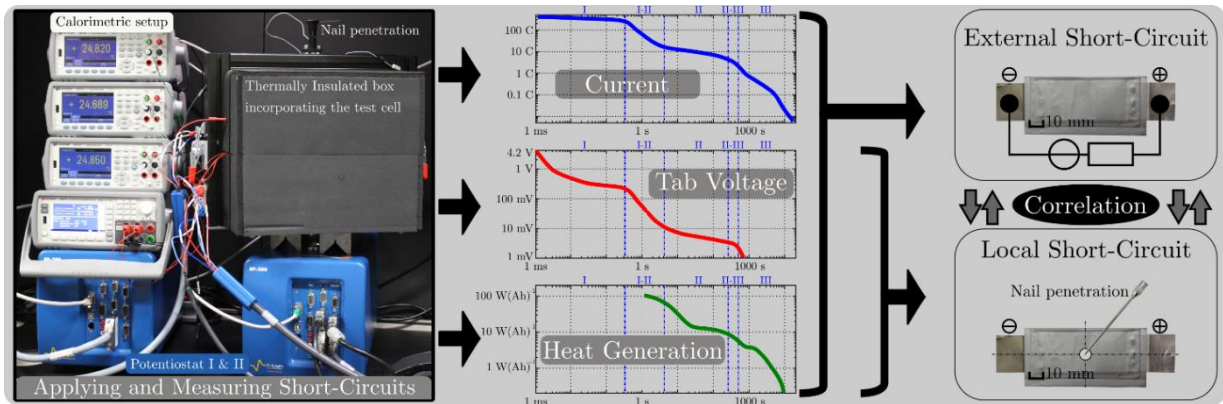
Characterization of the mechanical behavior at particle, electrode and cell level is carried out. This is done via in-situ X-ray diffraction (for particles), in-situ precision dilatometry (for electrodes) and various cell-level test setups which have been developed in-house, such as a 2D laser scanner to measure local cell expansion and various test benches that control cell expansion while measuring the resulting loads.

Modeling of Mechanical-Electrochemical Interactions

We also use coupled physicochemical-mechanical models to understand how cell expansion and external loads affect local current densities, overpotentials, material strain and stress, deterioration processes and the lifetime of lithium-ion batteries.

Modeling, Simulation and Validation

External and Local Short-Circuit Scenarios in Lithium-Ion Batteries



Test-bench (left) for applying external and local short-circuit scenarios to lithium-ion batteries. Measurement of current flux, tab voltage, and heat generation (center) facilitate correlation between external and local short-circuits (right).

Applying External and Local Short-Circuit Conditions

Emulating true, field-like internal short-circuits (ISCs) with experimental methods is a complex task with mostly unsatisfactory outcomes. However, understanding the evolution and impact of ISCs is crucial to mitigate safety issues related to lithium-ion batteries. Local short-circuit (LSC) conditions can be applied to pouch-type cells in a quasi-isothermal test-bench using the nail/needle penetration approach. Cell impedance, capacity, and the contact resistance at the penetration site are the main determinants of short-circuit current. This in turn largely determines the terminal voltage and heat generation rate associated with polarization effects and electrochemical rate limitations. It has been shown by both potentiostatic and calorimetric measurements that similar short-circuit behavior can be induced by external short-circuits (ESCs) at various short-circuit resistances.

As a result, local short-circuits caused by the needle penetration can be emulated by an ESC test with an appropriately chosen external resistance.

Modeling and Simulation of Short-Circuit Scenarios

Insights into the local potential distribution across the electrodes help to evaluate the measured electrical potentials of an externally and locally triggered shorting scenario. With the aid of multidimensional, multi-physics models, the resulting local polarization effects across the electrodes can be simulated and the short-circuit intensity can be correlated.

Researchers

Johannes Sturm
Sven Friedrich
Erfan Moyassari
Thomas Roth
Alexander Rheinfeld*

Publications

A. Rheinfeld et al., Quasi-Isothermal External Short-Circuit Tests Applied to Lithium-Ion Cells: Part I. Measurements, J. Electrochem. Soc., 2018.

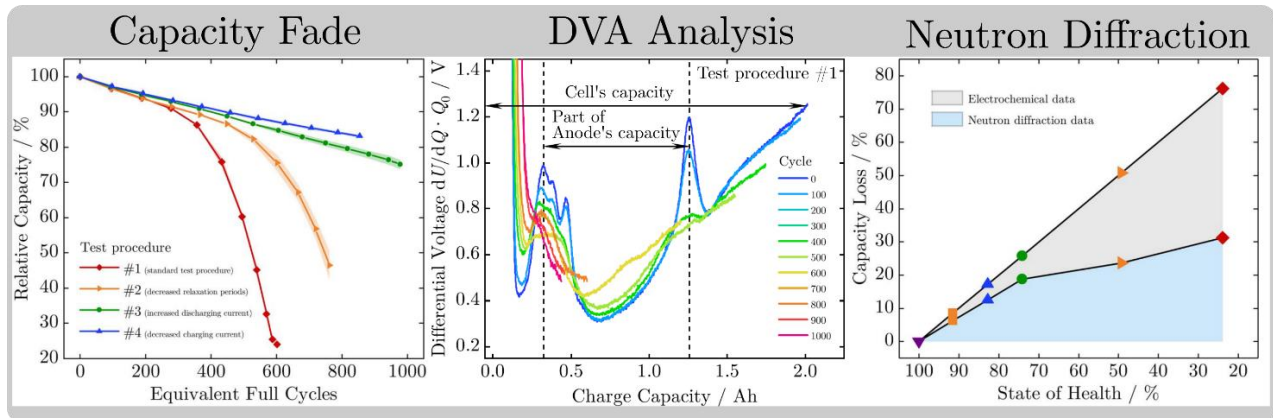
A. Rheinfeld et al., Quasi-Isothermal External Short-Circuit Tests Applied to Lithium-Ion Cells: Part II. Modeling and Simulation, J. Electrochem. Soc., 2019.

J. Sturm et al., On the Impact of the Locality on Short-Circuit Characteristics: Experimental Analysis and Multi-physics Simulation of External and Local Short-Circuits Applied to Lithium-Ion Batteries, J. Electrochem. Soc., 2020.

* Researchers graduated in 2019, and do not currently work at the Chair.

Modeling, Simulation and Validation

Aging Phenomena in Lithium-Ion Batteries



Results of an aging study applied to commercial, 18650-type C/NMC-111 lithium-ion cells reveal linear and non-linear aging capacity fade mechanisms (left), shifts and shrinkages in the differential voltage analysis curve (DVA, center), and correlation between capacity fade determination using potentiostatic methods ('Electrochemical') and neutron diffraction analysis (right).

Researchers

Franz Spingler
Markus Schindler
Luiza Streck
Jonas Keil
Christian v. Lüders*

Publications

J. Keil et al., Linear and Nonlinear Aging of Lithium-Ion Cells Investigated by Electrochemical Analysis and In-Situ Neutron Diffraction, J. Electrochem. Soc., 2019.

C. von Lüders et al., Modeling of Lithium Plating and Lithium Stripping in Lithium-Ion Batteries, J. of Power Sources, 2019.

F. Spingler et al., Capacity Recovery Effect in Commercial LiFePO₄ / Graphite Cells, J. Electrochem. Soc., 2020.

M. Naumann et al., Analysis and Modeling of Cycle Aging of a Commercial LiFePO₄/Graphite Cell, J. of Power Sources, 2020.

Aging Studies

For practical purposes, aging of lithium-ion cells typically implies capacity fade and power fade. In experimental studies, we seek to characterize capacity and power fade as a function of operating conditions and to ascertain the underlying electrochemical processes.

For this purpose, we use a variety of experimental and analytical methods, e.g. differential voltage analysis, high-precision coulometry, impedance spectroscopy, neutron diffraction, scanning-electron microscopy or X-ray spectroscopy.

Argon-filled gloveboxes allow us to safely open aged cells for examination and to further characterize the aged electrodes via fabrication of coin cells.

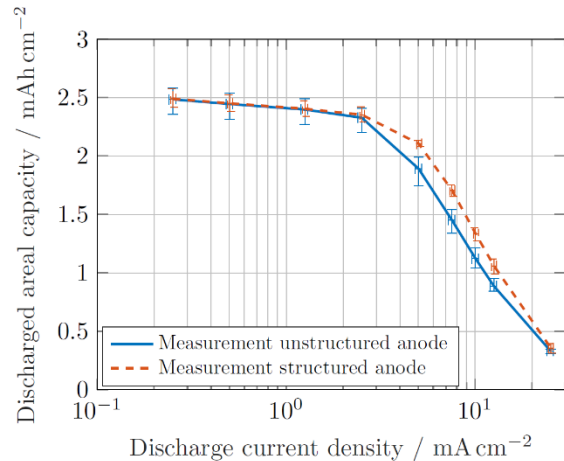
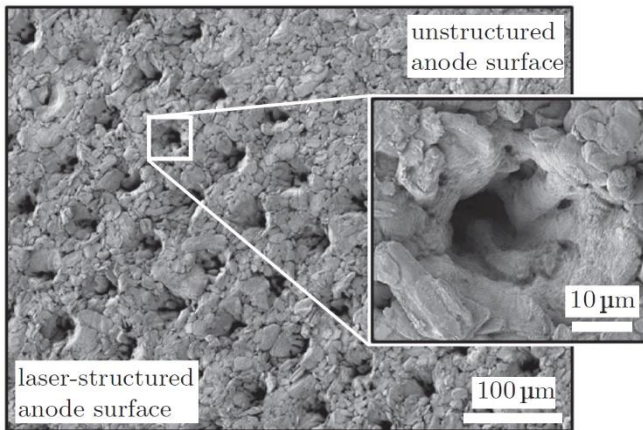
Empirical to Physics-Based Aging Modeling

We use empirical data to develop application-oriented models, i.e. for economic analyses, which predict performance parameters as a function of operating conditions over a battery's lifetime.

In contrast, physicochemical models are used to gain a better understanding of individual aging processes such as solid-electrolyte interphase growth and lithium plating.

Modeling, Simulation and Validation

Structured Electrodes for Enhanced Battery Performance



Scanning Electron Microscope (SEM) image of a laser-structured anode with structured and unstructured parts (left), and measured discharge capacity of cells comprising of unstructured and structured anodes (right).

Laser-Structuring of Electrodes

High charge and discharge currents can lead to transport limitations in the liquid electrolyte of lithium-ion cells. This effect is especially pronounced in graphite anodes with flake-like particles, which result in highly tortuous pathways in the through-plane direction of the electrode. Structuring electrodes helps to overcome this limitation by providing enhanced transport pathways for the lithium-ions. A femtosecond laser was used to produce hexagonal patterns of hole-like structures in graphite anodes. These are depicted in the left figure. The performance increase for discharge currents higher than 2.5 mA cm^{-2} or 1C in cells containing structured anodes can be seen in the figure on the right.

