Electrochemistry and Energy

Materials | Modelling | Components | Systems
Test Center | Production Research | Safety

Batteries

Fuel cells

Electrolysis

Hydrogen

Super capacitors

Zentrum für Sonnenenergie- und Wasserstoff-Forschung Baden-Württemberg

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Electrochemistry and Energy

Interview with Prof. Werner Tillmetz, Member of the Board of Directors

Energy with a future – that has been ZSW's motto for nearly three decades. Its efforts to develop new electrochemical energy technologies in close alliances with industry, science and government have been making huge strides. All the capabilities needed to investigate and develop innovative energy storage and conversion technologies are assembled under one roof at ZSW in Ulm.

How would you assess the global energy supply and the development of renewables?

What has remained unchanged despite many years of hard work is that fossil fuels still account for around 80% of the energy supply, around the world as well as in Germany. So far modern renewable energies merely play a secondary role. Take, for example, the fast-growing global automotive market. It relies almost exclusively on mineral oil-based fuels.

And the consequences are foreseeable?

Fossil fuels are synonymous with CO_2 emissions and climate change, which has now also hit Germany, causing major damage and setting off a mounting deluge of refugees. Add to this the impacts of pollutants in urban centers and the many geopolitical conflicts sparked by competition for a limited supply of fossil resources that we depend on so heavily.

What has to be done to drive the transition to renewables and electric vehicles?

Public policy is changing fast and investments in renewable energy technologies are reaching world-record levels. Now it's time to push for structural change in industries to accommodate new key technologies such as batteries and fuel cells. If we look at the automotive industry, the battery system accounts for up to 40% of electric vehicles' value-add. And many classic components of an automotive drive are no longer required.

What do you think is the best way of replacing fossil fuels with renewables?

We have a lot of catching up to do in applications, and we're still facing enormous challenges in power generation and heating sectors. Cross-sector energy storage will figure prominently in the future, with advanced energy storage elements such as batteries and hydrogen playing a decisive role in this capability.

You mentioned e-mobility, a topic that is near and dear to many. Efficiency is critical to it. How would you rate the efficiency of alternative drives?

Battery-powered electric drives achieve around 70 to 80% efficiency in day-to-day operation. That is worlds apart from the modern combustion engine, which utilises just 25% of the treasure in the fuel tank. And there are many compelling reasons to tap the sun and wind to generate electricity or hydrogen locally rather than importing fuel as we do with oil.

And what part does ZSW play in all this?

The Ulm-based Electrochemical Energy Technologies division focuses on developing batteries and fuel cells, supercapacitors for high-power storage, and new electrolysis technologies to generate hydrogen. Our research activities and services cover the value chain from end to end. This includes modelling and simulating electrochemical processes, synthesising and characterising active materials, optimizing components and their production processes, and qualifying new products in field-test sites. Working very closely with many allies from all industry sectors, including a growing number of international partners, we take an application-minded approach to R&D.

So ZSW is a melting pot of sorts that combines many years of know-how, scientific insights and the latest technologies to create solutions that appeal to the industry?

You could certainly see it that way. Our close collaboration with industry plays a crucial role, as do our alliances with other research institutes such as the Helmholtz Institute Ulm, many Ulm University institutes and a host of international scientists. This keeps us up to speed with the latest research findings and in touch with the up-and-coming young scientists and technicians we need for our projects. Often it's young research staff members who carry our know-how out into the industry when they embark upon their careers after completing a master's or doctoral thesis at ZSW.

What are your greatest accomplishments so far?

The build-up of eLaB, our battery research center, was definitely a milestone with its unique research platform for the industrial production of lithium-ion cells and the internationally renowned center for all types of battery testing. We developed and tested high-performance, 100 kW-class fuel cells, which is a great achievement in fuel cell research. And our industry partners have gained key insights from our application-centric lifetime tests and research into the impact of hydrogen quality on fuel cells.

What topics will feature in the future?

It's early days yet for commercial fuel cells and batteries in cars and in stationary applications. Their long-term market success will depend on many technological advances. New, sustainable materials will be a big factor in future Li-ion cells. Design is critical to making safe high-energy cells, and electrodes and separators will have to be optimised to this end. Cost-effective components and new manufacturing processes including quality assurance methods will play an important role in fuel cells.

How do you think the exit from nuclear and fossil-fuel energy will drive development in the next five years?

Competition for the best products in the hotly contested global arena is just getting underway. It will take many creative minds and excellent research infrastructure to compete, and that is what ZSW is all about.

Batteries’ capacity for storing electrical energy is a key 21st century technology. And one of the most significant scientific, social and economic challenges of our time is to make the most of this technology.

Batteries

Batteries

Applications, expertise and technologies

Applications

High-performance batteries are the very core of modern hybrid and electric drives. They have a tremendous impact on vehicles' cost, energy consumption, range and reliability, which is why lithium-ion technology is a strategic imperative for tomorrow's automotive industry. With the benefit of their superior cycle stability, lithium-ion batteries lend themselves to distributed storage of electricity generated locally by photovoltaic systems and the like. And with that, they offer a unique opportunity to tap the full potential of energy at its source. Batteries can also help improve power distribution networks and provide emergency power.

Expertise

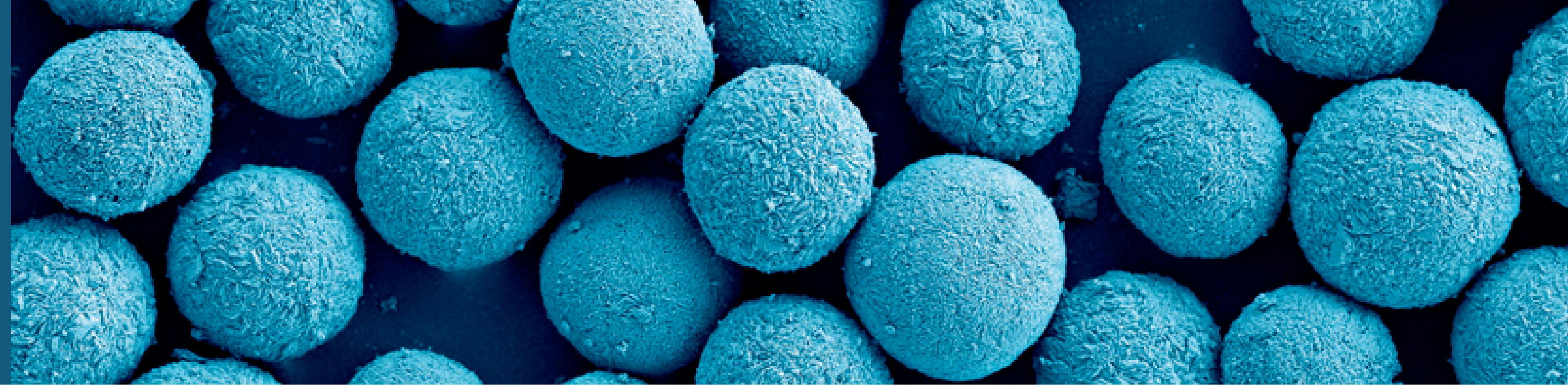
ZSW's skill set covers every link in the battery value chain. We synthesise and characterise active materials, model and simulate electrochemical processes, optimise components and technologies for mass production, prototype cells and pilot productions, and research industrial processes and manufacturing flows. Our test center conducts every type of battery test and investigates systems engineering and battery management issues.

Technologies

Lithium-ion technology is the power storage option of choice for many of today's consumer, automotive and stationary applications. Their energy density, performance and service life have increased enormously over the past 20 years with steady improvements in electrode materials and cell design. And lithium-ion technology's evolutionary trajectory is sure to stay on track for the next 20 years.

ZSW has engaged in all areas of battery research for the better part of three decades. The motivation behind these efforts is to continue increasing energy density while upholding safety standards, improving high- and low-temperature behaviour, and addressing questions about critical materials' availability. Our work is not all evolutionary in nature; we are also striving to create new storage technologies such as sodium-ion cells, metal-air systems, redox-flow technologies and asymmetric double-layer capacitors.

Materials research and cell chemistry



SEM image of a cobalt-free, high-energy cathode material for a lithium-ion batteries.

Our deep insight into the interrelationships between the structures and properties of active materials in electrochemical systems is based on by some 30 years devoted to researching these substances. The success of efforts to synthesise new materials like high-voltage cathodes very much depends on our understanding of the interaction with other cell components such as electrolytes and the very diverse requirements for properties such as cycle stability.

Synthesis reactor for manufacturing active material on a kilogramme scale.

Synthesis processes

Our core skills include the ability to synthesise new chemical compounds for storing energy and formulating powders and slurries tailored to coat specific types of electrodes. To this end, we rely on many established and new manufacturing practices, including precipitation processes and grinding technologies. The design of experiments and other methods serve to optimise powder morphology, particle size and particle coating. Our facilities are able to produce powder in amounts ranging from a few grams to the kilogramme scale. We synthesise inorganic materials and develop new materials for anodes and cathodes.

Analytics

The electrochemical behaviour of storage materials for lithium-ion batteries very much depends on their chemical composition and crystalline structure. Particles' morphology, distribution and surface properties largely determine their processing behaviour and therefore their suitability for the technical processes in battery manufacturing. One of our main objectives in research projects is to profile all of the materials' properties, to identify influential factors and to map and understand the relationships between their structures and properties.

Batteries' performance and storage capacity decreases over time. This aging may be caused by chemical agents that corrode materials or mechanical forces that wear down components. Our researchers are adept at investigating and understanding the effects of aging, and putting these insights into practice to improve materials and develop better cells. To this end, we apply standard chemical (ICP-OES), structural (XRD), microscopic (SEM, EDX) and surface (BET) analysis methods. We also perform high-resolution depth profile analyses to the same end. Our TG/DSC-MS and ARC thermo-analytical methods serve to track decomposition behaviour at higher temperatures.

"FUTURE ELECTRO-MOBILITY AND RENEWABLE ENERGIES REQUIRE NEW ENERGY STORAGE SYSTEMS. WE RESEARCH BATTERIES FROM THE POWDER TO THE FINISHED CELL."

Dr Margret Wohlfahrt-Mehrens
Head of Department
Accumulators Materials Research

A broad swath of future storage technologies

The dominant feature in today's R&D landscape is lithium-ion technology. However, there is a host of new technologies on the near horizon that we are already investigating. These include:

- Nanostructured nickel electrodes, iron-based anodes and novel manganese oxides as cathodes for alkaline high-performance cells
- Advanced pseudo-capacitive active carbons for asymmetric double-layer capacitors
- High-performance anode materials and electrolytes for sodium-ion technology-based
- Metal-air cells that combine a metallic (lithium, magnesium) electrode with an air electrode
- New concepts aimed to optimise performance

WHAT WE CAN OFFER

- Develop new active materials: high-voltage spinels, lithium-transition metal phosphates and silicates, titanates, alloy anodes and electrolytes, to include additives
- Optimise active materials via morphology, surface modification, etc.
- Analyse the interaction of the electrode/electrolyte and the anode/cathode
- Employ all state-of-the-art methods for electrochemical characterisations of materials
- Investigate aging effects in battery materials and components using standard chemical, surface, and depth profile analysis and thermo-analytical methods (TG/DSC-MS and ARC)
- Conduct in-situ investigations of materials in model cells and ex-situ investigations of materials from actual cells (XRD, Raman spectroscopy, TPS)

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Cell aging and post-mortem analysis

3D CT for non-destructive Li-ion cell testing.

