// Energy with a Future

Zentrum für Sonnenenergie- und Wasserstoff-Forschung
Baden-Württemberg (ZSW)

Center for Solar Energy and Hydrogen Research

Climate-neutral energy technologies are essential for a sustainable future. Our world needs energy concepts that are economically, ecologically, and socially viable. These are inextricably linked to the use of renewable energy sources and increasing energy efficiency. This is what ZSW is all about. We research and develop technologies that serve to source electricity from the sun and wind, to store energy in hydrogen and batteries, and to integrate renewable energies into the grid. ZSW joins forces with industry partners to bring these technologies to market. We also apply our technical skills to analyze systems and answer big-picture questions. Our experts are monitoring the Energiewende – Germany's exit from nuclear power and fossil fuels through the transition to renewables. They develop support schemes and assess their impact. In this way, ZSW supports the transformation of our energy system in a joint effort together with government and business partners.

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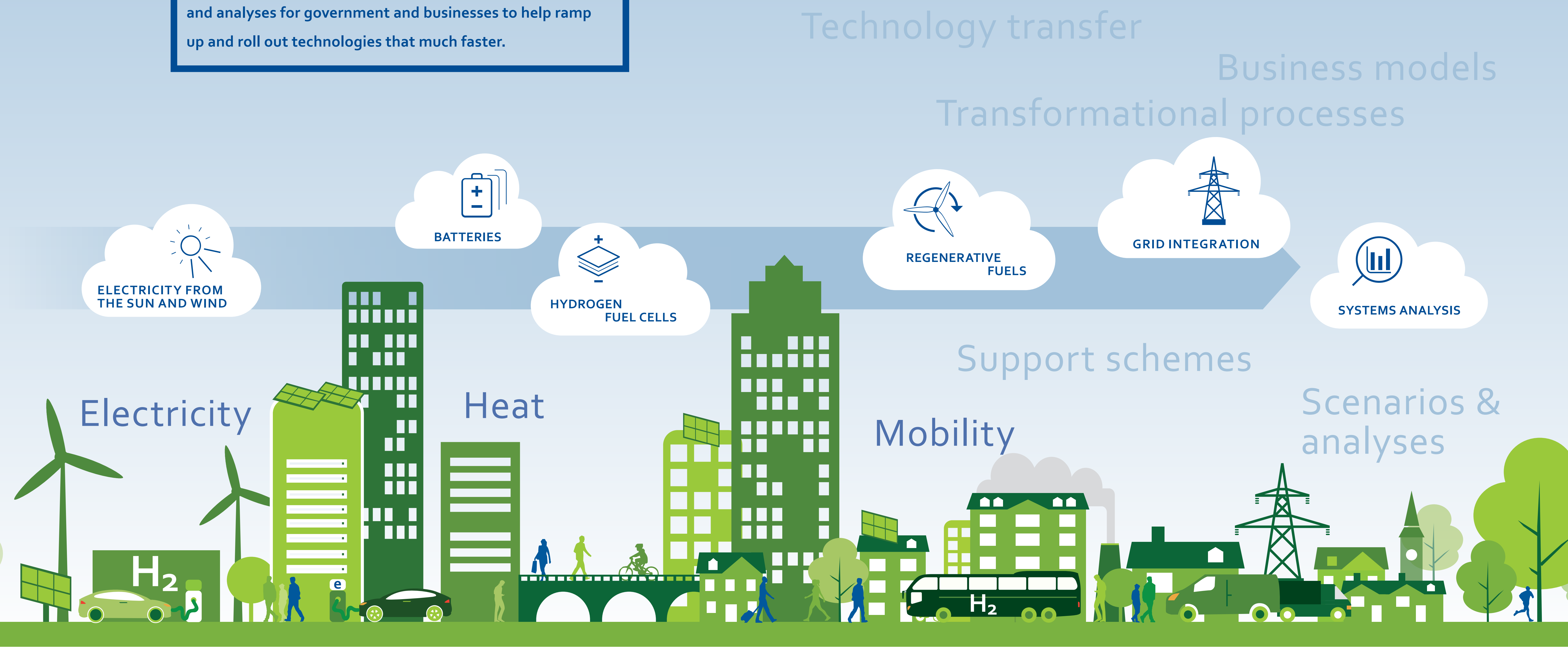
// ZSW's expertise

The drawing below illustrates the technology skills that ZSW puts to good use on the path to a sustainable energy system. They cover the entire value chain from researching materials and developing prototypes and production processes up to delivering viable systems, quality tests, and market analyses. Our institute also prepares proposals and analyses for government and businesses to help ramp up and roll out technologies that much faster.



To meet the demand for energy in a reliable, eco-friendly, and affordable way, society needs more than the right technologies. It also needs smart concepts for policymakers, businesspeople, and scientists. ZSW is here to provide it all.

// An energy system with a future

Many good ideas and innovations have been put forward to transform our energy system. ZSW assesses how they can be put into practice.

The success of new technologies very much depends on the prevailing market regulations. It is up to policymakers to create favorable conditions for renewables. ZSW provides calculations, analyses, and expert reports to support decision-makers' efforts at the state, federal, and EU levels. With sound science to base their decisions on, legislators can devise strategic concepts, enact laws such as Baden-Württemberg's Climate Protection Act, and develop incentive schemes such as the Renewable Energy Sources Act.

ZSW also prepares studies for the industry and government agencies. These reports afford insight into the performance of new energy technologies, the compatibility of economic and ecological goals, the consequences of restructuring the energy system, and the advantages and drawbacks of government intervention.

Our clients and partners can count on ZSW experts to be independent and objective, always. The expertise of our colleagues in the institute's technical divisions is an invaluable asset to everyone we serve.

How can new technologies for the transition to renewables integrate successfully in everyday life? And how can obstacles be overcome? ZSW researchers are investigating these questions jointly with economists and social scientists in projects which consider the transition to renewables as a process of social change.

// An energy system with a future

ZSW scientists observe, document, and assess the transition to renewables at the national and international levels, as well as in the local states, regions, and municipalities. Our recommendations for political action build on the insights gained from these observations.

// Proficient at monitoring the transition to renewables

A very important part of ZSW's mission is to monitor the Energiewende's progress. Our experts analyze this energy policy's practical implications as various agents put it into action. ZSW reports to the federal government and the state of Baden-Württemberg and offers recommendations when adjustments are in order.

ZSW is excellently equipped for these monitoring and assessment tasks because of the reliable sources and the sound database it has set up, maintained, and modernized over several decades. Our team excels at acquiring, assessing, preparing, and presenting information to answer many questions and serve many stakeholders.

It is not just government that relies on us for information. Scientific institutions, professional associations, and business enterprises are also among our many partners and clients.

ZSW set up the Working Group on Renewable Energy Statistics (AGEE-Stat) and headed it for many years. We are also a member of the Working Group on Energy Balances, which prepares an annual energy balance sheet for Germany. The federal government uses this statement to meet many of its reporting obligations. And we track and assess the economic impact of the increased use of renewable energy sources.

The Renewable Energy Sources Act (EEG) of 2000 set the stage for Germany's transition to renewables. It was to become a model widely emulated by many support schemes around the world. When legislators set out to draft this law, it was ZSW's expertise they relied on for guidance from the very beginning.

// Energy management concepts for regenerative fuels and alternative drive systems

Using renewables-based hydrogen and methane, as well as electric battery and fuel cell-powered vehicles offers the best prospects for reducing the carbon footprint of transportation with the added benefit of storing green electricity.

Batteries to power electric vehicles, hydrogen for fuel cells, regenerative methane, electricity-based liquid fuels – ZSW has a wealth of experience researching, developing, and manufacturing solutions in all these very dynamic disciplines. The institute's system analysts develop concepts for deploying these technologies on a large scale and for system-related use cases. With the insights they gain along the way, they are able to recommend actions to the industry and to legislators. These proposals aim to fast-track this transformative process in transportation and strengthen Germany's position as a hub of industry.

// Heat and efficiency

Renewable energy sources already account for more than a third of the electricity consumed in Germany. However, more progress is needed in the transportation and heating sectors, as well as in the efficient use of energy, in order to achieve European and domestic targets for the transition to renewables.

ZSW has had a formative hand in shaping the federal government's market incentive program, Germany's primary instrument for promoting renewables in the heating market for many years now. At the state level, the institute provides conceptual support for the efforts of the Baden-Württemberg Ministry of the Environment to encourage heat and power cogeneration. We stage the state's Leitstern Energieeffizienz [Energy Efficiency Lodestar] competition. The only one of its kind in Germany, this award is given to acknowledge urban and rural districts' excellence in energy efficiency.

Learn more at

// Electricity generation from sunlight and wind

Power generation by sunlight and by wind are two major pillars to support the transformation of our energy system. In the field of photovoltaics, ZSW works to improve the efficiency and extend the service life of solar cells and modules and to develop manufacturing processes and quality assurance practices. Our new test site for wind turbines in complex mountainous terrain promises to yield valuable information to benefit the industry. Our institute also provides weather-based feed-in forecasts for solar and wind energy to power plant operators.

Photovoltaic (PV) systems are our pipeline to the sun, a key source of renewable energy. Their costs have plummeted over the last decade with global market shares growing at a phenomenal rate. PV already accounts for 2% of the electricity generated worldwide. However, this growth will have to be even more dynamic to achieve our climate goals.