Modeling and Simulation

The underlying mechanisms responsible for the performance increase of cells containing structured anodes were identified by means of modeling and simulation. At low discharge rates the structuring process exerts very little influence, because the discharge process is not limited by lithium-ion transport. At higher currents, lithium-ion gradients in the graphite anode build up and limit the discharge process. Structured anodes with a reduced tortuosity enhance lithium-ion transport, decrease the resulting overpotentials and allow more capacity to be discharged from the cell before the cutoff voltage is reached.

Researchers

Ludwig Kraft
Alexander Frank
Alexander Rheinfeld*

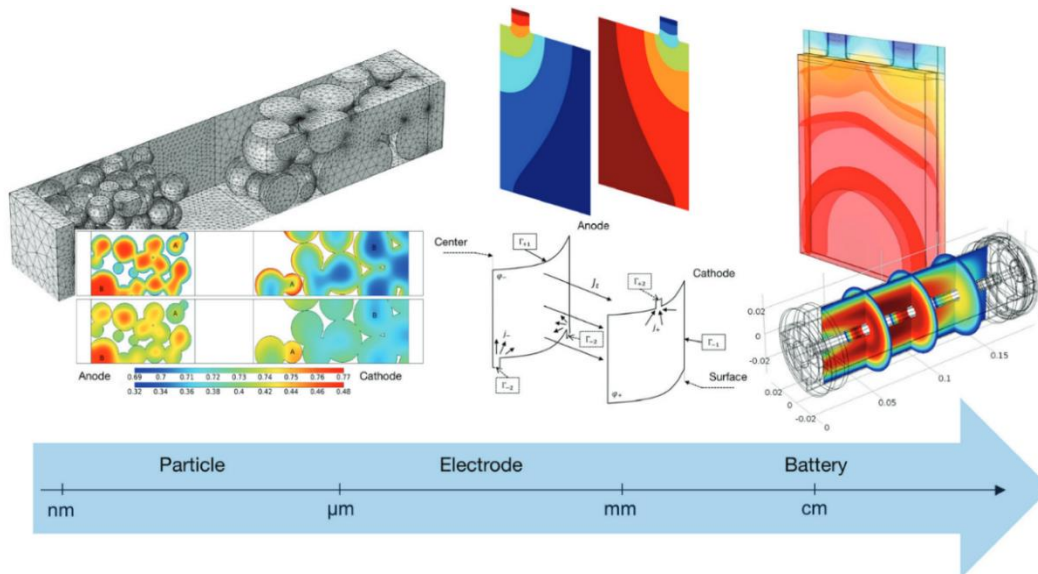
Publications

J. Habedank, L. Kraft et al., Increasing the Discharge Rate Capability of Lithium-Ion Cells with Laser-Structured Graphite Anodes: Modeling and Simulation, J. Electrochem. Soc., 2018.

L. Kraft et al., Modeling and Simulation of Pore Morphology Modifications using Laser-Structured Graphite Anodes in Lithium-Ion Batteries, J. Electrochem. Soc., 2020.

Modeling, Simulation and Validation

Multi-Scale Modeling and MuDiMod



Researchers

Alexander Frank
Johannes Sturm
Yulong Zhao
Alexander Rheinfeld*

Publications

S. Kosch et al., A Computationally Efficient Multi-Scale Model for Lithium-Ion Cells, J. Electrochem. Soc., 2018.

J. Sturm et al., Modeling and Simulation of Inhomogeneities in a 18650 Nickel-Rich, Silicon-Graphite Lithium-Ion Cell during Fast Charging, J. Power Sources, 2019.

A. Rheinfeld et al., Impact of Cell Size and Format on External Short-Circuit Behavior of Lithium-Ion Cells at Varying Cooling Conditions: Modeling and Simulation, J. Electrochem. Soc., 2020.

Multi-Scale Models

Multi-dimensional modeling is a powerful approach to access internal variables such as current density or temperature distribution within lithium-ion batteries. By coupling models acting at differing length scales, a comprehensive insight into batteries can be established at a reduced computational cost.

MuDiMod Framework

The MuDiMod consists of three different submodels that can be classified as:

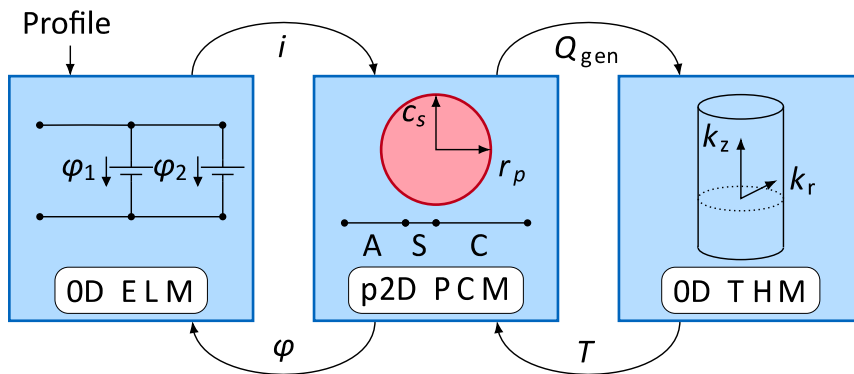
- Physico-chemical (p2D in the electrode and separator domain)
- Electrical (2D in the current collector domain) and
- Thermal models (3D in the entire cell domain)

The submodels are coupled either via scaled average values using a current balancing method or via node values using linear interpolation of the respective model variables of interest.

A thorough description of the cell behavior during operation can be performed while limiting computational cost by efficiently sectioning and discretizing the model geometry. It can be solved for cylindrical, prismatic and pouch geometries, for different electrode designs and tab configurations and under various operating conditions.

Modeling, Simulation and Validation

Serial and Parallel Connection of Battery Cells



Scheme of the electrical-physicochemical-thermal coupled simulation model (left) and the custom-made test bench for validation measurements (right).

Modeling and Simulation of Parallel Connected Systems

As cells with sufficient capacity are not yet established on the market, parallel connection is currently the preferred method to increase a battery system's capacity. One of the greatest uncertainties of parallel connections is the resulting inhomogeneous current distribution, which can be caused by both the connection properties and variations between cells. To study the causes of inhomogeneous current distribution, a model for describing serial and parallel connected battery cells during operation was developed. The multidimensional multi-physics model includes a physicochemical model describing the electrochemical behavior of each cell. The electrical model accounts for the conservation of electric charge and energy between the cells to reach electrical consistency according to the respective module topology and cell interconnections. Additionally, the thermal model quantifies the thermal behavior of each cell as well as external influences such as cooling strategies.

Validation through Test Bench Measurements

Systems connected in serial and parallel are often only examined by simulation. However, the validation of the findings using a test bench is crucial. The developed test bench therefore offers the possibility to measure the influence of the connection properties, varying system resistances and temperature gradients on current distribution. To this end, cell temperatures and path resistances can be adjusted individually for up to six cells. The test bench is suitable for both cell formats, 18650 and 21700.

Researchers

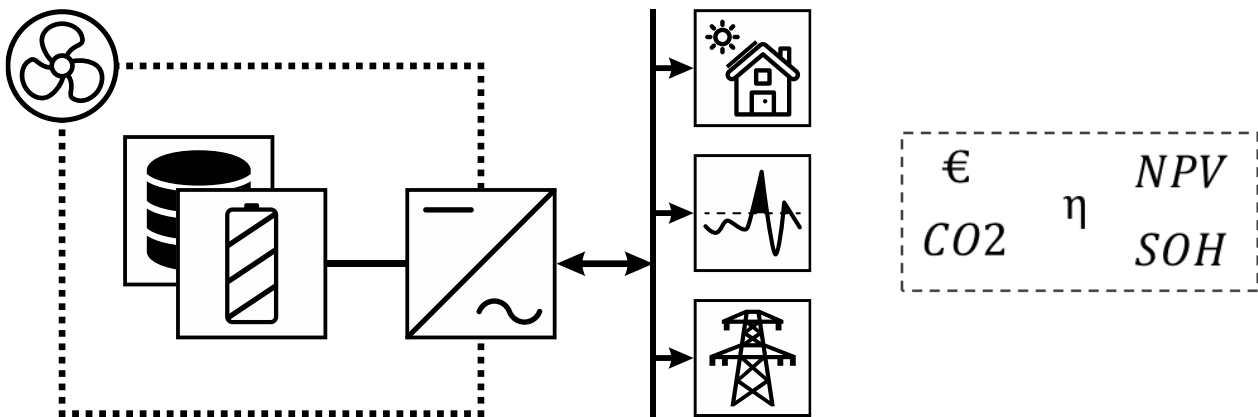
Markus Schindler
Axel Durdel

Publications

K. Rumpf et al., Influence of Cell-to-Cell Variation on the Inhomogeneity of Lithium-Ion Battery Modules, J. Electrochem. Soc., 2018.

M. Schindler et al., On the impact of Cross-Linking and Connection Properties on the Current Distribution in Lithium-Ion Battery Modules, (*submitted, in review*), 2020.

Stationary Energy Storage Systems



Researchers

Holger Hesse
Daniel Kucevic
Stefan Englberger
Anupam Parlikar
Benedikt Tepe
Marc Möller
Nils Collath

Publications

H. Hesse et al., Lithium-Ion Battery Storage for the Grid – A Review of Stationary Battery Storage System Design Tailored for Applications in Modern Power Grids, MDPI energies, 2017.

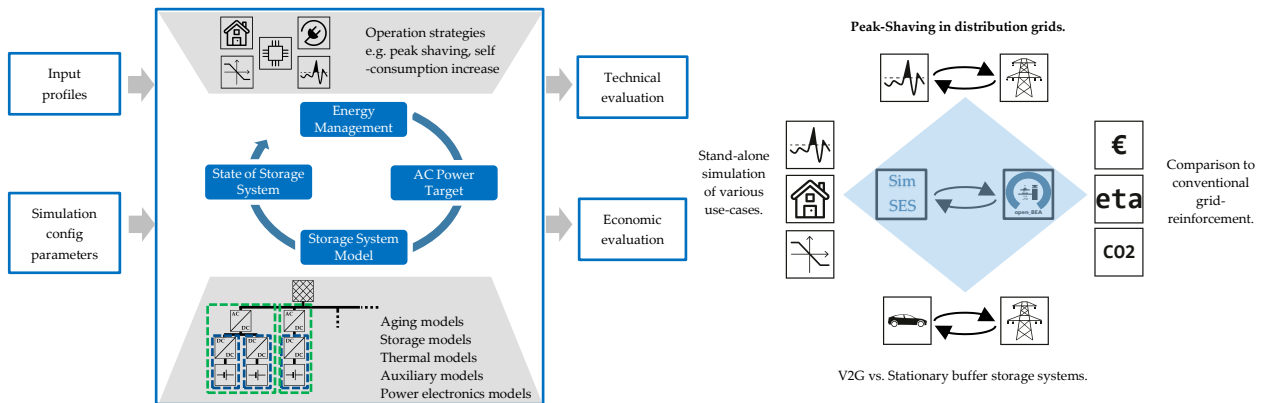
Stationary energy storage systems have garnered increasing interest for their potential to support the electricity grid. In particular, systems based on lithium-ion batteries have evolved rapidly with a wide range of cell technologies and system architectures available on the market. Other storage options, such as redox-flow batteries and power-to-gas are of increasing interest. Further challenges exist in deploying stored energy as different user needs imply distinct demands on and require distinct properties of the storage system.