As lithium-ion cells for electric cars, e-bikes and stationary energy storage elements make inroads into the market, the ability to analyse aging and defective batteries is becoming increasingly important. In the event of damage, these assessments often aim to determine what caused the impairment – improper use, manufacturing defects or design flaws.

Visual inspection and sampling of electrode strips that were washed and rolled out after opening the cell.

Aging mechanisms and life expectancy

Battery life forecasts have to be accurate. This is why we strive to improve our ability to predict lifetimes and provide timelines with more precise and meaningful battery degradation tests. And that requires penetrating insight into the interplay between cell materials, electrodes, cell design and aging mechanisms.

As layers of decomposition products and metallic lithium deposits on anodes (Li plating) build up, they induce cell degradation. To properly detect this kind of damage, battery cells have to be opened in a safe, reproducible and least invasive way so as not to falsify findings.

Once a cell is open, the electrode strips are rolled out as pictured on the left to take samples from the anode, cathode and separator for extensive physicochemical analysis. We use X-ray diffraction (XRD) to determine lattice constants, EDX and ICP for the chemical elemental analysis of electrodes, and GC-MS to analyse electrolytes. ZSW has also developed a method of accurately predicting the operating conditions of lithium-ion cells using reconstructed cells and reference electrode measurements.

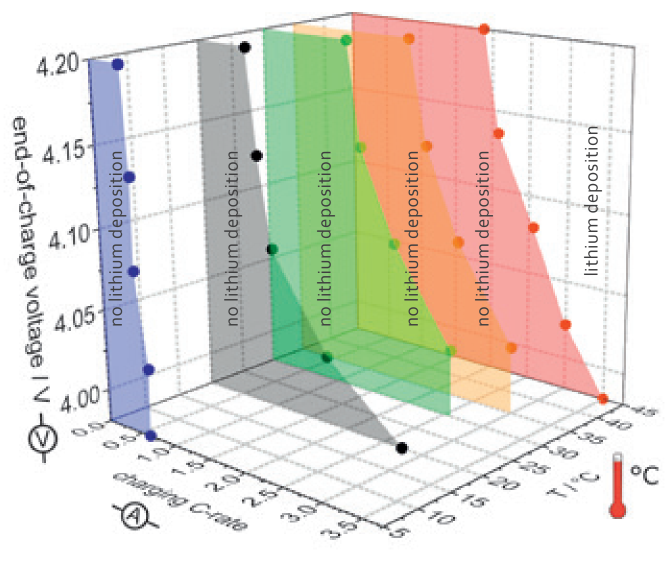
Non-destructive assessments of lithium-ion cells

ZSW is not only well versed in opening cells and conducting post-mortems; we also use X-ray computed tomography, a non-destructive 3D imaging tool, to examine batteries and cells. These three-dimensional views into a cell's interior provide key insights that we use to optimise cells and production processes. Armed with this knowledge, we can target specific improvements in materials and processes to benefit electrode and cell manufacturing and develop new test methods for the battery industry. These 3D analyses serve to assess damage in post-mortem analysis and assure new batteries' quality.

"WE CAN DEDUCE TYPICAL DEGRADATION MECHANISMS IN BATTERIES FROM THE RESULTS OF POST-MORTEM ANALYSIS."

WHAT WE CAN OFFER

- Certified ZSW expert with more than 20 years' experience in battery research (Bundesverband Deutscher Sachverständiger der Handwerks, BDSH)
- Professional workstations for opening all types of cells (including argon-filled glove boxes)
- 3D X-ray computed tomography system with a 300 KV microfocus tube and up to 1 µm detail detectability (especially well suited for larger cells and entire battery modules) as well as a nanofocus tube with 0.5 µm resolution
- Physicochemical methods for analysing degradation mechanisms (SEM, EDX, ICP-OES, XRD, GC-MS, GD-OES, DSC/TG/MS)
- Analyses of all cell components – anodes, cathodes, separators and electrolyte



Operating parameters' influence on Li deposition in pouch cells. Source: ZSW/T. Waldmann et al., J. Electrochem. Soc., 163, A1232 (2016).

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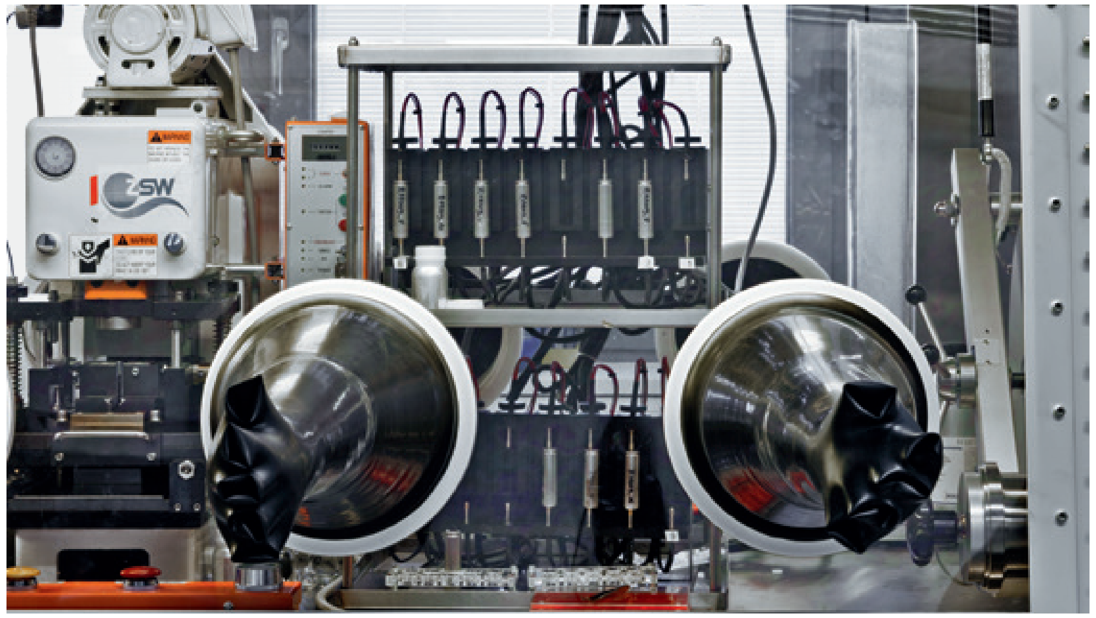
Electrode and cell technology

Pouch cell stacking and winding machine.

An innovative active material alone does not make for a good battery. The right particle morphology, selected additives and a tailored manufacturing process are key ingredients for a good electrode. The coating slurry's formulation and rheology, the coating and drying processes' parameters, and the electrodes' balancing are crucial to the cell's quality.



Lab device for closing and filling 18650 cells.

Electrode development and manufacturing

Requirements for the electrode's coating and structure vary depending on the application for which a lithium-ion cell with active material is designed. The coating of electrodes for high-power cells is thinner and contains more additives to enhance conductivity. The recipe for electrodes destined for high-energy applications generally calls for a thicker coating and the fewest possible additives.

Electrodes' porosity determines their kinetics during charging and discharging, and their power density. Manufacturing parameters have an impact on adhesive strength and stability. We use scanning electron microscopes (SEM), mercury porosimetry and electrochemical analyses to determine the optimum electrode configuration.

ZSW develops formulations and processing methods to attain advanced properties in materials and introduce them into the cell. With a well-stocked arsenal of analysis and testing equipment, we are able to assess in great depth the processing path's effect on the material and on electrodes and cells' properties.

? Did you know that?

Lithium-ion batteries for electric cars have to live as long as the host vehicle and endure many thousands of charging cycles, the exact number of which is determined by the type of drive and distance travelled. The battery's capacity may not dip below 80% of the nominal value during this time. The material researchers at Ulm succeeded in developing 18650 standard cells that retain more than 80% of their initial capacity after 17,000 full charging and discharging operations at a 2C rate.

From half-cells to full cells

The cell is tailored to a specific application by balancing the cathode to the anode. Priorities may vary so that the focus can be on cycle stability, the discharge current rate or a certain operating temperature range.

The results of an initial electrochemical analysis of electrodes in half-cells provide key indications as to what type of electrode balancing will work best. Further electrochemical analyses of various electrode combinations in full cells with a reference electrode provide deeper insight into how these components interact.

ZSW has the equipment to produce single-layer pouch cells, stacked pouch cells, wound 18650 cells and prismatic cells (PHEV-1).

"MASTERING ELECTRODE AND CELL TECHNOLOGY IS A DECISIVE STEP TOWARDS BRINGING ADVANCED ACTIVE MATERIALS TO MARKET."

WHAT WE CAN OFFER

We have every system needed to develop electrodes and cells (18650 and pouch) at our disposal:

- Various mixing technologies (from laboratory to industrial scale), ball mills, and a rheometer test bench and analysis lab
- Various coaters ranging from table units to pilot plants
- Drying room with winding (18650) and stacking-winding machines, a laser system for cutting, treating and contacting electrodes, a laminating machine, and a thermoforming unit for pouch cells
- Various electrolyte filling and formation devices, and 350 cycling stations

Lab mixer for electrode slurries.

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Production and process research

Lithium-ion cells cannot be brought to market without first mastering all manufacturing processes on an industrial scale. It is imperative that we first gain an understanding of how these workflows interact under real-world conditions in an industrial plant, as the cell's cost, service life and performance very much depend on the quality, speed and robustness of these processes.

Electrode coating system with a 20 m drying section and up to 30 m/min. belt speed.

Did you know that?

The German Federal Ministry for Education and Research (BMBF) furnished €25.7 million and the state of Baden-Württemberg's Ministry of Finance and Economy (MFW) contributed €6 million to this research platform for industrial manufacturing of cells. It is peerless worldwide.

A research platform for the industrial production of large lithium-ion cells

These systems enable us to explore and investigate, on an industrial scale, manufacturing processes for large cells such as those used in electric cars or for storing renewable energy. Our top priority is to optimise the individual steps of the process and validate new cell chemistry in standard cells. The Research Platform for the Industrial Production of Large Lithium-Ion Batteries (FPL) was set up to close a gap in the transition from laboratory-scale production to commercial mass manufacturing.

Our research focuses on:

- Demonstrating advanced active materials and recipes in standard cells
- Assessing new materials and components in an environment approximating that of an industrial factory
- Testing and optimising new production processes and system components in a modular, foolproof testing environment
- Developing and improving the process control and quality assurance methods that determine manufacturing quality and yield under much the same conditions encountered in factories

200 m² drying room for fully automatic assembly of wound prismatic cells.

"WITH THIS RESEARCH PLATFORM, WE CAN PROVIDE TO OUR PARTNERS IN INDUSTRY AND SCIENCE A STABLE BASE FOR JOINT PRODUCTION RESEARCH PROJECTS."

Dr Wolfgang Braunwarth
Head of Department
Production Research

This facility provides the means to develop, optimise and qualify, under factory-like conditions, all processes from inception to the final lithium-ion cell. This includes formula preparation, electrode production, cell assembly and charged cell formation. Our adaptive assembly method accommodates various cell formats. Able to produce one cell per minute, its workflow can be scaled all the way up to the level of industrial manufacturing. A stable parameter set is available for each step of production so that the reference process can be ported to the platform in individual steps or in its entirety.

