



# 33<sup>rd</sup> UMBRELLA SYMPOSIUM

27–29 May 2019, Forschungszentrum Jülich

PGI Lecture Hall – Building 04.8, 2<sup>nd</sup> floor, Room 365



Dear colleagues,

welcome to the XXXIII. Umbrella Symposium 2019 on Energy Conversion and Energy Storage.

A world that switches from fossil fuels to renewable energies will in future be increasingly dependent on energy storage and energy conversion.

Our joint energy research in the frame of JARA-Energy tackles the global challenges of climate change with the objective of achieving a socially and economically viable decarbonization

of the energy system and the subsequent decentralization and digitization.

Here at Forschungszentrum Jülich scientists contribute to these objectives by focusing on technology-oriented research activities which is supported by an overarching systemic approach. Scientific contributions to the transformation of the energy sector are made by research on renewable energies and storage technologies as well as by using Jülich's system competences along basic value chains and system chains. The following technologies are explored and developed at the Forschungszentrum:

- Photovoltaics focusing on further radical cost reduction, increased efficiency and new tailor-made technological solutions
- Battery storage systems characterized by new electrolytes and multicomponent materials with much higher performance and reliability potential
- Hydrogen generation from fluctuating renewable power by means of efficient electrolysis and the direct production of hydrogen from sunlight as well as co-electrolysis technologies for utilizing CO<sub>2</sub> for P-to-X processes
- Distributed electricity generation by efficient fuel cells with optimized lifetime
- Chemical energy storage technologies including gas separation and storage activities
- High-temperature materials for power generation

As a member of the Board of Directors at Forschungszentrum Jülich, I am pleased to host the Umbrella Symposium on our campus for the eleventh time. This year's sessions will cover a wide range of demanding topics connected to the challenges we face regarding our future energy demand. What makes our cooperation endeavour special is the combination of excellent scientists, university institutes with a technical focus and access to a unique research infrastructure. This combination helps to drive the development of new key technologies. Many young researchers participated and contributed in the last symposia and we hope to continue this tradition, wishing all friends and participants a successful meeting with inspiring discussions and captivating insights into new opportunities for joint research. Have a memorable visit to our centre!

A handwritten signature in blue ink, appearing to read 'Harald Bolt'. The signature is fluid and cursive, written over a white background.

Prof. Dr. Harald Bolt

*Member of the Board of Directors, Forschungszentrum Jülich*

## SCIENTIFIC PROGRAM 2019

Monday, May 27		
PGI Lecture Hall Building 04.8 Entrance E.2, Room 365	08:45-09:00	<b>Gathering</b>
	09:00-09:15	<b>Welcome Greetings and Introduction to the Topics</b> Harald Bolt – <i>FZ Jülich</i> Ulrich Rüdiger – <i>RWTH Aachen University</i> Wayne Kaplan – <i>Technion – Israel Institute of Technology</i>
	09:15-09:30	<b>Umbrella Award Ceremony</b> Sebastian M. Schmidt – <i>FZ Jülich</i> Ulrich Rüdiger – <i>RWTH Aachen University</i> Wayne Kaplan – <i>Technion – Israel Institute of Technology</i>
	09:30-10:30	<b>Presentation by the awardees</b> Francisco Guzman – <i>RWTH Aachen University</i> Xiaoyan Yin – <i>FZ Jülich</i> Lior Kornblum – <i>Technion – Israel Institute of Technology</i>
	10:30-10:45	<b>Coffee Break</b>
	<b>Session 1 – Chair: Wayne D. Kaplan</b>	
	10:45-12:00	<b>Renewable Energies</b> Georg Jacobs – <i>RWTH Aachen University</i> Yehonadav Bekenstein – <i>Technion – Israel Institute of Technology</i> Thomas Kirchartz – <i>FZ Jülich</i>
	12:00-12:15	<b>Coffee Break</b>
	<b>Session 2 – Chair: Wayne D. Kaplan</b>	
	12:15-13:30	<b>Alternative Fuels</b> Walter Leitner – <i>RWTH Aachen University</i> Gideon S. Grader – <i>Technion – Israel Institute of Technology</i>
Seecasino – Faculty Club Bulding 04.1	13:10-14:45	<b>Lunch</b>
Neutron Club Building 04.8 Entrance E.14, Room 337/338	14:00-16:00	<b>Heads of Delegation Meeting</b>
<b>Session 2 – continued – Chair: Egbert Figgemeier</b>		
PGI Lecture Hall Building 04.8 Entrance E.2, Room 365	14:45-15:35	<b>Alternative Fuels – continued</b> Sabrina Spatari – <i>Technion – Israel Institute of Technology</i> Phillip Wunderlich – <i>RWTH Aachen University</i>
	<b>Session 3 – Chair: Gideon S. Grader</b>	
	15:35-16:50	<b>Energy Storage</b> Yoed Tsur – <i>Technion – Israel Institute of Technology</i> Hans-Dieter Wiemhöfer – <i>HI-MS</i> Dina Fattakhova-Rohlfing – <i>FZ Jülich</i>
	16:50-17:00	<b>Coffee Break</b>
	<b>Session 3 – continued – Chair: Hans-Dieter Wiemhöfer</b>	
	17:00-17:50	Dirk Uwe Sauer – <i>RWTH Aachen University</i> Egbert Figgemeier – <i>FZ Jülich</i>
	18:15	Transfer by bus to Dinner location
	19:00	<b>Dinner at Belvedere Tower, Aachen</b>

Tuesday, May 28			
PGI Lecture Hall Building 04.8 Entrance E.2, Room 365	<b>Session 3 – continued – Chair: Yoed Tsur</b>		
	09:00-10:40	<b>Energy Storage</b> Florian Hausen – <i>FZ Jülich</i> Matthew Suss – <i>Technion – Israel Institute of Technology</i> Carsten Korte – <i>FZ Jülich</i> Dmitry Sergeev – <i>FZ Jülich</i>	
	10:40-11:00	<b>Coffee Break</b>	
	<b>Session 4 – Chair: Lorenz Singheiser</b>		
	11:00-13:05	<b>Energy Conversion – Electrolysis</b> Graham de Ruiter – <i>Technion – Israel Institute of Technology</i> Fabian Scheepers – <i>FZ Jülich</i> L. G. J. de Haart – <i>FZ Jülich</i> Martin Robinus – <i>FZ Jülich</i> Robert Sengpiel – <i>RWTH Aachen University</i>	
	Seecasino – Faculty Club Bulding 04.1	13:05-14:15	<b>Lunch</b>
	PGI Lecture Hall Building 04.8 Entrance E.2, Room 365	<b>Session 5 – Chair: Rüdiger-A. Eichel</b>	
		14:15-15:40	<b>Energy Conversion – Fuel Cells</b> Dario Dekel – <i>Technion – Israel Institute of Technology</i> Charles E. Diesendruck – <i>Technion – Israel Institute of Technology</i> Ghaleb Natour – <i>FZ Jülich</i>
		15:40-16:00	<b>Coffee Break</b>
		<b>Session 6 – Chair: Ghaleb Natour</b>	
16:00-17:30		<b>Computation</b> Georg Schmitz – <i>RWTH Aachen University</i> Nir Gavish – <i>Technion – Israel Institute of Technology</i> Michael Eikerling – <i>FZ Jülich</i>	
		18:30	Transfer by bus to Dinner location
	19:00	<b>Dinner at Burg Obbendorf, Niederzier</b>	

