



Technical University of Munich (TUM)  
Department of Electrical and Computer Engineering  
**Chair of Electrical Energy Storage Technology**

**5** Year  
Anniversary

**Editing and Layout**

Michael Schimpe  
Simon F. Schuster  
Christian Campestrini  
Stephan Kosch

**Contact**

Phone: +49 (0) 89 / 289-26967  
Fax: +49 (0) 89 / 289-26968  
Mail: sekretariat.ees@ei.tum.de  
Web: www.ees.ei.tum.de

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Technische Universität München  
Lehrstuhl für Elektrische Energiespeichertechnik  
Prof. Dr.-Ing. Andreas Jossen  
Arcisstr. 21  
80333 München

## Greetings from Professor Jossen

The Chair of Electrical Energy Storage Technology (EES) was founded in May 2010 within the Department of Electrical and Computer Engineering of the Technical University of Munich (TUM). At that time, the first electric vehicle with a lithium-ion traction battery was launched on the market. Already a few years before, research activities in the field of battery technology had been starting to increase. Today and even more in the future, energy storage systems are an important interface between the stationary grid and the mobile world and play a key role in the “more electric world”.

When starting at the newly rented building in Karlstraße 45, all the rooms were empty and I had to bring my own table and chair. The first two research assistants started two months afterwards and supported the laboratory set up as well as the teaching activities. With the help of the department and the related chairs it was possible to set up an operational chair within a short period of time. One year later, we were awarded a first publicly funded project and the team started to grow.

Energy storage is not only a theoretical topic; it requires laboratory investigations. To overcome the limitations of laboratory space, we decided to perform most cell tests with small cells and transferred the results afterwards to larger systems. Subsequently, we could start the work on battery modules and whole battery systems. High voltage experiments were an issue which we could not handle in the initial laboratory. In 2014, we finally got the possibility to install a high voltage battery laboratory for battery modules and packs in the machinery hall of the Chair of Energy Conversion Technology. Many thanks hereby to my colleague Prof. Dr.-Ing. Hans-Georg Herzog for providing us the necessary space.

Battery research is multidisciplinary. It is related to electrical engineering, chemistry, physics and mechanical engineering but also a topic of economic and environmental aspects. From the start, it was the chair's strategy to form strong cooperation with other chairs of the TUM and external partners. Today, these partners are from Munich, Germany, Europe, and Singapore. Actually, we are about to start stronger exchange and cooperation with US and Chinese research groups.

At the new building of the Center for Energy and Information (ZEI) in Garching, a shared battery test facility will be installed at the TUM within the next two years. This new laboratory will give us the possibility for advanced experimental work and further cooperation with other disciplines. The next step in about 5 years will be the moving of the chair to the Garching research campus.

What will happen in the next years? There is no doubt that the future power train of vehicles will be electric. Stationary battery systems are already starting to play an important role in today's electrical grids. All this will give us new possibilities and new challenges in battery research.

This brochure gives an overview of our work and the development during the first five years of the chair. As there are so many activities and so many people involved, it is not possible to describe everything in detail in this small brochure. Many thanks to the whole team, the technicians, the team assistances and the scientific staff for the continuous engagement in setting up and operating the chair.



**Prof. Dr.-Ing. Andreas Jossen**

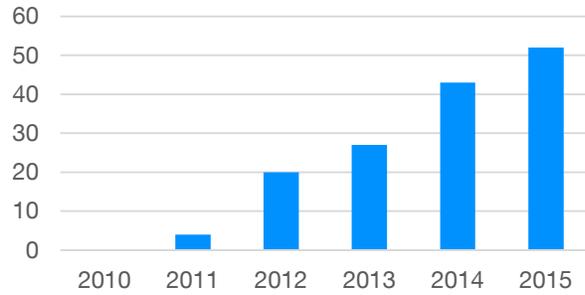
Phone +49 (0) 89 289-26967  
Fax +49 (0) 89 289-26968  
Mail andreas.jossen@tum.de

## The First Five Years of the Chair of Electrical Energy Storage Technology

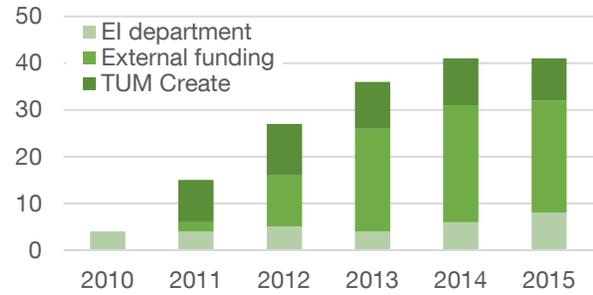
- 2010** Appointment of Professor Jossen as head of the Chair of Electrical Energy Storage Technology (EES) within the Department of Electrical and Computer Engineering at the Technical University of Munich (TUM).
- Start of TUM CREATE (Singapore), supervision of the research projects Energy Storage Engineering & Energy Storage Systems.
- 2011** First third-party funded project with academia & industry, LiSSi, focusing on the simulation of lithium-sulfur batteries.
- 2012** Start of the first project in European cooperation: ABattReLife, a project to improve battery technology for electric vehicles.
- Foundation of the Center of Excellence for Battery Cells at the TUM, ExZellTUM, under the chair's project management.
- 2013** Start of the interdisciplinary research project EEBatt on distributed stationary battery storage systems involving 13 chairs at the TUM as well as partners from industry under the chair's project management.
- 1<sup>st</sup> Workshop on the application of lithium-ion batteries at the TUM.
- Demonstration of the electric taxi EVA developed by TUM CREATE at the Tokyo Motor Show.
- 2015** Appointment of Professor Jossen as Editor of the MPDI Journal *Batteries*.
- Hosting of the *1<sup>st</sup> International Battery Safety Workshop* at the TUM.
- Demonstration of the stationary community energy storage system developed by the TUM in the project EEBatt.

# Facts & Figures

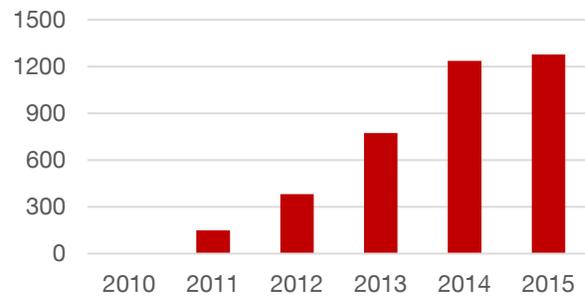
### Publications



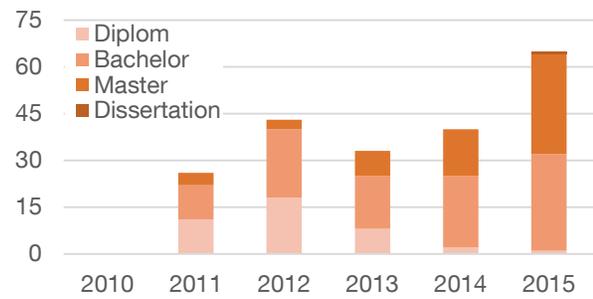
### Scientific Staff



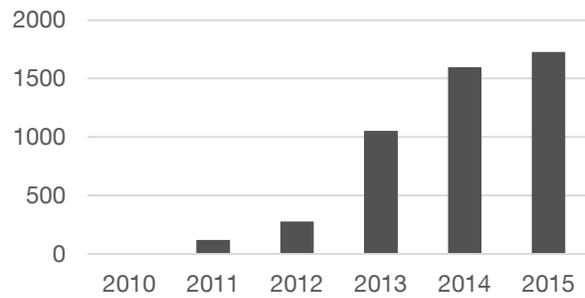
### Exams



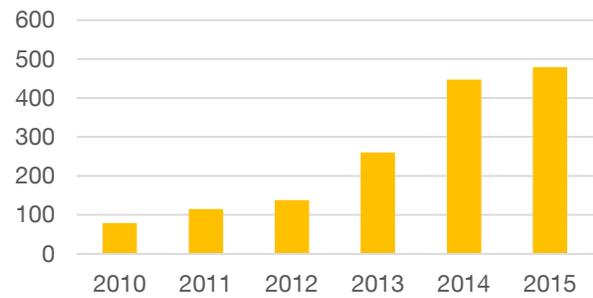
### Theses



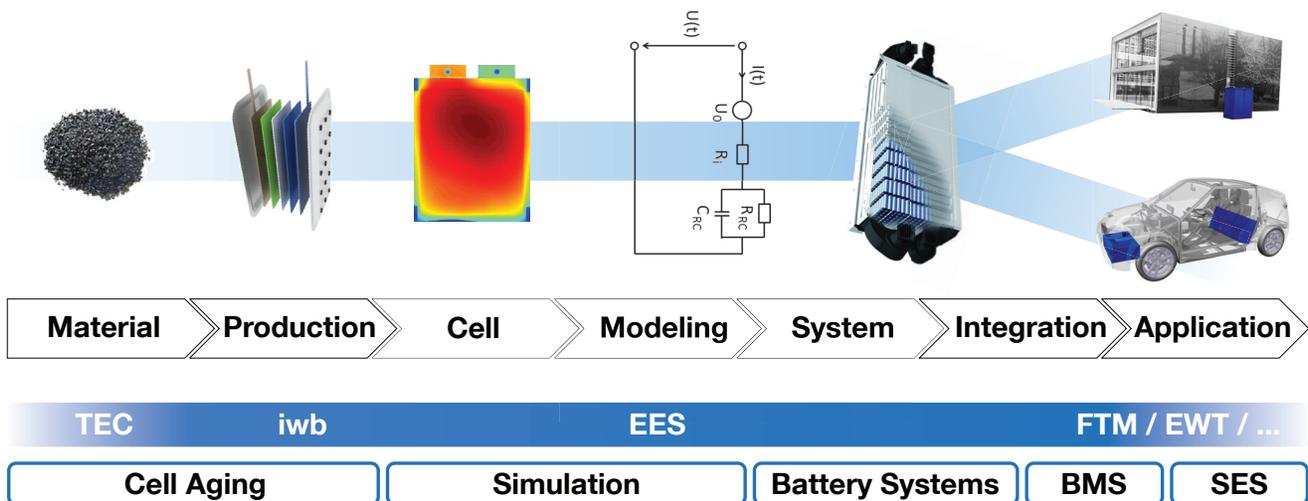
### Third-party funding (in 1000 €)



### Battery Test Channels



## Research Groups



EES research areas, partners and groups of the chair along the lifecycle of a lithium-ion cell.

### Cell Aging

The aging of a single lithium-ion cell, meaning capacity loss and impedance increase, leads to a limitation of the entire storage. Therefore, the research focus of this group is the detection and description of aging effects in a single cell and the prediction of the expected service life. From this, an optimized operating strategy can delay aging mechanisms and prolong the lifetime of the lithium-ion energy storage.

### Simulation

In the field of modeling and simulation, the detailed description of lithium-ion cell behavior is the main task. This involves determining internal cell variables such as concentrations, potentials and temperatures as a function of space and time. For this purpose, coupled models are

developed which are based on fundamental partial differential equations solved with the aid of commercial software. Describing the interaction of electrochemical, electrical and thermal processes together with finding sophisticated means of model validation are key research topics within this field.

### Battery Systems

The group is dealing with electrical, thermal and mechanical issues, arising during the development of battery systems. To optimize energy storage systems, a detailed survey and modeling of the properties and behavior for multicellular setups is necessary. Therefore, equivalent circuit networks and thermal 3D simulations are used.

### Battery Management Systems

To guarantee a secure and stable operation of lithium-ion batteries, a complex battery management system (BMS) is necessary to achieve a high level of reliability. The group investigates, optimizes and validates the whole spectrum of functionality of the BMS.