WHAT WE CAN OFFER

Slurry production

- Automated materials weighing and feeding
- Thermostat-driven mixing stations for preparing slurries in 60-litre batches

Electrode production

- Two-storey system for applying 500 mm width coating to both sides of electrodes at 30 m/min. belt speed using various types of applicators
- Precision calender with 600 mm roller width
- Slitter winder (30 m/min.) with interchangeable cutter modules with four blades each and a brush system for cleaning cut electrode strips

Cell assembly/formation

- Fully automated systems for winding, assembling and filling prismatic cells with a cycle time of 1 cell/min.
- 200 m² drying room with -60 °C dew point for testing new assembly technologies
- Fully automated formation with 240 temperature-controlled cycle stations and 2,016 storage stations

Pre-formation system for wound prismatic cells (PHEV-1 format).

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Center for electrical and safety testing

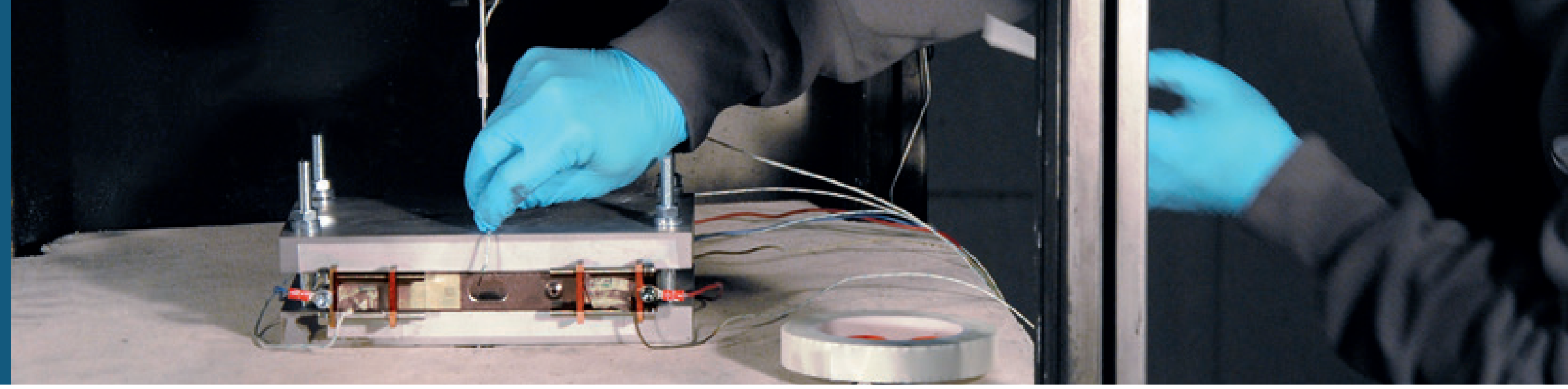
Batteries must deliver reliable performance throughout their service life and even under the most adverse conditions. A great deal of our testing efforts are devoted to characterising batteries under various operating conditions, determining accumulators' qualitative properties, and studying their behaviour in response to handling errors and accident scenarios.

Test bunker equipped with a press for 100-tonne crush tests and video surveillance.

Safety testing

Batteries that see day-to-day use have to be safe and dependable even in extreme situations. To ensure that they are, we analyse their behaviour under every conceivable condition. In order to identify potential hazards, we conduct destructive tests to assess accumulators' responses to extreme damage and their resilience to various forms of misuse and handling errors. Cells and entire battery systems are subjected to these tests in our safety center.

Our efforts focus on mechanical, thermal and electrical safety testing. Functional safety tests are carried out to specific customer specifications or in compliance with national and internationally recognised test regulations. We have test bunkers equipped with fire extinguishers, gas scrubbers, and video surveillance and high-speed data capture systems at our disposal for these tests.

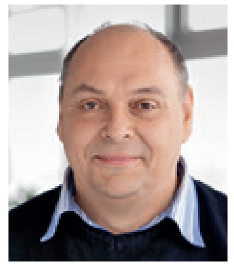


Prepping a lithium-ion cell for the nail test.

Electrical tests

Battery systems' performance and life cycle tests enable us to characterise their electrical properties, capacity and aging behaviour. Measurements are taken to gauge the physical variables of current, time, temperature and voltage, and quantities are then calculated mathematically based on this information. Further data may be sourced from the battery management system (BMS) via a CAN or LIN bus.

We conduct independent tests to determine if battery systems meet all safety specifications and are up to the demanding task of operating under the harsh conditions that prevail in automotive applications.



Dr Harry Döring
Head of Department
Accumulators

"AT THE BATTERY TEST CENTER, WE RESEARCH, TEST AND ANALYSE BATTERIES AND SYSTEMS IN FLEXIBLE, STANDARDS-COMPLIANT AND INNOVATIVE WAYS."

WHAT WE CAN OFFER

Characterising individual cells, modules and battery systems

- Tests to performance, capacity, service life and safety in compliance with internationally recognised test protocols and customer specifications
- Electric battery tests in temperature chambers at -40 °C to 80 °C, individually and inside cars
- Electrical battery tests on automated test stations for cells (up to 20 V, mA up to 3 kA), modules (up to 100 V, up to 600 A), and battery packs (up to 1,000 V, up to 900 A)
- Accelerated cycle and calendar service life tests
- Post-mortems of all storage technologies
- Testing and evaluation of supercapacitors and new storage technologies
- Electrical tests in conjunction with shock and vibration

Thermal, electrical and mechanical safety tests

- 100-ton, quasi-static crush tests
- Fire and thermal stability tests
- Penetration tests (nail, blunt object, screw, etc.)
- Vibration and shock tests
- Test bunkers with explosion proofing, fire extinguishers, gas scrubbers, video surveillance and measuring systems
- Short-circuit testing up to 15 kA, high-voltage testing up to 1,500 V/200 A and high-current testing up to 20 V/1,500 A
- Measurement monitoring via HD video, infrared and high-speed cameras
- Data logging system for various types of measured values up to 300 kHz

Temperature chamber for electric battery tests.

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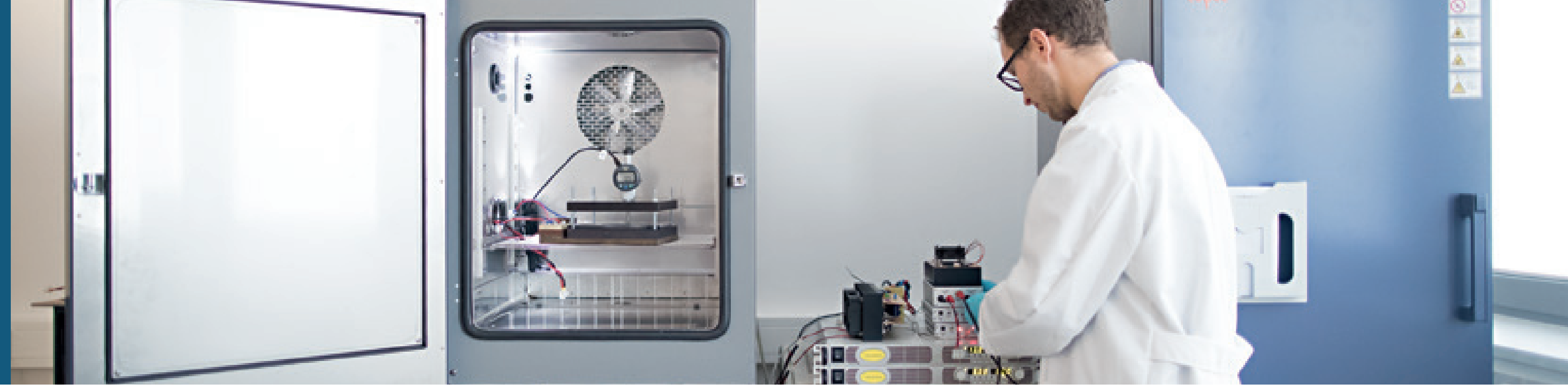
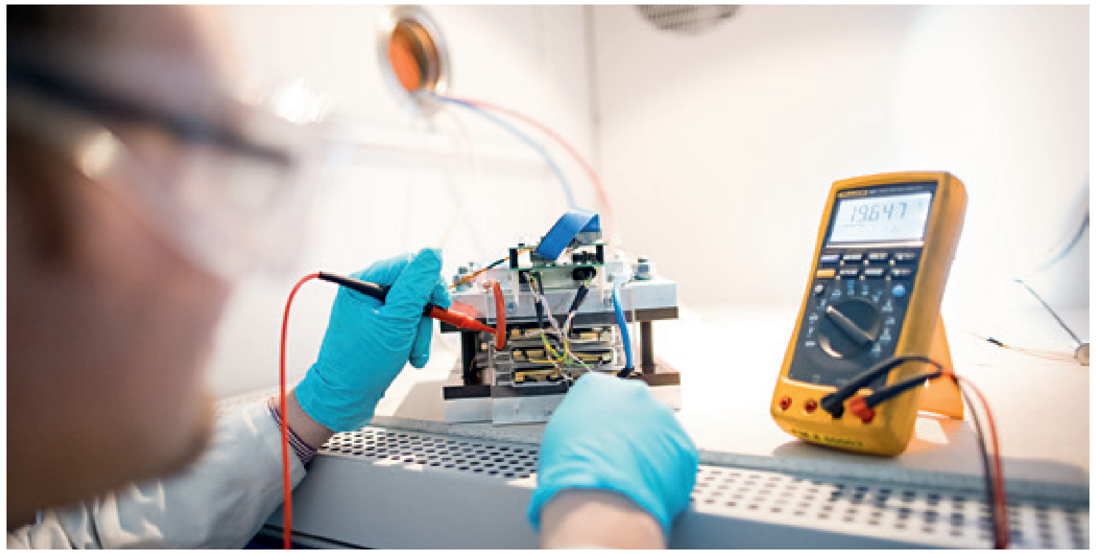
Systems engineering, modelling and simulation



Diagnostics of aging effects and diagnosis supported quick-charge.

Thermal and electrical modelling and cell and battery simulations are cornerstones of battery systems engineering. Our research covers a great deal of ground from characterising cells and developing battery models and management systems to characterising the storage element in its application environment.



Characterising battery cells via impedance spectroscopy.

Cell

The cell is the basic unit of battery-based storage. This is why we characterise its electrochemical, electrical, thermal and mechanical behaviours so extensively and in such great depth. Cells' vital signs are taken over time and across the frequency range with pulse measurement devices and electrochemical impedance spectroscopes. This affords us insight into the cell's transient dynamic behaviour and long-term aging mechanisms, which then flows into mathematical parameterised models and simulation environments.

The knowledge we gain about the cell's behaviour also serves to develop model-based algorithms that we use to assess the battery's condition, for power, energy and life expectancy forecasting, and to monitor and control the battery charge.

Battery module

The battery module is a combination of individual cells. Paired with a Battery Management System (BMS), it makes a functional unit for storing electrical energy.

Our effort at the module level focuses on the scattering in cell status like SOC or ageing in the serial and parallel connection inside a battery pack. This behaviour is described in corresponding models and the effect of battery management activities such as cell balancing can be studied. We also develop assets for the Battery Management System (BMS). These include algorithms, software and electronic circuitry for monitoring batteries, assessing battery condition, and diagnosing, forecasting and controlling the battery charge.