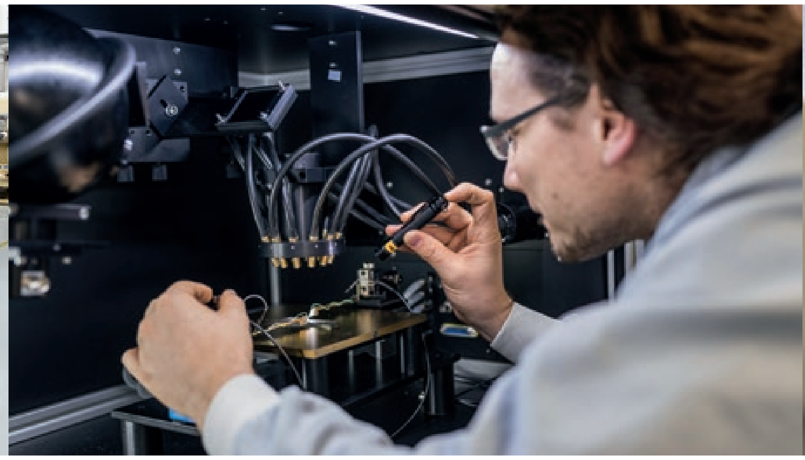
Germany, too, has a great deal of untapped potential, for example, on and around urban buildings. ZSW is doing its part to access this potential through joint research efforts with industry partners with goals to improve PV technologies' efficiency, cut costs, and usher innovations out of the lab and onto the market.

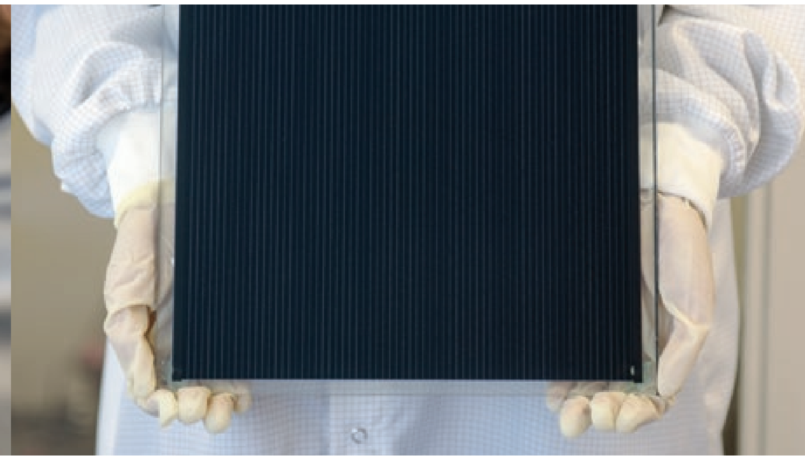
ZSW's photovoltaics research and PV-related services cover quite a lot of ground. We investigate materials, systems technology and manufacturing methods, test for quality, and provide consulting.

Wind is the second major source of energy that is driving the global transition to renewables. Wind farms are going up even in mountainous regions. This terrain poses towering challenges for wind turbines, which are far easier to operate in flatlands. The WindForS research cluster now aims to answer the question of how to optimize these systems' performance and extend their service life. ZSW is spearheading a 2018 project to build a research test field at Stöttener Berg near Geislingen an der Steige.

Wind, solar, and other renewables are already the most important energy sources for power generation. Germany was able to supply all its electricity needs with power from renewable sources for the first time on January 1, 2018, and repeated this feat soon after on May 1, 2018.

// Electricity generation from sunlight and wind





// CIGS thin-film solar cells and modules

Although crystalline silicon still dominates the market for PV technology, viable competitors with considerable cost-cutting potential are already out of the gate and joining the race – thin-film technologies. Their active layers are just a few micrometers thick. Thin-film manufacturing is nothing like silicon wafer-based production, where cells are made individually and then connected via electric circuits. Instead, an entire solar module with the connected cells is deposited on large glass panes in an integrated process that streamlines production, boosts efficiency, and accelerates throughput.

ZSW opted for a system of materials consisting of copper, indium, gallium, and selenium (CIS or CIGS for short). This combination achieves the highest level of electrical efficiency and is thus the best choice for bringing down the costs of generating solar power. Cost and efficiency are not the only selling points. The aesthetics are also persuasive. The uniform appearance of the matt black panels speaks for this technology, as do the custom color options that are available if desired. CIGS modules mounted on the sides and roofs of a building make for a handsome façade, as the ZSW building in Stuttgart pictured on the cover goes to show.
A term has been coined to describe the dual-purpose systems that generate electricity without monopolizing agricultural land. Called agrophotovoltaics, this promising option enables farmers to cultivate crops even with PV collectors in place.

The ZSW pilot plant manufactures CIGS modules on glass panels as large as 30 x 30 cm. In marked contrast to typical laboratory production lines, in-line coating equipment closely replicates industrial conditions. With the benefit of this equipment, ZSW is able to investigate issues of concern to industrial manufacturers, such as how to speed up mass production.

Our team has more than 30 years' experience and the infrastructure to analyze materials with SEM, TOF-SIMS, RFA, Raman, solar simulators, and other equipment. With these assets in place, we can probe deeply to gain insight into components and systematically drive the development of solar cells, modules, and production processes.

With just 800 g of semiconductor materials, CIGS thin-film solar panels can provide more than 30 years' worth of solar power to a single-family home in Germany.

Learn more at

Currently, CIGS demonstrates the highest power conversion efficiency of all thin-film PV technologies. ZSW is one of the world's best laboratories in CIGS development and has achieved several world records in this discipline. As of June 2018, the highest certified efficiency for CIGS solar cells is 22.9%. With that kind of performance, this technology is not just viable; it has all the potential for strong market growth. The CIGS story is one of successful technology transfer – one of our industry partners now sells turnkey manufacturing systems for CIGS solar modules on the international market.

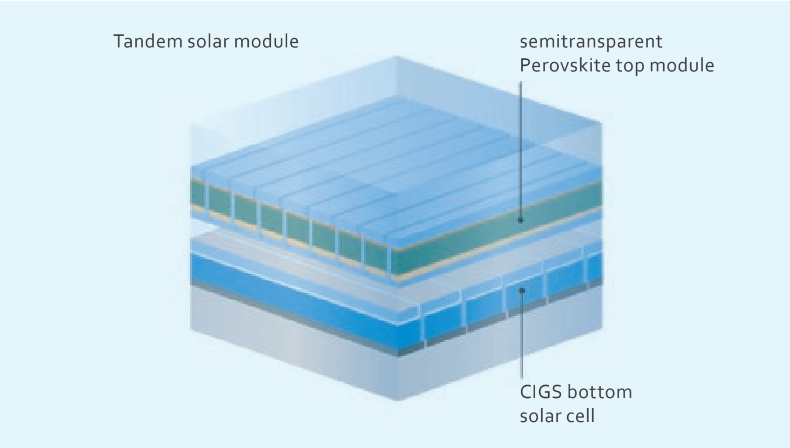
// Flexible solar cells and modules

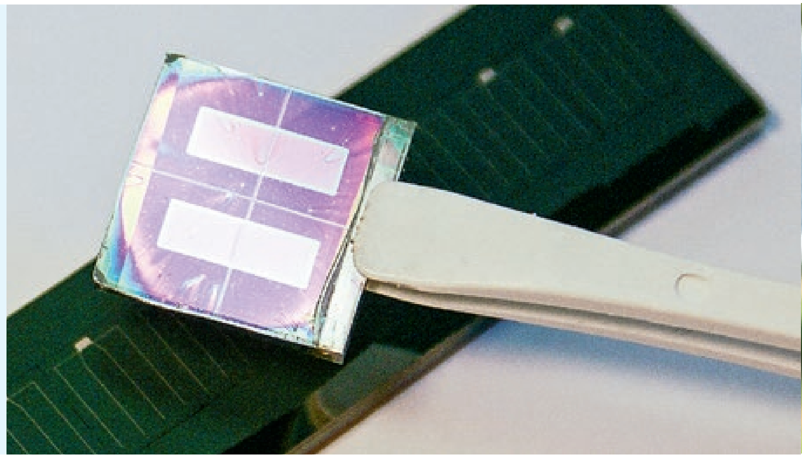
One of the main advantages of thin-film technology is that it can also employ lightweight, flexible substrates made of stainless and other steel, titanium, or polyimide, instead of rigid glass. These foils empower a whole new range of applications. Lightweight modules for industrial buildings with weak roofs, ultra-light solar modules for the aerospace industry, solar cells built into vehicles and integrated into textiles – all this is entirely possible.

Flexible modules can also help slash costs. For one, it takes much less energy to heat up the foils; for another, they can be processed in web coating lines like those used in printing plants. This is called roll-to-roll coating. Many of the steps developed to manufacture CIGS on glass substrates have yet to be adapted to the substrate foils needed to produce flexible solar modules.

Our researchers are keen to change that – they are using the ZSW pilot plant's roll-to-roll coating machine to develop this technology. This device simultaneously deposits a rear contact made of cathode-sputtered molybdenum, an absorber made by co-evaporating copper, indium, and gallium in a selenium atmosphere, and a cathode-sputtered zinc oxide front contact on a 30-cm wide strip of carrier film. It passes through the various stations continuously, in one vacuum chamber. This machine produces a single solar cell strip several kilometers long. It is then cut to size and processed further to make solar modules.