Wednesday, May 29		
PGI Lecture Hall Building 04.8 Entrance E.2, Room 365	<b>Session 7 – Chair: Joachim Mayer</b>	
	09:30-14:40	<b>Managing energy in a smart world</b> Dov Dori – <i>Technion – Israel Institute of Technology</i> Annegret Klein-Heßling – <i>RWTH Aachen University</i> Jochen Linßen – <i>FZ Jülich</i>
	10:40-11:00	<b>Coffee Break</b>
	<b>Chair: Rüdiger-A. Eichel</b>	
	11:00-11:30	<b>Closing remarks</b>
	Seecasino – Faculty Club Bulding 04.1	12:00
	13:00	<b>Departure to airport</b>

Francisco Guzman – RWTH Aachen University  
 Xiaoyan Yin – FZ Jülich  
 Lior Kornblum – Technion – Israel Institute of Technology

## EARLY FAILURE OF ROLLER BEARINGS IN WIND TURBINE GEARBOXES

**Dipl.-Ing. Francisco Guzman**

*RWTH Aachen University*

Despite their high reliability a large part of downtimes and repairing costs of wind turbines (WT) are caused by failures of mechanical components, with gearbox failures being the major cause of downtime. A closer look at the gearbox reliability shows that the gearbox bearings contribute majorly to the total of drivetrain failures.

A particular aggressive and unpredictable failure mode affecting roller bearings in wind turbine gearboxes (WTGB) are the so-called white etching cracks (WEC). This failure mode is characterized by three-dimensional cracks, bordered by regions of altered material microstructure, which eventually lead to cracking or flaking of the bearing's raceway. Despite enormous efforts and considerable progress made by both academia and industry there is no consensus regarding the root cause of WEC. Nonetheless, it has been shown that not only the operating conditions but also the material and lubricant properties play an important role in the occurrence of not only WEC but also of further bearing failure modes.

This presentation gives an overview over the state of the investigations regarding the influencing factors and the formation mechanism of WEC. Within this context failures due to WEC were reproduced using both bearing test rigs and a two-disc test rig. The resulting WEC were investigated with several characterisation techniques in order to determine the crack morphology and initiation depth.

## COMPUTATION ASSISTED MATERIAL DESIGN FOR SOLID OXIDE FUEL CELLS

**Ph. D. Xiaoyan Yin**

*IEK-2 – Forschungszentrum Jülich GmbH*

Solid oxide fuel cells (SOFCs) are one of the most efficient and environmental-friendly technologies for power generation. However, the performance degradation of SOFC stacks still limits commercialization. Computation methods can help to analyze the degradation issues of SOFC stacks, and additionally allow discovering new candidate materials for SOFC application. I will report on three recent complementary modeling approaches which have the potential to improve SOFC performance.

The degradation of the cathode has been identified as a major issue limiting the lifetime and durability of SOFC stacks. Calphad based thermodynamic calculations have been performed to understand the degradation issues of the state-of-art (La, Sr)(Co, Fe)O<sub>3-δ</sub> cathodes in SOFCs. The calculations show that Sr is a very active element in this type of cathode materials and related to several degradation issues in SOFC. Sr tends to segregate on the cathode surface and to react with gaseous Cr-species that evaporate from the interconnect, forming Sr-Cr-O secondary phases on the top of the cathode and in some cases at the cathode/electrolyte interface. In the presence of water vapor, gaseous Sr-species may also form. The volatile Sr-species diffuse through the porous (Ga, Ce)O<sub>2</sub> diffusion barrier layer, react with the ZrO<sub>2</sub>-based electrolyte and produce ionic insulated SrZrO<sub>3</sub> secondary phases.

Ab-initio based phonon calculations are demonstrated as a potential method to predict thermodynamic and mechanical properties of electrode materials in SOFCs. The thermal expansion coefficient of La<sub>0.5</sub>Sr<sub>0.5</sub>Co<sub>0.25</sub>Fe<sub>0.75</sub>O<sub>3</sub> has been calculated by this method and the calculated value is in a good agreement with experimental measurements. Besides, ab initio calculations can also be used to obtain various electrical and physical properties of materials, e.g. oxygen vacancy formation energies, making them suitable for computational doping based cathode material discovery.

Both thermodynamic calculations and experiments have demonstrated that Sr in the cathode material is related to several degradation issues. Therefore, a Sr-free cathode with sufficient physical, electrochemical, thermodynamic and mechanical properties is expected to have beneficial characteristics. As an example, lower oxygen vacancy formation energy is one of the expected properties. As assistance to computationally expensive ab initio calculations, machine learning algorithms can help to screen candidate cathode materials based on the oxygen vacancy formation energy.

## ELECTRONIC STRUCTURE AT OXIDE INTERFACES

### **Asst. Prof. Lior Kornblum**

*Andrew & Erna Viterbi Department of Electrical Engineering  
Technion – Israel Institute of Technology*

Oxide interfaces host a wide spectrum of physics that is of considerable interest both from fundamental and applied perspectives. One aspect of the problem is charge transport across the interface between different oxides. Oxide interfaces sometimes require to block current transport, for example in field effect devices, or to facilitate currents, such as in catalysis schemes. In many cases, this interfacial electronic structure dominates the functionality and performance of electronic and electrochemical devices. We study the band structure at oxide interfaces using spectroscopic approaches, and correlate it with the electrical behavior of the junction. This provides us with a wealth of chemical and electronic information, shedding light on the physics of the interface and its role in the functionality and performance of these device building blocks.