The stationary energy storage systems (SES) team investigates the characteristics and performance of storage systems in the above-mentioned applications and derives sets of technical, economic and ecological key performance indicators. It uses simulation models ranging from cell level to system level to develop efficiency loss analyses and degradation tracking. Parametrization is carried out using in-house measurements and via data-driven approaches. Peripheral issues related to storage including thermal management and inverter coupling are reviewed and analyzed.

Storage systems are employed for distinct applications such as increasing self-consumption from residential PV, industrial peak-shaving and provision of a frequency containment reserve. The team therefore develops operational strategies tailored for each individual use case. At the same time, new algorithmic approaches are implemented to address the challenge of distributing an application over multiple storage systems (swarm-storage) and to enable storage systems to serve multiple use cases in sequential or even concurrent fashion (multi-use operation).

A set of modeling and optimization tools (time-series modelling, linear and non-linear programs) have been developed by the team. These tools aid in ascertaining the optimal storage type, sizing, position and dispatch operation for a given task.

Modeling Battery Storage



Software for Techno-Economic Simulation of Stationary Energy Storage Systems (SimSES)

SimSES is a time-series based simulation tool for energy storage systems. With detailed models of power electronics and storage technologies set up in various topologies, long term simulations are conducted in order to examine the behavior of storage systems over a variety of applications. Aging effects and efficiency as well as economic aspects are analyzed. Furthermore, the detailed thermal behavior of the system and the storage technology is modeled. Lithium-ion batteries with different cell chemistries, redox flow batteries as well as power-to-Gas models with electrolyzers and fuel cells can be evaluated. A hybridization of all modeled storage technologies is possible in order to analyze advanced energy storage systems. SimSES is available as an open-source tool and can be integrated into other software tools.

Coupling of Power Grid and Storage Modeling Tools

As part of the project open_BEa, a holistic open-source modeling tool is being developed in cooperation with the Reiner Lemoine Institute Berlin and ZAE Bayern. SimSES is linked to a distribution grid model in order to analyze the effects of storage systems in different application modes on the power grid. The resulting software tool can be used to model how stationary storage systems should to be optimally positioned, dimensioned and operated in order to provide grid-related services or defer conventional grid reinforcement. Furthermore, the effects of increasing electric mobility (electric vehicles, storage buffer assisted charging stations) can be evaluated. In open_BEa standard battery profiles for various applications have also been defined and made available on an open-source basis.

Researchers

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Daniel Kucevic
Benedikt Tepe

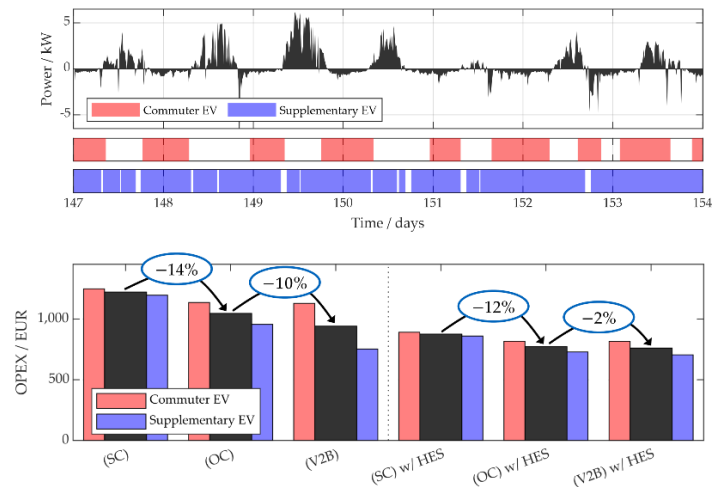
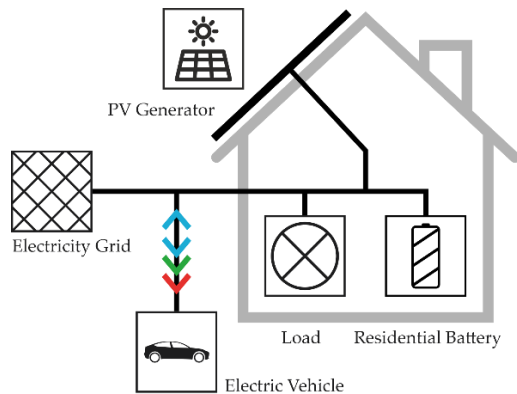
Publications and Open Source Tools

Open-source Modelling Tool
SimSES: www.simSES.org

M. Naumann et al., SimSES: Software for Techno-Economic Simulation of Stationary Energy Storage Systems, International ETG Congress, Berlin, Germany, 2017.

D. Kucevic et al., Standard Battery Energy Storage System Profiles: Analysis of Various Applications for Stationary Energy Storage Systems using a Holistic Simulation Framework, Journal of Energy Storage, 2020.

Optimizing the Energy Management



Researchers

Stefan Englberger
Holger Hesse

Publications

H. Hesse et al., Economic Optimization of Component Sizing for Residential Battery Storage Systems, MDPI energies, 2017.

S. Englberger et al., A Techno-Economic Analysis of Vehicle-To-Building: Battery Degradation and Efficiency Analysis in the Context of Coordinated Electric Vehicle Charging, MDPI energies, 2019.

S. Englberger et al., Simses Multi-Use: A Simulation Tool for Multiple Storage System Applications, 16th International Conference on the European Energy Market, Ljubljana, September, 2019.

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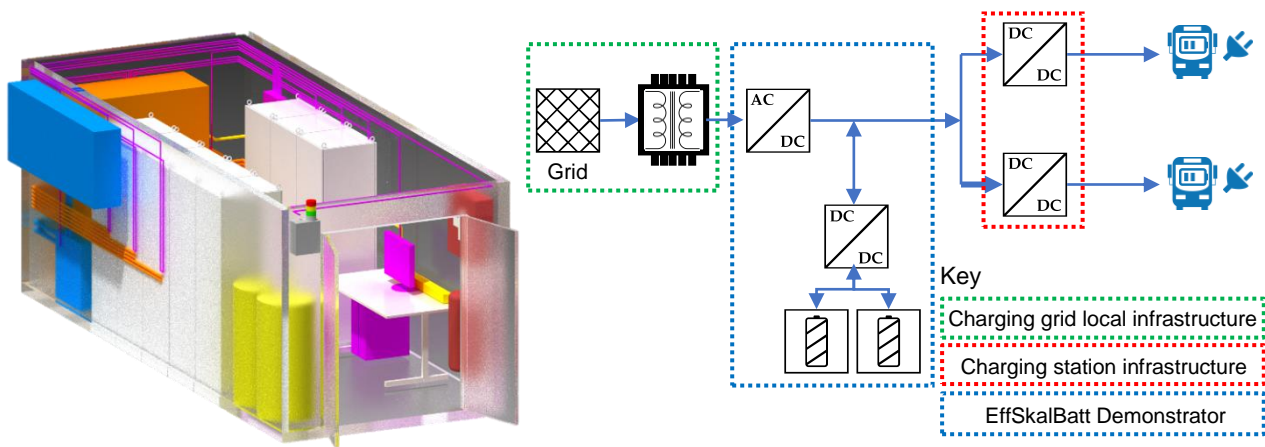
Size and Dispatch Optimization

In order to find the most suitable configuration, component sizing, and energy management operation, the team defines appropriate optimization problems, which are then solved with linear and mixed-integer linear programming algorithms. Using this strategy, cost-optimal sizing of battery and inverter components are determined. In addition, a dispatch strategy that considers degradation and dissipation losses is derived for a use case involving arbitrage. For all use cases, the tradeoff between degradation costs and attainable profits is optimized. Forecast errors are addressed through sensitivity analyses and statistical methods to counteract uncertainties.

Multi-Use and Multi-Storage Optimization

With efficient optimization algorithms, multiple applications are stacked and simultaneously serviced using a single storage system. Dynamic multi-use strategies enable significant increases in the economic potential of the storage device while optimizing its technical performance. To find the best solution, both the energy and power capacities of the storage device are allocated to multiple applications, including spot market trading, a frequency containment reserve, peak shaving, self-consumption increase, and the compensation of reactive power. In addition to the consideration of multi-use operation strategies, the optimization of multiple interconnected storage systems is also studied. This strategy taps into and utilizes the flexibility of not one, but multiple, battery storage systems.

Storage Demonstration and Monitoring



EffskalBatt: EES possesses expertise in design and assembly of grid-connected stationary BESSs. The demonstrator system 'Energy Neighbor' - built within the project 'EEBatt', was tested under real-world operating conditions at a site in Moosham, Bavaria. This system is to be repurposed within the 'EffSkalBatt' project to house a new demonstrator system, which will investigate important aspects relating to the use of second-life automotive battery packs for peak-load shaving. This system is to be installed at a city bus depot in Munich to aid in the charging of electric bus fleets.

SmartB4P: A holistic control strategy for behind-the-meter battery energy storage systems is currently being developed and will be validated through field tests at manufacturing facilities of industry partners. Special emphasis is placed on degradation modeling, inclusion of loads with demand side management in the control strategy and investigating the use of machine learning for controlling the system.

CoSES: A microgrid demonstrator has been installed at the TUM Munich School of Engineering. Multiple battery storage systems are currently being connected to an array of interlinked components including PV-panels, combined heat and power systems, synthetic loads, an electric vehicle charging station as well as specialized modules to emulate the storage, supply and demand for energy in the form of heat. The test facility allows the modeling and testing of five highly interconnected households with battery storage.

Researchers

Anupam Parlikar
Nils Collath
Marc Möller

Publications

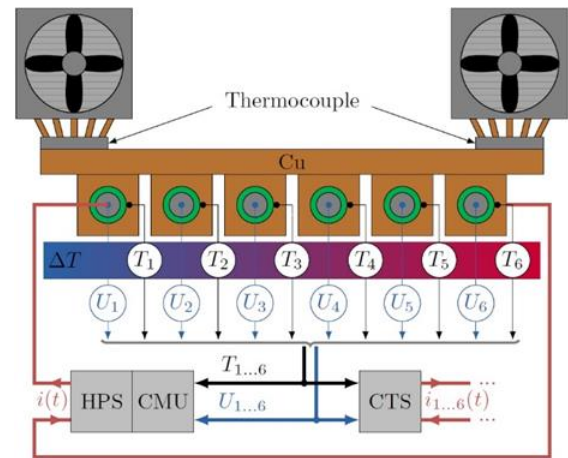
M. Schimpe et al., Energy Efficiency Evaluation of a Stationary Lithium-Ion Battery Container Storage System via Electro-Thermal Modeling and Detailed Component Analysis, Journal Applied Energy, 2018.