Battery module design and prototyping involves tasks such as constructing modules and cell connectors and addressing issues such as mechanical tension, sensors and cooling. All this goes to demonstrate and assess electrical behaviour models, heat flow models, battery management algorithms, and operating and cooling strategies.

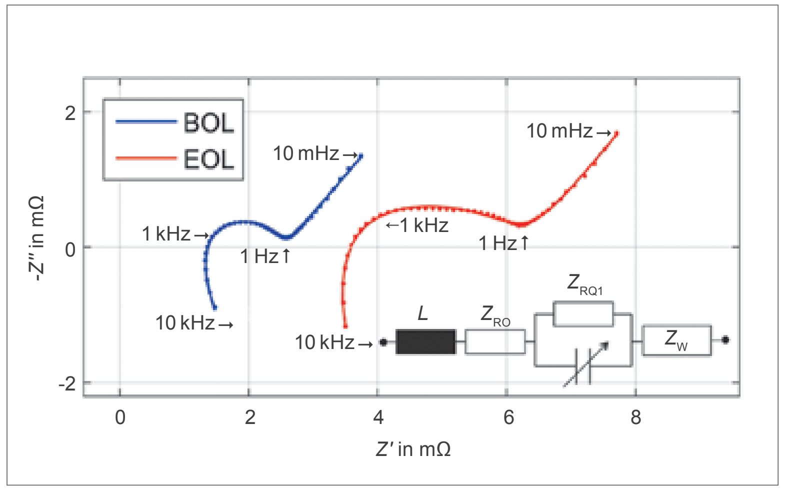
System

Batteries are deployed in diverse applications ranging from hybrid and traction batteries in electric vehicles to solar power storage systems. Of course, these environments' demands for performance, energy and service life are very different. Our systems engineers' first priority is to design and size storage systems to satisfy such diverse demands. They use models to devise the most economical and reliable solutions for storing electrical energy. The BMS has to be tied into the overall system's energy management to enable it to control, regulate and communicate. The object of this type of systems engineering is to develop optimised, efficient operating strategies for the battery and ensure safe operation throughout its service life. To this end, we take into account the interaction with power electronics, measuring systems such as smart meters, and dynamic loads.

WHAT WE CAN OFFER

Analysing, modelling and managing cells, modules and systems

- Physicochemical modelling of transport processes and overvoltage models
- Electrochemical, electro-thermal and electro-mechanical cell models
- Dynamic, non-linear and adaptive terminal voltage models
- Efficiency and energy flow models
- Aging and degradation models
- Charging strategies optimised for economy and durability
- BMS system algorithms for status detection and performance forecasting
- Energy management with optimised operating and cooling strategies
- Battery technology assessment, comparison and cost analysis
- Network integration and performance



Electrochemical impedance spectra of a cell at the beginning (BoL) and end of life (EoL).

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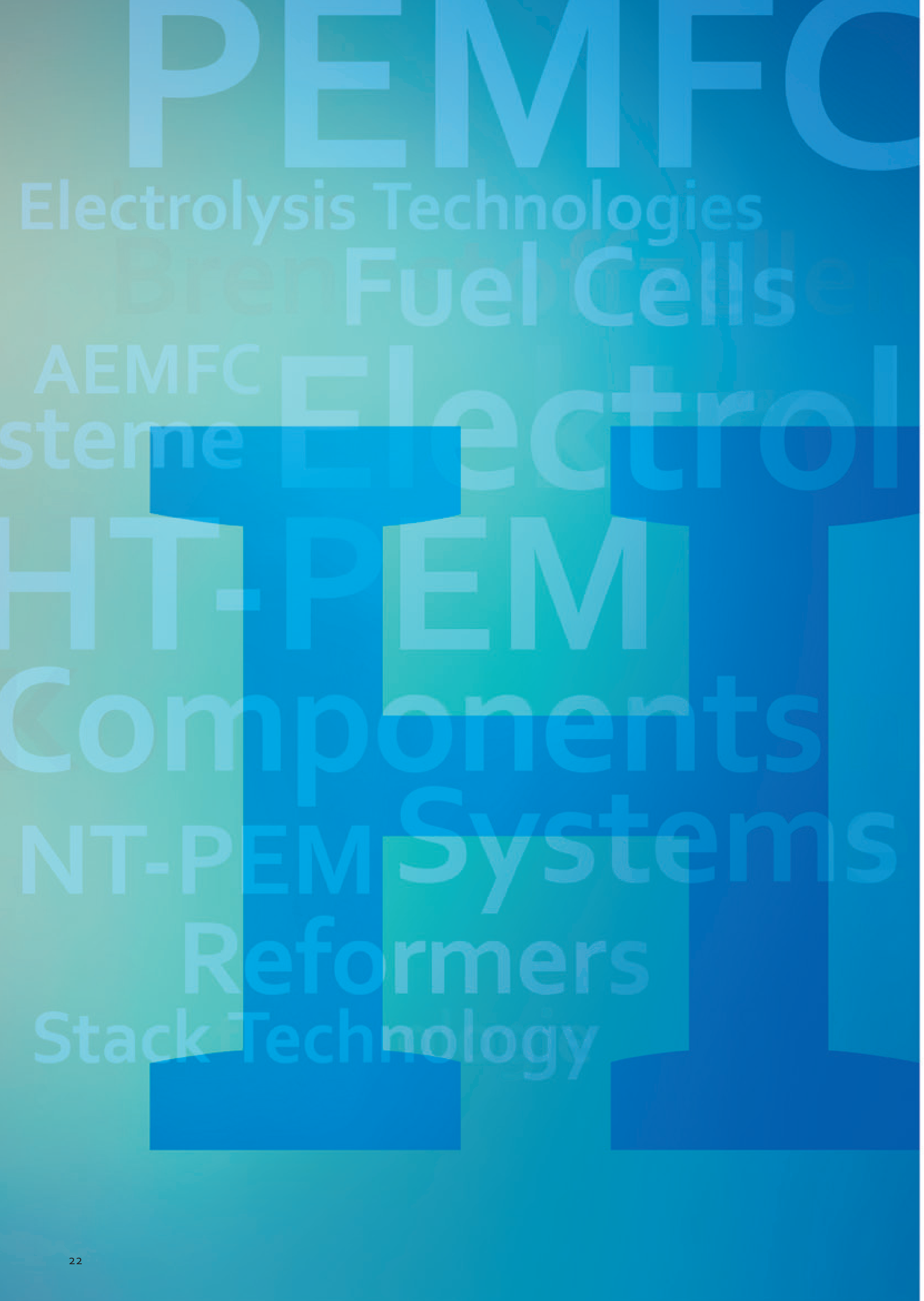


Fuel cells are electrochemical energy converters. They transform a fuel’s chemical energy directly into electric current, usable heat and water – with great efficiency, zero emissions and no detours. Hydrogen (H_2) is an ideal medium for storing renewable energies. It is the propellant that will enable tomorrow’s mobility with fuel cell vehicles.

2 Fuel Cells + Hydrogen

Applications, expertise and technologies

Applications

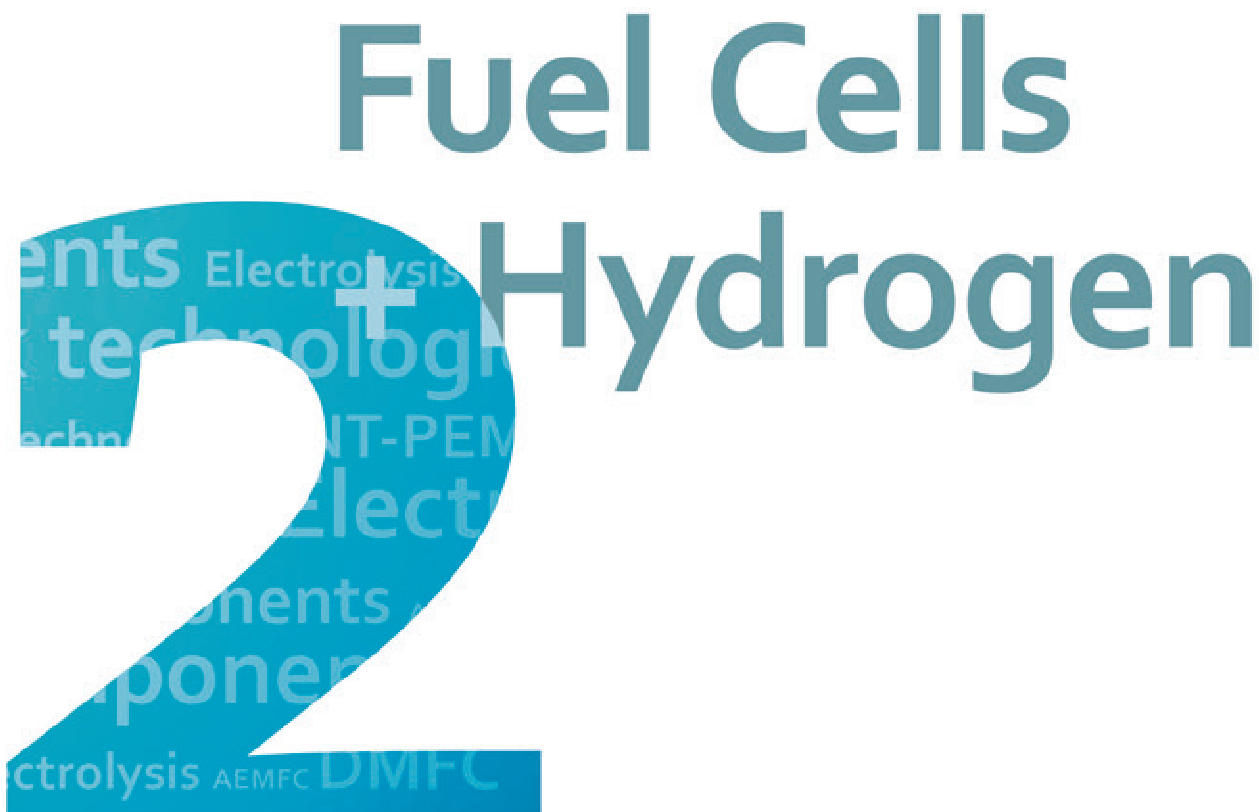
Fuel cells convert hydrogen, natural gas and methanol into electricity, heat and water. And they do this in a remarkably efficient, emission-free way. Electric drives in cars, city buses and ships, home electricity and heating systems, emergency power supplies – fuel cells are an excellent choice for all these applications. H_2 is not only a valuable resource for the chemical industry. It has also been hailed as the secondary energy source of the future because it can provide green energy for fuel cell vehicles (FCVs). What's more, H_2 produced from water via electrolysis is a clean chemical means of storing electricity sourced from fluctuating renewable energies.