// Electricity generation from sunlight and wind: Printed solar cells





Manufacturing thin-film solar cells with vacuum technology is very cost-effective. New combinations of materials and processes developed in our labs promise to bring costs down another notch. And the next generation of PV concepts is sure to offer even greater efficiency potential for researchers to tap.

The efficiency ratings of single cells in today's commercially available PV modules are pushing hard at the limits of thermodynamics and technology. Multi-junction cells and multi-spectral cells can convert more of the solar spectrum by stacking solar cells with different absorption ranges on top of each other and connecting them in series. The top cell has to be "semitransparent" to allow plenty of sunlight to reach the bottom cell while at the same time be very efficient. Experts expect the next big hike in efficiency will come with multi-junction cells.

// A winning team: CIGS and perovskite

New thin-film material systems such as perovskites, paired with cost-effective printing technologies, promise to advance the state of this particular art. An enticing and affordable option, perovskite makes for an excellent semitransparent top cell in multi-junction cells.

Its efficiency has surged from less than 4% in 2009 to over 22% today. With this material system and multi-junction solar cells at their disposal, researchers can boost legacy silicon and the efficiency of CIGS technologies to ratings between 25% and 30%, i.e. beyond the theoretical threshold for individual cells. However, several challenges have yet to be surmounted.

The efficiency for a semitransparent perovskite cell well suited for use as a top cell now stands at over 18%. Multi-junction cell stacks with a silicon bottom cell have already achieved efficiency ratings beyond 26%. Others paired with a CIGS cell have attained roughly 24%.

// Electricity generation from sunlight and wind: Quality assurance for PV modules and systems

// Module testing in the lab and in the field

Companies that make solar power modules generally extend long-term product and performance warranties. This quality has to be assured and ZSW, a research institute that actually develops solar cells, modules, and production processes, is well suited for this task. We have an arsenal of equipment for testing modules and materials in the lab and out in the field.

Investors, banks, manufacturers, and project developers rely on independent testing facilities to verify and assess PV modules' performance, long-term stability and operational reliability. Bringing a third party in to randomly test PV modules is a smart move – it mitigates risk for all the stakeholders involved in a project. This is called bankability: The backers of major multinational projects need to be sure that PV modules featuring this or that technology are suitable and have proven their merits for the given application.

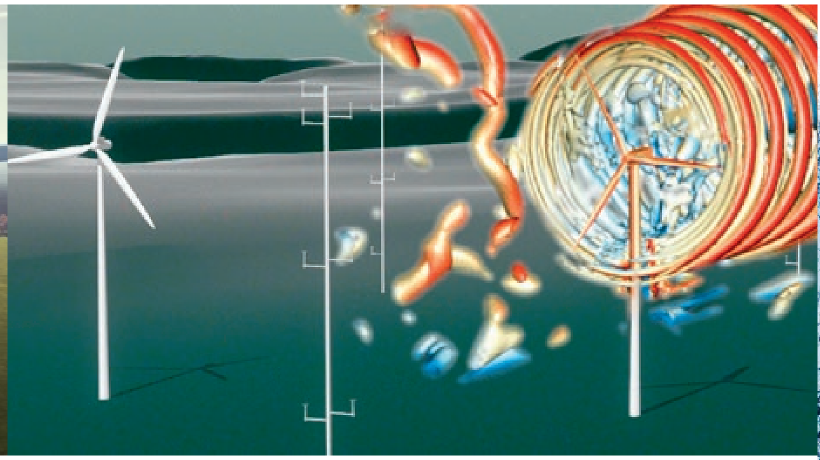
// Consulting and on-site inspections

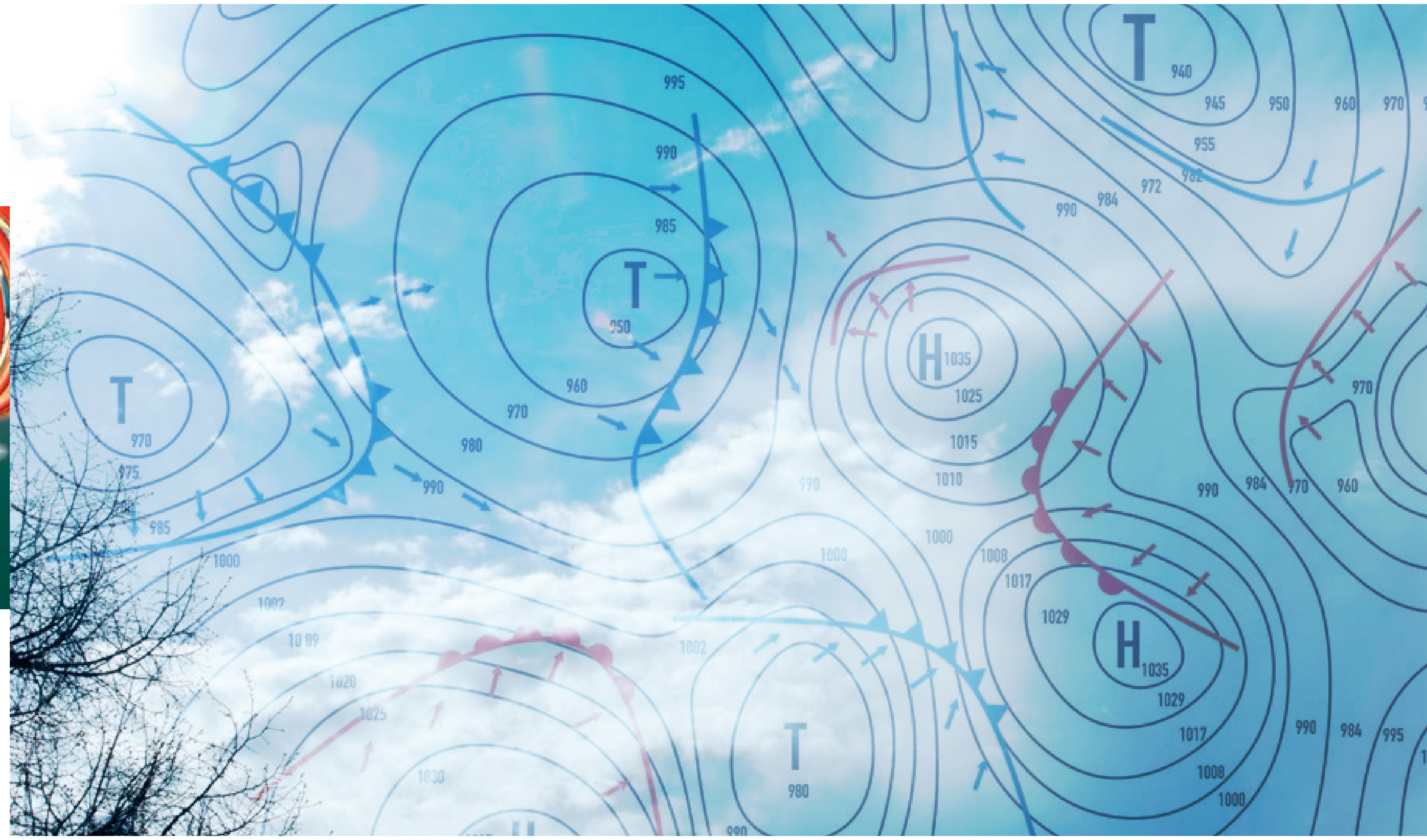
Every now and then, operators find fault with the energy yield of their PV systems or discover weaknesses in individual components. The mission of ZSW's PV testing center "Solab" is to probe the root causes of these issues. The specialists analyze yield data, pore over IR heat maps, and measure power output to pinpoint issues such as PID, micro-fissures, snail trails, LID, defective bypass diodes, and defective backing foils. Individual modules are measured in Solab or taken to the ZSW analytics lab to follow up with more exhaustive investigations. We also inspect PV systems and PV module factories around the world to assess their quality assurance practices.

The ZSW's Widderstall testing facility operates and monitors PV modules outdoors to complement the quality testing done in the lab.

ZSW Solab offers a smorgasbord of testing options for all PV technologies. ZSW's test lab measures performance and low-light response. It inspects insulation in wet conditions. And it conducts potential-induced degradation tests (PID) and accelerated aging tests such as the damp heat test (DHT), the thermal cycle test (TCT), and the UV illumination test.

// Electricity generation from sunlight and wind





// A wind test site in mountainous terrain

As wind energy picks up momentum, wind farmers are looking to mountainous areas for suitable spots. However, the turbulent and gusty winds in this rugged terrain can put turbines under tremendous mechanical strain and impact on yield. ZSW and its partners in the WindForS research cluster have set out in search of the best way to operate wind turbines and maximize yield in such demanding locations. And we have just the place to experiment – our testing grounds in the Swabian Alps near Geislingen an der Steige. This test site is unique in its research mission and complex mountainous terrain and provides invaluable information to benefit the development of wind turbines.

The test site features two wind turbines with a rated output of 750 kilowatts each and a hub height of 75 meters. Their rotor diameter is 50 meters and their total height, 100 meters. Both are fitted with many measurement sensors from the base to the rotor blades.