A. Parlikar et al., Topology and Efficiency Analysis of Utility-Scale Battery Energy Storage Systems. In: Proceedings of the 13th International Renewable Energy Storage Conference (IRES), Atlantis Highlights in Engineering, 2019.

BMS Module and Algorithm Testing Platforms



Modular EES BMS with several PCBs



Schematic of the battery module test bench

Researchers

Ilya Zilberman
Sebastian Ludwig
Johannes Sturm

Publications

I. Zilberman, S. Ludwig et al., Cell-to-Cell Variation of Calendar Aging and Reversible Self-Discharge in 18650 Nickel-Rich, Silicon-Graphite Lithium-Ion Cells. *Journal of Energy Storage*, 2019

J. Sturm, S. Ludwig et al., Suitability of Physicochemical Models for Embedded Systems Regarding a Nickel-Rich, Silicon-Graphite Lithium-Ion Battery. *Journal of Power Sources*, 2019

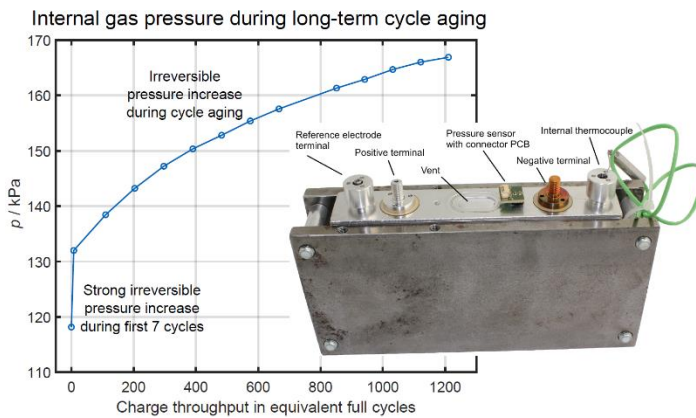
I. Zilberman, S. Ludwig et al., Online Aging Determination in Lithium-Ion Battery Module with Forced Temperature Gradient, *Journal of Energy Storage*, 2020

One of the main research interests of the battery management systems (BMS) team is use-case state estimation at both the cell and module levels. To have a flexible testing and validation platform, a proprietary modular BMS (figure on the left) was developed at EES. A rack-based system for plug-in printed circuit boards (PCBs) allows the BMS setup to be adapted to different test scenarios. The PCB hardware is separated between a common computational and interface PCB and an application PCB with specific functionalities, such as different kinds of balancing or voltage measurement circuits. A mutual backplane provides a power supply and data buses for communication with other PCBs or external bus participants.

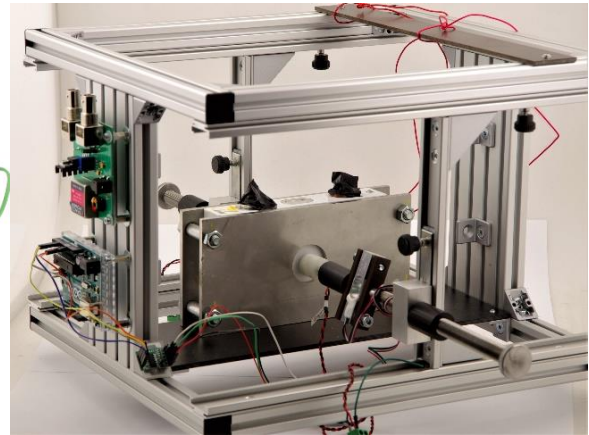
First usage of the platform was made by using a precise voltage measuring PCB to determine the reversible self-discharge. In cooperation with the simulation team, the micro-processor of the computation and interface PCB was used for benchmarking different variations of reduced order electrochemical cell models.

Since temperature plays a major part in aging and safety-related topics for lithium-ion cells, a battery module test bench (figure on the right) with an adjustable temperature gradient was developed at EES. In combination with either the modular BMS or commercial cell testers, the effects of temperature gradients on small modules or single cells can be investigated. The module test bench was used for evaluating an online algorithm, which uses cell balancing to detect temperature-induced aging differences in a module.

Novel Battery Sensors



Internal gas pressure during long-term cycle aging



Test bench for ultrasonic measurements

Together with partners from industry, the BMS team develops and evaluates large sized battery cells with integrated or attached sensors. These sensors enable the measurement of internal physical quantities such as temperature inside the jellyroll, the potential of a reference electrode or the gas pressure inside a cell. The team develops methods that use this additional information for both online state estimation and safety monitoring as well as to gain deeper insights into the processes occurring inside battery cells.

Furthermore, the team employs novel methods such as ultrasonic measurements, which have until now been rarely used in the field of batteries. These measurements use a pair of ultrasonic transducers to emit ultrasonic pulses on one side of the battery which are then recorded on the opposite face, thereby measuring the time of flight and attenuation of the pulse. Variations in these quantities are linked to mechanical changes in the cell, which are caused by cycling and aging. In order to evaluate and improve the efficacy of the ultrasonic measurements, a test apparatus has been developed by the group which allows closer control of the sensor positions and mounting pressure and use of high voltage excitation signals.

Researchers

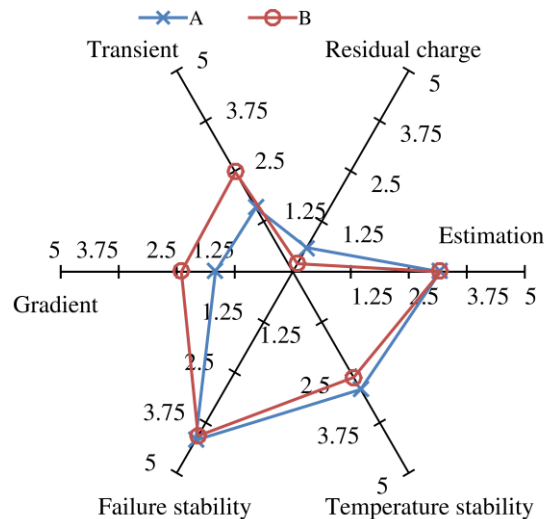
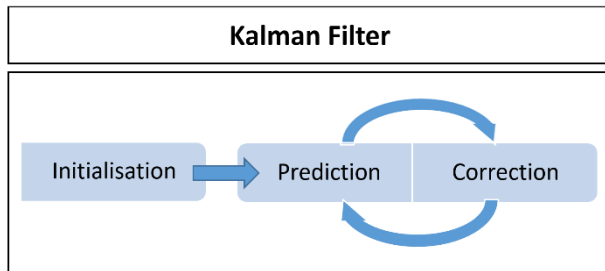
Sebastian Ludwig
Julius Schmitt
Andreas Oberbauer

Publications

J. Schmitt, B. Kraft et al., In-situ Measurement of Gas Pressure Inside Prismatic Lithium-Ion Cells during Operation and Abuse Scenarios, *Batterieforum Deutschland* 2019, 2019.

S. Ludwig, J. Schmitt et al., New Method for Analysing Ultrasonic-based Measurements for Lithium-Ion Batteries, *Kraftwerk Batterie* 2019, 2019.

State Estimation and Validation



Researchers

Julius Schmitt
Andreas Oberbauer

Publications

C. Campestri et al., Validation and Benchmark Method for Battery Management System Functionalities: State Estimation Algorithms, Journal of Energy Storage, 2016.

C. Campestri et al., A Comparative Study and Review of Different Kalman Filters by Applying an Enhanced Validation Method, Journal of Energy Storage, 2016.

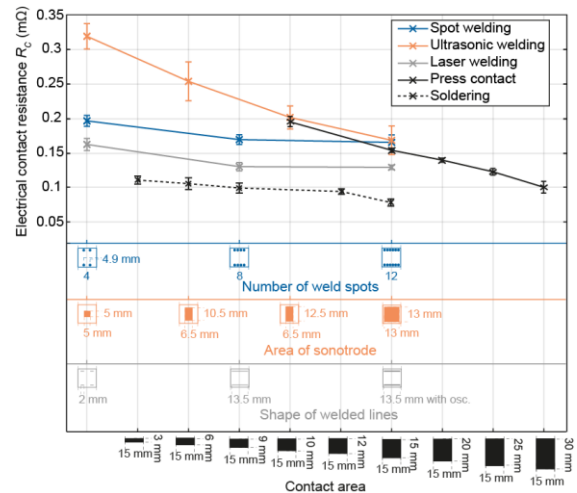
One of the central aims in battery research is to test the health of a battery. To achieve this, electrical characteristics, such as the state of charge or the state of health are measured with scientific measurement devices such as battery testers and electrochemical impedance spectroscopes supplied by BaSyTec or Gamry Instruments. The results help us to develop models and algorithms to monitor batteries using real-time battery management. In order to demonstrate the accuracy of the models, a validation and benchmarking method has been introduced at the Chair. For this purpose, we recommend three different validation profiles. One for weakly dynamic behavior, one for highly dynamic behavior and a profile for long term stability. Each algorithm is applied to each profile and is subsequently graded relative to its performance in various categories including estimation accuracy and transient behavior. The publication detailing the method in full has been listed to the left, and the validation profiles are accessible to the public via the homepage of the chair.

A commonly used algorithm for state estimation is the Kalman Filter in its different forms. The filter works using a recursive prediction-correction structure and can be applied to linear as well as nonlinear models. The previously mentioned validation and benchmark method was then used to perform a comparative study of the different filters. The method demonstrates a similar estimation accuracy and indicates the importance of filter tuning.

Current distribution in Parallel Connected Cells



Testbench to measure the current distribution within two parallel connected cells with optional individually controlled temperature of each cell.



Comparison of brass samples connected by soldering, spot welding, ultrasonic welding, laser beam welding, and press contact with regards to contact area.

Large battery systems require a high number of cells connected in series and parallel. Parameter variations between cells connected in parallel and their connection can lead to inhomogeneous current distribution as well as inhomogeneous aging of the cells. The resistance of soldered, spot welded, ultrasonic welded, laser beam welded, and press contacted cells have been investigated at EES. The short-term consequences of varying resistance and capacity of parallel connected battery cells have also been examined. The factors influencing current distribution in parallel connected cells have also been analysed.

The next challenge is understanding the aging of parallel connected cells and the measurement of low ohmic connections. This should indicate the factors leading to convergence or divergence of the current distribution across the cells with reference to the chosen connection.

