HYDROGEN EXPERTISE AT FRAUNHOFER

Focus on Innovations

Content

Imprint

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Hydrogen – enabling the global energy transformation

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Dear hydrogen enthusiasts,

by the middle of this century, the international community aims to reduce CO_2 emissions significantly, and to achieve climate neutrality. This commitment has propelled hydrogen to the forefront as a pivotal energy source. Renewable energies and sustainably produced hydrogen derivatives offer viable alternatives to fossil fuels and resources. While scientists have long been exploring hydrogen's diverse applications, its potential as a fuel, storage medium and foundational chemical is now being fully realized. The successful decarbonization of global energy systems hinges on a systemic shift. It involves integrating local electrification powered by renewables with a globally interconnected trade in certified, hydrogen-based energy carriers. A hydrogen economy opens numerous pathways to transition toward a climate-neutral, sustainable and efficient economic paradigm.

Setting the course for the hydrogen economy

The German government's National Hydrogen Strategy, initiated in 2020, laid the groundwork for fostering a sustainable and economically viable hydrogen economy. A subsequent update in 2023 outlines more targeted objectives. This strategy details Germany's utilization of green hydrogen across the industrial, transportation and energy sectors to meet climate targets, enhance competitiveness, and open new markets. Key objectives include accelerating hydrogen market development and establishing robust infrastructure to ensure adequate hydrogen availability across diverse end-user markets. Germany aims to lead in hydrogen technologies, leveraging its specialized companies spanning the entire value chain from material refinement through to system and component production.

Future challenges in the hydrogen economy

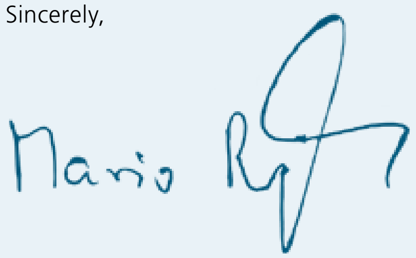
Beside the political framework, scaling up the hydrogen economy demands significant technological and organizational innovations. Many technologies and market segments along the value chain are still in early industrial stages. Substantial research and development efforts are therefore crucial, from fundamental materials research through to scalable production processes. These efforts are essential not only to secure technological leadership for Germany and Europe but also to generate opportunities across the value chain for German industries. Areas needing intensive research include digitalization in hydrogen technologies, scaling up fuel cell and electrolysis systems, achieving a climate-neutral chemical industry, promoting resource-conserving circular economies, advancing innovative electrolysis and power-to-X processes, and developing scalable, cost-effective direct air capture technologies. The Fraunhofer-Gesellschaft, renowned for its industrial proximity and scientific excellence, remains pivotal in driving innovation and facilitating the transfer of hydrogen technologies across various sectors.

Market expertise

As Europe's leading applied research organization, the Fraunhofer-Gesellschaft is dedicated to addressing society's most pressing challenges. It has swiftly tackled technical and systemic questions essential for the sustainable restructuring of energy systems, continually expanding its expertise and capabilities. For instance, the Cluster of Excellence »Integrated Energy Systems« (CINES) consolidates expertise from multiple institutes to optimize overall systems and address key technological and economic challenges of the energy transition. The Fraunhofer-Gesellschaft's Hydrogen Network coordinates efforts across 39 institutes, boasting over thirty years of experience in hydrogen technologies and a robust research infrastructure. With a cadre of exceptional researchers, the organization is poised to anticipate and tackle challenges in the global energy system, developing solutions and providing essential expertise to support this societal transformation.

In the following chapters, we invite you to explore our comprehensive expertise and service offer in hydrogen technologies. We showcase key aspects of Fraunhofer's hydrogen research and address industrial needs. Further details can be found on the websites of the Fraunhofer Hydrogen Network and individual participating institutes. We eagerly anticipate the challenges ahead and look forward to working with you toward a sustainable future.

Sincerely,



Prof. Mario Ragwitz
Spokesman of the Fraunhofer Hydrogen Network

Prof. Christopher Hebling
Spokesman of the Fraunhofer Hydrogen Network

Returning from a service deployment at the offshore installation

Flagship hydrogen project H_2Mare

Offshore conditions are ideal for generating renewable electricity. The production of green hydrogen in offshore plants, using wind energy without a grid connection, can significantly reduce costs compared to onshore production. The direct coupling of the wind turbine and the electrolyzer in an innovative system makes it possible to operate without a connection to the power grid. The flagship project H_2Mare, funded by the German Federal Ministry for Education and Research (BMBF), is researching the production of green hydrogen and other power-to-X products offshore, for the future large-scale production of offshore hydrogen. Besides other project partners, Fraunhofer IWES is supported by a cooperation with Fraunhofer IWU, IMWS, IGB and ICT.