One of this project's unique features is that scientists will have unrestricted access to all control technology and engineering data to analyze and adjust these systems' behavior with pinpoint precision.

These researchers aim to improve wind turbine technology in myriad ways. One goal outcome is to optimize the aerodynamics of the blades to make them quieter, lighter, and more powerful rotors. Another is to improve simulations and computer models. The results will be scaled up to large commercial plants to help the wider wind energy industry.

This test site also enables researchers to investigate the local ecosystem and learn more about interactions and interdependent relationships among organisms in and around the wind farm. Scientists want to study the behavior of endangered birds and bats to develop technologies that tap wind power without endangering the site's ecological diversity and wildlife. Image recognition systems like those developed for autonomous vehicles serve to identify protected birds.

Ecologists will be active at the wind test site to study and assess the potential impact of the turbines on animals and plants in the vicinity. There are also plans to post information boards on a trail around the site for interested citizens to learn more about it.

// Solar and wind power feed-in forecasts

Solar and wind power generation ebbs and flows, depending on the time of day, season, and weather. The share of these renewables in our electricity supply is steadily increasing as the Energiewende makes headway. Plant operators need a highly time-resolved prediction of the power they generate and feed into the grid. This information is indispensable for efficient managing of electrical transmission and distribution grids.

ZSW is looking into technologies that enable accurate wind power forecasting. This is a practical-minded effort that factors all the variables into the equation – the complex interplay of weather models, satellite data, meteorological measurements, and the historical and predicted wind yields of a particular site or entire region.

Machine learning figures prominently in this effort. These methods help improve the physical methods of measuring wind and solar irradiation to improve forecasts and, by extension, the performance of turbines. A system endowed with machine learning capability detects patterns and regularities in measurements taken over several years and applies them to the current weather situation. It automatically corrects for the systematic deviations that inevitably occur in physical models.

ZSW also prepares photovoltaic (PV) feed-in forecasts for distributed PV portfolios all across Germany and in the four control zones. (Germany's high and extra-high voltage grids are split up into four geographical zones, each with a transmission grid agency responsible for regional stability.)

// Batteries for electromobility and energy storage

Sunlight and the wind come and go. If we want to have the energy they furnish to us at our beck and call, we will have to find better ways of storing it. It takes high-performance technologies to do that – and to build the batteries that will make our transportation sustainable.

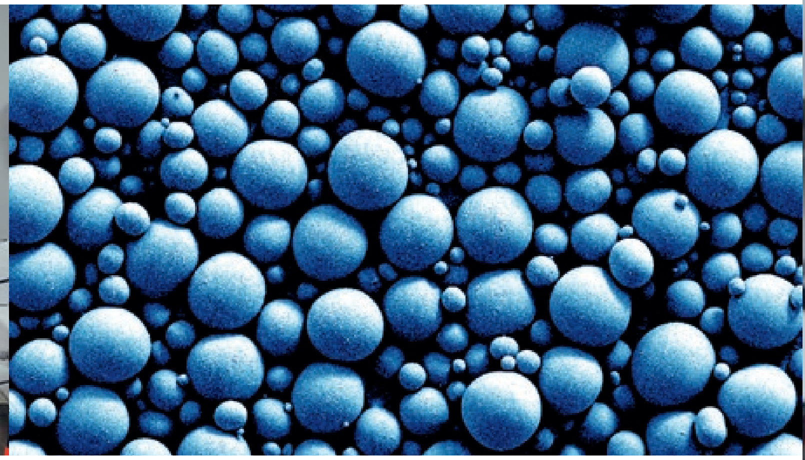
E-mobility and renewable energies – their interaction will require completely new, high-performance storage systems. Lithium-ion technology is today's energy storage medium of choice, as the global megatrend in this direction goes to show.

High-performance batteries are the core component in modern hybrids and battery electric vehicles. They have a tremendous impact on a vehicle's cost, energy consumption, range, and reliability. Batteries for stationary applications also have their benefits. For example, they offer a unique opportunity to maximize self-consumption of energy produced by distributed photovoltaic systems. They can also help improve power distribution grids and provide emergency power.

ZSW has been researching batteries for 30 years. Some of this investigatory work is evolutionary, such as our efforts to gradually step up their capacity to store energy in compliance with safety standards, to investigate their behavior at high and low temperatures, and to look into new classes of materials such as cobalt-free cathodes and silicon-based anodes for lithium-ion cells. Other projects are more revolutionary, for instance, our R&D aimed at discovering unprecedented approaches to electrochemical energy storage.

Electric mobility is a global growth industry. Production is surging with 1.2 million battery-powered electric vehicles rolling off assembly lines in 2017. That number is expected to increase to 20 million by 2025. Vehicles are getting more diverse. The batteries installed in new models tend to be larger, with capacities up to 100 kWh. Billions of euros will have to be invested to build as many as 20 giga-fabs with a capacity of 35 gigawatt hours each to make lithium-ion cells in those numbers.

// Batteries for electromobility and energy storage:
Materials research and post-mortem analyses



// New active materials development

New active materials are the stuff of which advanced, next-generation batteries will be made. When demand from mass manufacturers spikes and source materials grow scarce, they offer a way around these supply bottlenecks. ZSW's core expertise includes synthesizing new chemical compounds and making custom powders and slurries for electrodes. Our facilities produce powder in amounts ranging from a few grams to the kilogram scale. We know how to develop cathode materials such as high-voltage spinels, lithium-transition metal phosphates and silicates. The same goes for anode materials such as optimized carbon modifications, titanates, and alloy anodes. Electrolyte systems with special additives are also on the menu.

One focus of our research is on cobalt-free electrodes. All current configurations, even state-of-the-art variants, of lithium-ion cells use cathode materials that contain cobalt. However, cobalt is toxic, scarce, and expensive. Our scientists developed a new cobalt-free cathode material based on $Li_{1+x}Mn_{1.5}Ni_{0.5}O_4$ back in 2015. With a storage capacity beyond 240 mAh/g, it outperforms all other materials currently in use or under development. The discharge voltage is over 4.5 volts (V) which can increase the energy density of an entire battery by up to 40 percent. These improved batteries significantly extend the range of electric vehicles.

Our researchers are also looking into various post-lithium systems to make future technologies economically viable. ZSW is now investigating metal-air cells, lithium-, sulfur- and sodium-ion cells, supercapacitors, hybrid supercapacitors, and redox flow batteries.

// Analytics

The electrochemical behavior of storage materials for lithium-ion batteries very much depends on their chemical composition and crystalline structure. The shape, size distribution, and surface properties of these microscopic storage particles largely determine the material's processing behavior and thus its suitability for industrial battery manufacturing. One of our main objectives in research projects is to profile all of the material's properties, identify influential factors, and map and understand the relationships between their structures and properties.

The performance and storage capacity of batteries recedes over time. This aging can be caused by chemical agents that corrode materials and components or even mechanical forces that degrade. ZSW researchers excel at investigating and understanding the effects of aging and putting these insights into practice to improve materials and develop more robust cells.

Our teams use standard chemical (ICP-OES), structural (XRD), and microscopic (SEM, EDX) analytical methods to this end. We also examine surfaces (BET), analyze high-resolution depth profiles (GD-OES), and investigate decomposition behavior at higher temperatures using thermo-analytical methods (TG/DSC-MS and ARC).

// Failure analysis, lifetime prediction, and quality assurance

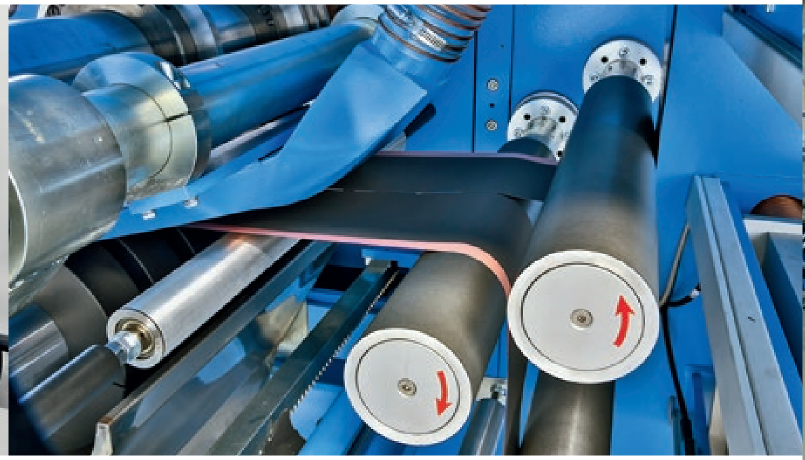
As lithium-ion cells for electric cars, e-bikes and stationary solar power storage units make inroads into the market, the ability to probe and analyze aging and defective batteries in exacting detail is becoming increasingly important. These assessments are used to determine what caused the impairment – improper use, manufacturing defects or design flaws. ZSW experts have many years' experience and the equipment needed to investigate all battery types from conventional and lithium-ion batteries to new supercaps.

Using professional cell opening and disassembly techniques, our experts take and analyze samples from the cell's individual components – anode, cathode, and separator – to determine the specific cause of the defect. Post-mortem analyses serve to identify the mechanisms that cause damage. For example, they enable experts to determine the impact of changing ambient temperatures on aging mechanisms, a key issue for cells in electric vehicles. Our lab also uses 3D X-ray computed tomography to examine the batteries' interior in a nondestructive way. With the benefit of these insights, we can optimize electrode and cell materials and manufacturing processes and develop new inspection methods for the battery industry.