Researchers

Philipp Jocher
Markus Schindler
Markus Hofmann

Publications

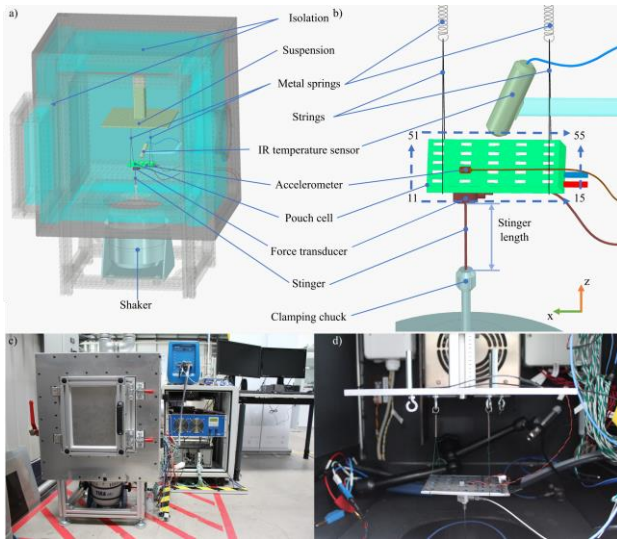
M. J. Brand et al., Current Distribution Within Parallel-Connected Battery Cells, Journal of Power Sources, 2016.

M. J. Brand et al., Detachable Electrical Connection of Battery Cells by Press Contacts, Journal of Energy Storage, 2016.

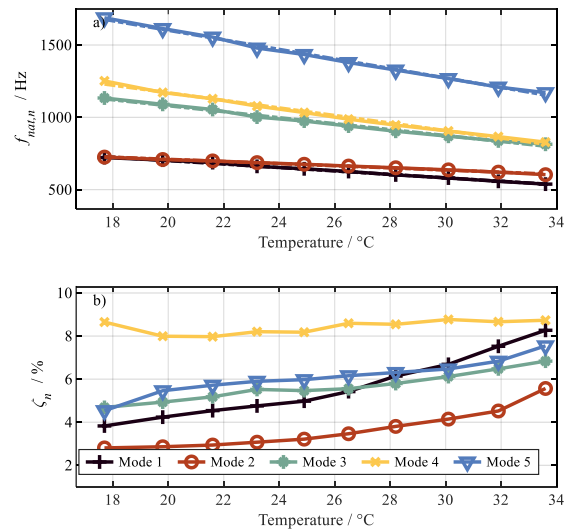
M. J. Brand et al., Electrical Resistances of Soldered Battery Cell Connections, Journal of Energy Storage, 2017.

M. Hofmann et al., Dynamics of Current Distribution Within Battery Cells Connected in Parallel, Journal of Energy Storage, 2018.

Structural Dynamics of Lithium-Ion Cells



Schematic and depictions of the test bench and setup: a) temperature-controlled safety chamber with shaker and measurement setup, b) zoom on measurement setup with the cell as SUT and DOF location matrix, c) complete test bench setup photography, d) photography of the cell under test inside the safety chamber.



Variation of temperature showing a high sensitivity of both a) natural frequencies $f_{nat,n}$ with linear fits (dashed line) and b) damping ratios ζ_n .

Researchers

Jonas Soellner
Philipp Berg

Publications

P. Berg et al., Structural Dynamics of Lithium-Ion Cells - Part I: Method, Test Bench Validation and Investigation of Lithium-Ion Pouch Cells, Journal of Energy Storage, 2019.

P. Berg et al., Structural Dynamics of Lithium-Ion Cells - Part II: Investigation of Large-Format Prismatic Cells and Method Evaluation, Journal of Energy Storage, 2020.

P. Berg et al., Durability of Lithium-Ion 18650 Cells under Random Vibration Load with Respect to the Inner Cell Design, Journal of Energy Storage, 2020.

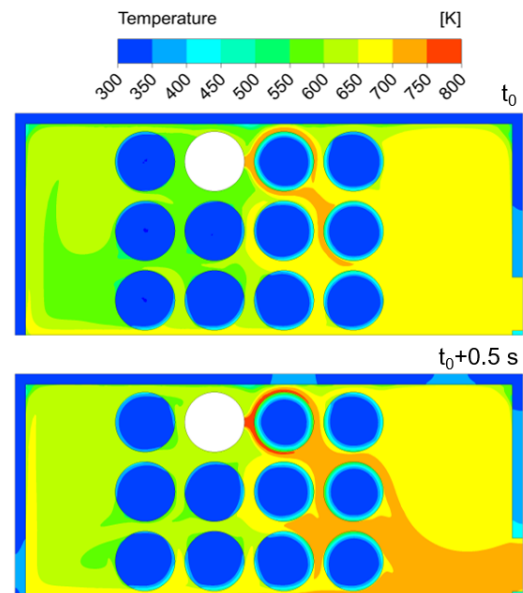
The failure mechanisms that govern the durability of lithium-ion cells under vibration loading are inadequately understood. For effective durability testing, it is essential to comprehend which factors might affect cell damage and fatigue. Experimental modal analysis is used to reveal the structural dynamics of lithium-ion pouch cells in terms of natural frequencies, damping ratios, and mode shapes. A test bench for free-free testing has been developed and validated at EES.

Dependences on cell parameters such as state of charge, state of health, temperature, and on excitation amplitude were established. Strong sensitivity of the structural response to excitation amplitude due to nonlinear softening and nonlinear damping was found. Significant softening with a linear relationship to increasing temperature, most probably due to changes in the visco-elasticity of the separator, was also observed. In contrast, the state of charge showed only minor sensitivity to temperature, whereas cyclic aging caused a strong increase in stiffness of the cells. These results can be used to build finite element simulation models to complement vibration durability research, to define which parameter sensitivities might determine the level of fatigue during vibration testing and to test the impact of high dynamic stress on lithium-ion pouch cells through resonance excitation.

Thermal Runaway Propagation



Fresh commercial cylindrical lithium-ion battery (at the top) and a battery after a thermal runaway showing side rupture (at the bottom).



Temperature results of CFD-model showing the thermal runaway propagation inside an almost fully enclosed battery module. The module consists of twelve serial connected cells with one thermal runaway triggered cell.

Battery systems are not only expected to be compact, but also intrinsically safe. Under improper operating conditions, as well as due to unsuitable storage and manufacturing defects, Li-ion batteries can enter a state of thermal runaway (TR) which results in overheating and can potentially lead to fire, smoke or explosion. TR in a single cell can propagate to adjacent cells and may destroy an entire storage system. Due to the resource intensive nature of thermal propagation testing for large and complex systems, modeling and simulation can deliver insights into TR and its propagation, with significantly lower resource consumption.

If no gas release due to cell bursting or side rupture is expected, conventional standard thermal models can be utilised to predict TR propagation. If cell venting occurs, around 70 to 80 % of the accumulated heat is released with the gas. Our team simulates TR propagation using a CFD model to simulate the flow of gas. For the model to be effective, information about the venting process and gas characteristics, e.g. temperature, velocity and mass flow rate, are required. Armed with the information about the effects of venting which is gleaned from the model, the location of venting can be established, and mitigation strategies can be more effectively developed and investigated. Furthermore, a standard method to parametrize the model is also carried out.

Researchers

Elisabeth I. Gillich (maiden name Kolp)
Marco Steinhardt

Publications

E. I. Kolp et al., Thermal Modelling of Thermal Runaway Propagation in Lithium-Ion Battery Systems. Workshop: Safer Li-Ion Batteries, European Commission, 2018.

E. I. Gillich et al., Modeling Thermal-Runaway Propagation – Effect of Venting, Battery Safety Summit, Alexandria, 2019.

Laboratory Facilities

Custom Cell Manufacturing



Electrical Characterization



Thermal Characterization



Mechanical Characterization



Short-Circuit Analysis



Module- and Pack Testing



Mechanical Engineering

Korbinian Schmidt

Electrical Engineering

Jens Dietrich

Laboratory In-charge

Korbinian Schmidt

Franz Spingler

Andreas Aufschläger

Cell Manufacturing

A dedicated production line for laboratory cells enables the EES to investigate the entire battery lifecycle from manufacturing to post-mortem analysis. The produced cells range from coin cells to pouch cells of sheet sizes up to 250 mm x 300 mm.

Cell, Module and Pack Testing

Over 600 test channels are available for electrical characterization with a maximum current rating of 900 A for large format cells. Entire battery modules or packs can be analysed at up to 900 V and 400 A in a special high voltage laboratory. In addition, channels for high precision coulometry are available since 2020.

Specialized Testing

One of the core competences of the EES is the development of specialized test benches. One such testbench simulates various approaches to achieve cell cooling, ranging from convectional air cooling and liquid cooling to tab-cooling. Another testing rig tracks the volumetric work of the cell during cycling using a laser to scan the surface with an accuracy of 2 μm . A recently developed test bench allows for mechanical characterization by applying an external pressure of up to 3 MPa to the cell and recording its compression. For aging studies, mechanical compression can also simulate specific conditions inside battery modules. Processes that occur under external short-circuit conditions can be identified by a short-circuit tester.

International Collaboration

Project	Topic / Aim	Duration / Date	Partners	Financial Grant No.	Joint Publications
SPICY	Silicon and polyanionic chemistries and architectures of Li-ion cell for high energy battery	01.05.2015 – 31.07.2018	CEA, vito, IK4 CIDETEC, RECUPYL, PROLLiON, TUM, KIT, TEKNA, beLife, EMPA, Kurt Salmon, PEP, Hahn Schikard	The European Commission under grant No. 653373	M. Schimpe et al., Comprehensive Modeling of Temperature-Dependent Degradation Mechanisms in Lithium Iron Phosphate Batteries, J. Electrochem. Soc., 2018.
EVERLASTING	Electric Vehicle Enhanced Range, Lifetime And Safety Through INGenious battery management	01.09.2016 – 31.08.2020	vito, CEA, SIEMENS, TUM, TÜV SÜD Battery Testing, ALGOLiON, LION Smart, RWTH AACHEN University	The European Commission's Horizon 2020 under grant No. 713771	M. Schimpe et al., Energy Efficiency Evaluation of a Stationary Lithium-Ion Battery Container Storage System via Electro-Thermal Modeling and Detailed Component Analysis, Applied Energy, 2018.
HighSafe	Sustainable, environmentally friendly, safe, and high energy density lithium batteries: materials, cells and models	01.11.2017 – 31.10.2020	<u>From Germany:</u> ZSW, HIU (KIT) and TUM <u>From Taiwan:</u> NTHU, NUTN, NTUST and NCTU	German Federal Ministry of Education and Research „BMBF“ under grant No. 03XP0138B	Y. Zhao, F. Spingler et al., Localized Swelling Inhomogeneity Detection in Lithium-Ion Cells using Multi-Dimensional Laser Scanning, J. Electrochem. Soc., 2019.
International Battery Safety Workshop	Battery safety topics, such as definition of battery safety problems, evaluation and validation, as well as solutions to enhance battery safety	August 25 th till 26 th , 2015	International cooperation	US DOE and Ministry of Science and Education (BMBF)	W. Ai, L. Kraft et al., Electrochemical Thermal-Mechanical Modelling of Stress Inhomogeneity in Lithium-Ion Pouch Cells, J. Electrochem. Soc., 2019.
TUM CREATE (Singapore)	Collaboration in research areas including new battery materials, EV design, computer modelling and simulations, and transportation systems design	2010 – 2016	TUM and Nanyang Technological University (NTU) in Singapore	National Research Foundation of Singapore	
Collaboration with Imperial College	Exchange of knowledge, students and joint publications	Since 2017	TUM and Imperial College London, UK	Imperial-TUM Summer School Program	
Collaboration with Tsinghua University	Hosted joint-research stay for Prof. Zhe Li in Munich.	08.2017 – 10.2017	TUM and Tsinghua University, Beijing, China	Funded by Tsinghua University	
Exchange of PhD Students	Michael Schimpe Exchange of PhD Student and joint publications	08.2016 – 11.2016	National Renewable Energy Laboratory (NREL), USA	Funded by the project EEBatt (2013 - 2016)	
	Daniel Kucevic Exchange of PhD Student, Teaching Duties, and Joint-research	02.2020 – 03.2020	National University of Singapore (NUS), Singapore.	TUM Graduate School	