## LIFETIME OF WIND TURBINE DRIVE TRAINS

### **Prof. Dr.-Ing. Georg Jacobs**

*MSE – Institut für Maschinenelemente und Systementwicklung – RWTH Aachen University*

Wind turbines are designed to reach a minimum lifetime of 20 years. In the field premature failures of roller bearings, gearboxes, generators and power electronics are observed. The biggest part of the gearbox failures as well as some of the generator failures are caused by roller bearings again. Reasons for this observation are on one hand the underestimation of operating loads during the design phase and on the other hand specific failure mechanisms like White Etching Cracks and Smearing. The presentation will deliver explanations why these specific failure mechanisms show up in wind turbines more frequently than in other applications and propose future qualification test procedures. Journal bearings are identified as technical alternative to roller bearings but need an extension of the today design methods to assure a safe operation in wind turbines. Newly developed design methods and a patented bearing design will be introduced.

## LOW DIMENSIONAL PEROVSKITE NANOCRYSTALS AS MODELS FOR NEXT GENERATION ENERGY MATERIALS

### Asst. Prof. Yehonadav Bekenstein

*Department of Materials Science and Engineering  
The Solid State Institute  
Technion – Israel Institute of Technology*

Thermodynamic considerations suggest correlation between efficient photo conversion and luminescent. Lead-halide perovskites have emerged as important optoelectronic materials with excellent efficiencies in photovoltaic and light-emitting applications. Low-dimensional colloidal nano-crystals of cesium lead halide are shown to demonstrate exceptionally high photo luminescent quantum yields and unusual room temperature transformation not common to other semiconductors nanocrystals. Properties that suggest a near equilibrium crystal system. In a series of studies we follow the formation and transformations of these nanocrystals. Our findings enable us now to grow quantum confined cesium lead halide nanocrystals with cube, plate and wire geometry and with atomic precision. This unique colloidal system enables the study of excitons in perovskites within a controlled quantum confined shape. We demonstrate how quantum confinement and dimensionality dictate the photophysical properties of these crystals. In the case of 2D plates we observe increased excitonic interaction and increased absorption coefficient. In the case of nanowires we show that the broken symmetry manifests in polarized emission which enables fabrication of highly functional films through 3D printing. In addition by changing the anion composition facile band gap tunability at room temperature throughout the visible spectrum is achieved. The resulting high QY, combined with the synthetic versatility, position colloidal perovskites as a unique model system for the study of charge dynamics and thermodynamic transformations at the nanoscale, which is important in the greater context of understanding next generation materials for energy conversion applications. Future developments in perovskites, such as lead-free materials will also be discussed.

## HIGH OPEN-CIRCUIT VOLTAGES IN LEAD-HALIDE PEROVSKITES

### Prof. Dr. Thomas Kirchartz

*IEK-5: Photovoltaik – Forschungszentrum Jülich  
Faculty of Engineering and CENIDE – University of Duisburg-Essen*

Efficiencies of lead-halide perovskite based solar cells have increased over the last several years at a speed that is unprecedented in the history of photovoltaic technologies. What is striking is in particular how relatively little engineering was needed to achieve high open-circuit voltages ( $V_{oc}$ ) that even now come similarly close to the Shockley-Queisser limit than those of Si solar cells after 60 years of technological development. This development inspires two questions, namely how far can we go technological and how do we characterize and understand these results. Here, I will present experimental results on very high open-circuit voltages and discuss the transient and steady state characterization of these high  $V_{oc}$  materials and devices. In the second part of the talk I will discuss what we know about non-radiative recombination in these semiconductors and discuss why the material properties of lead-halide perovskites are beneficial for achieving low recombination rates at a given charge carrier concentration.

## CATALYTIC CONVERSION OF CARBON DIOXIDE: CHALLENGES AND OPPORTUNITIES AT THE INTERFACE OF ENERGY AND CHEMISTRY

### Prof. Dr. Walter Leitner

*Max Planck Institute for Chemical Energy Conversion*

*Institute of Technical and Macromolecular Chemistry – RWTH Aachen University*

The industrial transformation of carbon-based raw materials into valuable products forms the basis of today's global economy and modern societies. With products ranging from energy carriers, through plastics and advanced materials, to biologically active compounds, chemistry is essential to cope with the global challenges of our time. Moving towards a more sustainable future, there is an increasing need for broadening the raw material basis by developing and using non-fossil resources together with the deployment of carbon-free energy technologies. The present contribution will discuss the opportunities and challenges of this approach for catalytic CO<sub>2</sub> conversion and present examples of new products and processes based on it.

### References:

*Sustainable conversion of carbon dioxide: An integrated review of catalysis and life cycle assessment*, W. Leitner, A. Bardow, et al. *Chem. Rev.* 2018, 118, 434–504; *Selective Catalytic Synthesis Using the Combination of Carbon Dioxide and Hydrogen: Catalytic Chess at the Interface of Energy and Chemistry*,

J. Klankermayer, W. Leitner, et al. *Angew. Chem. Int. Ed.* 2016, 55, 7296-7343.

## POROUS ELECTROSPUN NANOFIBERS AS A SUBSTRATE PLATFORM

### Prof. Gideon S. Grader

*The Wolfson Department of Chemical Engineering*

*Technion – Israel Institute of Technology*

Electrospinning is a simple approach to produce polymer, ceramic and composite nanofibers of various materials. Ceramic nanofibers with designed morphology, chemical and physical properties are desirable for functional materials. For example, the Fe-Al-O system is used for heterogeneous catalytic reaction converting hydrogen and carbon dioxide (CO<sub>2</sub>) into liquid fuels. Usually, the electrospinning stage is followed by a thermal treatment step to remove the polymer and obtain the final structure and phase. This step often includes shrinkage, deformation, and phase and morphology changes. Hollow nanofibers, nanobelts and mesoporous fibers receive significant attention due to their superbly high area to volume ratio. Precursor composition, mat thickness and heating rate were found to alter the final morphology from solid nanofibers to lamellar-like nanofiber [1], nanobelts or hollow nanofibers in the Fe-Al-O system. The morphology transformation mechanism governing the formation of hollow nanofibers, nanobelts and lamellar structures as a function of thickness, composition and heating rate is discussed. The proposed mechanism suggests that this structure is possible with other material systems, providing a route to explore other functionalities. The obtained results are beneficial for production of nanofibers with controlled morphology and underlining the connection between nano-morphology and process conditions. In summary, the presented nanofibers open new research direction in material science and are suitable particularly for applications requiring an accessible large surface area porous media.