Technologies

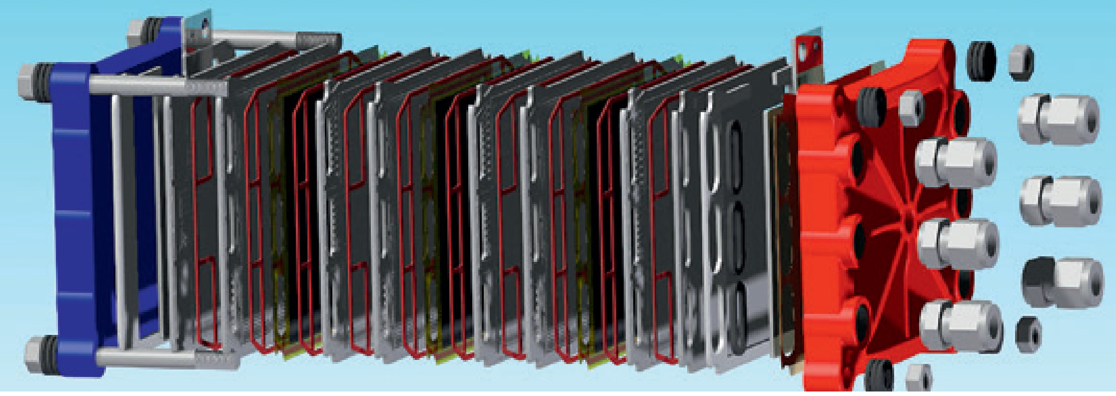
The polymer electrolyte membrane fuel cell (PEMFC) has emerged as the most versatile of all the many fuel cell technologies. Our big-picture research across all applications focuses on cost-effective materials and manufacturing processes. We have narrowed the focus for vehicular applications with our efforts to increase power densities and optimise operating performance. Quality assurance in general – and impurities analyses in particular – is critical when hydrogen serves as a fuel for vehicles. If this fuel is to gain wide acceptance, there will have to be a sweeping network of H_2 filling stations that people will be inclined use. That means these fuel points will have to be fitted with high-pressure, 700 bar systems equipped with accurate meters. Conventional alkaline electrolysers and polymer membrane electrolyte technologies both have great potential and may well be the solutions of choice for future water electrolysis. Our priority for PEMFCs is to develop low-cost catalysts and electrodes. And we are seeking to optimise electrodes and cell designs to boost efficiency and power density in alkaline electrolysis.

Expertise

ZSW is at the vanguard of application-centric research in this field. Our expertise is built on nearly 30 years experience developing fuel cells. This solid grounding in fuel cell R&D gives us a firm foundation on which to develop components, stack prototypes, entire systems and test programs to build solutions that meet real-world industry needs. Hydrogen as a fuel is another top priority at ZSW. With the knowledge and insight gained investigating materials for batteries and fuel cells, we are able to turn up advanced electrolysis technologies, for example, new electrode microstructures based on nanomaterials.

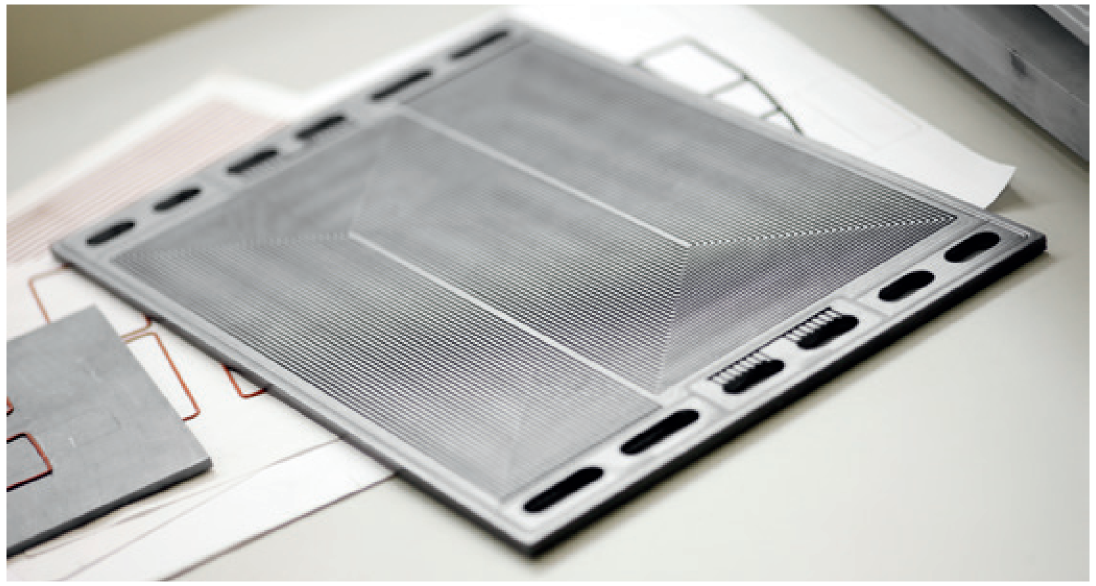


Fuel cell components



Exploded view of a ZSW fuel cell stack with 100 cm² active surface area.

The success of efforts to entrench fuel cells on the market hinges on a triple play of key properties – high power density, good cold-start performance and long service life even under highly dynamic loads. The challenge for researchers is to develop low-cost components and then fine-tune their interaction to maximise the overall system's performance.



Bipolar plate with an optimised gas manifold structure.

Developing components for fuel cells

PEMFC technology has long been a priority at ZSW. We have devoted years to developing polymer electrolyte membrane fuel cells and investigating the interaction of their component parts. Our research also focuses on direct methanol fuel cells (DMFC), high-temperature membrane fuel cells (HT-PEMFC), and fuel cells with alternative membrane (such as AEMFC) and electrode materials that make Pt-free catalysts a viable option.

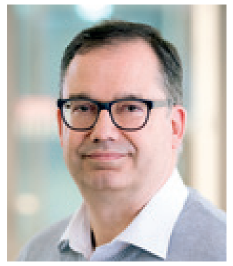
Our scientists and engineers collaborate with component manufacturers to develop new functional materials for membranes (MEAs), gas diffusion layers (GDLs), catalysts, electrodes and bipolar plates designed to improve performance, service life and reliability. To this end, we draw on a deep well of expertise in water transport processes in all cell areas and structures. Our scientists' penetrating insight into the interaction between materials, design and operating strategy is also an invaluable asset.

Methods for characterising components

Our labs carry out special tests, tailored to customers' specifications, to characterise fuel cell components using standard ZSW cells and sophisticated test-bench technology. We also employ specially developed methods such as locally resolved current density measurement as well as impedance spectroscopy (EIS) and cyclic voltammetry (CV) for electrochemical characterisations.

Flexural strength and compression tests for gas diffusion layers and the like serve to assess components' mechanical properties. Optical devices such as white light interferometers measure gas distribution structures, while 3D microcomputer tomography (micro CT) enables us to characterise gas diffusion layers' microstructures. Our X-ray and synchrotron tomography equipment provide powerful tools for analysing water transport processes in the cell. We have various methods of measuring contact angles, analysing pores and characterising electrodes.

The full analytics toolset, including electron microscopy (SEM) and XRD imaging, is available to us for post-mortem analysis, too.



Dr Joachim Scholta
Head of Department
Fuel Cell Stacks

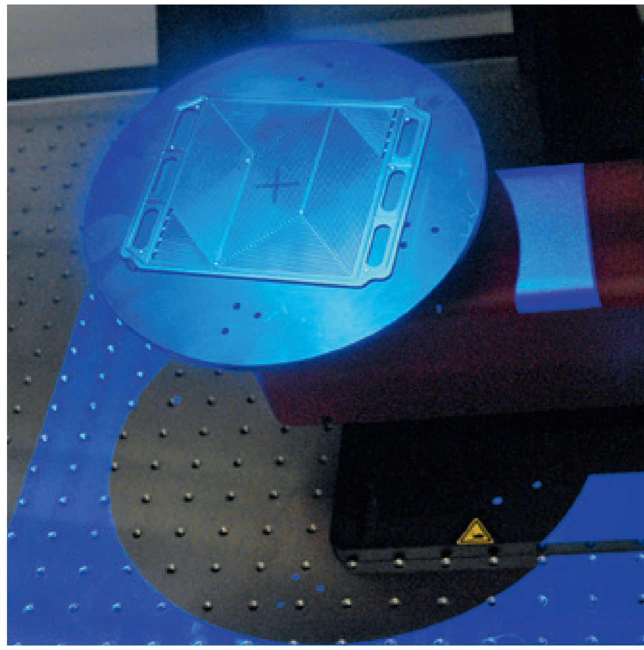
WHAT WE CAN OFFER

Electrochemical characterisation in standard cells
- Impedance spectroscopy and cyclic voltammetry
- Locally resolved current density measurement

Mechanical and electrical characterisation
- X-ray microcomputer tomography
- Tension/compression testing machine, flexural rigidity and compressibility
- Geometric tests and CAD matching (white light interferometer and X-ray µ-computer tomography)

Water balance analysis
- In-situ X-rays and synchrotron and µ-computer tomography and ex-situ investigations (Leverett J-function)
- Contact angle measurements: Drop contour, liquid sorption measurements, inverse gas chromatography
- Hydro head, bubble point, vapour sorption

Damage and post-mortem analysis
- An extensive set of analytical methods



Measuring gas distribution structures using a white light interferometer.

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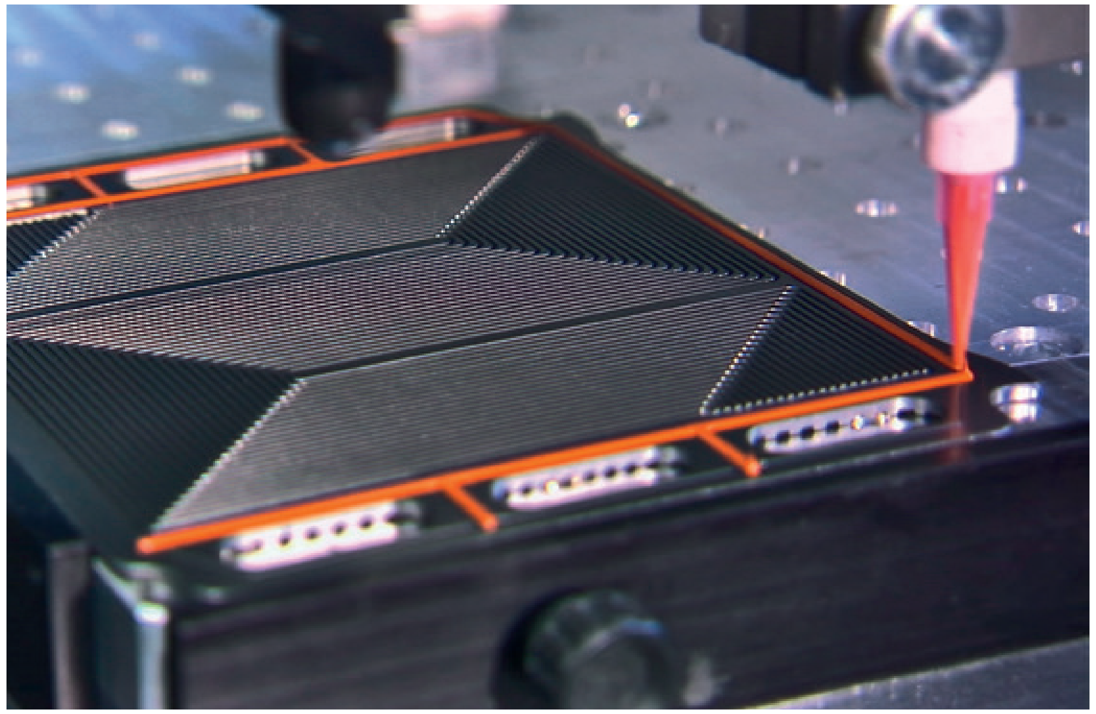
Fuel Cells + Hydrogen

Design and manufacturing technologies

The recipe for making high-performance fuel cells such as those used in electric vehicles is complicated: Take hundreds of individual cells, each consisting of a thin 20-micrometer membrane that swells in operation. Add fine, one-millimetre bipolar plates with delicate gas distribution structures. Blend in gas diffusion layers made of compressible, porous carbon-fibre nonwovens. And top it all off by matching, fine-tuning and stacking all components.