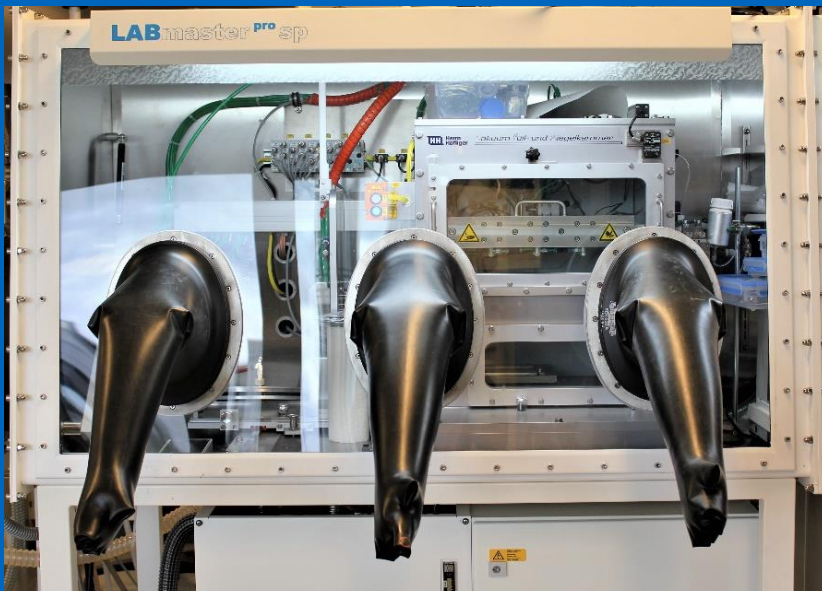


Projects at EES

Collaborative research is highly desired and actively encouraged by the Technical University of Munich. This not only includes collaboration among research groups at each institute, and with other institutes of TUM, but also within the scientific community at large. The EES, pursuant in this objective of establishing robust knowledge transmission linkages, works with a host of partner universities, research facilities, and corporate partners at the German, European and global level.

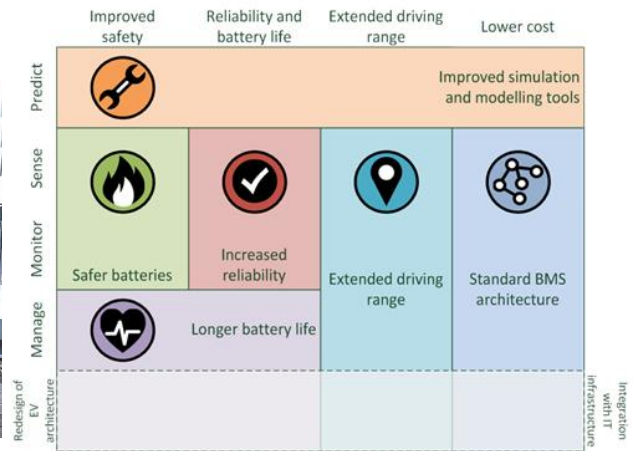
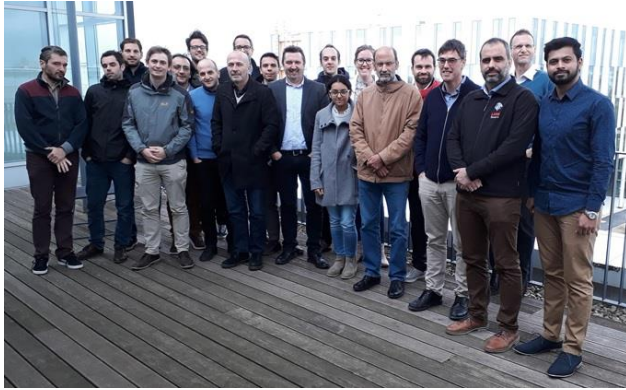


Cathode material being prepared for cell fabrication.



Electrolyte-filling and sealing station for pouch cells housed within a glove box.

EVERLASTING



Project Partners

Chair of Electrical Energy Storage Technology (EES)

Vlaamse Instelling voor Technologisch Onderzoek (VITO)

Commissariat à l'Energie Atomique et aux Energies Alternatives (CEA)

Siemens

TÜV SÜD Battery Testing

ALGOLiON

RWTH Aachen University

LION Smart

Eindhoven University of Technology (TU / e)

Voltia

VDL Enabling Transport Solutions

Funding

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 713771.

The EVERLASTING (Electric Vehicle Enhanced Range, Lifetime and Safety Through INGenious battery management) project will develop innovative technologies to improve the reliability, lifetime and safety of lithium-ion batteries by developing more accurate, and standardized, battery monitoring and management systems. This enables the prediction of battery behavior in all circumstances and over its full lifetime. It also assists in proactive and effective management of the batteries, leading to improved safety, reliability, and the prevention of problems, rather than solely their mitigation.

Moreover, by monitoring the interaction between the battery and the vehicle, more accurate range predictions can be made thereby reducing the range anxiety for the driver and allowing the battery to be kept in a safe and optimal operational state. This has the benefits of improving the lifetime of the battery (target +20%) and safe utilization of the battery to its full capacity, leading to lower overall costs. The EES contributes towards:

- Improved simulation and modeling tools to determine battery performance in all conceivable operating conditions over its entire lifetime
- Signal recording and use beyond the previous scope of standard signals (current-voltage-temperature)
- Monitoring the current state of the battery by evaluating sensor data
- Active and effective control of battery behavior based on an accurately determined actual state (efficient thermal management and charging strategies)
- Defining a standardized BMS structure and the necessary interfaces

Center of Excellence for Battery Cells at the
Technical University of Munich



The Center of Excellence for Battery Cells at the Technical University of Munich aggregates the complete process chain for the manufacturing of high-capacity electrical energy storage systems in one competence center. It was launched in 2012 and has demonstrated its continuing success by beginning its third phase in November 2019. The interdisciplinary competence center links the scientific and technical fields of chemistry, physics, electrical and mechanical engineering on one site.

Within the framework of the German Federal Ministry of Education and Research (BMBF) funding initiative "Competence Cluster for Battery Materials (ExcellBattMat)", the research focus of ExZeITUM III lies on the material, chemical and electrochemical characterization and analysis as well as the modeling of next-generation anode and cathode materials. On the cathode side, the focus is on over-lithiated and low-cobalt or cobalt-free NCM materials. These cathodes are combined with high capacity silicon anodes.

Further development of electrochemical models offers an opportunity for characterization and analysis of lithium-ion cells using next generation anode and cathode materials. The results can be fed directly into the BMBF innovation pipeline (ProZell cluster) in order to enhance the production of next generation lithium-ion cells and strengthen battery manufacturing in Germany. New findings will help to understand the aging mechanisms of anodes with a high silicon content ($\approx 70\%$) in large-sized lithium-ion cells and bring silicon anodes closer to the ultimate goal of commercialization.

Project Partners

Chair of Electrical Energy Storage Technology (EES)

Chair of Technical Electrochemistry (TEC)

Institute for Machine Tools and Industrial Management (*iwb*)

Research Neutron Source Heinz Maier-Leibnitz (FRM II)

Funding



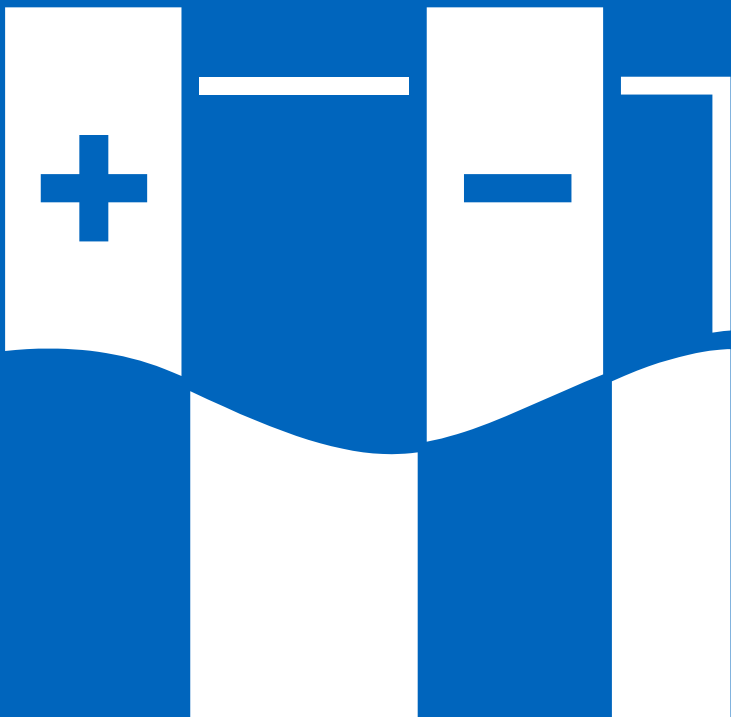
Federal Ministry
of Education
and Research

Running Projects

		Funding
Everlasting	Enhanced range, lifetime and safety through ingenious battery management for electric vehicles	EU
HighSafe	Sustainable, environmentally friendly, safe high-energy lithium-ion batteries: materials, cells and modeling	BMBF
ReViSEDBatt	Resonances, vibrations, shocks, external force application and detection methods for lithium-ion batteries	BMWi
INI.TUM II	End-of-life tests in battery production with simulation models	Industry
StorageLink	Prediction-based optimization of operating strategies for multi-use of large-scale energy storage systems	StMWi
OparaBatt	Optimal parallel connections of batteries	BFS
open_BEA	Integration and coupling of battery models with open-source grid models	BMWi
KlemA	Classification of electro-mechanical aging of lithium-ion cells	BMBF
InnoCase	Innovative housing concepts for large-format lithium-ion cells	BMBF
ProFeLi	Production techniques for solid-state batteries with lithium-metal anodes	BMBF
iMoBatt	Innovative integrated functional module design for modular battery packs	BMWi
EffSkalBatt	Efficient and scalable battery system design for stationary applications	BMWi
LImeS	Lithium-Ion cells for integration with enhanced sensor technologies	BMBF
SmartB4P	Smart battery control in industrial application scenarios	BFS
ExZellTUM III	Extension of ExzellTUM II	BMBF
Tandem project with University of Applied Sciences, Munich	Mobility and transport research	BayWiss