»H_2Mare is making a key contribution to the implementation of the National Hydrogen Strategy and the energy transition. By linking innovative wind turbines and electrolyzers, in the future it will be possible to directly produce green hydrogen and other power-to-X products at low cost offshore. Fraunhofer supports industrial companies in developing the necessary technologies.«

Dr. Nadine Menzel
Group Manager for Electrochemical Analytics, Fraunhofer IWES, Project Coordinator of H_2-Wind

Investigation, analysis and modeling of stack components and their degradation behavior

In the field of stack component analysis, Fraunhofer IWES conducts chemical, electrochemical and mechanical testing series on laboratory cells and stacks (25 cm²) and on a research stack developed in collaboration with Fraunhofer IWU, in order to determine specific material properties, performance and degradation behavior under simulated offshore conditions. Changes in material properties are evaluated at a microstructural level and correlated with macroscopic measurements, operating conditions, and environmental factors. This helps to identify causal relationships using models and to derive recommendations for membrane and material optimization. The ultimate aim is to construct a suitable test infrastructure.

100 m³ seawater tank as a test rig for water treatment

Within the project, Fraunhofer IWES is also building a test rig for testing seawater desalination plants connected directly to a PEM electrolyzer. The aim is to use the waste heat generated during electrolysis to supply the process heat required by the desalination plants. This could significantly increase the overall efficiency of hydrogen production. Current research focuses on the mutual compatibility of the components and the system behavior with the highly dynamic electrical output from a wind turbine. The electrical connection of the PEM electrolyzer is initially intended for simple electrical tests, but during the project it should be possible to connect real wind turbines to the test field, or to carry out dynamic electrical tests using a hardware-in-the-loop (HIL) simulation.

Techno-economic simulations for optimal system dimensioning

Co-simulation in the H_2Mare project is an essential tool for the development of modular energy systems. The interchangeability of models through a standardized interconnection concept leads to shorter development times and increases the reusability of simulation models. At Fraunhofer IWES, models are established to map the entire value chain, and are linked together by functional mockup units (FMUs) in co-simulation. A simulation platform with an integrated interconnection concept for models and optimization via co-simulation was developed for this purpose. Co-simulation plays a central role in the project. It enables the reuse of models and their reconnection in a new context without any major additional work. Overall, operation and maintenance, wake calculations (Foxes), operational management and the WEA-ELY system are the focus of investigations.

The H_2Mare flagship project and its sub-projects started in April 2021 and are scheduled to conclude in 2025. The goal is to obtain key insights and demonstrators for direct-coupled hydrogen electrolysis, to pave the way toward a demonstrator in the MW range and initial projects in the North Sea later this decade.

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Pressure electrolysis block for hydrogen production

Hydrogen production by electrolysis and other processes

Many paths lead to hydrogen! Beside the increased use of renewable energies and electrical energy storage systems, the production of sustainable hydrogen as a precursor for synthetic fuels is the third central building block of the energy transition.

During electrolysis, water is broken down into the gases hydrogen (H_2) and oxygen (O_2) using an electric current. If the electricity used is generated from renewable sources, the hydrogen is referred to as »**green** hydrogen«. Each type of electrolysis offers specific advantages, so the choice of technology varies according to the application scenario.

While alkaline electrolysis and proton exchange membrane (PEM) electrolysis are already technologically advanced, there are still unresolved technical issues with alkaline membrane electrolysis and high-temperature electrolysis. For many decades, alkaline electrolyzers have proven to be a robust and reliable technology in power stations and chemical plants, in stationary operation with a constant load. Now, however, a paradigm shift is imminent: load fluctuations due to renewable energies mean that new concepts are needed.

PEM electrolysis is a more recent development than alkaline electrolysis and has various advantages: the current density used can be very high and the design extremely compact.

The process is dynamic and the cell can be operated at high pressure. However, due to the acidic medium, PEM electrolysis requires very robust materials, which necessitates for example the use of precious metals in the electrodes. PEM electrolysis is currently in the scale-up and cost reduction phase, and is thus well on the way toward mass production.

More compact electrolyzers and cost-effective catalyst materials can be achieved using alkaline membrane electrolysis cells. Most of the basic processes are understood in sufficient detail, so the focus is currently on application issues.