An automated dispenser applies seals.

Did you know that?

In recent years, ZSW has made more than 1,000 fuel cell stacks with various power ratings for a wide range of applications.

Designing, engineering and prototyping

ZSW has been designing, engineering and building fuel cell stacks in the 50 W to 100 kW power range for some 30 years. Our ability to successfully develop, prototype and deliver stacks is rooted in this deep interdisciplinary know-how. A range of application-specific ZSW designs attest to this ability. Our prototypes vary in terms of their active area per cell, bipolar plate design, pressure drop and operating temperature range.

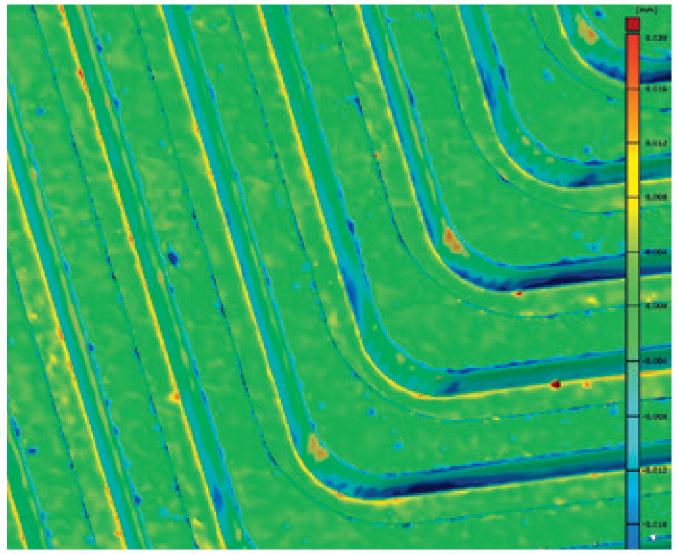
Fuel cell end plate with media and power ports.

"WE OPTIMISE THE SERVICE LIFE, PERFORMANCE AND DYNAMICS OF FUEL CELLS WITH ALL THEIR COMPONENTS."

But what all ZSW stacks have in common is the capacity to deliver high specific performance and operate safely and reliably within the intended ranges. Adjustments can be made to accommodate specific customer requirements. Our teams are staffed with highly qualified experts who have what it takes to develop fuel cell stacks to customers' specifications – including extensive experience in CAD design, modelling (CFD, FEM), manufacturing technologies and fuel cell testing.

Manufacturing technologies

With state-of-the-art manufacturing technologies and our experts' extensive skill set, ZSW has the hardware and human resources to make fuel cell stacks with up to 100 kW output. Our track record bears this out: We have delivered more than 1,000 stacks over the years. The focus of these efforts is on developing joining technologies, cell manufacturing processes, robot-assisted stack assembly processes and testing methods. Quality assurance has always been a priority. We also began exploring automated stack assembly at an early stage with the aim of developing processes that readily adapt to the targeted unit production numbers and enable us to test our stack designs. This experience has honed our automation skills: We know to handle components, apply seals, and join and stack cells in automated processes.


CAD data are compared with measured 3D data to verify bipolar plates' quality.

WHAT WE CAN OFFER

- Sealing and bonding technology
- Robot-assisted stack assembly
- Prototypes with various bipolar plate designs, pressure drop and operating temperature ranges
- Active surface areas from 50 to 560 cm²
  (custom adaptations are an option)
- Comprehensive testing technology

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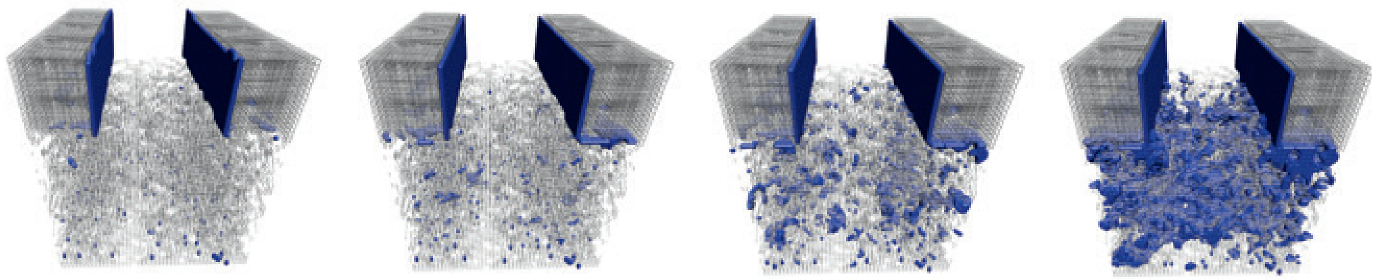
Fuel Cells + Hydrogen

Modelling and simulation

Mathematical models afford scientists an insight into the physical and chemical processes that transpire inside a fuel cell. Engineers can build on this insight to develop entirely new technologies. Models are also a key asset for researching and developing fuel cells and optimising systems. Computer-assisted simulations make it easier to target and improve specific properties. This speeds up development, cuts costs and helps us gain a better understanding of a fuel cell's physical and chemical properties.



A Monte Carlo simulation showing the effect of varying amounts of PTFE on water distribution in the GDL.

Modelling fuel cell components, stacks and systems

At ZSW, we use commercial and in-house simulation tools to model fuel cell components, stacks and systems. These models help us understand electrochemical processes and expedite our engineering efforts. Of course, we verify simulated results by obtaining meaningful data in real-world experiments conducted with actual hardware. Our capabilities run the gamut from microscopic to macroscopic, from investigating water distribution in gas diffusion layers to constructing full-blown systems.

Probing water distribution in gas diffusion layers (GDL)

At ZSW, we certainly conduct experiments to investigate water distribution in the GDL. However, we also use and develop diverse modelling technologies to the same end. These include macroscopic CFD (computational fluid dynamics) methods and locally resolved modelling to determine the projected water distribution within a GDL. A custom model based on Monte Carlo (MC) methods serves to probe the cell's operating conditions and diagram the materials' structure and wetting properties. Our software experts maintain and refine the in-house simulation code that this model is built on. We can also modify and augment the MC model to suit the customer's specifications.

Modelling cells and stacks

Our simulation skill set covers practically every aspect of cell and stack design, whereby Fluent™ and AVL FIRE™ modelling software is our tool of choice. These skills include identifying and optimising the concentration and distribution of local media and current densities to develop new cell designs. We can also branch out to look at local GDL effects and study two-phase flows in channels

Using microcomputer tomography (μ-CT) to characterize porous fuel cell components ex-situ.

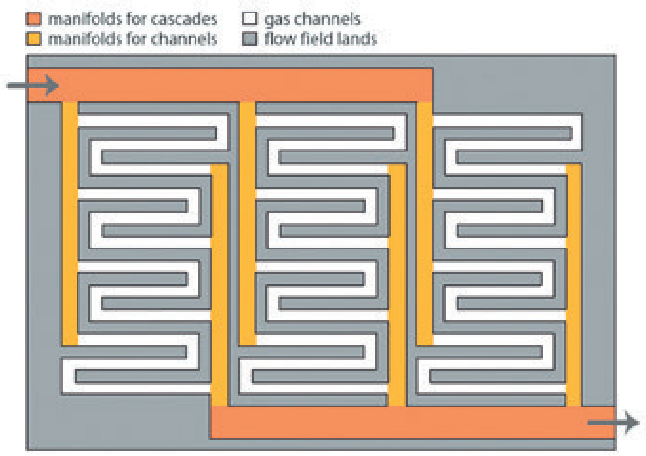
(volume of fluid, or VOF for short). CFD modelling helps us examine and improve existing designs. ZSW has taken CFD modelling in fuel cell development to the next level: We are now able to explore virtually every topic of interest from sizing media distribution channels in the bipolar plate to designing entire fuel cell stacks.

FEM numerical simulation for designing stacks

FEM, short for finite element method, is a numerical simulation technique. It enables us to size fuel cell components on the virtual drawing board to achieve the most beneficial dimensions, weight and stack tensioning. Components such as bipolar plates can be tested in advance by subjecting them to the load and forces they are expected to encounter when the fuel cell is in operation. Then we optimise these parts' dimensions, weight and reliability.

Operating behaviour and system simulation

Modelling software provides excellent tools for optimising and simplifying systems; ZSW has the best available for designing fuel cell systems. These tools enable us to compile data, make informed forecasts and take an iterative approach to developing and building optimised systems for steady-state and dynamic scenarios. IPSEpro provides a reliable means of simulating steady states; MATLAB®-Simulink software simulations effectively mimic the dynamics of fuel cell systems.



CFD simulation of flow field structures.

WHAT WE CAN OFFER

- Simulate fuel cell flow fields and components, including multiphase studies (CFD, Monte Carlo (MC))
- Describe fuel cells with mathematical models
- Analyse components and assemblies via CFD and FEM
- Run simulations to model and map velocity, concentration and current density distribution, water balance, temperature distribution and pressure drop
- Run quantum mechanics simulations of elementary processes
- Simulate stack systems to render entire plants
- Develop flow field structures while factoring materials transport in porous structures and electrochemistry into the design equation

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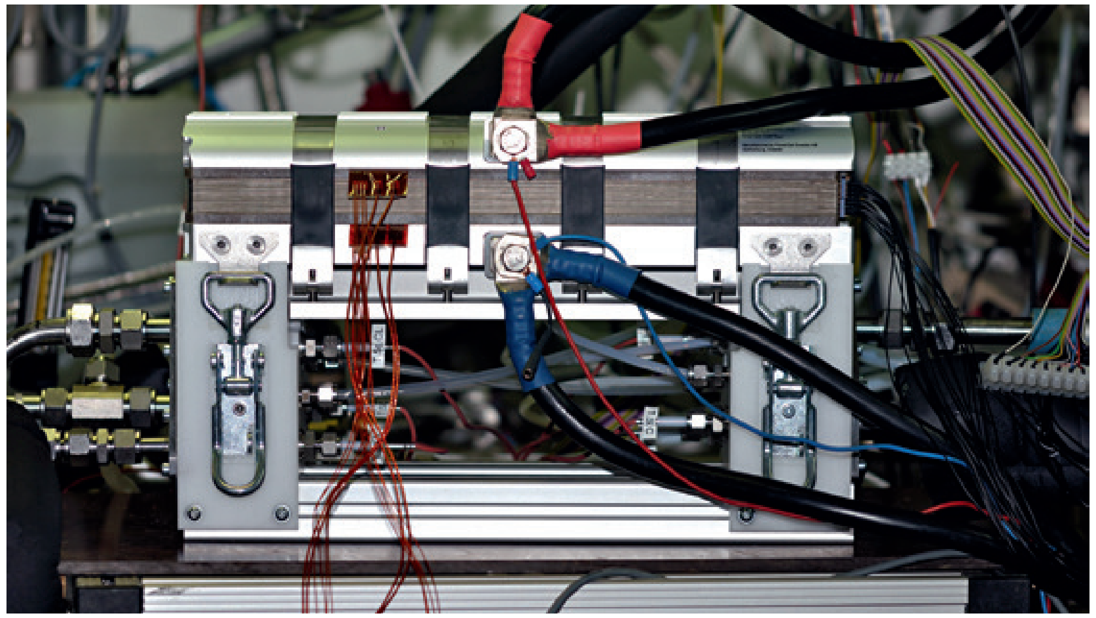
Fuel Cells + Hydrogen

Fuel cell test center

Demand for independent testing facilities is growing as manufacturers gear up to roll out fuel cells for mobile and stationary applications around the world. ZSW set up a fuel cell test field more than 20 years ago, and we have been improving and extending our capabilities ever since. Today, we have one of the world's largest independent test fields for fuel cell stacks with up to 120 kW_{el} output. At the latest count, we had 25 fully automated test benches in place.