ZSW has facilities to test all types and formats of batteries up to 400 ampere hours – conventional, lithium-ion, or even supercapacitors.

Learn more at

// Batteries for electromobility and energy storage:
Researching manufacturing practices and processes



New materials drive advances in battery performance. When researchers incorporate these materials in electrodes and full cells, they can study their properties and interactions with other cell components and analyze their fitness for real-world applications.

// Formulations and processing methods for electrodes and cells

The requirements for the coating of an electrode with active material and its structure vary depending on the lithium-ion cell's given application. The coatings on electrodes for high-power cells are thinner and contain more conductivity-enhancing additives. Electrodes destined for high-energy applications usually have thicker coatings with minimal additives in the mix. An electrode's porosity determines the power density as well as the kinetics during cell charging and discharging. The electrode coating's adhesive strength and stability may also be adjusted by varying the manufacturing parameters.

ZSW develops formulations and processing methods aimed to employ the material's properties in the battery cell. To this end, researchers first determine what the best electrode structure will be. Then they use scanning electron microscopy, mercury porosimetry, and electrochemical analysis methods to assess how processing will affect the material, electrode, and cell.

We match the cathode to the anode to tailor the cell to a specific application. For example, the focus may 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.

From drying rooms to analysis equipment, we have all the systems needed to develop and manufacture fully functional electrodes and cells from new active materials and components. The possibilities range from laboratory-scale single-layer and stacked pouch cells and "jelly roll" 18650 and 21700 cells to industrially manufactured large lithium-ion cells in PHEV-1 format.

If short- and medium-term projections are anything to go by, billions of euros – surely a double digit figure – will have to be invested in new factories to manufacture batteries for electric vehicles. Manufacturers will also need advanced new battery cells and cutting-edge industrial production technologies.

// Researching industrial manufacturing and processes

The "Research Platform for the Industrial Production of Large Lithium-Ion Batteries (FPL)" was set up at ZSW in Ulm in 2014 to develop the capability to build the best batteries for powering electric cars and storing wind and solar power locally in Germany. This platform focuses on developing the process engineering and production technology know-how needed to make large-format lithium-ion cells in industrial plants. Industrial enterprises and research partners are welcome to use this plant to develop cell technologies and manufacturing processes.

Every step in the process chain for industrial lithium-ion cell manufacturing has an impact on these batteries' performance, quality, and costs. This is why ZSW's research is constantly striving to improve materials and components and test new production processes and plant components. Our scientists also investigate process parameters that are decisive to the quality and yield of manufactured cells. And they develop new quality assurance methods to meet the automotive industry's high standards for safety and quality.

Our modular production system provides the means to develop, optimize, and qualify all processes from formula preparation and electrode production to cell assembly and formation under near-series conditions. The fully automatic cell assembly line adapts to accommodate various cell formats. It is designed for one cell per minute. A specially developed process control system serves to assure the quality of individual steps or the entire process chain. The data captured from this production line affords us insight on the interaction of the components and provides the input for models and simulations.

// Batteries for electromobility and energy storage:
Battery test center and systems engineering

// Battery safety and performance test center

Battery safety is paramount in every scenario from routine use cases to the most extreme situations. With this imperative in mind, we analyze the behavior of batteries under every conceivable condition. The work in our battery test center focuses on characterizing storage devices and studying their behavior in response to handling errors and accident scenarios. The tested batteries are used for stationary energy storage in electrical grids, in portable devices, and in electric vehicles' drive trains.

Identifying potential hazards is a priority, so we conduct destructive tests to assess the response of accumulators to extreme damage and their resilience to various forms of misuse and handling errors. ZSW performs mechanical, thermal, and electrical safety testing in bunkers equipped with fire extinguishers, gas scrubbers, video surveillance devices, and high-speed data capture systems. We perform these tests according to the customer's specifications or in compliance with national and internationally recognized test protocols.

Electrical battery tests serve to gauge the functionality and performance of cells, modules, and systems and to determine their expected service life under defined loads and environmental conditions. ZSW characterizes single cells, modules, and entire battery systems under all applicable operating conditions. We have the necessary tools to conduct these tests in a power range spanning from a few milliwatts up to 320 kilowatts and at up to 1,000 volts.

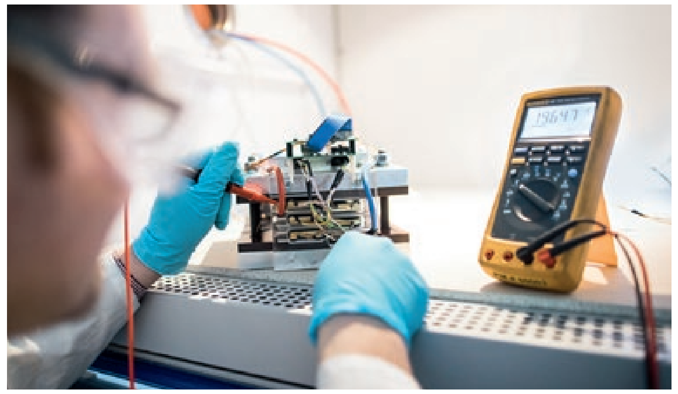
Our testing activities focus on characterizing batteries under diverse operating conditions and investigating their behavior in the event of handling errors and accident situations.

// System engineering and battery management

Thermal and electrical modeling and simulations of cells and batteries are the cornerstones of battery systems engineering. ZSW's research runs the gamut from characterizing cells and developing battery models and management systems to investigating the storage unit in its application environment. The goal is to enable dynamic, reliable, and economical operation throughout the battery's service life.

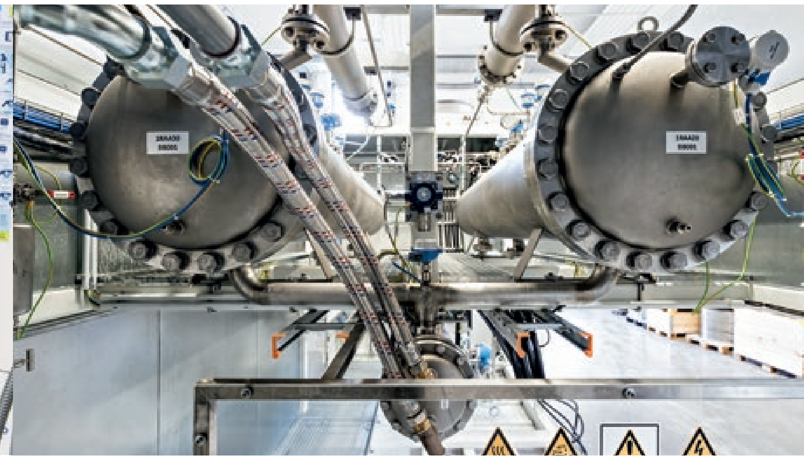
Our tasks are many: We study batteries' electrochemical, electrical, thermal and mechanical behavior, run model-based algorithms to determine charging and aging statuses, forecast system performance, optimize charge management – particularly under fast-charging conditions – and improve energy management systems. We also assess battery use cases and cost developments.

Batteries have many applications – for traction power in electric vehicles, for in-building PV storage and as a component of the power grid. Each application has very different demands on their energy density, performance, efficiency, reliability, safety, and costs. These have to be determined and prioritized accordingly. Not only that: Our systems engineering teams analyze the big picture of how the storage unit interacts with its environment – that is, power electronics, loads, measurement, and communication – to determine the best operating conditions for a given scenario.



// Hydrogen-powered mobility and energy storage

Hydrogen is a key chemical storage medium for electricity sourced from renewables. As such, it can be used in the electricity, heat, or transportation sector. As a clean fuel for fuel cell vehicles, it helps reduce greenhouse gas emissions. Hydrogen may also be processed further to create regenerative natural gas and synthetic fuels called e-fuels.