### Stationary Energy Storage

The increasing share of renewable energy results in drastic challenges on the energy system. Stationary battery systems can serve various supporting applications in electrical grids such as facilitating high shares of renewable energy or providing ancillary services for grid stability. The goal of the group is to investigate the technical and economic aspects for electrical storage integration in energy systems.

## Members of the Chair



Members of the chair at their colloquium in 2015, Lenggries.

### Head of the Chair

Andreas Jossen  
Holger Hesse

### Administration Staff

Stefanie Käfer  
Carolin Nierwetberg  
Ute Thomas

### Technical Staff

Michael Brandt  
Jens Dietrich  
Korbinian Schmidt

### Scientific Staff

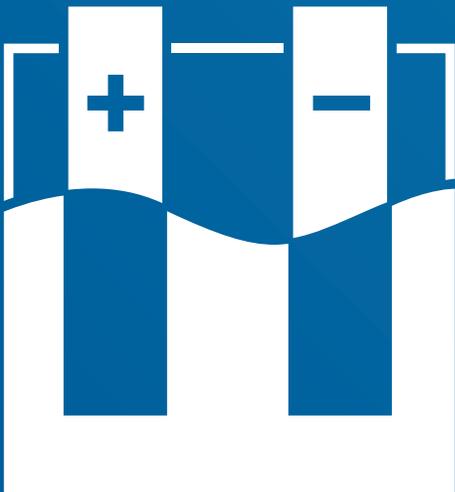
Philipp Berg  
Martin Brand  
Christian Campestrini  
Simon Erhard

Thomas Heil  
Markus Hofmann  
Max Horsche  
Christian Huber  
Ralph Karl  
Jonas Keil  
Peter Keil  
Frank Kindermann  
Elisabeth Kolp  
Stephan Kosch  
Marcus Müller  
Maik Naumann  
Andreas Noel  
Patrick Osswald  
Gudrun Rahn-Koltermann  
Alexander Rheinfeld  
Bernhard Rieger  
Katharina Rumpf  
Michael Schimpe

Simon Schuster  
Nam Truong  
Christian von Lüders  
Jörn Wilhelm  
Yao Wu  
Ilya Zilberman  
Thomas Zimmermann

### TUM Create

Sabine Arnold  
Raghavendra Arunachala  
Eliud Cabrera Castillo  
Jan Geder  
Andreas Hauser  
Reinhold Koch  
Kamyar Makinejad  
Nora Martiny





## Research Activities

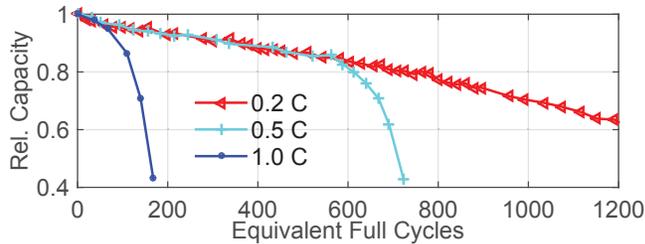
The chair has conducted research on a wide range of topics with electrical energy storages over the last five years. Research activities have focused mainly on rechargeable lithium-ion batteries. Key competences in the beginning were accelerated lifetime tests of batteries, battery modeling and battery systems mainly under the focus of automotive application. Parallel to the research activities at the chair in Munich, two research groups were set up within the joint research project *Electromobility in Megacities* at TUM CREATE in Singapore. In the next years, the research has extended to physical-chemical battery modeling, battery management systems and optimized operation modes. The storage use in the context of the energy turnaround in Germany from nuclear and fossil towards renewable energy and stationary storage systems came more and more into focus.

The laboratory started with four battery testing units and two controllable climatic chambers. From this, the equipment for cell fabrication, holistic cell testing from single cells over battery modules to complete systems was acquired, developed and built over the years. Our instruments enable measurements beyond the state of the art and allow characterization of cells and modules but also the validation of our simulation models. Thanks to the already concluded research projects in stationary and mobile applications, the chair has access to a self-developed stationary community energy storage system and an electric vehicle. Thus, the chair has a platform available that enables research from the fabrication of the cell over modeling and lifetime testing to the application of battery systems.

Today, the chair works in close collaboration with multiple other chairs and departments at the TUM and at other universities, research institutes as well as industrial partners from Germany, the European Union and Singapore.

The extensive collaborations have been made possible thanks to the financial support of TUM through departmental funding and positions as well as through national and international funding such as by Federal Ministry of Education and Research (BMBF), Federal Ministry for Economic Affairs and Energy (BMWi), Bavarian State Ministry for Economic Affairs and Media, Energy and Technology (StMWi), Bavarian Research Foundation (BFS), European Commission (EC) and Singapore's National Research Foundation (NRF).

# Lithium-Ion Cell Aging Fundamentals



Relative capacity vs. equivalent full cycles for a lithium-ion cell with graphite anode and lithium-nickel-manganese-cobalt-oxide (NMC) cathode. With an increased charging rate (legend), the occurrence of the phenomenon of nonlinear aging is promoted: by a reduction from 1.0C to 0.5C, the occurrence can be delayed by at least 500 equivalent full cycles; for the smallest charging rate, i.e. 0.2C, nonlinear aging can be completely avoided within the experiment duration.

## Researchers

Simon F. Schuster  
Ralph Ch. Karl  
Peter Keil  
Maik Naumann  
Yao Wu

## Publications

Y. Wu et al., Understanding the impacts of temperature and discharge rate on the aging of lithium-ion batteries, EEVC, Brussels, December 2015.

S.F. Schuster et al., Nonlinear aging characteristics of lithium-ion cells under different operational conditions, J. Energy Storage 1 (2015) 44-53.

S.F. Schuster et al., New Charging Method to Avoid Nonlinear Aging of Lithium-Ion Batteries, Batteries Event, Nice, October 2015.

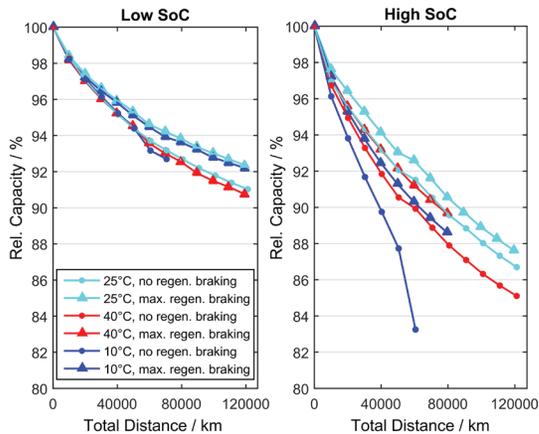
## Influence Factors of Aging Mechanisms

Generally, lithium-ion cells suffer from calendar aging when inactive and from cyclic aging when in operation. Consequences of aging are, basically, a loss of capacity and power capability with the latter originating from an increase of impedance. The reasons for aging can be divided into three groups, namely the loss of active materials, loss of usable lithium and deteriorated ionic kinetics. The latter mainly results from passive layer growth, which in turn originates from electrolyte decomposition.

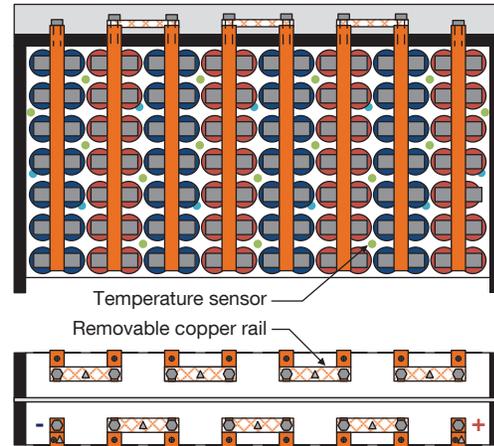
Besides of the evolution of passive layers in the interfaces of electrodes and the electrolyte (e.g. “solid electrolyte interphase” at the anode side), the most relevant aging mechanisms are: irreversible structural changes in the cathode active material; loss of particle-to-particle or particle-to-collector bonds as a result from intercalation-induced volumetric changes in the active materials; lithium plating.

Understanding the aging of lithium-ion cells is complex, as the single mechanisms emerge superimposed and are partially interacting. However, if influence factors of aging mechanisms are known, optimized storage and operational conditions can be derived. In general, for inactive lithium-ion cells, calendar aging is increased with rising states of charge and temperature. For cells in operation, extreme temperatures, high current rates and charge/discharge cycles, lead to pronounced cyclic aging. Especially during the charging process, low temperatures, high charging rates and charging end voltages are crucial with regard to the occurrence of lithium plating. As this aging mechanism is linked to the phenomenon of nonlinear aging, a new charging method which suppresses lithium plating was developed by the Chair of Electrical Energy Storage Technology to considerably extend the service life of a lithium-ion battery.

# Lithium-Ion Cell Aging Electric Vehicle Application



Impact of regenerative braking on battery aging. The best battery life is achieved with a low average state of charge (SoC), a low cycle depth, unrestricted regenerative braking and a moderate temperature of 25 °C.



Battery module used for aging investigations. The removable copper rails enabled individual capacity measurements for the 8 blocks of 14 cells connected in parallel. 25 temperature sensors were used to monitor the temperature distribution inside the module.

## Lifetime Analyses for Lithium-Ion Traction Batteries

Today, the traction batteries of electric vehicles usually consist of high-energy lithium-ion cells. The target battery life is at least as long as the vehicle life to avoid an expensive replacement during service life.

Within several experimental aging studies, we investigated the calendar and cycle life of lithium-ion batteries in electric vehicle applications. For these studies, dynamic load profiles were used which represent real driving scenarios. Furthermore, key aging parameters, such as temperature, cycle depth and average state of charge were varied to evaluate their impact on battery aging. From the yielded results, optimized operational strategies can be derived, which help to achieve the target battery life in electric vehicles. Our study on regenerative braking showed that recuperation does not lead to increased aging, but extends battery life by reducing the cycle depth. Our study on module aging elucidated the impact of temperature inhomogeneity and cell balancing on battery life.

## Researchers

Peter Keil  
Christian Campestrini  
Simon F. Schuster  
Ralph Ch. Karl

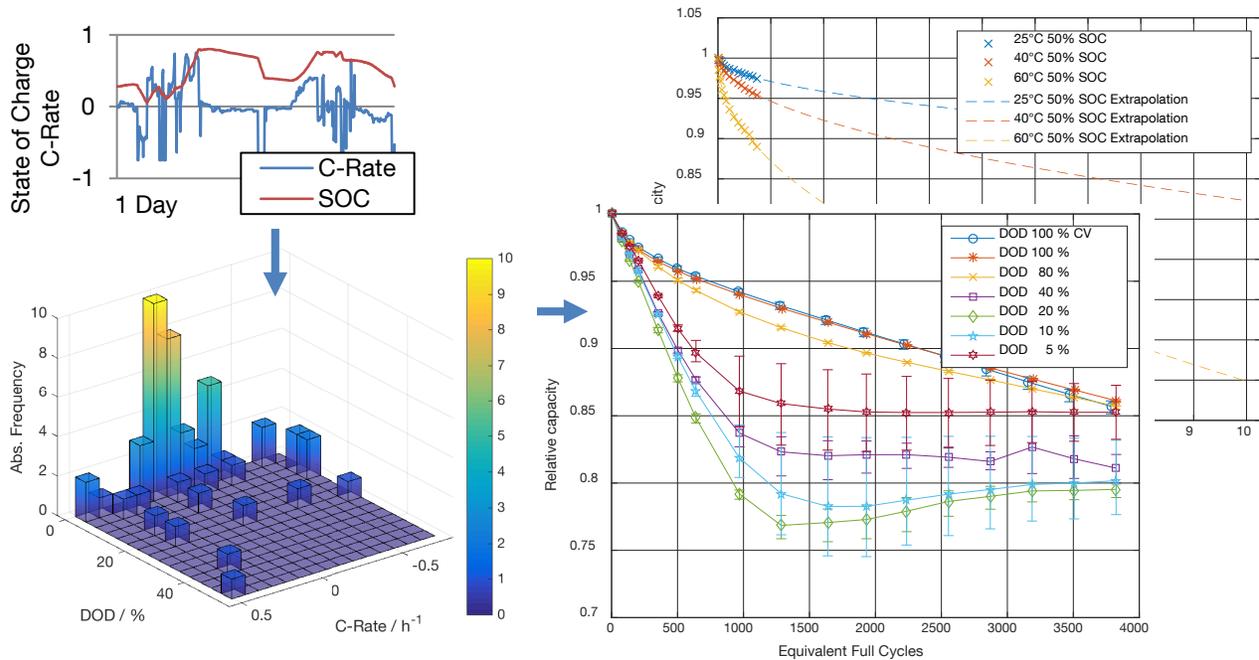
## Publications

P. Keil et al., Aging of Lithium-Ion Batteries in Electric Vehicles: Impact of Regenerative Braking, 28th Electric Vehicle Symposium, Goyang, Korea, May 2015.