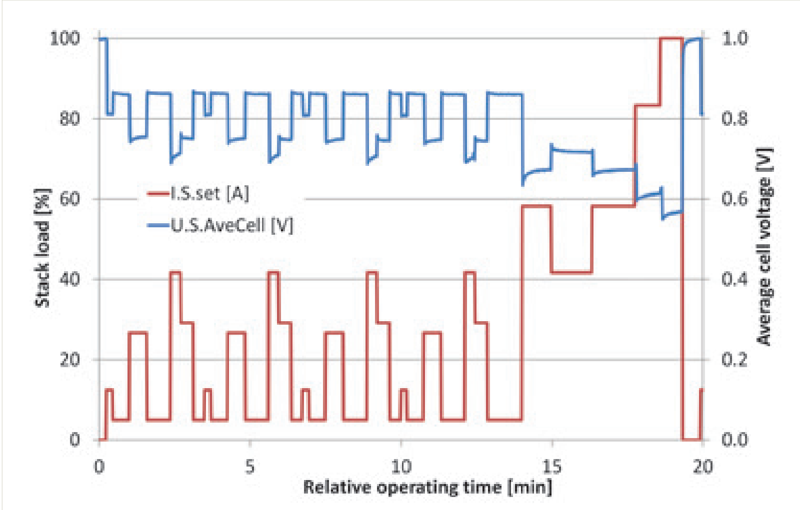
A short stack of a vehicular high-performance fuel cell on the test bench.

Expertise in testing

The ZSW test center assesses the performance of fuel cell modules with hydrogen or hydrogen mixes ranging from 100 W to 100 kW_{el}. Our team of professionals investigates and characterises fuel cells, stacks and systems, delivering robust results that can be relied upon. At the time of printing, we had 25 test benches in place to run continuous 24/7 tests. We can also conduct tests in compliance with specifications such as DIN IEC 62282-2, and even bring an accredited certification and inspection body on board.

Rather than simply carrying out tests, we also perform qualified test analyses and identify target parameters for optimisation. Materials and components in the cells interact in myriad ways. It takes a thorough understanding of this interaction to interpret test results, which is why we use a host of instruments, methods and simulations to analyse the process and our findings.

The purpose of these trials for vehicular fuel cells, for example, is to gauge their electrical performance under the kind of dynamic workload that cars cycle through day in and day out.



Fuel Cell Dynamic Load Cycle (FC-DLC), a harmonised life-cycle test developed by ZSW.

Dr Alexander Kabza
Head of Department
Fuel Cell Systems

"OUR AUTHORITATIVE EVALUATIONS HELP DRIVE PRODUCTS' DEVELOPMENT. TESTS ARE SUPPORTED BY SIMULATIONS AND IN-SITU ANALYSES AS THE SITUATION REQUIRES."

WHAT WE CAN OFFER

- A power range from a few watts to 160 kW (full-size automotive stacks and systems)
- Remarkably versatile test benches supported by a proprietary control program and in-house workshops
- Test bench calibration before or during testing
- Fully automated, 24/7-operation tests
- The complete DIN IEC 62282-2 test regimen
- Accelerated aging tests, also in compliance with DoE
- Pollutant gas tests
- A wide range of reactant supply lines

Did you know that?

In 2015, a 100 kilowatt automotive-grade fuel cell impressively demonstrated its ability to power a car by logging more than 5,600 kilometres in one week. The fuel cell was subject to a set of harmonised, dynamic test cycles in a test bay that also furnished key information about the fuel cell stack's performance and aging behaviour. Hydrogen consumption under a peak load came to 7.8 kilogrammes per hour, equivalent to 1,450 standard litres per minute. This is a considerable quantity, and it attests to the ZSW fuel cell test center's performance capability.

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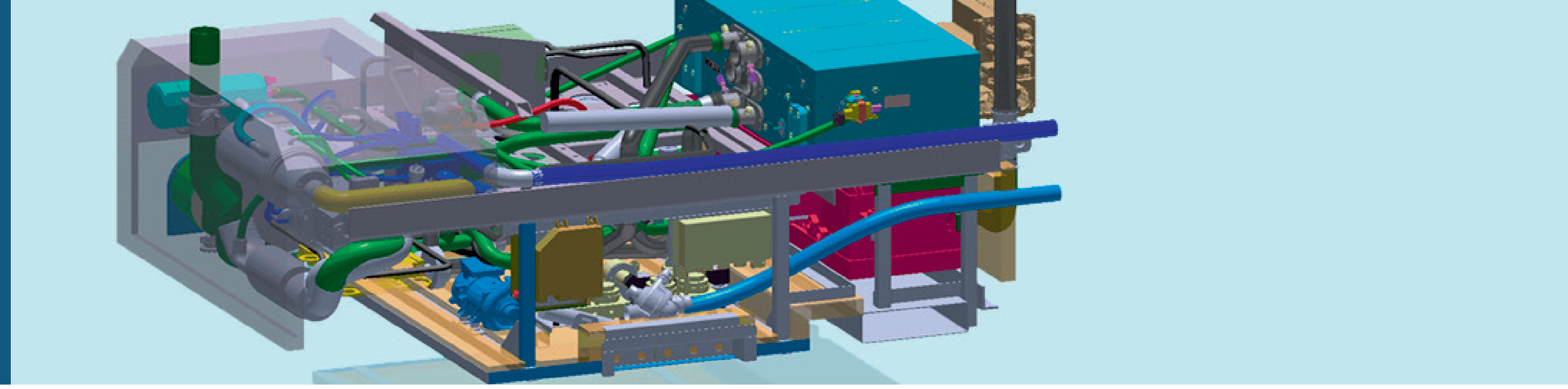
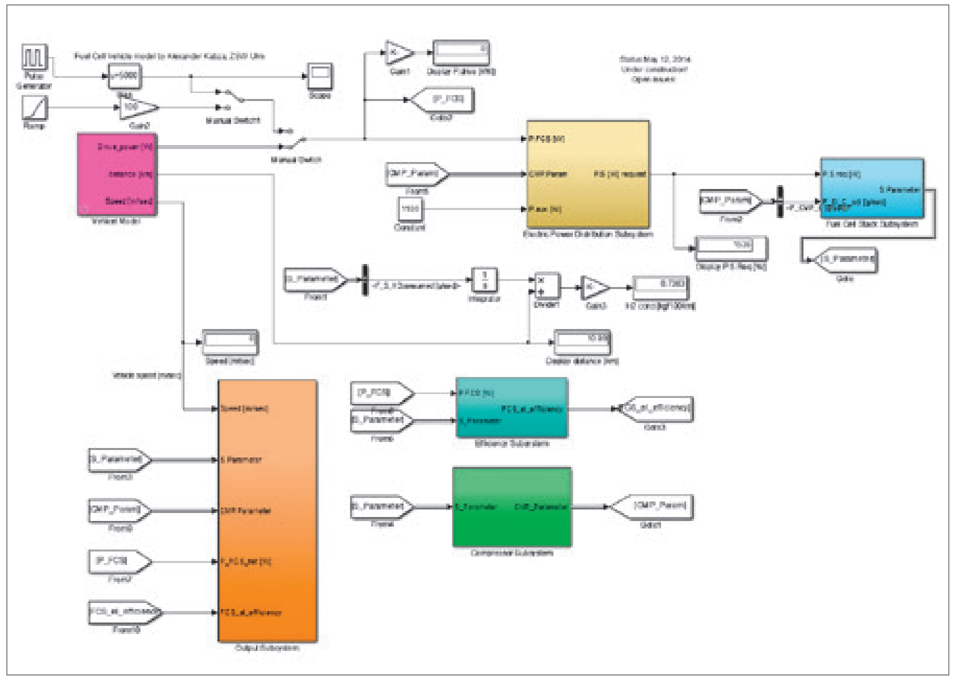
Fuel Cells + Hydrogen

Systems and reformers



CAD rendering of a fuel cell system for buses.

An air compressor, a hydrogen recirculation pump, a humidifier and a cooling circuit – fuel cells need all these ancillary components to operate. And when hydrocarbons are used as a fuel gas, they also need reformers to convert hydrocarbons into hydrogen. Each of these components is critical; a fuel cell simply cannot run properly without these add-ons. They come in very different guises determined by the type of application, be it a vehicular drivetrain, a residential combined heat and power (CHP) system, an off-grid power supply or a charger/range extender.



MATLAB® Simulink® simulation of a fuel cell system.

Developing and optimising systems

ZSW develops solutions for a wide range of applications. Systems development entails tasks such as planning and designing with simulation-assisted tools, as well as building, characterising and qualifying prototypes. These systems' output can range from a few watts to 100 kW to serve a wide range of applications – methanol- or alcohol-fuelled, off-grid power supplies, home energy supply systems with upstream fuel reforming, H_2/O_2 systems for maritime and aviation applications, on-board power supplies, and drive systems for utility vehicles.

ZSW also supports industry partners by testing and qualifying system components, conducting safety assessments, packaging studies and hardware-in-the-loop (HIL) testing during product certification.

We also have excellent modelling tools that help us optimise and simplify fuel cell systems. These tools enable us to compile the data needed to make informed forecasts. Then we can join forces with our customers to iterate, develop and build optimised systems for steady-state and dynamic scenarios.

Reformers for liquid fuels

Hydrogen is close to ideal for fuel cells: It converts directly into electricity with utmost efficiency and is easily sourced from renewable energies. And hydrogen and high-pressure storage elements are a near-perfect combination for vehicles.

Liquid fuels such as methanol or ethanol hold a lot of energy and are easy to store. This makes them interesting alternatives for many other applications. They can be converted into a hydrogen-rich gas for fuel cells by way of a chemical process that involves reforming and subsequent reactant processing. Natural gas and liquefied petroleum gas are also readily available and affordable, and they too may be converted into hydrogen-rich gas made suitable for fuel cells via a similar reforming process.

ZSW develops ultra-compact reformers for methanol and builds integrated reformer-fuel cell systems for methanol, ethanol, natural gas and other fuels. Our R&D efforts center on planning and designing systems with the help of simulation tools, alongside building and characterising prototypes.

WHAT WE CAN OFFER

Systems

- Design, develop and build reformer and fuel cell systems for all types of applications
- Develop system components and perform hardware-in-the-loop tests
- Simulate systems and develop operating strategies
- Analyse and test systems
- Devise highly integrated components for reforming methanol and converting the products to fuel gas suitable for fuels cells
- Build and develop off-grid fuel cell power supply systems and battery charging units with built-in reformers for methanol and ethanol
- Develop residential combined heat and power (CHP) systems with built-in reformers for natural gas

Airport Scooter with a fuel cell drive.