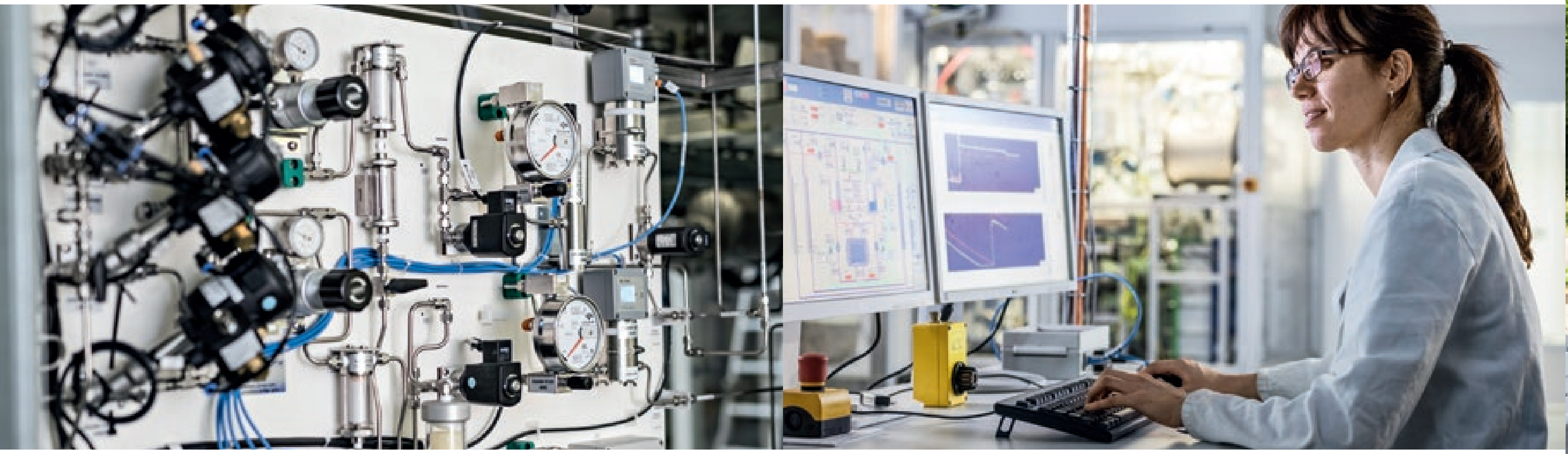


The term 'e-mobility' covers more than just hybrids and battery-powered vehicles. It also encompasses electric vehicles that generate their own electricity from hydrogen in a fuel cell. Hydrogen fuel cells are a more-from-less solution, with greater energy efficiency and lower pollutant emissions than combustion engines. Fuel cell vehicles can travel roughly as far and refuel as fast as gasoline and diesel vehicles – only their fuel is hydrogen produced by water electrolysis using renewable electricity.

Fuel cells are electrochemical energy converters that transform the chemical energy of a fuel such as hydrogen, natural gas, or methane into electricity, heat, and water. Hydrogen fuel cells are emission-free at the point of use. They can serve a wide range of applications – as electric drives in cars and ships, for electricity and heating systems in the basements of homes, and for emergency power units. The hydrogen-powered polymer electrolyte membrane (PEM) fuel cell is the most versatile among the many fuel cell technologies. And natural gas-powered fuel cells provide highly efficient, eco-friendly heat and electricity for stationary home energy supply systems.

ZSW specializes in advanced electrolysis processes and PEM fuel cells. This ranges from modelling and simulation to the development of automated manufacturing processes as well as demonstration and test systems, including the examination of the refuelling and gas quality at hydrogen refuelling stations (HRS).

// Hydrogen-powered mobility and energy storage:
Producing hydrogen, turning it into fuel



If the transition to renewables is to succeed, scientists will have to find ways of storing renewable electricity from one season to the next and transforming the transportation sector into a climate-friendlier industry. ZSW is addressing both of these challenges by developing processes to manufacture and use heating and motor fuels. Our top priorities now are renewable electricity-based hydrogen electrolysis and power-to-gas (P2G®) methane production.

// Hydrogen produced by electrolysis

Widely seen as the secondary energy carrier for the future, hydrogen (H_2) is well suited for storing and delivering large quantities of green electricity across sectors. It can be converted back into electricity. It can serve as an emission-free fuel for fuel cells and as a starter material for manufacturing chemicals. And it can be processed into e-fuels that contain hydrocarbons. These synthetic fuels are produced using hydrogen and carbon dioxide (CO_2) in power-to-gas or power-to-liquid processes.

ZSW is investigating every step of the electrochemical hydrogen production chain. We develop energy-efficient electrodes, design advanced plants, and build and operate research and demonstration systems. These include atmospheric and pressure electrolyzers with power ratings ranging from a few kilowatts for test benches to demonstration plants with megawatt outputs.

Conventional alkaline electrolytes and polymer membrane electrolytes (PEM) are sure to feature prominently in the future. ZSW focuses on developing cost-effective catalysts, optimizing cell and block designs, boosting the operating reliability of plants, and developing innovative electrode microstructures for both technologies.

// Power-to-gas (P2G)

Power-to-gas involves converting surplus green electricity into hydrogen (H_2) by way of electrolysis. If the need arises, it may even be combined with carbon dioxide from biogenic sources such as biogas plants to be converted into methane (CH_4), the main ingredient in natural gas. Both H_2 and CH_4 can be fed into the natural gas network and stored there loss-free for months.

The gases produced by the P_2G® process can also serve to power fuel cell and natural gas cars. Other processes related to P_2G® produce liquid e-fuels such as synthetic kerosene for aircraft, liquefied petroleum gas for ships, and synthetic gasoline or diesel for heavy trucks.

ZSW and its partners in science and industry have been using this process for years. We built a 25-kilowatt plant at the institute in 2009 and, three years later, a 250-kilowatt plant that is able to respond flexibly to fluctuating wind and solar electricity feeds and sudden interruptions. ZSW also helped ramp up an industrial P2G® plant with a connected load of six megawatts. And we are contributing to the research done in a real-world lab for electricity-based hydrogen at the Wyhlen hydroelectric power station on the Upper Rhine. This initial design is designed for a total electrical connected load of 1.3 megawatts.

// Hydrogen (H_2) as a fuel

In parallel with the market launch of the first fuel cell series vehicles, hydrogen infrastructure is developing and hydrogen refuelling stations (HRS) are increasing around the world. The standard pressure level for refuelling compressed hydrogen (CGH_2) is 700 bar. Compared to liquid fuels like gasoline and diesel, hydrogen requires new techniques to quantify the amount dispensed at a filing station.

Impurities and particles can contaminate hydrogen when the gas is produced, transported to the filling station, compressed, and refueled. These impurities can damage the vehicle's fuel cells.

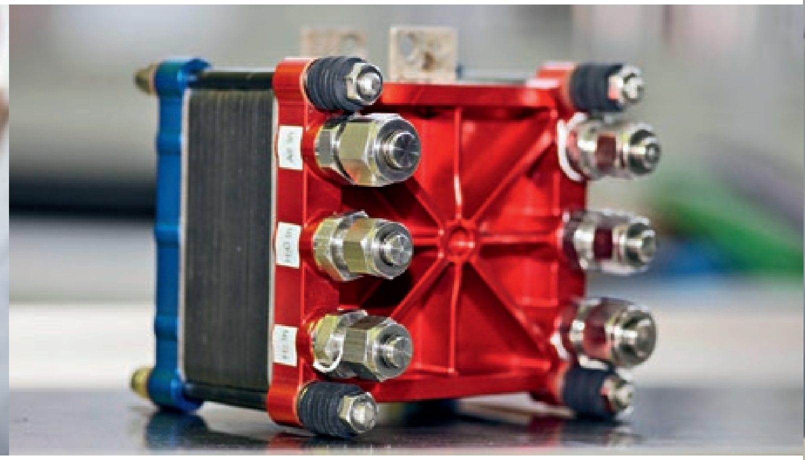
Therefore, the hydrogen quality as well as the refuelling quality at the HRS has to be inspected before they are put into operation and regularly checked afterwards.

ZSW is putting its many years' experience with fuel cell technology and hydrogen to good use in several projects aimed to build up European hydrogen infrastructure. Our specialists have the expertise to independently verify international refuelling and hydrogen standards according to SAE J2601 and ISO 14687-2. We have developed a mobile certification system and set up a hydrogen laboratory with suitable analytical tools to this end.

At the time of printing, 260 hydrogen filling stations were in operation worldwide, but the count is expected to rise to 3,500 by 2025. 600 are planned in the USA, 830 in Asia and 2,000 in Europe. Germany plans to extend its installed base of around 25 stations to 400 by 2025. The number of fuel cell vehicles is expected to rise from 6,500 to over 300,000 in the same time period.

Learn more at

// Hydrogen-powered mobility and energy storage:
Fuel cell technology



// Optimizing fuel cells

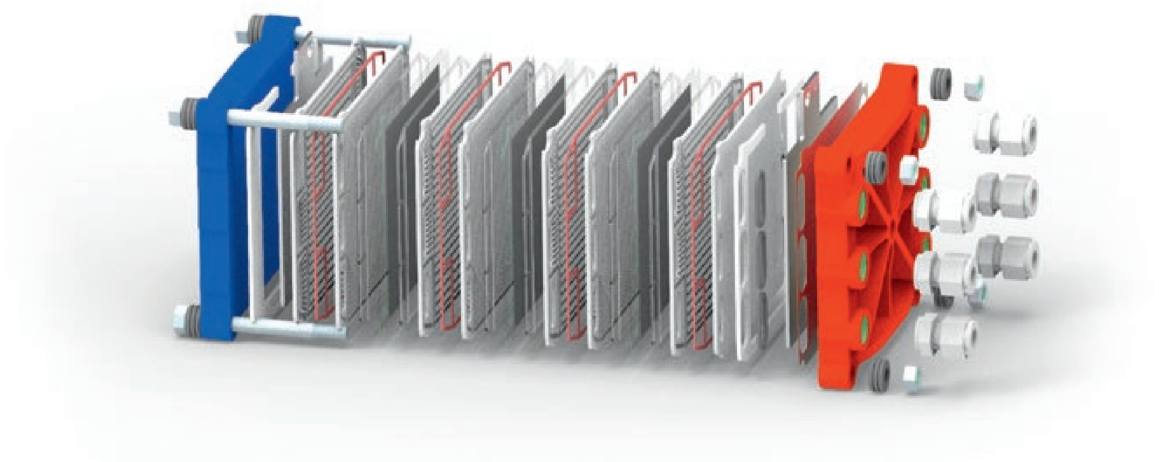
The recipe for vehicular fuel cells' success calls for three ingredients – high power density, good cold-start properties, and long service life even when cars are driven very dynamically. The challenge for engineers is to develop affordable components, fine-tune their interactions, and optimize their functions. ZSW strives to improve the performance, efficiency, service life, and space requirements of fuel cells. The research focus here is on polymer electrolyte membrane fuel cell (PEMFC) components ranging from the electrode to the bipolar plate (BPP).