Completed Projects

QaliBat	Methods for battery quality control	Industry
Pilebi	Charge algorithms for NiMH batteries	Industry
LiSSi	Investigation into Lithium-Sulfur technology	BMBF
VisioM	Novel concepts for electric vehicles in urban areas	BMBF
SafeBatt	Active and passive measures for inherently safe batteries	BMBF
ExZellTUM I & II	Excellence centre for battery cells at TUM	BMBF
ABattReLife	Second-life investigations	BMW
ESPEN	Comparison of electrochemical energy storage with other technologies	BMW
FORELMO	Electric powertrains of tomorrow	BFS
PowerLab	Competence centre for hybrid and fully-electric aviation powertrains	StMW
DriveBattery	Investigations into large-scale and modular battery systems	BMW
DriveBattery II	Modular battery technology based on parallel/series connection of high-voltage batteries	BMW
iHEM	Intelligent home energy management system and optimization	BMW
Spicy	Silicon and polyanionic chemistries, architectures of Li-ion cells for high-energy batteries	EU
MiBZ	Multi-functional intelligent battery cells	BMBF
EffiForm	Efficient cell production for enhanced lifetime, reliability, safety and cost reduction	BMBF
NexHOS	Achievable yields of automotive batteries in stationary applications	Industry
DIMG – EMS	Planning and design of control, prediction and optimization for island microgrids with distributed energy storage systems for reduction of diesel generator usage	BMBF
Battery-Testing	Performance and lifetime testing of battery cells for industrial partners	Industry
Application-Study	Achievable yields of automotive batteries in stationary applications	Industry
Home-Battery-Study	Diverse system-related investigations into energy storage systems	Industry
INI.TUM	Lithium-Ion cells for application in electric and hybrid commercial vehicles	Industry
Second-Life-Studie	Second life concepts for lithium-ion cells from electric vehicles	VDE
Grid-Control-Study	Research questions around grid frequency regulation with energy storage systems	Industry
Cell-Formation-Study	Literature review into cell formation and end-of-line tests for lithium-ion cells	Industry
Researcher Mobility Funding	Electrical short-circuit of lithium-ion cells	Bay-France



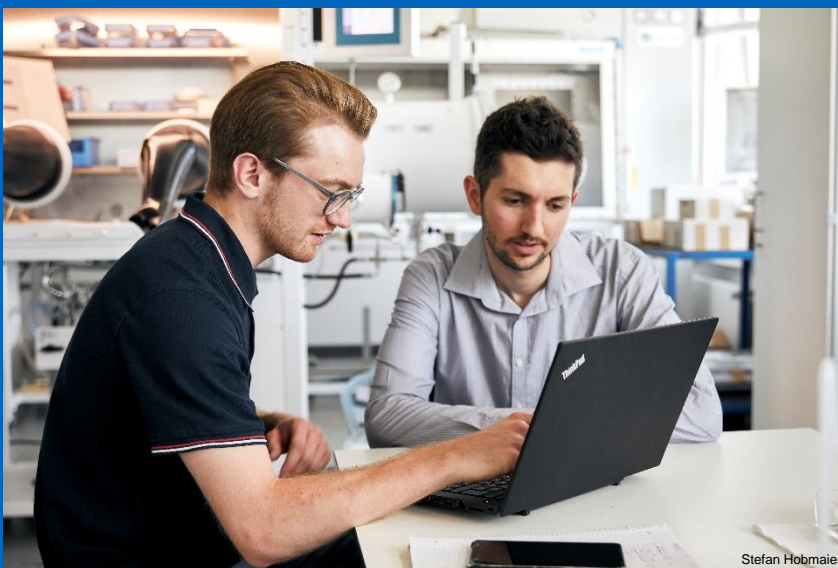
Teaching at EES

The Chair of Electrical Energy Storage Technology offers TUM students a variety of lectures, seminars and practical courses in the field of electrical energy storage. Most of our students are typically pursuing a degree with the department of electrical engineering, but a large part of our teaching program is also open to students of mechanical engineering and management and technology programs.

Propelled by the Energiewende (german for 'Energy Transition') and very favorable employment prospects in the industry, student interest in this field has been high. Each year, our staff supervises around 40 student theses and 20 research internships. Around 70 students per annum benefit from our practical courses and another 40 participate in seminars. Roughly 1000 written exams are administered every year.

We also actively support the student hands-on projects eCARus and TUfast, in which students develop and build battery powered electric vehicles.

On the international level, we are committed to teaching as part of the Bachelor's program at TUM-ASIA in Singapore.



Hands-on teaching in the laboratory.

Stefan Hobmaier

Teaching

Bachelor

Fundamentals of Electrical Energy Storage

This course covers basic concepts of energy storage. Participants learn the physics behind a variety of energy storage technologies such as pumped-storage hydroelectricity and compressed air.

Photovoltaic Stand-Alone Systems

How do we combine solar generators with batteries to supply electrical energy in off-grid areas? The working principles of solar generators, charge controllers and lead-acid batteries as well as system dimensioning and economic evaluation are covered.

Electrical Energy Technology (TUM-ASIA Singapore)

Held in Singapore as part of the TUM-ASIA program, this lecture covers generation of electrical energy, energy storage and electric traction systems.

Master

Battery Systems

The fundamentals of electrochemical energy storage and their application to batteries. Different battery technologies, materials, cell design and characterization methods are reviewed in-depth.

Battery System Technology

Battery module and pack design as well as operational aspects of battery systems like charging methods, detection and monitoring of state variables, temperature control and safety precautions.

Grid Integration of Stationary Energy Storage Systems

Selected energy storage technologies and potential applications in grid energy storage are introduced. Based on current examples, students learn how to evaluate storage systems from a combined technological and economic perspective.

Innovative Concepts for Energy Storage (Lecture Series)

In this lecture series, the latest trends in energy storage technologies are explored from fundamentals to products, along with business models of start-up companies from the Munich area.

Energy Storage

Participants learn about the principles and application of various energy storage systems from electric, magnetic and hydraulic to mechanical storage systems. This lecture is open exclusively to students of the Master's program Power Engineering (MSPE).

Teaching

Laboratory Courses

Electrical Energy Storage Lab

In this laboratory course, students learn the appropriate handling of battery cells and testing equipment. Fundamental and advanced characterization methods and cell technologies are reviewed in theory and practice.

Modeling of Lithium-Ion Cells Lab

After some specific classes on physico-chemical modeling of lithium-ion batteries, students put theory to practice in an intense, 1-week lab phase, where they learn how to use commercial modeling tools effectively.

Hardware Design for Battery Systems

A deep dive into hardware engineering. Participants develop, design, manufacture and assemble their own microcontroller-based battery management system in small groups. The course is concluded with individual project presentations.

Advanced Seminar on Electrochemical Energy Storage

In this seminar, students work on advanced research topics in the field of electrochemical energy storage and learn how to write a scientific paper. The seminar concludes with individual oral presentations in front of peers and EES staff.

Seminars

Seminar on Energy Storage Technologies

This seminar is exclusively for students of the Master's program Power Engineering (MSPE). Participants learn how to write a scientific paper on an electrical energy storage topic and present their findings in front of peers and researchers.

Efficient Scientific Writing

Participants learn the basics of scientific writing and project management for bachelor's and master's theses. The course also covers effective research and evaluation of literature.

Doctoral Dissertations



A total of twenty-four doctoral theses have already been successfully defended at EES under the supervision of Prof. Dr.-Ing. Andreas Jossen. Most theses combine theoretical, experimental and modeling/simulation topics to achieve new results within their research field. Since 2017, in addition to monographic theses, cumulative theses have also been accepted. This format can be advantageous to doctoral researchers, as they benefit from early feedback from independent reviewers and can streamline the entire process of conducting research and writing of the thesis.

**Lepiorz, Matthias
(2015)**

Operation-Dependent Aging of Lithium-Ion Batteries in Stationary and Mobile Applications

**Schuster, Simon
(2016)**

Reuse of Automotive Lithium-Ion Batteries: An Assessment From the Cell-Aging Perspective.

**Erhard, Simon
(2017)**

Multi-Dimensional Electrochemical-Thermal Modeling of Lithium-Ion Batteries

**Osswald, Patrick
(2017)**

Advanced Thermodynamic Measurements as Degradation Tracking Technique in Lithium-Ion Cells

**Rieger, Bernhard
(2017)**

Methodology to Model the Mechanical Behavior of Lithium-Ion Cells

**Huber, Christian
(2017)**

Phase Change Material in Battery Thermal Management Applications: An Assessment of Efficiency and Safety

**Bauer, Marius
(2017)**

Electrical and Mechanical Methods for the Detection of Aging Effects in Lithium-Ion Batteries

**Keil, Peter
(2017)**

Aging of Lithium-Ion Batteries in Electric Vehicles

**Kindermann, Frank
(2017)**

Implications of Current Density Distribution in Lithium-Ion Battery Graphite Anodes on SEI Formation

**Brand, Martin
(2017)**

Behavior of Lithium-Ion Battery Cells and Systems under Dynamic Electric Loads

**Koch, Reinhold
(2017)**

On-Line Electrochemical Impedance Spectroscopy for Lithium-Ion Battery Systems: Estimation, Compensation and Avoidance of Measurement Deviations

Doctoral Dissertations

Campestrini, Christian (2018)	Practical Feasibility of Kalman Filters for the State Estimation of Lithium-Ion Batteries
Müller, Marcus (2018)	Stationary Lithium-Ion Battery Energy Storage Systems: A Multi-Purpose Technology
Martiny, Nora (2018)	Temperature Inhomogeneity in Lithium-Ion Pouch Cells
Naumann, Maik (2018)	Techno-Economic Evaluation of Stationary Battery Energy Storage Systems with Special Consideration of Aging
Wu, Yao (2018)	Non-Invasive Aging Detection Methods of Lithium-Ion Batteries
Rumpf, Katharina (2018)	Causes and Effects of Inhomogeneity in Lithium-Ion Battery Modules: A Physicochemical Modelling Approach
Arunachala, Raghavendra (2018)	Influence of Cell Size on Performance and Lifetime of Lithium-Ion Batteries
Schimpe, Michael (2019)	System Simulation of Utility-Scale Lithium-Ion Battery Energy Storage Systems: An Assessment of the Energy Efficiency, the Battery Degradation, and the Economics of System Operation
von Lüders, Christian (2019)	Experimental and Simulative Investigation of Lithium Plating and Lithium Stripping in Lithium-Ion Cells
Truong, Cong Nam (2019)	Assessment and Optimization of Operating Stationary Battery Storage Systems
Nguyen, Tam (2019)	Degradation of Automotive Lithium Batteries during Mobile and Stationary Load through Big Data Analysis
Rheinfeld, Alexander (2019)	Performance and Safety of Lithium-Ion Electrodes and Cells: Modeling, Simulation, and Validation at Elevated Temperatures and Currents
Makinejad, Kamyar (2019)	Advanced Monitoring Algorithms for Battery Storage Systems in Electric Vehicles

Highly Cited Publications

“Calendar Aging of Lithium-Ion Batteries - I. Impact of the Graphite Anode on Capacity Fade”

P. Keil, S. F. Schuster, J. Wilhelm, J. Travi, A. Hauser, R. C. Karl, and A. Jossen, *Journal of The Electrochemical Society*, 2016.