C. Campestrini et al., Module ageing of Li-ion cells with active balancing compared to the ageing behaviour on cell level. 28th Electric Vehicle Symposium, Goyang, Korea, May 2015.

# Lithium-Ion Cell Aging

## Stationary Energy Storage Application



From the analysis and characterization of load profiles to application specific calendar and cycle life experiments.

### Researchers

Maik Naumann  
 Ralph Ch. Karl  
 Simon F. Schuster  
 Christian Campestrini

### Publications

R.Ch. Karl et al., Long-Lasting Storage System for Renewable Energies, IRES, Berlin, November 2011.

M. Naumann et al., Charakterisierung von Lastprofilen verschiedener Batterieanwendungen zur qualitativen Beschreibung der Alterung, Design & Elektronik, Munich, February 2014.

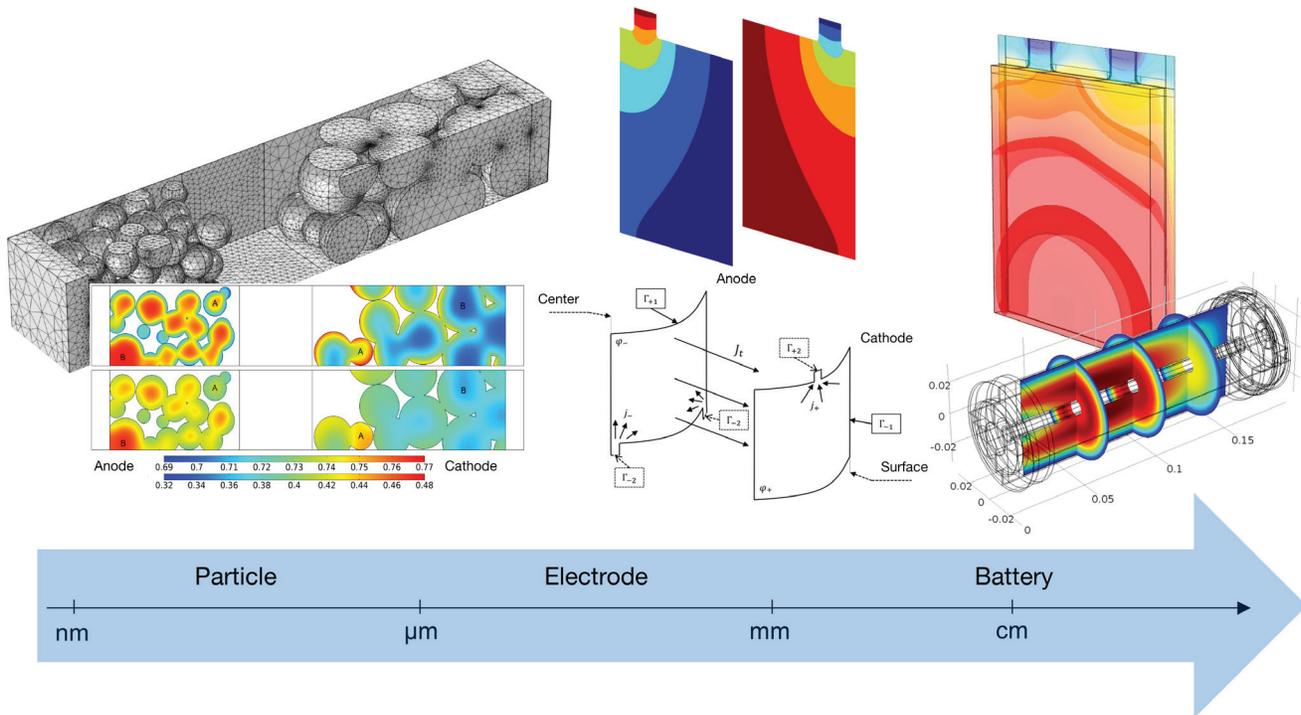
### Modeling and Testing

In the field of stationary energy storage, the technology of lithium-ion batteries currently gains importance. Consequently, the formerly commonly used lead-acid batteries are now driven out from the market.

In addition to currently propagating technologies like cells with graphite anodes and lithium iron phosphate (LFP) cathodes, future cell materials such as lithium titanate oxide (LTO) anodes are object of investigation. Based on the analysis of distinct stationary applications' load profiles, realistic and application-specific aging experiments are performed. With yielded results, fundamental statements on application-specific aging behavior can be given for the inspected cell technology. Additionally, aging models can be developed to predict the expectable service life of a stationary energy storage for a certain mode of application. By optimization of the latter, aging models can even contribute to extended stationary battery storage lifetimes.

# Modeling, Simulation and Validation

## Cell Design: From Particles to Batteries



Schematic overview of the modeled length scales: from particle to battery level.

### Multi-Scale Models for Battery Optimization

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

### Cell Design Approach

Several effects within lithium-ion batteries are influenced by design parameters such as tab configuration, number of windings, coating area and electrode ratio. With models developed at the EES, full-range cell design studies are carried out for optimizing battery performance with respect to aging and safety.

### Researchers

Simon V. Erhard  
Stephan Kosch  
Alexander Rheinfeld

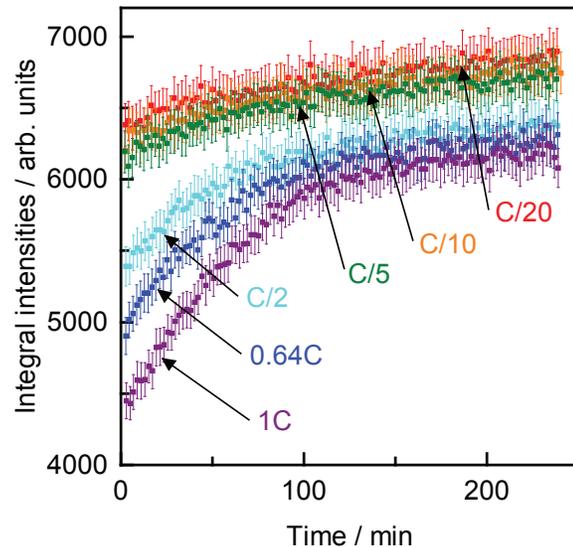
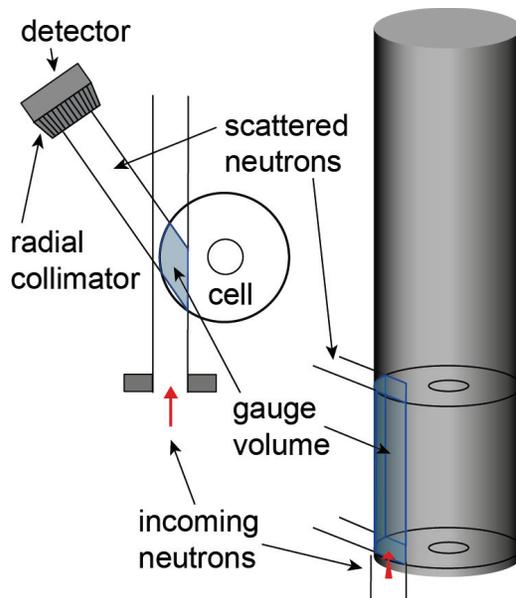
### Publications

S.V. Erhard et al., Simulation and Measurement of Local Potentials of Modified Commercial Cylindrical Cells II: Multi-Dimensional Modeling and Validation, *J. Electrochem. Soc.* 162 (14), 2015, A2707-A2719.

S. Kosch et al., Effects of Electrode Design on Electrical and Thermal Behavior of a Li-ion Pouch Cell, *Kraftwerk Batterie*, Münster, Germany, 2014.

## Modeling, Simulation and Validation

### Lithium Plating Investigated by In-Situ Neutron Diffraction and Overcharging Reactions



Schematic setup of a neutron diffraction experiment showing the position of the gauge volume in the cell (left) and derived reflection intensities in order to identify the lithium diffusion process after lithium plating (right).

#### Researchers

Christian von Lüders  
Jonas Keil

#### Publications

V. Zinth et al., Lithium plating in lithium-ion batteries at sub-ambient temperatures investigated by in situ neutron diffraction, *J. Power Sources* 271 (2014) 152-159.

J. Keil et al., Physiko-chemische Modellbildung zur Beschreibung des Spannungsverhaltens von Li-Ionen-Batterien im Überladezustand, *Batterieforschung Deutschland*, Berlin, 2015.

#### Lithium Plating

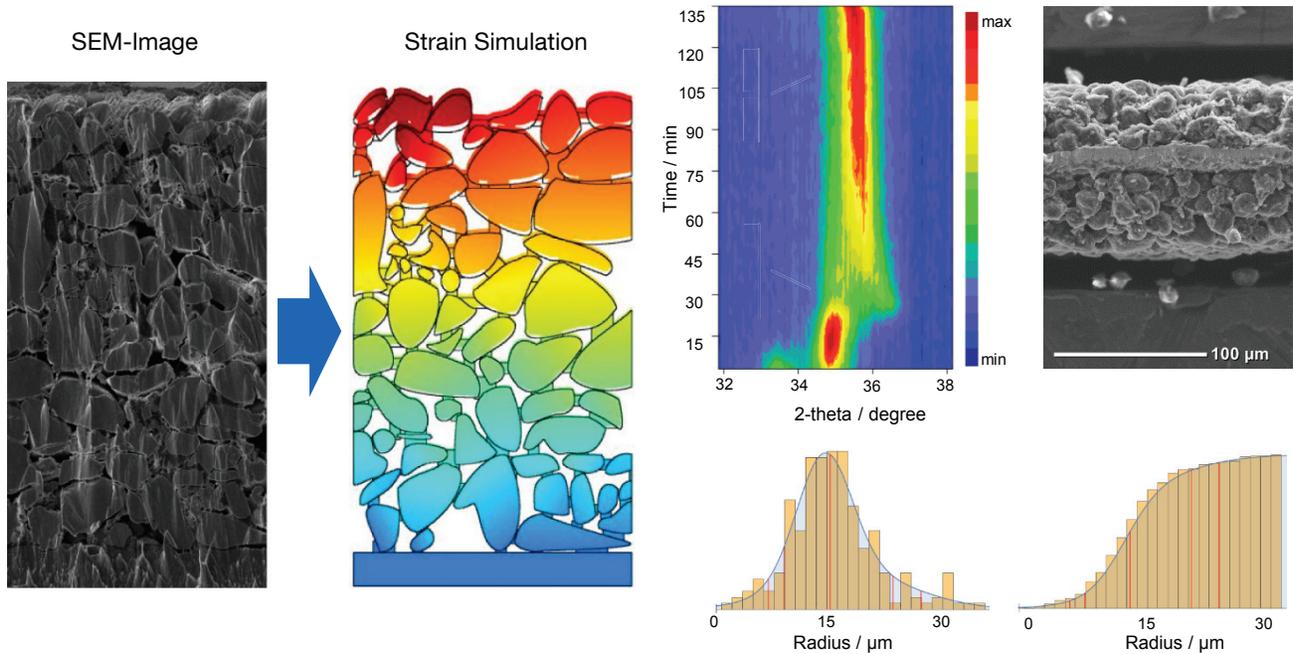
Lithium plating in commercial cells can be studied in-situ by neutron diffraction. The process of lithium plating consumes a part of the active lithium in the cell and competes with the intercalation of lithium into graphite. As a result, the lithiation degree within graphite is lower at higher currents during and immediately after charge. If the cell is subjected to a rest period after charge, a gradual transformation of remaining  $\text{LiC}_{12}$  to  $\text{LiC}_6$  can be observed, indicating diffusion of metallic lithium into graphite.