## LIFE CYCLE ASSESSMENT TOOLS FOR EMERGING RENEWABLE FUELS, CHEMICALS, AND MATERIALS

**Assoc. Prof. Sabrina Spatari**

Faculty of Civil and Environmental Engineering  
Technion – Israel Institute of Technology

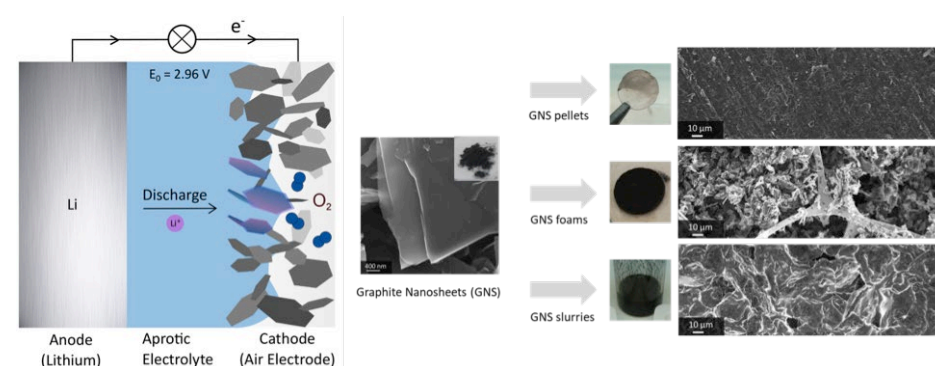
Biofuels are currently under development to meet policy goals for diversifying energy supply, reducing the carbon-intensity of transportation and other sectors, and stimulating rural economic growth. At present biochemical and thermochemical technologies are under development at laboratory and pilot scale to investigate the technological needs of scaling biofuels and value-added co-products. Ethanol, higher alcohols, and fully infrastructure compatible fuels (with 0% oxygen – physically and chemically similar to current petroleum based fuels) are being developed at different scales, including farm scale (up to 200 dry metric tons/day) and industrial scale (2000 dry metric tons/day and higher) to utilize diverse lignocellulose resources. Life cycle assessment (LCA) is a method for evaluating the environmental performance of biofuels and biomaterials emerging through R&D, and a necessary tool for judging the compliance of those biofuels under different policies. This presentation reviews the development of and results from LCA and techno-economic analysis (TEA) models for transport fuels and co-products under development via biochemical and thermochemical conversion of multiple biomass resources (agricultural and forest residues, and dedicated energy crops) and benchmarks them relative to conventional fuels made from petroleum. Some of the challenges in modeling early stage biomass conversion and upgrading to fuels and chemicals are discussed along with strategies for overcoming them.

## AIR ELECTRODE ARCHITECTURES FOR HIGH-CAPACITY LITHIUM-OXYGEN BATTERIES

**M. Sc. Phillip Wunderlich and U. Simon**

Institute of Inorganic Chemistry – RWTH Aachen University

Lithium-oxygen batteries promise cheaper, bigger and more sustainable electrochemical energy storage than the lithium-ion batteries for today's electric vehicles. After 15 years of research without the anticipated breakthrough, the seemingly simple Li-O<sub>2</sub> electrochemistry still sets numerous challenges for rechargeability and practical energy densities. We demonstrate that it is possible to reach high discharge capacities (47 mAh/cm<sup>2</sup>, 6700 mAh/g<sub>carbon</sub>) with graphite nanosheets (GNS) as air electrode active material, enabled by an optimized set of parameters such as current density, oxygen pressure or electrolyte volume. The ways GNS are processed into electrodes result in microstructured-dependent characteristics investigated with galvanostatic battery tests, EIS, XRD, Raman and SEM. Diving into the realm of deep discharge, we encounter new categories of problems like massive volume changes, structural damage to the carbon and possibly further reaction of the main discharge product. The experiments are critical advances towards practical lithium-oxygen cells and eventually also a reality check for the pursued dream of high energy densities.





## IMPEDANCE SPECTROSCOPY STUDIES OF ELECTROCHEMICAL SYSTEMS

### Assoc. Prof. Yoed Tsur

*The Wolfson Department of Chemical Engineering  
Technion – Israel Institute of Technology*

The physical phenomena underlying the resulting data in EIS are related to the relaxation times in the sample. The inverse problem of finding the distribution function of relaxation times (DFRT) is a demanding one. We have developed a modified Genetic Programming (GP) method for this task. It gives a functional form of the DFRT in the sample. The most important parts of the evolutionary force drag the population of solutions toward lowering the discrepancy between the model's prediction and the measured data while keeping the model simple in terms of the number of free parameters that are used. The program seeks DFRT that has the form of a peak or a sum of several peaks, assuming the Debye kernel. All the peaks are known functions. By finding a functional form of the DFRT, one may develop a physical model and examine its behaviour over time and/or environmental changes. The different peaks, which can sometimes be related to processes, can be analysed separately. The approach has been demonstrated on several systems, including for instance on cathode and anode reactions in solid oxide fuel cells, on supercapacitors, on degradation processes of PEMFCs and more. It has a particular advantage for studying degradation mechanisms in electrochemical systems, since the model is typically staying the same (e. g. two peaks of a certain type) while only the parameters are changing during initial degradation.

## HYBRID ELECTROLYTES FOR ALL SOLID-STATE BATTERIES

### Prof. Dr. Hans-Dieter Wiemhöfer

*HI-MS – Helmholtz-Institute Münster  
IEK-12 – Forschungszentrum Jülich*

Enhanced safety concerns as well as the challenges of the all solid state batteries drive the search for alternative lithium ion conducting electrolytes. In this presentation, the concept of hybrid electrolytes is discussed and illustrated using results from recent work [1-4]. The primary idea of a hybrid electrolyte is to combine the properties of different crystalline, polymeric and liquid components in order to fulfill a variety of requirements. Recent examples are self-organized triblock-copolymers with very good lithium ion conductivity [2], multi-layer electrolytes based on solid crystalline and polymeric electrolytes [3] and microporous interpenetrating polymer networks [4].

- [1] A. Pelz, M. Grünebaum, H.-D. Wiemhöfer, in: K. Wandelt (Ed.), Encyclopedia of Interfacial Chemistry: Surface Science and Electrochemistry, Vol. I: 1.1 Experimental Methods, 1.2 Surface Science under Environmental Conditions, Elsevier, Amsterdam 2018, pp. 660-673.
- [2] A. Pelz, T. Dörr, P. Zhang, P.W. de Oliveira, M. Winter, H.-D. Wiemhöfer, T. Kraus, Chem. Mater. 2019, 31(1), 277-285.
- [3] S.C. Yu, S. Schmohl, Z.G. Liu, M. Hoffmeyer, N. Schön, F. Hausen, H. Tempel, H. Kungl, H.-D. Wiemhöfer, R.A. Eichel, J. Mater. Chem. A 2019, 7, 3882-3894.
- [4] E. Cznotka, S. Jeschke, H.-D. Wiemhöfer, Solid State Ionics 2016, 289, 35-47.