Our scientists specialize in characterizing these components, optimizing their performance, and extending their service life. To this end, they develop advanced manufacturing techniques, investigate the structural and surface properties of materials, assess aging processes, and analyze faults. Our labs experiment with functional materials, electrode and membrane electrode assemblies (MEAs) and look into the durability of gaskets, gas diffusion layers, and bipolar plates. We employ special simulation software for fuel cells to develop, and test completely new approaches.

// Manufacturing technology for fuel cells

Fuel cell stacks for vehicles have to satisfy very demanding requirements as to their volume (<30 liters) and power (100 kW continuous output). Several hundred components must be assembled and bonded with the kind of exacting precision that only a machine can achieve. However, the manufacturing technology needed to do this is still in its infancy worldwide.

ZSW researchers are tasked to develop methods to assure the quality of components and ultra-precise machines to assemble fuel cells and stacks. For example, they develop joining technologies, cell manufacturing processes, robot-assisted stack assembly processes, and testing methods. Years of experience pursuing many research projects and building more than 1,000 prototypes serve us well in these efforts.



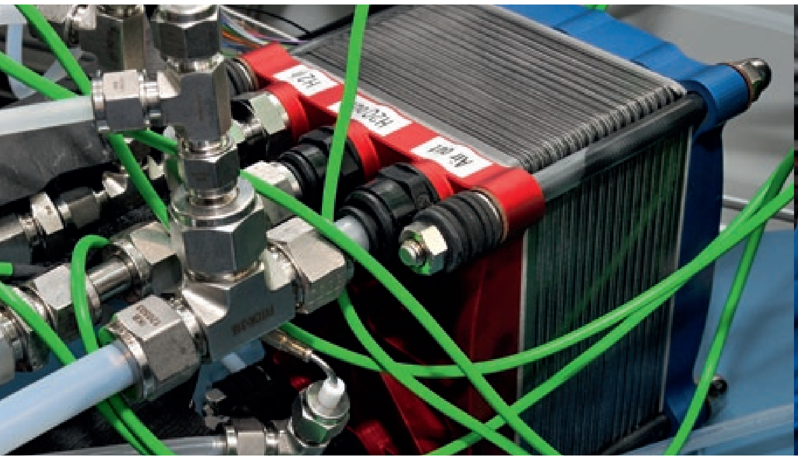
// Modeling and simulating electrodes and cells

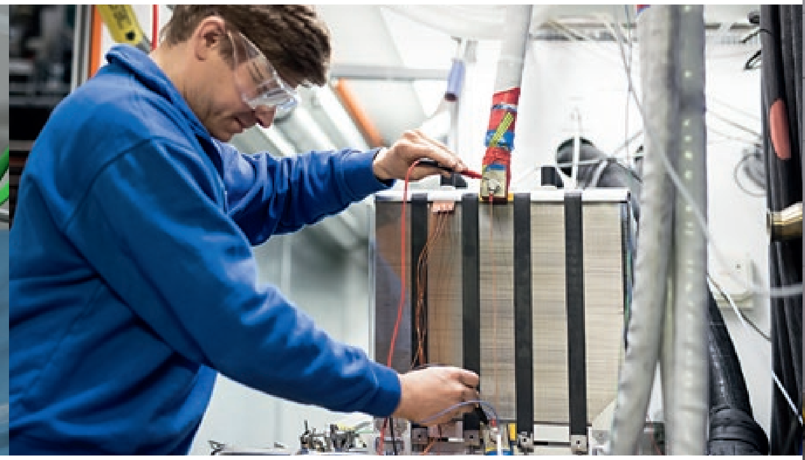
Mathematical models afford insight into the physical and chemical processes that transpire inside a fuel cell. Our scientists build on this insight to develop new technologies for constructing stacks and optimizing systems. Models are thus valuable R&D tools that enable us to target specific properties and improve them to bring down research costs and fast-track development.

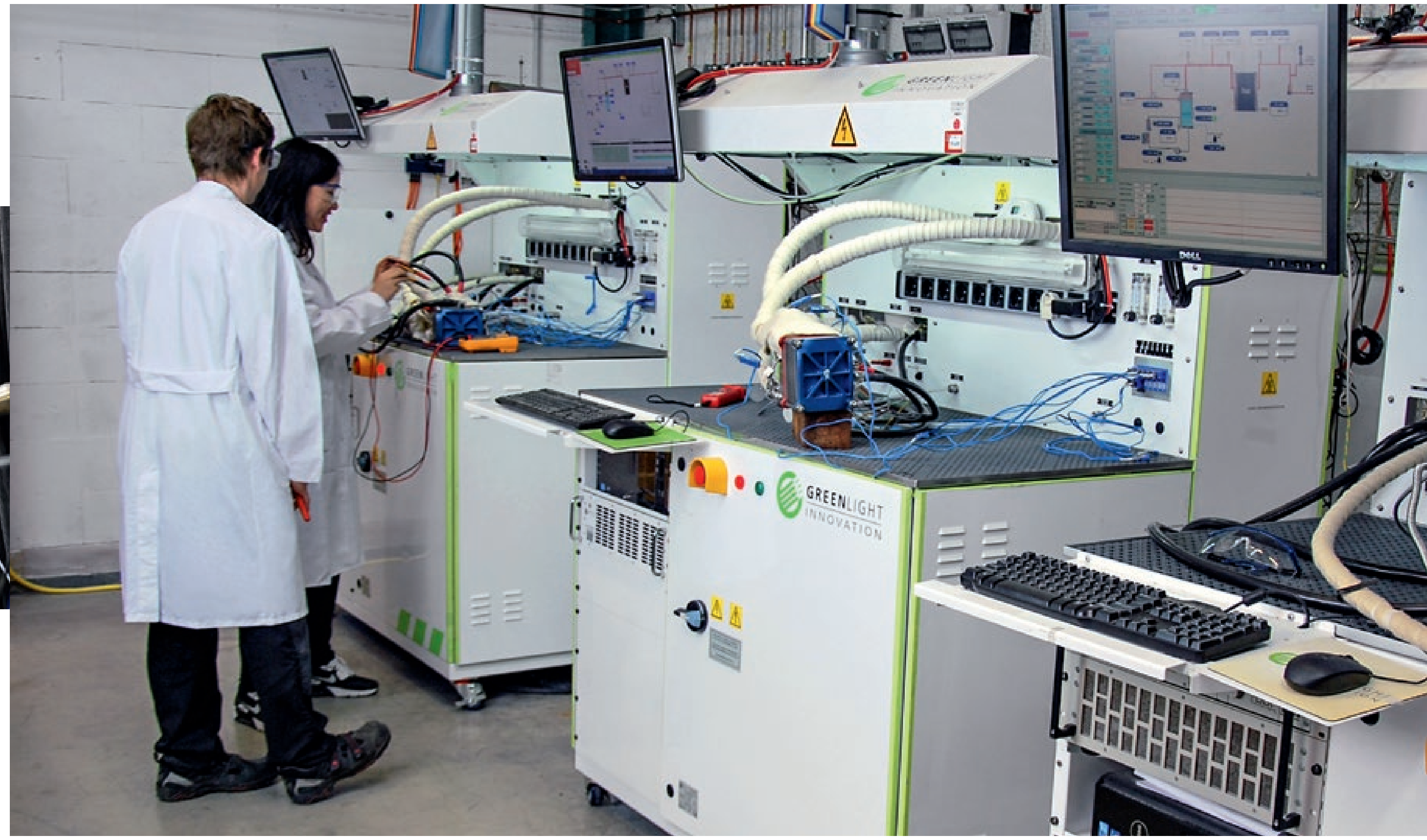
At ZSW, we use commercial and proprietary simulation tools to build both design models and electrochemical models of fuel cell components, stacks, and systems. Our scientists investigate microscopic processes such as water distribution in gas diffusion layers using Monte Carlo (MC) and kinetic Monte Carlo (KMC) simulations, macroscopic processes by way of CFD and FEM simulations, and the design of entire systems with Ipse-Pro and Matlab-Simulink tools. As part of the design effort, we model channels up to whole cells, also half and full cells. We also include consideration of multiple phases (gas, liquid) and analyse the distribution of media within a stack and the water discharge behavior for various gas flow field geometries. Finally, we verify simulated results with realistic hardware experiments.

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

// Hydrogen-powered mobility and energy storage: Our 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. It is imperative that the electrical behavior of these fuel cells is safe and reliable, particularly under the dynamic workloads that cars cycle through day in and day out.