#### Overcharging Reactions

Leaving the voltage range of a lithium-ion battery, side reactions such as shuttle mechanisms or electrolyte decomposition can occur. These processes are studied by extended electrochemical models and measurements performed at safety laboratories of our partners.

# Modeling, Simulation and Validation

## Intercalation Processes and Mechanical Stress Evolution in Porous Electrodes



SEM-image of electrode structure for model geometry implementation and simulated distribution of vertical displacement (left), diffraction data of relaxation after discharge, SEM-image of the studied graphite electrode, particle radii probability distribution and cumulative distribution extracted from SEM (right).

### Mechanical Behavior of Porous Electrodes

Mechanical simulation on a microscopic scale provides insight into stress generation in porous electrodes and the macro-mechanical behavior of lithium-ion batteries. The intercalation-induced thickness change of porous electrodes is modeled based on SEM-images. Thereby, local variations in the stress distribution are identified, which lead to binder degradation and contact loss of the active material particles.

### Diffraction Measurements of Intercalation Processes

Neutron diffraction is a non-destructive method to measure the intercalation of lithium-ions into active material and the subsequent change in crystal structure in-operando. It allows to validate model predictions of state of charge distributions in batteries during and after current loads along with subsequent relaxation processes.

### Researchers

Bernhard Rieger  
Jörn Wilhelm

### Publications

B. Rieger et al., A multi-scale investigation of the thickness change of a commercial pouch-type battery, Kraftwerk Batterie, Aachen, 2015.

J. Wilhelm et al., Neutron Diffraction Measurements of Li-Ion State of Charge Distribution, UECT, Ulm, 2014.

## Modeling, Simulation and Validation

### Cell Manufacturing for Rapid-Prototyping



Sealing module (left) and glovebox with integrated vacuum filling and sealing station by Harro Höfliger (right) for semi-manual, highly flexible manufacturing of single- to multi-layer pouch cells at industry-related standards.

#### Researchers

Frank M. Kindermann  
Andreas Noel  
Simon V. Erhard

#### Publications

F.M. Kindermann et al., Long-term equalization effects in Li-ion batteries due to local state of charge inhomogeneities and their impact on impedance measurements, *Electrochim. Acta* 185 (2015) 107-116.

#### Cell Manufacturing

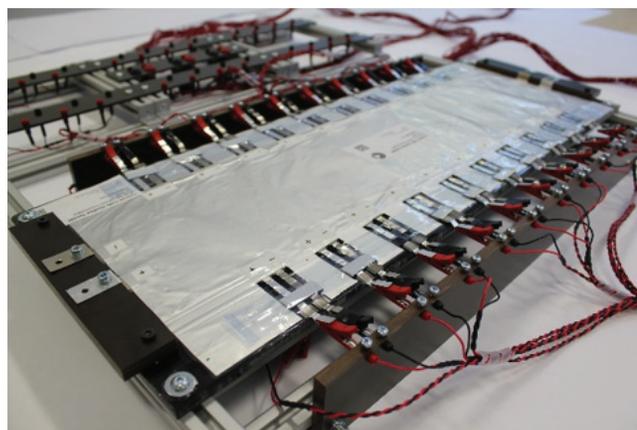
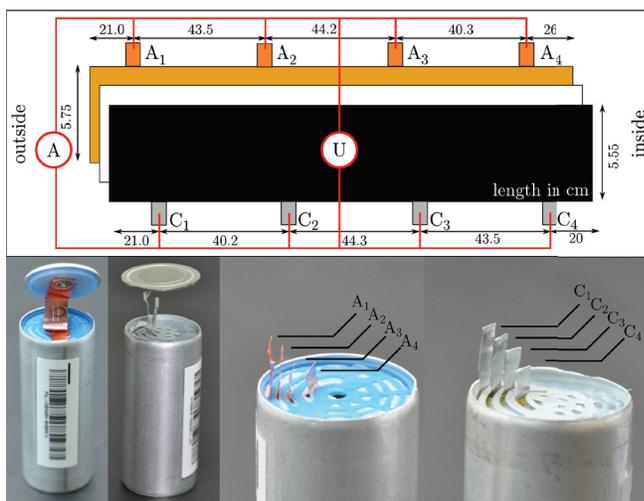
With our own manufacturing equipment we are able to build prototype pouch cells for validating our battery models and integrating sensors for in-situ measurements. Cell designs include single- as well as multi-layer cells and sheet sizes up to 250 x 300 mm. By studying formation protocols, we analyze the beginning of a battery cell's electrical life.

#### Advantages of In-House Prototyping and Modeling

Amongst others, relaxation processes have a major impact on subsequent diagnostics, such as state of charge estimation or impedance measurements. Building tailored prototype cells in combination with spatially resolved models helps to gain fundamental understanding of current density and state of charge distribution throughout formation, cycling and aging.

# Modeling, Simulation and Validation

## Cell Modification for Enhanced Model Validation



Opened commercial cell with disconnected terminals and a schematic drawing of tab placement (left) and single-layered multi-tab cell within fixation for purpose of local potential measurements (right).

### Modification of Commercial Cells

When investigating modified commercial cells, a high level of reproducibility of measurements can be established. By opening, modifying and resealing the investigated cell, the cathode and anode tabs can be addressed individually. Applying a multi-dimensional model combined with local potential measurements enhances the understanding for internal state variables.

### Prototype Cells with Multi-Tab Design

This approach is extended by designing a single-layered pouch cell with multiple tabs for local potential measurements. Local state of charge, current density distribution and cell impedance can be investigated using various tab configurations.

### Researchers

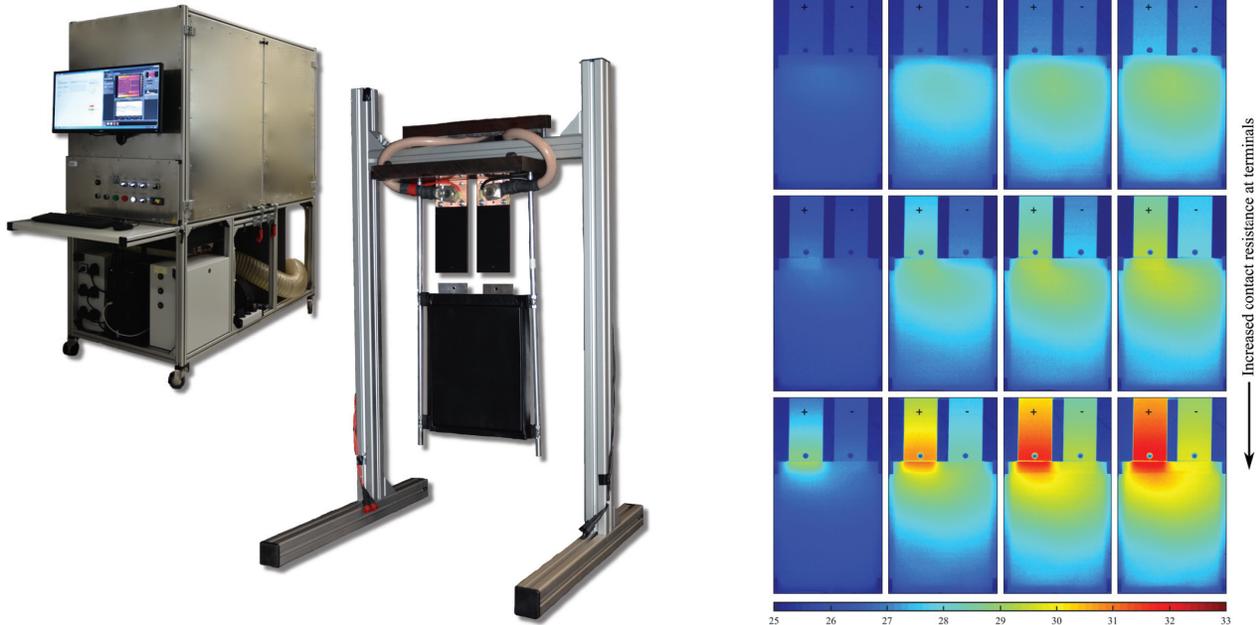
Patrick J. Osswald  
Simon V. Erhard  
Peter Keil  
Jörn Wilhelm

### Publications

P.J. Osswald et al., Simulation and Measurement of Local Potentials of Modified Commercial Cylindrical Cells I: Cell Preparation and Measurements, J. Electrochem. Soc. 162 (10), 2015, A2099-A2105.

# Modeling, Simulation and Validation

## Thermal Characterization Techniques



Preparation of a lithium-ion pouch cell (left) and gained infrared thermography measurements during operation (right).

### Researchers

Alexander Rheinfeld  
Simon V. Erhard  
Katharina Rumpf  
Peter Keil

### Publications

A. Rheinfeld et al., Modelling of temperature distribution within a large format Li-ion battery during discharge, Kraftwerk Batterie, Münster, 2014.

P. Keil et al., Thermal characterization of Li-ion batteries, Lecture Notes on Impedance Spectroscopy, Volume 5, 2015.

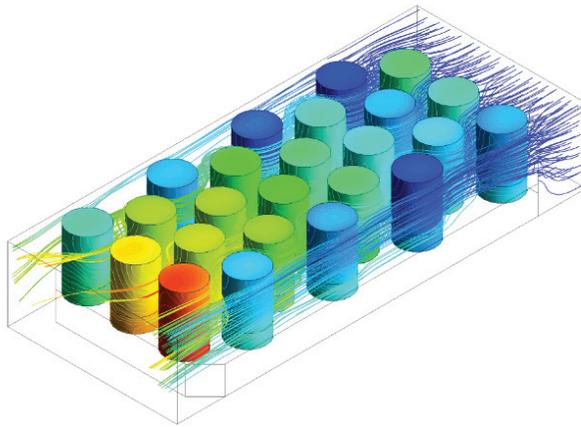
### Model Validation

In order to judge the quality of the chosen modeling approach, the accordance of simulation data with measurements needs to be quantified. With increasing cell size, depicting local thermal effects is crucial. To achieve a high level of model validation, reproducing the test conditions is essential. By focusing on these key aspects, precise thermal imaging techniques are developed at the EES.