## CERAMIC MATERIALS AND TECHNOLOGIES FOR THE DEVELOPMENT OF SOLID-STATE BATTERIES

### Prof. Dr. Dina Fattakhova-Rohlfing

*IEK-1: Materials Synthesis and Processing – Forschungszentrum Jülich GmbH  
Faculty of Engineering – University of Duisburg-Essen*

Solid-state batteries are currently seen as the solution to overcome the current limitations of conventional lithium ion batteries such as the lack of long-term-stability, limited safety and low energy density. The main challenge of solid-state batteries is, however, the low ionic conductivity of the available solid electrolytes, coupled with high interfacial resistances between the electrolyte and active materials. Significant improvements in solid-state battery performance can be expected from the use of materials with improved conduction and optimization of the interface characteristics, including morphology, to balance electron and ion flow in a complete device.

I will give an overview of the solid state battery development at the Institute of Energy and Climate Research (IEK-1, Forschungszentrum Jülich), with a special focus on the critical bottlenecks in the battery performance and the challenges associated with the processing of ceramic materials to full battery cells and their proper operation. One of the important issues is a possibility of processing thick composites cathodes with percolating pathways for ion and electron transport, where the compatibility of the materials in individual processing steps becomes of vital importance. Furthermore, the use of metallic lithium anodes and the problems associated with the lithium metal deposition inside of solid electrolytes is another challenge in the solid state battery development. I will discuss the strategies to solve these problems and will show the concepts for the mitigation of critical steps.

## BATTERY AGEING AND ACCELERATED LIFE TESTING

### Prof. Dr. Dirk Uwe Sauer

*Institute for Power Electronics and Electrical Drives / Power Generation and Storage Systems  
RWTH Aachen University*

A major challenge for Europe's industry is to establish an own lithium-ion battery cell production. Asian manufacturers are dominating the market and in a key technology area for the future. But, if want to have chance to catch up we need to accelerated the development process. Today, production and optimization of lithium-ion batteries are based on comprehensive experience. Material formulation or production process are changed only in small steps to analyse the impact on performance, safety and lifetime. However, lifetime tests easily can take a year or more until we get significant results. Complex combinations of different stress factors such a current rates, high and low temperatures, underpressure and overpressure, vibrations and shocks, of compression on battery cell housings make it almost impossible to conform with high statistical significance the safety and the required lifetimes of cells under all relevant operating conditions.

The presentation will give an overview on the ageing processes occurring these days in modern lithium-ion batteries. In addition, a concept will be presented based on a holistic concept to reduce the duration of the qualification of new cells drastically. A combination of tests on test benches, of post mortem analysis of new and aged cells on microscopic material levels, advanced simulation tools, and advanced data correlation techniques should help us to achieve the goal. This requires strong interdisciplinary approach. Accelerated lifetime prediction will allow to vary parameters in material formulation and production processes much faster and therefore will allow to close the gap to the Asian cell manufacturers in relative short times.

## MECHANICAL AGEING IN LITHIUM ION BATTERY CELLS

**Prof. Dr. Egbert Figgemeier**

*HI-MS – Helmholtz-Institute Münster*

*IEK-12 – Forschungszentrum Jülich*

Degradation and reliability are key factors for extending the range of applications for Lithium ion batteries. The scientific literature dealing with degradation mechanisms in full Lithium ion cells has spent a large effort on investigating chemical and electrochemical causes. For example, it is well understood that the loss of Lithium inventory due to the reaction of Lithium at the anode is one of the major mechanisms for capacity fade. Also, subsequent growth of deposition layers on the anode beyond the solid-electrolyte interface has been identified as failure mode. Several other mechanisms have been postulated and described in the literature depending on the chemistry of the active and passive materials.

In contrast to chemistry related degradation mechanisms, mechanical and form factor related failure has been considered to a much lesser degree. Such mechanisms seem to be of less interest for academic researchers since they seem to be rather an engineering task than a scientific challenge and they have not been recognized as significant contributor to degradation yet. Nevertheless, during the last years a number of studies have been published showing how mechanical issues caused by extensive charge-discharge cycling or temperature can play a significant role in degradation and need to be considered in the overall understanding of reliability of Lithium ion battery cells.

In the current presentation, an overview of mechanical deformation issues in cylindrical Lithium ion battery cells will be given. This will be exemplified by a detailed study by computer tomography combined with electrochemical performances. It will be shown how charge/discharge cycling contributes significantly to geometric changes of the electrode jelly roll and how the volume changes of the electrode layers lead to this degradation mechanism.

## SMALL SCALE EFFECTS IN BATTERY MATERIALS STUDIED BY IN-SITU ATOMIC FORCE MICROSCOPY

**Prof. Dr. Florian Hausen<sup>1,2,3</sup>**

**Svenja Benning<sup>1,2</sup> | Nino Schön<sup>1,2</sup>**

<sup>1</sup> *IEK-9 – Forschungszentrum Jülich GmbH*

<sup>2</sup> *Institute of Physical Chemistry – RWTH Aachen University*

<sup>3</sup> *JARA-Energy – Jülich-Aachen Research Alliance, Section: JARA-Energy*

Batteries require a detailed knowledge of surface and interfacial reactions at a process relevant scale, i.e. nanometer and small micrometer range, as key for developing materials with advanced functionality. Atomic Force Microscopy (AFM) is an ideal tool for such investigations because of its ability to work in numerous environments with high spatial resolution. In the first part of the presentation the formation of the solid electrolyte interphase (SEI) and the lithiation of anode materials in view of the mechanical properties, such as roughness and Young's modulus, during in-situ electrochemical control, is discussed.

In a second part the relationship between the microstructure of a solid state electrolyte on the local Li-ion conductivity is presented. For LATP,  $\text{Li}_{1.3}\text{Al}_{0.3}\text{Ti}_{1.7}(\text{PO}_4)_3$ , significantly reduced Li-ion mobilities in secondary phase areas are observed. The contribution of grain boundaries to the overall ionic conductivity is discussed in view of electrochemical impedance spectroscopy experiments.