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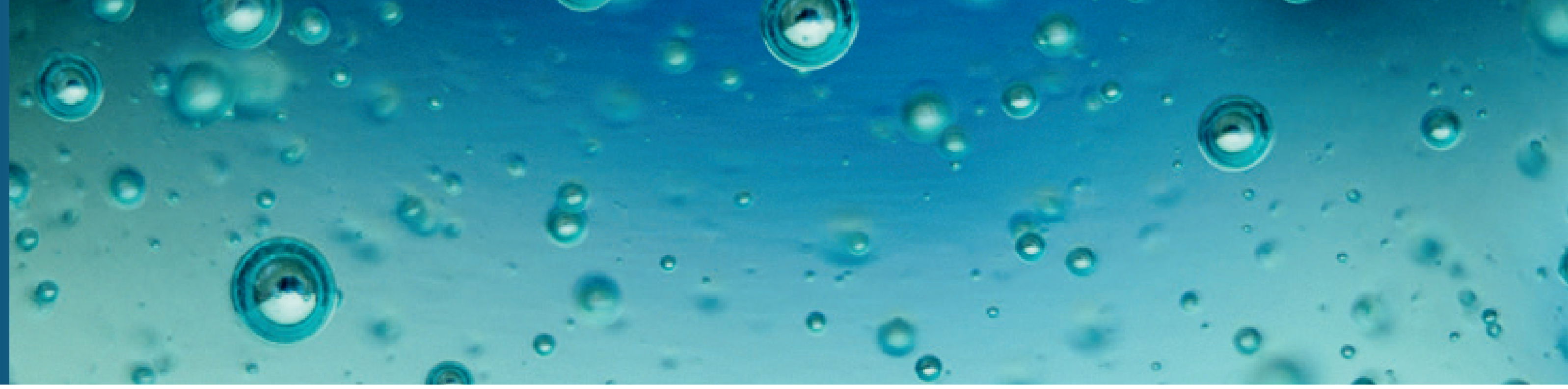
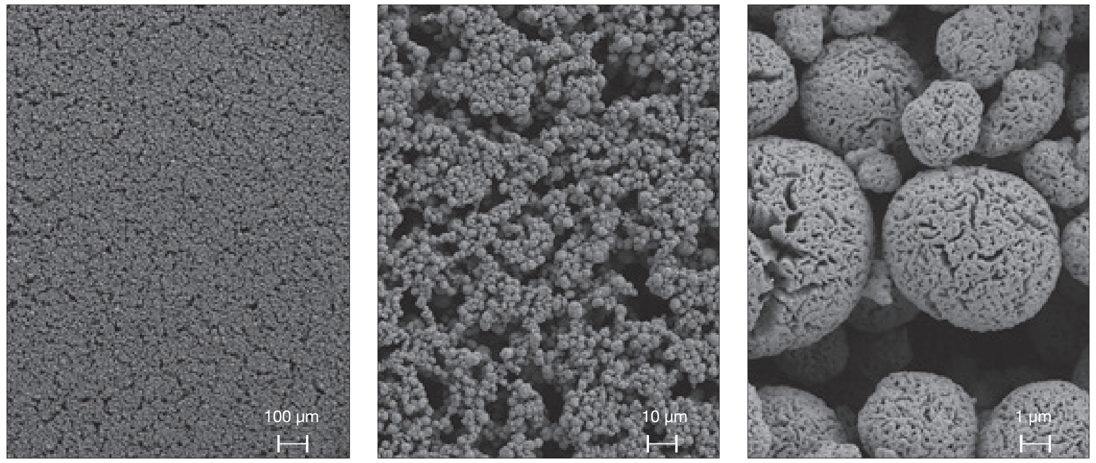
Fuel Cells + Hydrogen

New electrolysis technologies



So far, hydrogen (H_2) produced on an industrial scale is sourced mainly from natural gas or other fossil fuels and serves as a raw material for the chemical industry. However, an H_2 fuel would certainly help protect the climate if it were sourced from renewables and used as a carbon-free secondary energy carrier in vehicles. Photovoltaic and wind power plants are intermittent sources of renewable energy, and water electrolysis is a near-perfect technology for converting their fluctuating electricity into hydrogen. And there is considerable room for improving their cost, efficiency and stability while being operated with fluctuating power supply.



SEM images of surface nickel electrodes showing a coating of nanostructured nickel particles on nickel foil.

Did you know that?

The German government launched a programme in September of 2016 to develop cost-effective, marketable electrolysers. Called Hydrogen and Fuel Cell Technology 2016 – 2026, this initiative aims to map out a technology path to help decarbonise the transport sector and Germany and Europe to secure a big share of the value-add in this very dynamic global industry.

Electrolysis methods

An interesting way of generating hydrogen is to split water into its constituent parts. The increasing availability of excess regenerative electricity makes this an even more appealing proposition. There are three methods of electrolysis, as determined by the chosen electrolyte.

A potassium hydroxide solution serves as the electrolyte for alkaline electrolysis. Alkaline electrolysers have proven their merits, viability and robustness over many decades. The electrodes work without expensive precious metals, but this option is limited in terms of maximum power density. Acidic polymer electrolyte membranes serve as electrolytes in PEM electrolysers, as they do in PEM fuel cells. This option requires precious metal catalysts. PEM electrolysers can achieve very high power densities. Today, alkaline and PEM electrolysers are used in demonstration projects in load-cycling mode, coupled directly with electricity from solar or wind power plants. The third electrolyser technology works with a ceramic electrolyte and high temperatures.

This technology may significantly reduce the amount of electricity consumed in the process, but it also requires a high-temperature heat source.

In our team, we focus on developing new electrode microstructures for alkaline and PEM electrolysis. ZSW has pooled a great deal of expertise in making production and shaping catalysts. We tap into this pool to adapt and evolve the composition, morphology and microstructure of catalytically active materials and transform these materials into innovative electrode structures.

Dr Ludwig Jörissen
Head of Department
Fuel Cell Fundamental

"WITH MANY YEARS OF EXPERIENCE AND THE RIGHT INFRASTRUCTURE, OUR TEAM HAS WHAT IT TAKES TO QUICKLY VERIFY AND DEMONSTRATE NEW TECHNOLOGIES ON A LABORATORY SCALE."

Alkaline electrolysis at atmospheric pressure in a lab cell.

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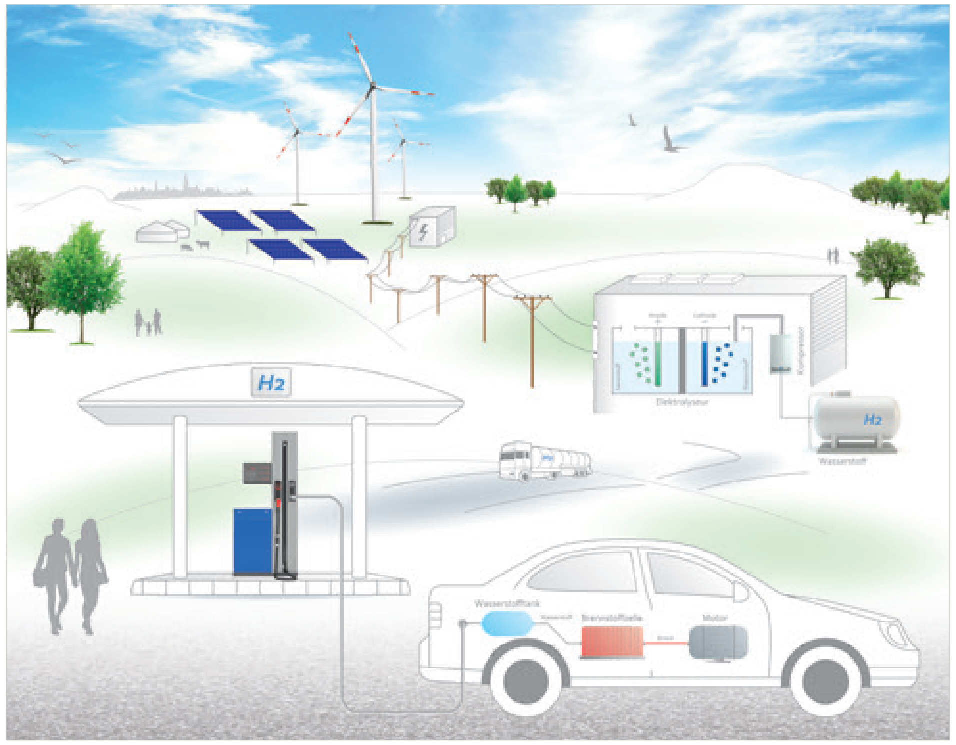
Hydrogen as fuel

Hydrogen filling station at ZSW in Ulm.

A network of hydrogen filling stations and hydrogen generation and storage facilities will have to be in place to launch fuel cell vehicles on a large scale. Related to this, two needs have to be met: quality assurance to rule out impurities in H_2 and a reproducible fuelling process.



Clean refuelling – this is how renewables are turned into H_2, a greener fuel for FCVs.

Did you know that?

... s can be refueled in three minutes with enough H_2 to travel 500 km?
... 400 hydrogen filling stations will be built in Germany by 2023?
... many hydrogen filling stations are already in place today?

https://cleanenergypartnership.de/kundenbereich/h2-tankstellen/

ZSW has many years' experience working with fuel cell technology and H_2 to its credit, and we are contributing to several projects aimed setting up Europe's hydrogen infrastructure. Our recent research has two major objectives – to enable FCVs to refuel and operate in compliance with H_2 quality standards. The current standard for refuelling is 70 MPa hydrogen pressure as set out in SAE J2601. The hydrogen quality norm is spelled out in SAE J2719/ISO14687-2.

Assessing the quality of hydrogen samples

There is always the risk of impurities such as carbon monoxide infiltrating hydrogen during its production and transport. They can adversely affect fuel cells' performance and service life. ZSW's sample analysis capabilities cover most specifications set out by ISO 14687-2.

Our research focuses on monitoring, certifying and optimising the quality of refuelling at hydrogen stations in compliance with the SAE Directive. We rely on a sample collection system to this end. These gas samples enable us to assess the quality of hydrogen at delivery and when it is dispensed to FCVs. Trace analysis is a mainstay of these investigations, but we are also working on concept that calls for quick, easy online evaluations to assess hydrogen quality for fuel cells.

Certifying hydrogen filling stations according to CEP guidelines

Hydrogen filling stations have to be certified before they are put in use, and regularly checked for H_2 quality and properly calibrated meters once they are in use. ZSW has developed government-approved devices to certify hydrogen filling stations in compliance with the SAE J2601 protocol and in accordance with the Clean Energy Partnership (CEP).

WHAT WE CAN OFFER

Fuel Station Test Module (H_2 FSTM)

- Mobile, TÜV Nord-approved test device for certifying hydrogen stations
- Tests according to CEP in compliance with SAE guidelines (SAE J2601)
- Compliance monitoring for pressure and temperature thresholds, vehicle/filling station infrared communication and hydrogen quantity metering
- Sampling during and after refuelling

Gas analysis

- Analyse hydrogen quality and detect impurities according to ISO 14687-2 specifications
- Analyse reformate gas compositions
- Remotely monitor filling stations' hydrogen quality via a cost-effective online tool

Analytical laboratory for determining hydrogen samples quality according SAE J2719/ ISO 14687-2.

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