### Model Parameterization

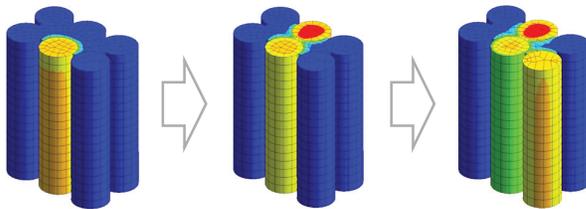
To further improve the quality of thermal cell models, thermal parameters such as the cell's heat capacity and anisotropic thermal conductivity need to be determined. A thermal test bench capable of thermal impedance spectroscopy, defined convective heat flux and IR thermography is used for measuring these parameters.

## Thermal Management: Ensuring Performance, Lifetime and Safety



Temperature level, profile and uniformity have significant impact on the electrochemical reactions and therefore the performance, safety and lifetime of battery systems.

Keeping the battery cells within an optimum temperature range is hence the main objective of battery thermal management. This includes the selection of an adequate thermal management concept, dimensioning of heating/cooling components and the definition of smart control strategies.



Simulation models of thermal runaway propagation contribute to the design of intrinsically safe battery modules.

### Safe and Efficient Thermal Module and Pack Design

Starting from experimentally determined thermal battery properties, numerical models for multi-cell modules and packs are developed. Based on obtained simulation results and experimental validation, module layout and thermal management concepts can be derived and iteratively optimized.

### Further Research Activities

Further investigation includes the coupling of thermal and electrical behavior within modules and the consideration of different cell connecting systems. Detailed cell models are coupled with macroscopic thermal-electrical module models by interconnecting different FEM simulation tools such as ANSYS and COMSOL.

### Researchers

Elisabeth Kolp  
Christian Huber

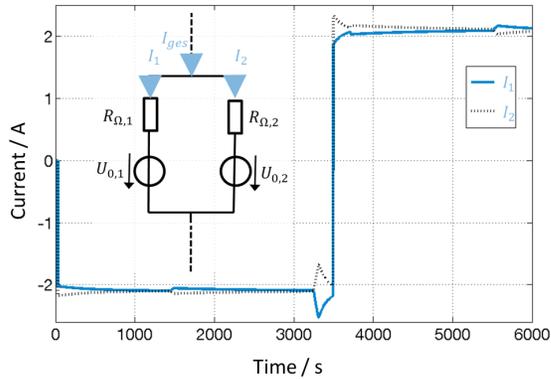
### Publications

C. Huber et al., Thermal management of batteries for electric vehicles, *Advances in Battery Technologies for Electric Vehicles* (2015).

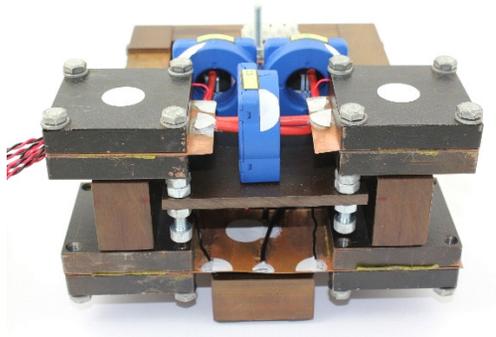
C. Huber et al., Novel Latent Heat Storage Devices for Thermal Management of Electric Vehicle Battery Systems, *Sustainable Automotive Technologies* (2013).

# Battery Systems

## Analysis and Equivalent Circuit Modeling



The diagram shows the current distribution of parallel connected battery cells. As the impedance, open circuit voltage and capacity usually differ, cell currents are different. This affects safety, thermal behavior and aging.



The test bench allows to identify the current distribution of two parallel connected cells. Different sensors make it possible to measure small and high currents with sufficient precision. Additionally, the set-up does not influence the current distribution due to its minimal impedance.

### Researchers

Markus Hofmann  
Elisabeth Kolp  
Martin J. Brand

### Publications

M.J. Brand et al., Stromverteilung bei parallel geschalteten Li-Ionen-Zellen, Virtuelle Instrumente in der Praxis, 2013.

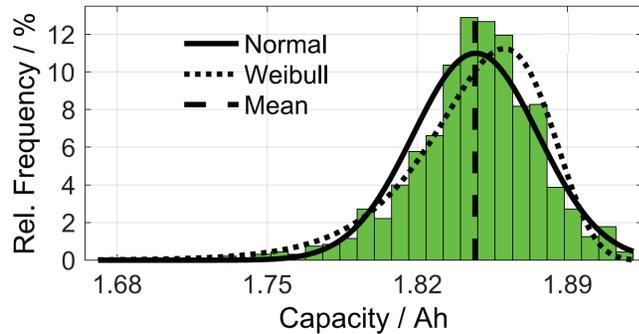
M.J. Brand et al., Welding techniques for battery cells and resulting electrical contact resistances, J. Energy Storage 1 (2015) 7-14.

### Current Distribution in Parallel Connected Cells

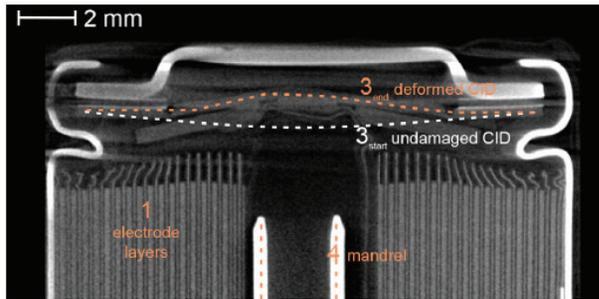
Batteries for automotive or grid storage applications consist of a high number of parallel and serial connected cells. Parameter variation leads to cell-to-cell inhomogeneities during battery operation. Hence, parallel connected cells do not carry the same current. Depending on their impedance, open circuit voltage and capacity, there are short- as well as long-term current differences. With an equivalent circuit simulation model and a suitable test bench, the dependencies of this effect are analyzed. Influences on important battery storage characteristics like safety, efficiency and lifetime are detected.

Furthermore, the cell connection method affects the battery system. Analysis of welding techniques shows considerable differences for the transfer resistance between cell tab and cell connector. These aspects are also considered in the equivalent circuit model of connected battery cells.

## Battery Systems Lithium-Ion Cell Failures



484 new and 1908 aged lithium-ion cells of two BEV were characterized by capacity and impedance measurements. The figure shows histogram and distribution fits for 954 cells out of one BEV. Increased variation and alteration from Normal to Weibull distribution as a consequence of aging could be observed.



Lithium-ion cells of the well-known 18650 and pouch formats were investigated regarding the impact of sinusoidal vibration, shock loads and long-term vibrations. The figure shows mechanical deformation of the current interrupt device (CID) due to a loose mandrel and disordered electrode layers after 300 standardized shocks according to UN 38.3 T4.

### Reliability Analysis

Reliability of lithium-ion batteries is a new field of research which currently gains importance. New and more demanding applications such as aeronautics require a deep and detailed understanding of the causes and impacts of failures and the corresponding reliability. Recent publications address intrinsic and extrinsic origins of cell failures, which are: increasing cell-to-cell parameter variation due to aging under real life battery electric vehicle (BEV) operation; impact of vibrations and shocks.

Future investigation will deal with the effects of resonance frequencies on safety, reliability and lifetime. Besides, the focus will shift to multi-cellular battery systems. Furthermore, stochastic methods are used to describe dependencies of failure modes, causes and effects to support experimental results.

### Researchers

Philipp Berg  
Martin J. Brand  
Simon F. Schuster

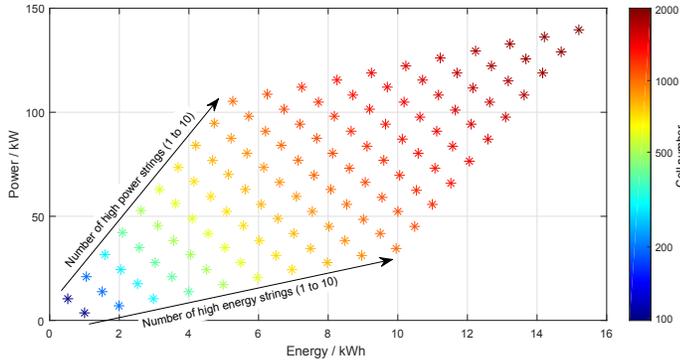
### Publications

S.F. Schuster et al., Lithium-ion cell-to-cell variation during battery electric vehicle operation, *J. Power Sources* 297 (2015) 242-251.

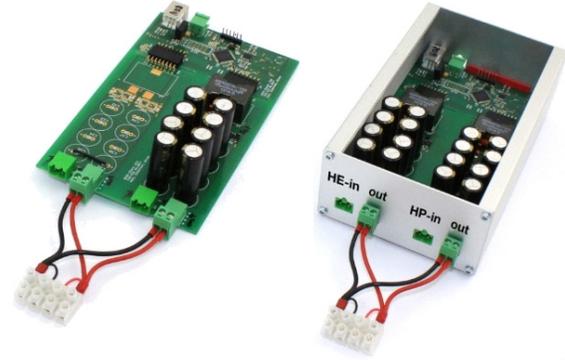
M.J. Brand et al., Effects of vibrations and shocks on lithium-ion cells, *J. Power Sources* 288 (2015) 62-69.

# Optimized Energy Storage Systems

## Design and Performance Testing



Hybrid energy storage systems provide optimized solutions for various applications with different power and energy requirements by combining high-energy and high-power energy storage technologies.



DC-DC converter boards for hybrid energy storage systems to examine various combinations of high-energy and high-power cells on a small laboratory scale.

### Researchers

Markus Hofmann  
Thomas Zimmermann  
Peter Keil  
Max F. Horsche

### Publications

P. Keil et al., Hybrid Energy Storage Systems for Electric Vehicles: An Experimental Analysis of Performance Improvements at Subzero Temperatures, IEEE Transactions on Vehicular Technology (2015).

### Hybrid Energy Storage Systems

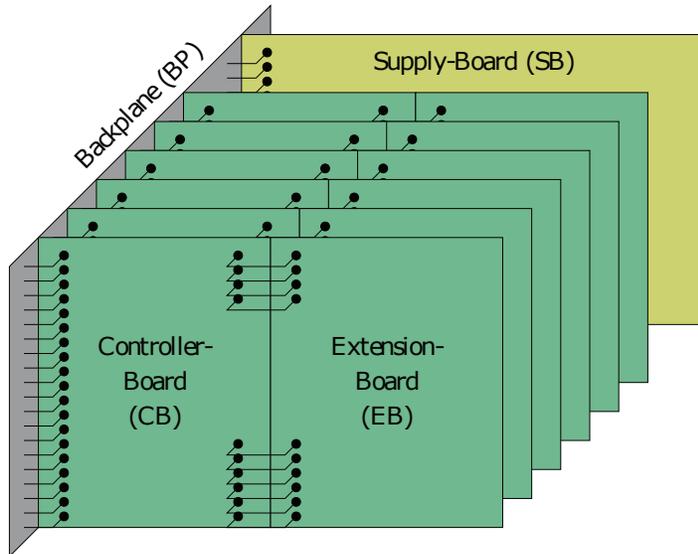
Hybrid energy storage systems (HESS) combine high-energy and high-power storage technologies to generate synergies for the overall energy storage system.

Our research activities cover the evaluation of different topologies and design optimization of HESS, especially for electric vehicle applications. In addition to basic calculations and simulation studies, we develop test benches for experimental investigations. These test benches enable validation of simulation models and comprehensive performance and cycle-life testing.

For several combinations of high-energy and high-power lithium-ion batteries or capacitors, we have experimentally demonstrated performance improvements at subzero temperatures by using HESS. Furthermore, cycle-life studies are conducted to examine the impact of HESS on battery life.

# Battery Management Systems

## A Research Plattform



Schematic representation of the flexible and modular research platform for a rapid and efficient development of battery management systems.