## NOVEL ELECTROCHEMICAL SYSTEMS FOR SIMULTANEOUS ENERGY STORAGE, CONVERSION AND WATER DESALINATION

**Asst. Prof. Matthew Suss**

*Faculty of Mechanical Engineering*

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In recent years, various electrochemical systems originally intended for energy storage have emerged as viable water treatment technologies. One of the most prominent examples is capacitive deionization where supercapacitor-type cells are used for simultaneous energy storage and water desalination. I will here present our group's recent work exploring such technologies towards water treatment applications. Notably, we have discovered methods to enhance and tune size-based ion selectivity by nanoporous carbon capacitive deionization electrodes, through use of electrode surface functionalization. Such functionality can be leveraged to fill key niche applications in water treatment requiring ion-ion selectivity. We have also developed a desalination technology which requires solely chemical energy as input, so that no electricity, high pressure or thermal inputs required. The latter technology is based on a chemical-to-electrical energy conversion process, similar to a fuel cell, and thus can deliver electricity and desalted water simultaneously. We show our first generation cell can desalt water with a salinity about that of sea water while simultaneously generating up to 23.5 kWh/m<sup>3</sup> electricity and requiring as little as 3.9 kWh/m<sup>3</sup> net (chemical) energy requirements. Cost analysis show that the latter cell has the potential to deliver ultra-low cost desalted water (< \$0.5/m<sup>3</sup>) when using low-cost reactants to drive desalination.

## KINETICS OF THE IONIC CHARGE TRANSFER BETWEEN SOLID AND LIQUID LITHIUM ELECTROLYTES

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The operation of Li-O<sub>2</sub> and Li-S cells can be substantially improved, if the anodic region can be separated from the cathodic region. In the case of Li-S cells it prevents the diffusion of polysulfide species to the anode; in the case Li-O<sub>2</sub> cells it allows the use of a non-aqueous, aprotic anolyte and an aqueous, protic catholyte. The separation can be realised by using a solid Li<sup>+</sup> electrolyte membrane [1]. This may also avoid short circuits by dendrite grow, when using metallic lithium anodes. Only few studies on ionic transfer between solid/liquid electrolytes can be found despite the impact on future Li battery systems [2,3].

In this contribution the kinetics of the Li<sup>+</sup> charge transfer between a liquid electrolyte LiPF<sub>6</sub> + EC/DMC (LP30) and a solid electrolyte Li<sub>7</sub>La<sub>3</sub>Zr<sub>1.6</sub>Ta<sub>0.4</sub>O<sub>12</sub> (LLZO:Ta) is investigated. A symmetric liquid/solid/liquid DC polarisation cell with six potential probes and two current loaded Li electrodes has been used to measure the electrochemical potential drops  $\Delta\mu_{\text{Li}^+}/F$  at the solid liquid interfaces [2]. Electrolyte concentrations  $c_{\text{Li}^+}$  between 0.001 and 1 mol/l were used.

The symmetric S-shaped polarization curves can be described by a thermally activated process ( $E_a \sim 0.7$  eV) in addition to a constant ohmic resistance  $R_{\text{SLEI}}$  ( $E_a \sim 0.4$  eV). At low electrolyte concentrations  $c_{\text{Li}^+} < 0.1$  mol/l the polarisation resistance  $R_p$  is concentration dependent and obeys a power law. At higher concentrations  $c_{\text{Li}^+} > 0.1$  mol/l  $R_p$  is limited by  $R_{\text{SLEI}}$  and reaches a constant plateau of  $\sim 600 \Omega \text{ cm}^2$ . The thermally activated ion transfer process yields an exchange current density  $i_0$  of  $\sim 400 \mu\text{A}/\text{cm}^2$  and a symmetry factor  $\alpha$  of  $\sim 0.4$  ( $c_{\text{Li}^+} = 1$  mol/l). Only for very low electrolyte concentrations  $c_{\text{Li}^+} < 0.01$  mol/l the polarization curves show a strong asymmetry, due to mass transport limitations [4].

A Butler-Volmer like transfer kinetics can be applied [3]. The constant ohmic resistance  $R_{\text{SLEI}}$  can be attributed to a low conducting surface layer, a solid-liquid electrolyte interphase [3]. It may be formed by degradation reactions with air/liquid electrolyte and is highly increased if traces of water are added [4].

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## RECIPROCAL SALT SYSTEMS FOR THERMAL ENERGY STORAGE

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One of the most promising renewable technologies is concentrated solar power (CSP) plants, which play a major role in solving the world's present and future electricity problems with zero emissions of greenhouse gases. This technology requires the development of powerful energy storage systems. Currently, only sensible thermal energy storage (TES) is used for CSPs, but latent TES with phase change materials (PCM) would be more effective. However, in the case of latent TES with one PCM some heat energy will be utilized as sensible heat, only. In order to maximize the heat capacity over a certain temperature range, cascaded latent heat storage (CLHS) with different type of PCMs can be used.

The PCMs should have phase transitions with a large enthalpy within the operating range of the heat storage system. Furthermore, they should preferably melt congruently, which is not only the case for many stoichiometric compounds but also for any eutectic mixture. Reciprocal salt systems based on the cations Na<sup>+</sup>, K<sup>+</sup>, Ca<sup>2+</sup> and the anions Cl<sup>-</sup>, NO<sub>3</sub><sup>-</sup> are considered as potential PCMs to design CLHS. This is possible by following different compositions along a univariant line on the liquidus surface of a multicomponent system. Such type of compositions has the potential of covering a wide temperature range from 100 °C to 800 °C.

In order to select suitable systems, it is necessary to build a consistent and validated thermodynamic database, which includes thermodynamic information about pure compounds, phase diagrams, enthalpies of phase transitions, enthalpy increments and information about the thermal stability. In this work thermodynamic properties of various compositions of the above mentioned reciprocal system were studied using differential thermal analysis, differential scanning calorimetry, and Knudsen effusion mass spectrometry. All experimental results were used for the optimization of the thermodynamic parameters using the CALPHAD method to obtain a Gibbs energy dataset. The new assessed dataset allows calculating the enthalpy increment of the selected mixtures with high precision, which can be applied for numerical PCM screening in the multicomponent system Na<sup>+</sup>, K<sup>+</sup>, Ca<sup>2+</sup> // NO<sub>3</sub><sup>-</sup>, Cl<sup>-</sup>.

## TOWARDS EFFICIENT SMALL MOLECULE CATALYSIS WITH EARTH ABUNDANT METAL CATALYSTS

**Asst. Prof. Graham de Ruiter**

*Schulich Faculty of Chemistry – Technion – Israel Institute of Technology*

Here we present a series of first-row transition metal complexes; [M(BDI)](OTf)<sub>2</sub> (M = Fe and Co) that feature a redox-active bipyridine-diimine ligand (BDI). Access to these metal complexes enabled exploration of its rich electrochemistry demonstrating a total of five unique oxidation states (M = Fe). Not only were we able to access three unique redox states of the BDI ligand, we were also able to exploit the reversible multi-electron chemistry for the cobalt catalyzed hydrosilylation of unactivated alkenes which will be discussed in this presentation.