Calendar aging of lithium-ion batteries is strongly influenced by anode potential. This paper presents an experimental calendar aging study, conducted using three different lithium-ion chemistries. A special feature of this study is its high resolution in the states of charge (SoC), at which the cells were stored. The 16 SoCs from 0 to 100% demonstrate that calendar aging does not increase steadily with the SoC. Instead, there is a strong correlation between the capacity fade and the potential of the graphite anode: lower anode potentials aggravate the degradation. To maximize battery life, the times spent at the region of lowest anode potential should be minimized.

“Nonlinear Aging Characteristics of Lithium-Ion Cells under Different Operational Conditions”

S. F. Schuster, T. Bach, E. Fleder, J. Müller, M. Brand, G. Sextl, and A. Jossen, *Journal of Energy Storage*, 2015.

Although the reuse of aged lithium-ion batteries has been investigated by many authors, there is a lack of understanding of the dynamics of aging in such batteries. Despite the linear relationship between cyclic capacity loss to charge throughput, a transition to nonlinear aging progression is observed after an approximate loss of capacity of 20%. Its appearance is accelerated by high charging rates and voltages as well as low temperatures. SEM images reveal thick surface films at the anode, suggesting that Solid Electrolyte Interphase (SEI) growth is the dominant aging mechanism before the turning point is reached. Afterwards, lithium plating occurs even at moderate temperatures and charging rates. An optimized operational strategy could extend the life of lithium-ion batteries by retarding the appearance of the turning point.

“Lithium Plating in Lithium-Ion Batteries at Sub-ambient Temperatures Investigated by In-situ Neutron Diffraction”

V. Zinth, C. v. Lüders, M. Hofmann, J. Hattendorff, I. Buchberger, S. Erhard, J. Rebelo-Kornmeier, R. Gilles, and A. Jossen, *Journal of Power Sources*, 2014.

Lithium plating in $\text{LiNi}_{1/3}\text{Mn}_{1/3}\text{Co}_{1/3}\text{O}$ / graphite cells at sub-ambient temperatures was studied by neutron diffraction. Lithium plating consumes a portion of the active lithium in the cell. As a result, the degree of graphite lithiation during and after charge is lower. Comparison of graphite lithiation after a fast charging cycle with a much slower reference cycle revealed a lower degree of graphite lithiation in the first case as more LiC_{12} and less LiC_6 were present. If the cell is subjected to a rest period after charge, a gradual transformation of the remaining LiC_{12} to LiC_6 can be observed, indicating lithium diffusion into the graphite. During the rest period, the degree of graphite lithiation can be estimated to increase by 17%, indicating that at least 17% of the active lithium is involved in lithium plating.

Highly Cited Publications

This review paper serves as a guideline for the best choice of battery technology, system design and operation for lithium-ion based storage systems to match a specific system application. It provides an overview of lithium-ion battery technologies and their characteristics with respect to performance and aging as well as state-of-the-art system design, which is analysed in detail based on an evaluation of real-world projects. The review also provides a summary of typical storage system applications and publicly available modelling tools for technical and economic analysis. Optimization approaches for system sizing, positioning and dispatch operation are also evaluated.

“Lithium-Ion Battery Storage for the Grid - A Review of Stationary Battery Storage System Design Tailored for Applications in Modern Power Grids”

H. C. Hesse, M. Schimpe, D. Kucevic, and A. Jossen, MDPI energies, 2017.

This paper examines the costs and revenues for Electrical Energy Storage (EES) computed with the batteries' Levelized Cost Of Energy (LCOE) and the Return On Investment (ROI). An enhanced techno-economic model for EES cost and revenue analysis is presented: Evaluations depend on different scenarios of electricity price and economic input data, battery size and storage replacement strategy. Furthermore, the operational wear of particular battery systems, together with the corresponding technical and economic consequences are analyzed. Finally, ROI curves achieved for a residential customer with a 'solar-plus-battery' system and the conditions needed to surpass the break-even point in different scenarios are evaluated.

“Lithium-Ion Battery Cost Analysis in PV-household Application”

M. Naumann, R. C. Karl, C. N. Truong, H. C. Hesse, and A. Jossen, Energy Procedia, 2015.

Increasing consumption by households of the energy generated by their rooftop photovoltaic systems is the most popular application for battery systems in Germany. However, market uptake has struggled because of high prices. In 2016 Tesla Motors, Inc. announced a novel battery system for a 75% lower price than the market average at that time. This economic breakthrough motivated this paper, with the aim to analyze the economic value of residential battery systems. Various assumptions, such as system coupling, aging characteristics, electricity price, remuneration rates, and subsidy schemes were investigated. The simulations reveal three key-factors affecting economic value: the gap between electricity price and remuneration rate, the upfront cost of the system and the usable capacity.

“Economics of Residential Photovoltaic Battery Systems in Germany: The Case of Tesla's Powerwall”

C. N. Truong, M. Naumann, R. C. Karl, M. Müller, H. C. Hesse, and A. Jossen, MDPI batteries, 2016.

Spin-offs from EES



Li.plus

battery diagnostics: fast. precise. simple

Li.plus GmbH

With its innovative battery test, Li.plus has been offering a fast, precise and simple alternative to existing measurement technologies since 2016. Based on a novel load profile, a unique system response is generated and programmatically analyzed. The measurement data, which can be obtained in a fraction of a second, allows a completely analytical parameterization of an equivalent circuit network, and thus, reliable conclusions on the quality, aging and safety status of any battery system. Li.plus devices are currently used along the entire value chain from single cells to large battery packs and have been shown to offer significant cost and time advantages in R&D, production quality control and recycling. Customer specific testing devices and contacting solutions further increase the utility of the system and complement the product portfolio. Based on years of experience and an extensive dataset, Li.plus also supports its customers by consulting on battery system layout, test bench setups and design of experiments.

Battery Dynamics GmbH Measure and Understand Battery Degradation



BATTERY
D Y N A M I C S

Battery Dynamics was founded in 2018 by Dr. Peter Keil and develops high resolution battery testers. The testers provide outstanding long-term precision in current measurements and ampere-hour integration. This enables high precision coulometry measurements, which identify even small quantities of aging side-reactions, such as lithium plating. Moreover, the high voltage resolution of the testers makes them ideal for voltage relaxation and entropy measurements. Battery Dynamics also offers battery testing and consulting services to help engineers and researchers better understand the degradation behavior of their lithium-ion batteries and optimize the lifetime of their battery systems.

Spin-offs from EES

crino GmbH

Crino GmbH is the latest spin-off from the EES and was founded in 2019. Crino's innovative technology enables fast and reliable self-discharge tests for the production of lithium ion cells. The use of crino's battery testers supersedes the traditional storage based methods and consequently reduces both capital commitment and testing costs. Moreover, the special software allows real time measurements, statistical analysis and visualization of the data generated in the tests. In addition to its application in battery production, crino also offers cell characterizations and small-scale test equipment for developers and researchers. Crino is supported by the Federal Ministry of Economics and Energy and the European Social Fund within the EXIST program.



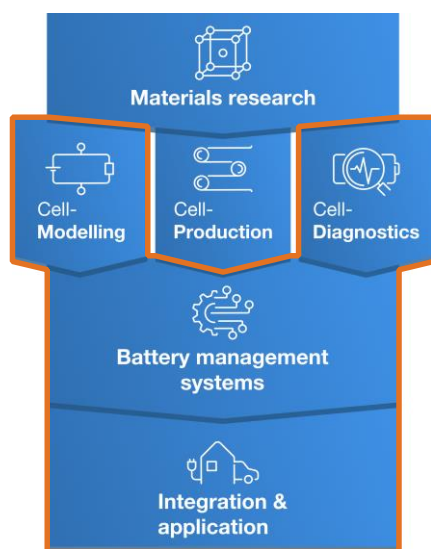
STABL GmbH

STABL Energy sets a new standard for large battery storage. Its new inverter technology elevates it to the state-of-the-art of current systems. The STABL inverter features several substantial benefits for battery storage: lethal high battery voltage is avoided, the modular approach is fail-operational in the presence of battery malfunction and energy losses are reduced by up to 70%. Each battery module is used selectively, which increases usable capacity and enables economical second-life concepts. The technology is based on a multilevel converter approach, whereby instead of being hard-wired to a high-voltage battery pack, each module is equipped with an inverter module. These dynamically connect the modules to generate the desired output voltage.



STABL

Battery Research at TUM



Partner Institutes at TUM

Chair of Electrical Energy Storage Technology

Chair of Inorganic Chemistry with Focus on Novel Materials

Chair of Technical Electrochemistry

Chair of Theoretical Chemistry

Associate Professorship of Synthesis and Characterization of Innovative Materials

Institute for Silicon Chemistry and Wacker Chair of Macromolecular Chemistry

Professorship for Physics of Energy Conversion and Storage

Chair of Functional Materials

Institute for Machine Tools and Industrial Management

Institute for Automotive Technology

Chair of Robotics, Artificial Intelligence and Embedded Systems – Electrochemical Research Group

Research Neutron Source Heinz Maier-Leibnitz (FRM II), Group of Advanced Materials

In addition to the EES, battery research at the Technical University of Munich (TUM) is aggregated within the interdisciplinary TUM.Battery network. This aims to present the expertise and research activities taking place at TUM in the field of battery research to the global community at large.

Battery systems across their entire value chain are researched in an interdisciplinary association of eight different chairs and two institutes with twelve professors and more than 100 scientists from different disciplines at the Technical University of Munich. For the development of various state-of-the-art and future storage technologies, interdisciplinary research activities range from the fundamental materials research at the atomic level undertaken in the natural sciences to the integration of lithium-ion cells and their applications from a user's perspective. The findings of the electrochemists and electrical engineers relating to cell development and process technologies are integrated into production technologies developed by mechanical engineers. Once in operation, battery management systems supervise interconnected lithium-ion cells. The transfer of know-how from research to application is facilitated through strong networks with industrial, economical, and political partners. Further information can be found on the websites of the individual partners listed on the left to find out more about their respective research areas.

The EES focuses on cell modeling, cell diagnostics, battery management systems as well as integration and applications (see research activities p. 9 ff). For cell modeling, detailed, spatially resolved physicochemical, thermal and mechanical models as well as aging models and models to describe multi-cellular systems are parameterized, simulated and validated. Cell diagnostics at EES attempts to quantify and ensure safe and reliable operation using methods including state of charge determination and cell balancing systems. The chair optimizes intelligent battery management systems to deal with electrical, thermal, and mechanical issues arising in interconnected lithium-ion cells. The integration of stationary energy storage in power supply systems covers a range of topics from network connection topology, optimization of operating, and control strategies to economical, and ecological considerations.

For further information, visit www.mse.tum.de/battery





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