### Flexible and Modular Approach

The boom in solar- and wind-technology, as well as the emerging market of electric vehicles caused an increased demand for research in battery systems. A battery management system (BMS) is an important part of every powerful battery storage system. BMS are an important research topic. In the last few years many different BMS were developed at the Chair of Electrical Energy Storage Technology. However, it is difficult to compare the research results due to the variety of distinct BMS topologies. The presented work aims at improving the issue of comparability by outlining a scalable concept for BMS.

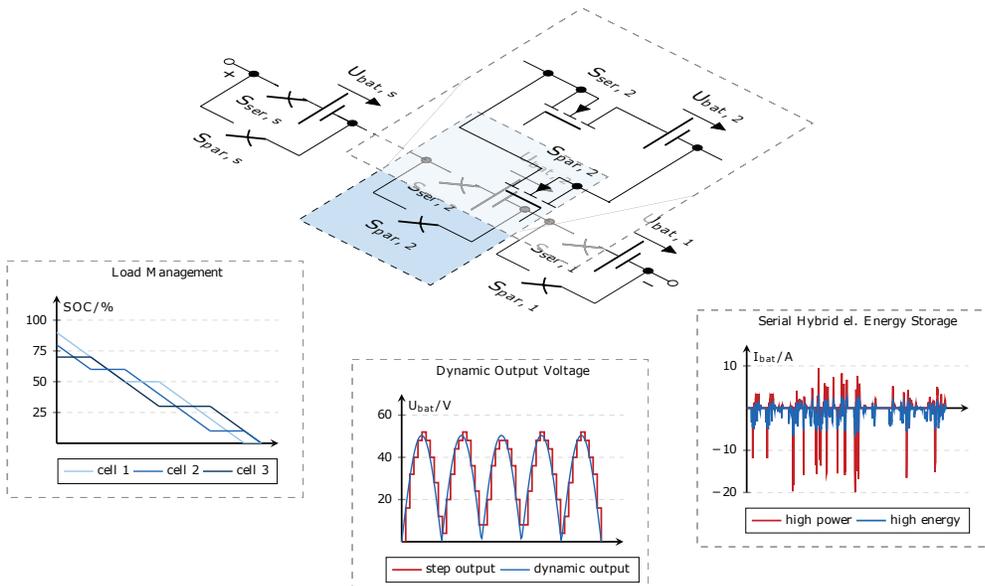
With the developed concept, innovations should be easy to implement and evaluate. In order to achieve this, a flexible design of the BMS is the key issue. The figure shows a modular BMS with different modules for each functionality. For example, there are separate modules for voltage-, current- and temperature measurement as well as for balancing and communication. This partitioning helps to develop and compare new hardware modules more efficiently. A powerful microcontroller is used on every module to enable implementation of highly complex algorithms. If a hardware- or software-module is replaced, the other parts of the BMS stay unaffected. As a result, it is easy to measure the impact of newly developed components. First results show that this concept is a very promising approach to a BMS for research purposes.

### Researchers

Thomas Zimmermann  
Max F. Horsche  
Ilya Zilberman  
Christian Campestrini  
Thomas Heil

# Battery Management Systems

## Switching Circuits at the Battery Cell Level



Battery module with switching circuits at the cell level. The three research main issues: load management to ensure maximal utilization; dynamic output voltage generation; serial hybridization.

### Researcher

Max F. Horsche

### Active Load Management, Dynamic Output Voltage and Hybridization

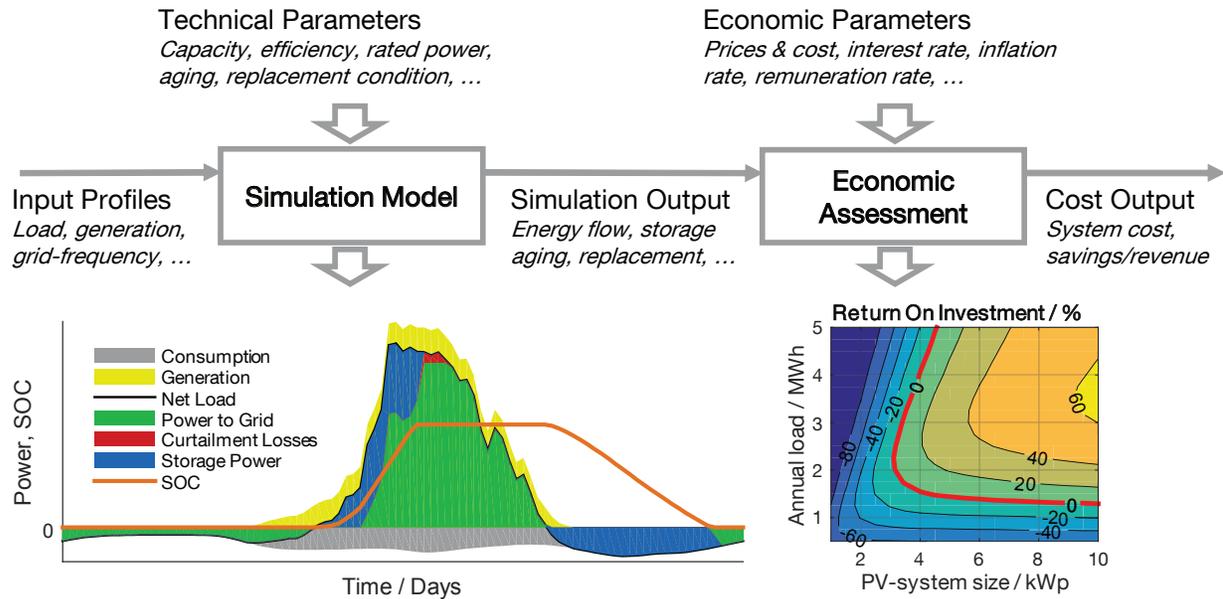
A common problem of electric vehicles is the strongly limited driving range. Up to now, traction battery research and development is the key issue in the automotive industry.

Actual battery systems of large-scale applications like electric vehicles consist of static networks. Generally, several cells are clustered to guarantee a decent level of modularity. However, as every battery cell participates in every situation, all of them have to perform equally in a serial connection to satisfy the load requirements of the respective application. One approach to influence the current flow through the battery pack is the implementation of switching circuits. Two switching elements are required for each cell (or at least for every parallel cell compound) to be separated and bypassed or, alternatively, integrated in the serial connection. Metal-oxide-semiconductor field-effect-transistors (MOSFET) are used to realize the switching function. Thus, by optimizing at the cell level, the performance of the whole traction battery is improved.

The topic of switching circuits motivates for further subjects of investigation:

- active load management
- dynamic output voltage
- serial hybrid electrical energy storages

# Stationary Energy Storage Systems Techno-Economic Analysis



Economic analysis of battery operation based on detailed simulation model. Storage usage for a residential PV customer is shown for an exemplary day (left) and overall economic analysis (right).

## Economics of Stationary Battery Systems

Battery systems are technically capable to serve many applications for stationary energy storage. However, the economic value of battery systems is a key performance indicator to evaluate their suitability and advantage over other competing storage technologies.

Battery systems are subject to several aging mechanisms that impair the system's performance. This results in decreased performance and reduction of potential revenue generation. Furthermore, advanced aging leads to the necessity of replacing batteries in order to ensure the system's effectiveness.

Consequently, the aging characteristic of batteries is an important factor to consider when evaluating the economics of battery systems. Other factors such as system size, operational strategy and investment cost as well as electricity price further influence the overall economic situation of battery systems.

As such, it is necessary to analyze the impact of all above mentioned parameters to allow for an economically optimized battery storage system design for a specific application.

### Researchers

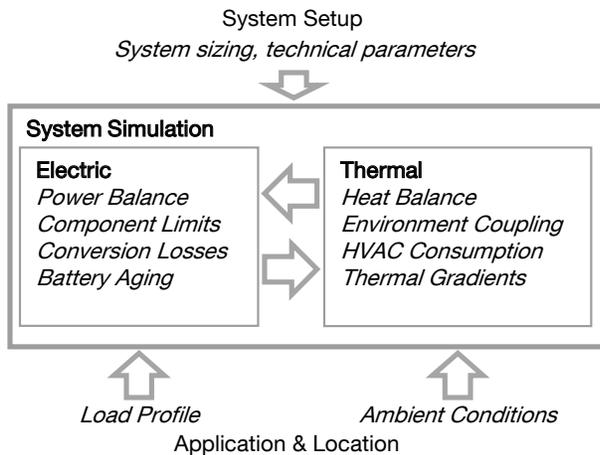
Maik Naumann  
Nam Truong  
Holger Hesse

### Publications

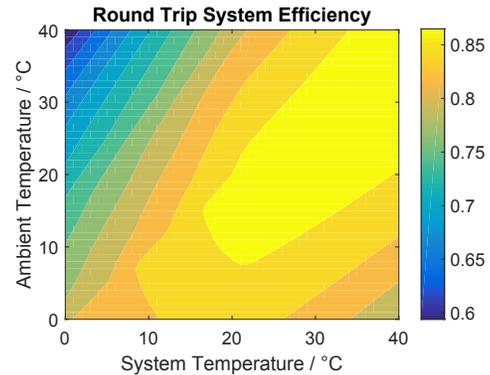
M. Naumann et al., Lithium-ion Battery Cost Analysis in PV-household application, Energy Procedia 73 (2015) 37-47.

# Stationary Energy Storage Systems

## Holistic Electric and Thermal System Simulation



Structure of a holistic stationary battery system model including electric and thermal management.



System efficiency of a container battery system over system and ambient temperature. Application: PV-generator coupled battery.

### Researchers

Michael Schimpe  
Maik Naumann  
Marcus Müller  
Holger Hesse

### Publications

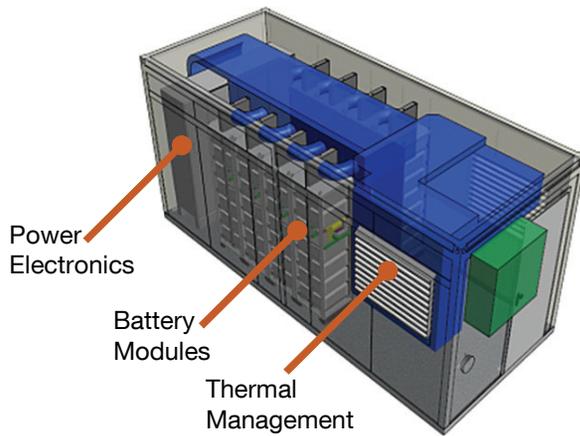
M. Müller et al., Evaluation of the Aging Behaviour of Stationary Lithium-Ion Battery Storage Systems for Different Photovoltaic-Driven Applications in Low Voltage Grids, EUPVSEC 2015 Proceedings, 3092 – 3098.

### Lifetime Simulation in varying Climatic Regions

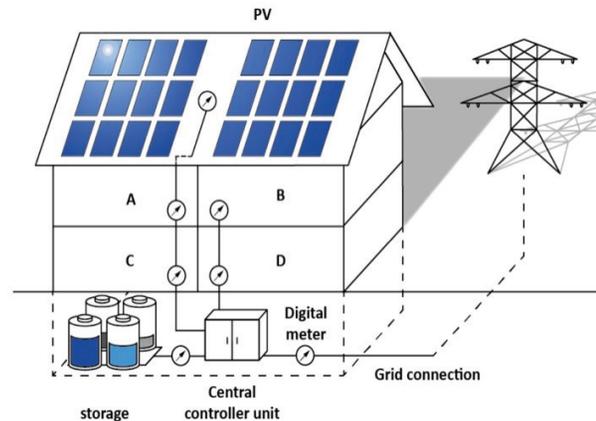
Several storage system applications, such as grid services or the integration of renewable energies in distinct climate regions (including extreme conditions such as arctic or desert regions), are investigated and evaluated. For demonstration and validation purpose, simulation and experimental data obtained for a 200 kWh container system (“Energy Neighbor”, developed by the TUM) is used which has recently been installed in the Bavarian village Moosham.