ZSW set up a fuel cell test center more than 20 years ago, and we have been improving and extending our capabilities ever since to meet this demand. With our state-of-the-art testing facility and the know-how born of many years' research into fuel cell systems, ZSW has a lot to offer partners seeking to develop tomorrow's products. In publicly funded projects, our scientists collect valuable data and gain experience, which is published and thus available to the community. Industrial partners tap this expertise to further develop and qualify their products, and have their safety verified by an independent lab.

Our test center can assess the performance of fuel cell modules with hydrogen or hydrogen mixtures from 100 W to 160 kW_{el} capacity. We have 25 test benches in place to cost-effectively run around-the-clock endurance tests. They put in around 40,000 operating hours per year, which speaks volumes about our facility's ability to meet the great demand for safety testing.

We can also conduct tests in compliance with international quality standards such as DIN IEC 62282-2, and bring on board an accredited certification and inspection body (ZÜS). Our engineers do more than merely run tests. They also document all processes and identify parameters for optimizing fuel cells. It takes a thorough understanding of the myriad ways in which cell materials and components interact to interpret test results. This is why we use supporting analysis tools and simulations to shed additional light on our findings.

Learn more at

// Fuel cell systems

Fuel cell systems need air compressors, hydrogen recirculators, humidifiers, and cooling circuits to operate efficiently and flawlessly. Of course, vehicular drive trains, combined heat and power (CHP) systems in households, off-grid power supplies, and battery chargers/range extenders have very different requirements, so these components come in very different guises determined by the type of application.

ZSW has years of experience developing fuel cell systems, as our skill set in this area attests. We plan and design using simulation-assisted tools. We build, characterize, and qualify prototypes. And we test and qualify system components, carry out product certifications or safety assessments, and conduct packaging studies on behalf of the industry.

ZSW has been operating a fuel cell test center for over 20 years. With 25 fully automated test benches and a power range of up to 160 kilowatts, it is one of the world's largest test centers for fuel cell stacks at an independent research institute.

// Grid integration and energy management

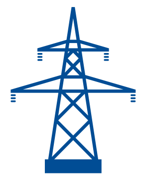
New technologies have to be placed efficiently into the energy system to manage the energy transition. Viable strategies, sound economic concepts, and reliable forecasts of power generation and load are required to match generation and consumption through demand side management and storage technologies at any given time. ZSW develops smart solutions to this effect.

If we want to integrate large amounts of power generated from fluctuating solar and wind sources into the energy supply, we will have to orchestrate the interaction of electricity generation, consumption, and storage, as well as the conversion of electric power into heat and green fuels. Consumption of electrical power has to match generation at any given time. For the resulting "smart grid", ZSW develops storage solutions and control algorithms.

A "smart grid" is equipped with features and technologies that adapt to fluctuations in generated power. It uses storage, shifts loads by rescheduling electricity consumption, and converts a surplus of electricity to heat or fuels. The term extends beyond hardware. Smart grids require new business models and regulation to provide incentives for players in the energy sector to expand the infrastructure, including storage, and to improve load-handling capabilities to create a stable sustainable energy system.

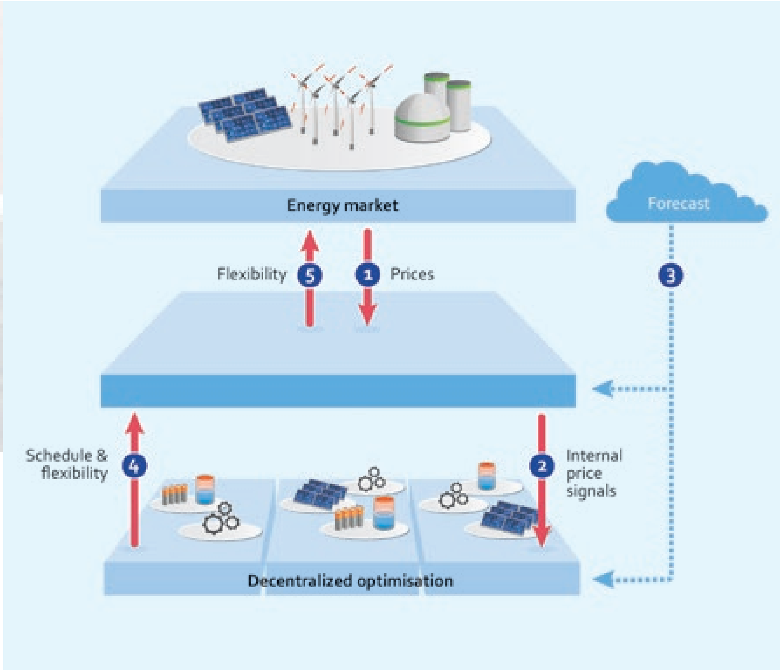
// Integrating solar power into the grid

One way to address the power balancing issue is to optimize load shifting and integrate electrical and thermal storage systems. These techniques increase the local consumption of solar power and thereby lighten the grid load. Grid integration is a research topic of great interest to ZSW. In field tests, we develop and verify the potential for self-consumption of solar power, dimensioning of PV storage systems, and algorithms to manage storage and generation. Our researchers investigate the options to operate distribution grids with a large share of solar power. For example, we look into state-of-the-art control rooms with predictive management capabilities and low-cost ways of mapping out grid expansions. Grid simulations, forecasting techniques, and optimization tools are applied to existing or typified distribution grids to develop these predictive management tools.



Electricity producers and grid operators have to balance power generation and consumption in a cost-effective way. To do that, they need operating schedules and options for managing flexible loads and storage on the fly. ZSW develops algorithms that enable this clientele to make the most of existing grids and power plants.

// Grid integration and energy management



// Examples of sector coupling

If we wish to make the most of our energy system, we will have to take a holistic approach that connects the dots between the electricity, heat, and transportation sectors. This connected approach has come to be known as sector coupling. One example is the practice of piping renewable gas converted from electricity into the natural gas grid and using it to power natural gas vehicles. A second example is heat pumps with thermal storage tanks that provide space heating and hot water to the industry and in private households. If they are timed to do this at noon when the power provided by rooftop solar panels on industrial and residential buildings is highest, this brings down the PV feed-in and reduces the strain on the grid.

Another way to balance the load is to take advantage of the time electric vehicles spend in the parking lot at work or at home and to recharge them when the production of renewables peaks. ZSW collaborates with stakeholders, such as municipal utilities and industry players, on these topics. We analyze demand and generation profiles and the design of systems based on these profiles to explore how they deploy and control charging stations, manage grid loads, and tap local power storage units. These customers also benefit from our feed-in forecasting capabilities (see p. 17).

// Price signals, a language of demand-side management (DSM)

Shifting electricity demand of appliances at home or processes in industry to match generation and load is a powerful tool to ease supply fluctuations and reduce peak demand. Termed "demand-side management", or DSM for short, it can drive down cost for grid operation and reduce grid loading. A central entity tasked with DSM would have to have deep insight into the specification for power demand and degrees of freedom of participating power-consuming entities. An efficient alternative is to communicate with those entities in a language understood by everyone. Money talks: With the benefit of price signals, every power-consumer can "decide" when to buy power to meet their demand in a cost-effective way. This creates a de facto cost-optimized DSM solution. ZSW uses simulation tools and agent-based models to investigate these possibilities and assess their benefits for the user and for an improved grid integration of renewables.

Connecting the power sector with the end-use sectors of heating and transportation creates flexibilities to relieve the electrical grid and reduces greenhouse gas emissions. ZSW is working to make that happen.

// Economically, ecologically, and socially viable concepts for the energy system

ZSW is an applied energy research institute. As such, we have the technical, analytical, and economic wherewithal to transfer technologies to the market. As you have gathered from the preceding chapters, our institute provides solutions for electricity sourced from the sun and wind, hydrogen for fuel or as a storage medium, and the batteries and fuel cells that drive electric mobility. We also have photovoltaic and wind power forecasting capabilities and very specific know-how regarding solar and wind power plant operations. And to round out our technical skill set, we possess the tools to model virtual power plants and simulate grids and grid conditions.

Our scientists not only develop technology for specific use cases; they also provide services to address the larger issues. For example, we monitor the transition to renewables and develop and assess incentive schemes.

With this unique combination of technical and economic expertise, ZSW provides valuable support to partners pursuing the projects that are transforming our energy system.

Learn more at

// A partner for business, research, and government

ZSW has a 30-year track record of trusted collaboration with many industrial enterprises, research institutes, and public policymakers. Our alliances cover a lot of ground. We team up with mechanical engineering companies that manufacture solar modules and lithium-ion batteries, automakers and automotive suppliers, municipal utilities and power companies, state and federal ministries, nonprofit associations, and many more allies.

These customers value ZSW experts' insight into industrial processes, appreciate the agility and can-do spirit with which they take on jobs, and benefit from their holistic skill set. Their knowledge of materials runs deep. And they have the know-how to develop production processes, application-specific testing tools, and system solutions. Our scientists also work in a broad network of university and non-university research institutions. With all these assets, we are ready to tackle the challenges of next-generation technologies and beyond.

ZSW's analysis skills have been honed over many years of developing scenarios and incentive schemes and preparing market studies. The institute prepares calculations, analyses, and expert reports for state, federal and EU ministries. For example, we are part of Energie der Zukunft (Energy of the Future), a commission with a panel of experts who scientifically respond to and comment on the German government's regular monitoring of the transition to renewables.

Let's talk about what we can do for you. You can reach us at any of the addresses on the right.

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