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## CHALLENGES AND OPPORTUNITIES IN THE DEVELOPMENT OF MEMBRANE ELECTRODE ASSEMBLIES FOR PEM WATER ELECTROLYSIS

**M. Sc. Fabian Scheepers**

*IEK-3: Electrochemical process engineering – Forschungszentrum Jülich GmbH*

Wind and solar plants are key technologies in a fully renewable energy system. However, the challenge ahead is not only to generate a sufficient total amount of electrical energy via these, but to ensure a continuous, stable supply to meet demand. To achieve these goals efficiently, storage technologies are required. If large amounts of electric energy are to be stored for longer periods of time, this can be achieved by converting it into chemical energy via the electrolytic production of hydrogen, for example by means of polymer electrolyte membrane (PEM) electrolyzers. This research aims to increase the efficiency of such electrolyzers in order to reduce production costs and the amount of energy needed, ultimately reducing overall costs. While experiments are mostly conducted on a laboratory scale, there are challenges when these experiments are scaled up to pilot plants. This presentation provides insight into the production of the core of a PEM electrolyzer, namely the *membrane electrode assembly*. The individual process steps and their underlying challenges are highlighted in their importance for the entire production process chain. Based on the understanding of the process gained, advanced approaches can be developed, as are also demonstrated in this contribution.

## HIGH-TEMPERATURE CO-ELECTROLYSIS

**Dr. L. G. J. de Haart**

*IEK-9 – Forschungszentrum Jülich GmbH*

The direct high-temperature co-electrolysis of water and carbon dioxide offers a suitable technology to provide ‚white‘ syngas. Syngas is a mixture of hydrogen and carbon monoxide which is used in chemical industry for the synthesis of many basic chemicals as well as synfuels. Using renewable energy sources and the climate gas CO<sub>2</sub> the high-temperature co-electrolysis technology presents a sustainable alternative to conventional processes. The technology allows the adjustment of the H<sub>2</sub> to CO ratio required for various downstream catalytic processes in one step.

Within the framework of the German Kopernikus Project „P2X: Flexible use of renewable resources – research, validation and implementation of ‘Power-to-X’ concepts“ a systematic analysis of the performance and syngas ratio during high-temperature co-electrolysis was performed. Investigated were the influence of temperature, feed gas composition and fuel utilisation. Experimental results were furthermore compared to theoretical calculations of syngas production on a thermodynamic and partially kinetic level.

## THE ROLE OF CHEMICAL ENERGY STORAGE IN THE ENERGY TRANSITION

**Dr.-Ing. Martin Robinus**

*Forschungszentrum Jülich GmbH*

In line with the global climate goals of the 2015 Paris Agreement, Germany is pursuing an ambiguous national greenhouse gas reduction strategy with national climate goals of 80-95% CO<sub>2</sub> emission reduction (compared to 1990). The central part of the investigation can be represented by a highly temporal resolved national energy system model for Germany, and the so called FINE-NESTOR has been developed precisely for this purpose. This model was designed to minimize the total system costs of the entire German energy system while considering the energy sector and all end-use sectors are part of the optimization. This is implemented on the basis of a quadratic programming approach with a focus on cost uncertainties, and therefore provides robust solutions over a variety of future cost scenarios. Moreover, the model makes use of time series aggregation techniques, includes seasonal storages, and implements a wide range of cross-sectoral technologies totaling to 50 pathways. In order to face the upcoming challenges of the energy transition, the results are further improved by the iterative coupling of other energy system related models. This involves a highly-resolved geospatial renewable energy potential model, hourly simulation of wind and PV generators, a European power flow model, and a global infrastructure model for the sustainable supply of synthetic fuels such as hydrogen and methane. Moreover, many of these models have been published open-source. Based on these aspects, different strategies for the reduction of CO<sub>2</sub> emissions as well as their impact on the energy system are presented. The focus of the presentation will be on the contribution to CO<sub>2</sub> abatement of cross-sectoral technologies, which are investigated within a consistent energy scenario.

## THE ELECTROLYTE MATTERS: STABLE SYSTEMS FOR HIGH RATE ELECTROCHEMICAL CO<sub>2</sub> REDUCTION

**Dipl.-Ing. Robert Sengpiel  
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*Chemical Process Engineering – RWTH Aachen University*

The electrochemical CO<sub>2</sub> reduction is a promising technology to reduce greenhouse gas emissions to the atmosphere by using power from regenerative resources. Today, research mainly focuses on the development of catalysts with improved activity and selectivity. However, many studies are conducted at low current densities, unstable electrolyte systems and electrochemical reactors, which are not suitable for industrial application. A paradigm change is needed in order to obtain reliable results at conditions which resemble the industrially relevant environment and which can thus be transferred to reactors with a high capacity. Recently, we have shown that the cell and electrode configuration of an electrochemical membrane reactor highly influences the product spectrum and energy efficiency. In this presentation, we highlight the appropriate choice of electrolyte and membrane, which is imperative for a long-term stable operation. We employ a stable system for the syngas production and optimize the gas diffusion electrode fabrication as well as electrolyte composition for a high rate production of carbon monoxide.

## ANION EXCHANGE MEMBRANE FUEL CELLS

**Assoc. Prof. Dario Dekel**

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After a few years of intensive research, recent studies of Anion Exchange Membrane Fuel Cells (AEMFCs) finally show cell performance at the required levels for automotive applications. This achievement was mainly due to the successful development of anion exchange membranes (AEMs) with considerable high hydroxide conductivity (100 mS cm<sup>-1</sup> and above). Based on these high-performance membranes, AEMFCs with power densities and limiting current densities higher than 1 W cm<sup>-2</sup> and 4 A cm<sup>-2</sup> have been recently achieved, which only a couple of years ago seemed far from possible. In order to make the next breakthrough and bring the AEMFC technology to the next levels, the following challenges need to be addressed: (A) the need for Pt-free (and PGM-free) catalysts highly active towards hydrogen oxidation reaction in alkaline medium, (B) carbonation issues while working with ambient air feed, and (C) barriers in cell performance stability. Dekel's group at the Technion focuses its activities on these state-of-the-art topics, aiming to keep making a significant impact in the AEMFC research community. Latest achievements of our group in these AEM-FC challenging fronts will be presented and discussed during the talk.

## CHEMICAL DECOMPOSITION OF ANION-EXCHANGE MEMBRANES BY UNSOLVATED HYDROXIDE

**Asst. Prof. Charles E. Diesendruck**

*Schulich Faculty of Chemistry – Technion – Israel Institute of Technology*

Anion-Exchange Membrane Fuel Cells (AEM-FCs) are among the most promising technologies to address present energy issues. However, this technology is currently limited by the low chemical stability of membrane. While this problem has been addressed many times in the past years, there is still no system that meets practical commercial requirements. In this talk, I'll present our recent work on understanding the role water plays in the chemical decomposition issue, looking at how hydroxide microsolvation affects some of the classic organic chemistry reactions which cause the membrane decomposition.