Battery cell aging and overall efficiency are amongst the most important technical parameters of the storage system. The impact on these parameters is simulated and analyzed with respect to system conditions (e.g. system internal and ambient surrounding temperature). By consideration of these findings, the operation mode can be optimized. Results show, that several effects are partially compensated through other coupled effects during the service life of the battery system. Therefore, holistic system lifetime simulation is necessary to analyze the sophisticated parameter dependencies on the performance of stationary energy storage systems.

## Stationary Energy Storage Systems Multifunctional Storage Usage Approach



Stationary container battery system, "Energy Neighbor".



Concept for integration of battery storage systems into multifamily-houses with shared PV generation system.

### Fragmented System Simulation and Business Models

Distinct applications can be served by stationary battery energy storage systems (BESS) depending on their sizing and grid connection: Whilst large-scale BESS in mid-voltage grids may e.g. only provide control reserve, coordinated storage integration in low-voltage grids allows further applications, such as low-voltage grid support, peak shaving and optimization of photovoltaic self-consumption.

Different applications are combined and simulated at the system level with the aim to improve the utilization ratio of BESS as well as to maximize profitability. Regarding the hardware side, fragmentation of storage in sub-units with separate metering is a concept studied - however it is worth mentioning, that besides of existing technical challenges, legal uncertainties must be clarified here. Another novel business case model studied is a shared use of BESS in multifamily-houses. Such systems are analyzed and assessed for houses up to over 100 tenants. Results show, that the integration of battery storage systems in multifamily-houses can lead to a profitable broad roll-out of storage technology in urban regions and cities.

### Researchers

Marcus Müller  
Michael Schimpe  
Nam Truong  
Holger Hesse

### Publications

M. Müller et. al., Fragmentierte Ortsnetzspeicher – Kombination von Anwendungen zur ökonomischen Optimierung von Batteriespeichern in Ortsnetzen, 3. Zukünftige Stromnetze für Erneuerbare Energien Konferenz, Berlin, 2016.

# Battery Laboratories and Device Development

## Structure and Formation in the First Five Years



### Test Equipment as of 2015

Test systems for cells, modules and packs	450 channels
Cell measurement unit for voltages and temperatures	600 channels
Potentiostats for electrochemical impedance spectroscopy	30 channels
Environmental simulation chambers for cells and packs	20 chambers



### Infrared Test Bench

Function: reliable thermal characterization of lithium-ion cells with varying form factors, such as cylindrical, prismatic and pouch cells; controlled ambient conditions (air flow, temperature, thermal contact) and precise sensor technology (IR imaging, PT100, impedance).

Specs: controlled temperature range from 15 °C to 35 °C; air flow range from 1 m·s<sup>-1</sup> to 3 m·s<sup>-1</sup>; thermal resolution of 30 mK and absolute preciseness of 0.2 K.



### Laser Test Bench

Function: to detect local volumetric changes of lithium-ion cells, two 3D laser scanners scan the cell from both sides; a high-precision local thickness information of the cell is generated by rasterizing the cell geometry.

Specs: controlled temperature range from 20 °C to 35 °C; simultaneous measurement of the cell thickness at 100 points; repeatability of 2 μm for every measurement point, resolution of 1 μm.



### Climate Chamber with Mounted Frequency Generators

Function: this test bench consists of a climate chamber in which lithium-ion cells are tested for frequency-dependent aging effects; 32 integrated frequency generators, which provide alternating currents with varying frequencies;

Specs: controlled temperature range of 15 °C to 40 °C; frequency range of 30 kHz to 10 Hz, with 0 A to 5 A direct and 0 A to 2 A alternating current.

### Technical Staff

Korbinian Schmidt  
Mechanical Engineering

Jens Dietrich  
Electrical Engineering

Michael Brandt  
Information Technology

The chair started 2010 with a small amount of test systems. In the following years, the number of test equipment increased rapidly and additional rooms for an electronic development laboratory, a high-voltage laboratory and a battery production plant were organized. After establishing workshops and laboratories, a major focus was placed on the development and manufacturing of devices for the battery test environment. These commercially unavailable test benches make it possible to investigate a large number of cells, modules and packs. In autumn 2015, the EES owns more than 450 test channels, seven laboratories and workshops at three different locations in Munich and the surrounding area.



## 1<sup>st</sup> International Battery Safety Workshop Munich, Germany – August 25<sup>th</sup> & 26<sup>th</sup> 2015



In August 2015, we organized the 1<sup>st</sup> International Battery Safety Workshop at the Technical University of Munich. Together with Bor Yann Liaw (University of Hawaii, USA), Chao-Yang Wang (Pennsylvania State University, USA), Daniel Doughty (Battery Safety Consulting, USA), Peter Lamp (BMW, Germany) and Jürgen Garche (FCBAT, Germany), more than 60 experts from both industry and academia as well as representatives from the U.S. Department of Energy (Brian Cunningham) and the German Federal Ministry of Education and Research (Peter Schroth) were invited and took part in the workshop.

During two days and four sessions, the current status of academic and industrial research and development within the field of battery safety was reviewed and discussed vividly. The focus was on defining the term “battery safety” from various perspectives, overviewing the current methods of safety validation, emphasizing novel means of diagnostics and prognostics in that area and finally presenting possible solutions and tools to enhance battery safety.

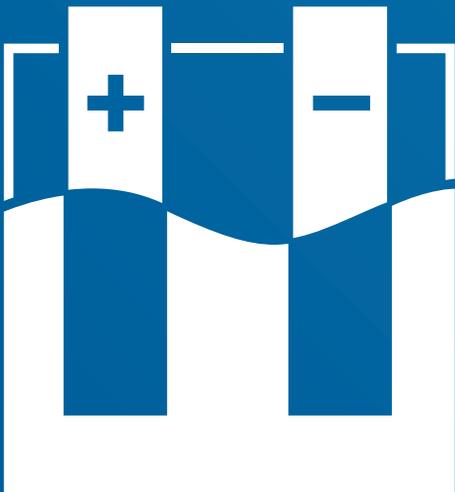
Due to the overwhelmingly positive response of the participants, the workshop will be continued at varying locations every year.

### **Organizing Committee**

Alexander Rheinfeld  
Jonas Keil

### **Scientific Committee**

Prof. Andreas Jossen (Technical University of Munich, Germany)  
Prof. Bor Yann Liaw (University of Hawaii, USA)  
Prof. Chao-Yang Wang (Pennsylvania State University, USA)  
Dr. Daniel Doughty (Battery Safety Consulting, USA)  
Dr. Peter Lamp (BMW, Germany)  
Prof. Jürgen Garche (FCBAT, Germany)





## Selected Projects

The chair is highly active in the acquisition of third-party funding since its founding and thereby participated in 15 research projects so far, cooperating with national and international partners from academia and industry. About 85 % of the projects are publicly funded (State of Bavaria, Germany and European Commission), whereas about 15 % are funded by bilateral industrial partnerships.

Among the various projects, the chair is responsible for the project management in two major projects at the TUM: ExZellTUM and EEBatt. These projects bring together a joint work of up to 13 chairs at the TUM to initiate, accelerate and deepen the university's interdisciplinary research and pioneering achievements for the next generation of battery cells and systems.

The research projects Energy Storage Engineering and Energy Storage Systems at the joint research institute with Singapore, TUM CREATE enabled the first major international collaboration of the chair.

# ExZellTUM

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

## Material Development and Prototype Manufacturing

The manufacturing of large format cells is initially tested on the laboratory scale. Suitable material systems for the negative and positive electrode are selected and characterized morphologically, individually and in suspension. Electrodes are manufactured for the electrochemical characterization and assembled to half and full cells.

Tests on the process steps such as blending, coating, assembling and further diagnostic measurements are also carried out on the laboratory scale.



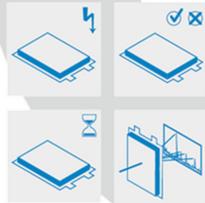
## Cell Design and Cell Optimization

A simulation-based design enables the researcher to forecast and optimize the electrical and thermal characteristics of the battery. Thereby, concrete statements about the cell geometry and battery components can be made in the development stage of a battery. They are of high relevance because particularly in large-scale cells an inhomogeneous distribution of the current density can lead to local overheating, plating of metallic lithium and accelerated aging.



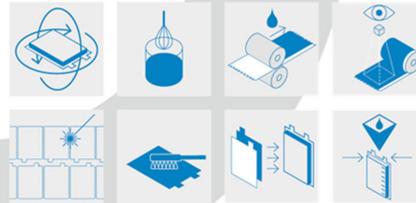
## Formation and Test Strategies

The passivation layers built in the cell during the formation have a big influence on the resulting cell characteristics such as performance, quality, aging behavior and safety. These characteristics are to be measured by primarily dynamic measurement methods. The necessary test systems are integrated into the production line so that the time and logistic input can be minimized. In addition to that, investigation methods with neutron radiation are available at the research reactor.



## Cell Manufacturing

In the context of this part of the project, a comprehensive research production line for lithium-ion cells comes into being. The entire value chain from the coating of the electrodes to the complete pouch cell is built up and scientifically observed. The fields of research are divided into the following aspects:  
Cross-process quality assurance, Blending, Coating, Optical technologies for quality assurance, Laser cutting, Electrode cleaning Cell assembling, Electrolyte filling and sealing



## Project Partners

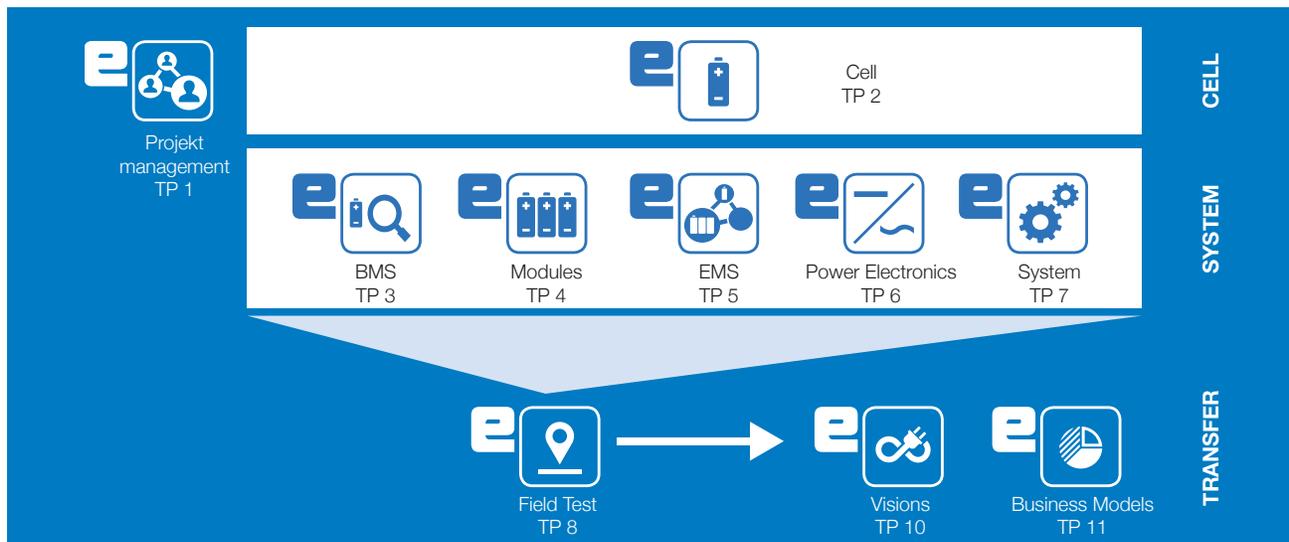
Brückner Maschinenbau GmbH  
BMW AG  
Fraunhofer Projektgruppe RMV  
Manz Tübingen GmbH  
TÜV SÜD Battery Testing GmbH

## Funding

Federal Ministry of Education and Research (BMBF)

The “Exzellenzzentrum für Batterienzellen an der Technischen Universität München“ (Center of Excellence for Battery Cells at the Technical University of Munich) covers the complete process chain for the manufacturing of high-capacity electrical energy storage systems in one competence center. It links the scientific and technical fields of chemistry, physics, electrical and mechanical engineering interdisciplinary at one site. The project of ExZellTUM focuses on the optimization of existent products and manufacturing processes as well as on the development of future electrical energy storages systems. This is possible by means of a closed quality loop system, which analyzes and optimizes all product and manufacturing parameters with reference to their quality and performance.

Distributed Stationary Battery Storage Systems for the Efficient Use of Renewable Energies and Support of Grid Stability



The Research Project EEBatt “Distributed stationary battery storage systems for the efficient use of renewable energies and support of grid stability” is a multidisciplinary project run by the TUM’s Munich School of Engineering (MSE) under the project lead of EES. Combining the strength of 13 chairs and departments of the Technical University of Munich, the industry partner VARTA Storage GmbH and the Bavarian Center for Applied Energy Research (ZAE Bayern), a multidisciplinary team of researchers works together on a wide range of issues concerning stationary storage of electrical energy. Driven by the actual evolution in the energy market, the main goal of the project is to investigate, develop and produce a decentralized energy storage device, which ensures that locally generated electrical power can be consumed locally. Based on the actual and expected results for lithium-ion technologies, EEBatt uses lithium iron phosphate (LFP) and lithium titanate oxide (LTO) chemistry for the setup. Together with the KWH Netz GmbH, a regional power supplier company in Haag/Upper Bavaria, the obtained results of the research project will be evaluated and implemented. The energy turnaround implicates not only a change in the technologies used for energy production, it also means a structural change towards a large number of decentralized time-dependent production facilities. The resulting fluctuations in the power production and imbalanced charging of the power grid make the use of storage technologies essential.

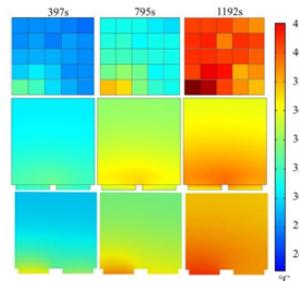
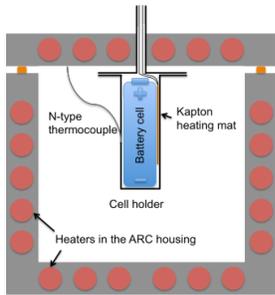
**Project partners**

VARTA Storage GmbH  
 Bavarian Center for Applied Energy Research (ZAE Bayern)  
 KWH Netz GmbH

**Funding**

Bavarian State Ministry for Economic Affairs and Media, Energy and Technology (StMWi)





Surface temperature distribution during 3 C discharge  
 Top: thermocouple measurements  
 Middle: fully coupled 3D simulation  
 Bottom: 3D thermal only simulation

ARC setup for measuring the heat capacity of batteries.

**Project Partners**

Samsung SDI Korea  
 City University of Hong Kong  
 Singapore Centre on Environmental Life, Sciences and Engineering  
 Institute for Microwave Technique and Photonics (TU Darmstadt, Germany)  
 Chair of Renewable and Sustainable Energy Systems (TUM)  
 Chair of Technical Electronics (TUM)

**Funding**

National Research Foundation Singapore (NRF)

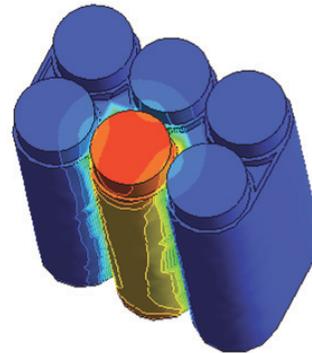
A key challenge that needs to be tackled when dealing with lithium-ion batteries is safety. Our research applies different measures and tests to predict failures. Results collected are studied and then fed into cell design and battery management systems to optimize the behavior. This helps to ultimately prevent fatal failures. Tests under normal operation conditions and abuse tests help our scientists to explore the limits and to discover how cells can be adjusted to deliver the best and most reliable performance. Another issue which is addressed, is the capacity fade over lifetime. High temperatures accelerate this phenomenon. Our researchers study the various causes and effects that contribute to this behavior with the goal to seek optimal operation conditions for lithium-ion batteries. 3D monitoring considers data from measurements and helps to simulate different abuse scenarios.

Our state-of-the-art laboratory gives our researchers and partners from academia and industry the unique opportunity to contribute to the development of breakthrough energy storage technologies. Our laboratory therefore features among others:

- Battery operation testing with over 70 test channels, with the ability of handling battery cycle tests for single cells with current profiles ranging from 0.2 A to 1200 A.
- Battery Safety Chamber: We are able to conduct extremely targeted and well-designed abuse tests such as over-charge, over-discharge, nail penetration, crash tests, short, hot plate and flame tests in an extremely safe environment, allowing us to test hazard severity levels of battery cells.
- Accelerating Rate Calorimeter: This quasi-adiabatic calorimetric measurement technique is used to track exothermal reactions in reactive blends. It helps to simulate thermal phenomena under adiabatic (worst-case) conditions.



The RP 6 electric vehicle battery pack was developed to allow a range of 130 km on one charge with continuously running air conditioning and 15 min. charge time to meet the demands of a taxi application in a tropical megacity. With a charging power of 160 kW, the RP 6 battery pack surpasses the Tesla Supercharger by 30 %.



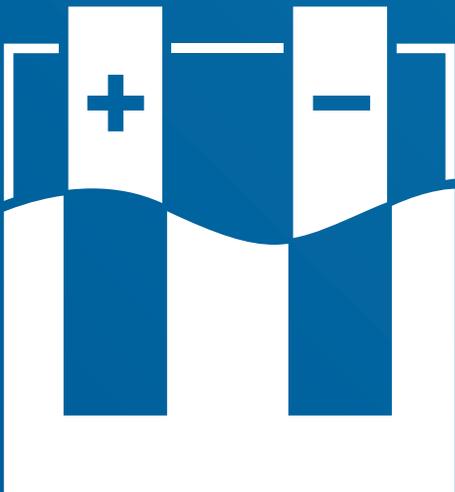
3D thermal simulations of battery modules and packs, supported by measurement results gained with a hot disk setup as well as with an accelerating rate calorimeter (ARC) form the basis of the investigation of new cooling methods and topologies, with a special focus on phase change material to buffer spikes in heat generation during charge or discharge.

The mission of RP 6 is comprehensive research on the battery system level. To achieve that goal, the largest university-level battery research laboratory in the ASEAN region was established; the laboratory and workspaces were used to create the cornerstone of the TUM CREATE electric vehicle demonstrator (EVA), a high-voltage and high-current drivetrain battery with a total capacity of 50 kWh that can be fast-charged to 80 % State of Charge within 15 minutes.

Current research focuses on new cooling methods for battery modules and packs using phase-change materials, in-vehicle battery diagnostics with a focus on inner cell temperature as well as determination of State of Charge/State of Health, high-frequency behavior of battery systems to increase battery performance for non-constant load scenarios and State of Safety investigations on cell and pack level which include an investigation of cell pressure changes during charge, discharge, compression and mechanical impact analysis and modeling.

**Funding**

National Research Foundation  
Singapore (NRF)





## Teaching

Since its founding, the Chair of Electrical Energy Storage Technology offers students of the TUM a variety of lectures, seminars and practical lab courses which deal with the topic of electrical energy storage technology from different perspectives.

Besides, all doctoral candidates are obliged to supervise Bachelor's and Master's students preparing their degree theses. The chair also supports the student's hands on projects eCARus and TUfast, in which students develop and build electric vehicles.

By participating in the Bachelor's program at TUM-ASIA in Singapore, the Chair of Electrical Energy Storage Technology is additionally involved in international teaching.

## Teaching

### Lectures at the TUM

#### Basics of Electrical Energy Storages

The lecture covers the basic concepts of energy storages on an abstract and technology-independent level. The participants will in addition gain insight into the physical principals of a variety of storage systems such as pumped hydro storage or compressed air storage systems.

BSc WS

#### Photovoltaic Stand-Alone Systems

Photovoltaic systems allow the provision of electrical energy in regions without widespread power distribution. In the lecture, selected topics about the technical structure, design and economic efficiency of these systems are introduced and evaluated.

BSc SS

#### Power Supply of Mobile Devices

The lecture addresses basics regarding the design and integration of energy storage systems using examples of modern applications such as mobile phones.

BSc WS

#### Battery Systems

Participants of this course learn the fundamentals of electrochemical battery systems. This includes electrochemical processes inside different battery systems, their composition and methodologies for characterization.

MSc WS

#### Battery System Technology

Battery system technology forms the basis of battery storage systems' correct handling. Content of the lecture focuses on charging methods, detection of state variables, cell interconnection topologies and battery system safety precautions.

MSc SS

#### Grid integration of Stationary Energy Storage Systems

After a short survey to challenges of the German Energiewende, selected energy storage technologies are presented and potential application schemes for grid integrated storage are discussed. Based on examples, problem statements for storage system design and calculations on the economic value of storage are conducted.

MSc SS

#### Energy Storage (MSPE)

An overview of various energy storage systems is provided in the lecture. Emphases of this course are on electric, magnetic, hydraulic and mechanic storage systems. The lecture is offered to students of the Master's program Power Engineering (MSPE).

MSc SS

### International Lectures

#### Electrical Energy Technology

The lecture covers topics related to electrical power systems with energy storage, generation of electrical energy and electric drives. As a part of the TUM-ASIA initiative, the lecture is given in Singapore.

BSc SS

## Lab Courses

### Electrical Energy Storage Lab

The laboratory course covers seven selected topics on electrical energy storages. During the course participants learn the correct handling of different electrical energy storages, including the usage of several battery testers.

MSc SS

### Physicochemical Modeling of Lithium-Ion Batteries

Students learn how to simulate and evaluate the behavior of lithium-ion batteries with standard software tools applied in industry and academia. The course is split into two parts, a theoretical lecture during the semester followed by a one-week practical part.

MSc WS &amp; SS

### Hardware Design for Battery Systems

The scope of this laboratory course consists of developing, manufacturing and assembling of small microcontroller boards. Main aim at the end of the course, is that the board can cope with simple battery management tasks.

MSc WS

## Seminars

### Advanced Seminar on Electrochemical Energy Storages

The seminar covers a wide range of topics related to the field of electrochemical energy storage systems.

MSc WS &amp; SS

### Seminar on Energy Storage Technologies (MSPE)

Selected topics about electrical energy storage technologies are discussed and evaluated. The seminar is offered to students of the Master's program Power Engineering.

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## Student Projects

### TUfast

A student project to construct a lightweight racing car: rooted in the „Formula Student“ framework, the manufactured vehicle is challenged by international competitors.



### eCARus

Students design in the self-organized project an electric vehicle without competitive character. Development includes the electric power supply, IT, wiring system and testing and thus improves their practical skills.