## JÜLICH STACK DESIGN FOR VARIOUS OPERATION MODES FOR ELECTROCHEMICAL CONVERSION DEVICES

**Prof. Dr. Ghaleb Natour  
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JÜLICH is developing solid oxide fuel cells since the beginning of the 1990s. The development covers the whole chain from basic materials research, stack design till complete stand-alone systems.

15 years ago a stack design was developed in Jülich that has been used for multiple operation modes. First feasibility studies and later profound investigations using the standard F10 stack design for many variations of materials, components and testing conditions as well as parameters has led to a huge database of test results available for comparisons and optimisations.

The standard Jülich stack design, so called F10, is developed initially for operating in fuel cell mode at a temperature range between 700°C and 800°C. A stack of this kind has reached recently 100000h.

The main focus of cell development is lowering the operating temperature below 600 °C in order to create new, extended application possibilities, such as range extenders for mobile applications. First results achieved with a short stack will be presented.

Growing interest on high temperature electrolysis (SOE) is recently observed. Using the standard short stack design, called F10, several stacks have successfully been tested in electrolysis mode. An overview over the latest results will be given.

During the last years, the operation of the solid oxide cells in reversible mode (rSOC) is being investigated. One of the major benefits of an rSOC plant is that the same SOC-stack can be used as electrolyzer (SOEC) and as fuel cell (SOFC). This is ideal to deal with the time discrepancy occurring between energy demand and supply in electricity producing renewable energy systems like photovoltaic and wind power. The feasibility of the reversible solid oxide cell (rSOC) was demonstrated in short stacks and became the basis for the rSOC system development.

Rechargeable oxide battery (ROB) comprises high temperature solid oxide cells (SOC) as energy converters and a metal/metal-oxide as storage material. Instead of externally storing the fuel, a stagnant atmosphere consisting of hydrogen and steam is used as an oxidizing and reducing agent for the storage material. The selected ROB storage materials were integrated in JÜLICH's F10-design SOFC stacks with modified interconnect. The characterization results of the battery performance gained from the stack tests will be shown.

Next step will be the integration of a high temperature oxygen transport membrane into the Jülich F10-stack design for first feasibility tests.



## INTEGRATED COMPUTATIONAL MATERIALS ENGINEERING ICME: A SUCCESSFUL METHODOLOGY TO OPTIMIZE NOT ONLY STRUCTURAL MATERIALS AND THEIR PROCESSING

### Dr. Georg J. Schmitz

*Access e. V. at RWTH Aachen University*

Following an introduction to Integrated Computational Materials Engineering “ICME” the presentation focuses on ongoing ICME activities at RWTH Aachen University. Microstructures of metals and alloys as a key ingredient of ICME are modelled during various processing steps and process chains. Examples being presented comprise microstructures of light metals, steels, and superalloys during solidification, heat treatment, welding, and operation. The benefits of interaction of different models – both continuum and discrete – crossing time and length scales will be demonstrated. The status of the integration of digital experimental microstructures into such simulation scenarios will be shortly presented.

The presentation continues with the AixViPMaP® – the Aachen Virtual Platform for Materials processing – and will highlight its underlying concepts and show some demonstrator workflows. The presentation will conclude with some first examples of ICME being applied to functional materials in the energy sector.

### Acknowledgement

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## HIGH-ORDER STERIC POISSON-NERNST-PLANCK MODELS

### Assoc. Prof. Nir Gavish

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The Poisson-Nernst-Planck (PNP) theory is one of the most widely used analytical methods to describe electrokinetic phenomena for electrolytes. The model, however, considers isolated charges and thus is valid only for dilute ion concentrations. The key importance of concentrated electrolytes and ionic liquids in applications has led to the development of a large family of generalized PNP models. However, the wide family of generalized PNP models fails to capture key phenomena recently observed in experiments and simulations, such as self-assembly and under-screening in concentrated electrolytes. In this talk, we present a thermodynamically consistent mean-field model for concentrated solutions that goes beyond the PNP framework. We show that the model describes bulk and interfacial pattern-formation, map the parameter regimes of distinct self-assembly behaviors and the relevant bifurcation associated with them, and consider their effect on electrostatic screening and transport. In particular, we reveal a novel mechanism of under-screening.



## INTELLIGENT SOLID-STATE DC SUBSTATION FOR FLEXIBLE ELECTRICAL GRIDS

**Dr. Annegret Klein-Heßling**

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The change of the electrical supply system to more environmentally-friendly energy sources requires the development of a new grid infrastructure. Next to the increasing penetration of large scale renewable energy sources such as offshore wind farms, the change of consumer behavior in the distribution grids from consumer into producer due to the installation of decentralized energy generation such as rooftop solar systems may result in a bottle neck in the distribution grids. Local or regional balancing between loads and generations is found to be a better solution for the future electrical grids that can be effectively realized with direct current (DC) technology. Compared to the classical alternating current (AC) technology, DC grids are also less prone to instabilities and more flexible to control via intelligent DC substations. The presentation will focus on intelligent solid-state DC substations as the key enabler technology for future flexible DC distribution grids with renewable energy sources.

In a first part, the presentation will elaborate the construction of an intelligent solid-state DC substation based on dual-active bridge DC/DC converter topology for the DC underlay grids. The high efficiency, compact size and galvanic isolation between input and output offered by this topology makes it an attractive solution for future grids. The second section of the presentation will deal with advanced dual-active bridge control strategies and the handling of fault scenarios in DC grids with intelligent solid-state DC transformers.

## COMPARATIVE ANALYSIS OF INFRASTRUCTURES: HYDROGEN FUELING AND ELECTRIC CHARGING OF VEHICLES IN GERMANY

**Dr.-Ing. Jochen Linßen**

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Electric drivetrains are key elements of low carbon energy-efficient transport based on renewable energy sources. Furthermore, a transportation system with zero local emissions will substantially improve people's quality of life, especially in urban areas currently struggling with air quality issues. Both Battery and hydrogen fuel cell electric vehicles feature these important characteristics. However, large scale integration of these vehicle technologies requires new infrastructures.

The contribution presents a detailed design analysis of the required infrastructure for supplying battery and fuel cell electric vehicles in Germany at multiple scales. The underlying question concerns the investments, costs, efficiencies and emissions for an infrastructure capable of supplying between one hundred thousand to several million vehicles with hydrogen or electricity.

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