High-temperature electrolysis takes place at temperatures above 700 °C, and offers the greatest advantages where waste heat is available: no precious metals are required to catalyze the reactions, and very high electrical efficiencies can be achieved. The systems can be used in both electrolysis and fuel cell mode. They also enable co-electrolysis, which involves the cracking of water into hydrogen and oxygen, and the cracking of carbon dioxide into oxygen and carbon monoxide. Together with hydrogen, carbon monoxide is a »synthesis gas«, which serves as a precursor for the manufacture of numerous chemical products. Comparable co-electrolysis is also possible at lower temperatures (< 100 °C), for example using PEM-based electrolyzers. In addition to the production of synthesis gas (hydrogen / carbon monoxide) from carbon dioxide and water, the synthesis of other chemical precursors such as formic acid, ethylene or ethanol is also possible. These processes therefore contribute significantly to the defossilization of chemical products, and to the synthesis of sustainable fuels for aviation or shipping, for example, by closing the carbon cycle. This concept is known as carbon capture and utilization (CCU) technology.

Currently, most so-called »**grey** hydrogen« is produced by steam reforming of natural gas, but this is associated with considerable carbon dioxide emissions. A sustainable alternative is to replace natural gas with biogas (from biomass gasification). If biogenic residues are used, this process is sustainable. In addition to natural gas, coal can also be used as a fossil fuel. So-called »**black** hydrogen« is produced via hydrothermal gasification with steam.

»**Blue** hydrogen« is the term used when the carbon dioxide released during steam reforming is captured and stored in underground geological reservoirs. This process is known as carbon capture and storage (CCS). Although the carbon dioxide is not released into the atmosphere, storing it permanently and safely presents a challenge. »**Turquoise** hydrogen« is produced from natural gas in a process known as methane pyrolysis, in which methane is split into gaseous hydrogen and solid carbon through the introduction of thermal or electrical energy. The solid can be easily stored, and serves as a precursor for a wide range of applications. Blue and turquoise hydrogen are currently being proposed as a bridging technology until the reduced production costs for electrolyzers and a growing global supply of inexpensive electricity from wind and solar energy ensure that **green** hydrogen is available in sufficient quantities.

Another process uses sunlight to generate green hydrogen directly, using semiconductors to absorb the light and catalytically split water on their surface. This process takes place in photoelectrochemical cells (PECs), in which charge carriers are generated that then ensure the reduction to hydrogen or oxidation to oxygen. In the future, direct PEC splitting of water by light could offer simple setups with low system complexity. In practice, however, the technology is still at an early stage of technological maturity.

The use of photosynthetic or (photo)fermentative microorganisms is a purely biological method of producing hydrogen. Some microorganisms (e.g. bacteria) and also a few eukaryotic unicellular organisms (e.g. green algae) produce hydrogen as a metabolic product. However, photocatalytic and biological processes are still at an early stage of development and cannot yet be conclusively assessed for their potential marketability.

SkalPro – Scalable production processes for highly efficient electrodes in alkaline electrolysis

In order to mass-produce highly active electrodes for alkaline water electrolysis in the near future, further innovation steps are required. The Fraunhofer Institute for Manufacturing Technology and Advanced Materials IFAM has set the goal of developing and testing a manufacturing process for electrodes. This process will enable the production of highly active electrodes in large quantities and at low cost. Scalable production processes like this are currently not widely available on the market. The overall aim of the project is to develop an efficient, cost-effective and resource-saving production chain on a pilot plant scale for the manufacture of highly efficient and durable electrodes that meet the requirements of the electrolysis industry.

Integrate – Innovative designs for alkaline membrane electrodes for the cost-effective production of green hydrogen on a gigawatt scale

The complete transformation of the energy sector by 2050, from an economy based on fossil fuels to one based on renewable energies: this is the ambitious goal of the industrialized countries. In Germany alone, this will result in an annual hydrogen demand of 78 terawatt hours (TWh) by 2030 and 294 TWh by 2050. The electrolysis capacity required depends heavily on the efficiency of the technology, but will be in the order of 44 gigawatts (GW) of capacity by 2030 and 213 GW by 2050. This model assumes a 12 % increase in the efficiency of electrolysis technology between 2030 and 2050. To achieve this, existing electrolysis technologies (alkaline electrolysis – AEL, polymer electrolyte membrane electrolysis – PEMEL, solid oxide electrolysis cells – SOECs) must be further developed and new, more efficient technologies must find their way to market maturity.

A project at the Fraunhofer Institute for Manufacturing Technology and Advanced Materials IFAM is focusing on anion exchange membrane electrolysis (AEMEL) as the most promising technology for improving efficiency with cell voltages of 1.8 V at a current density of 1.5 A/cm² by 2030. The main advantage of this technology is that the ohmic internal resistance can be radically reduced by using an anion exchange membrane (AEM) similiar to PEMEL. In contrast to PEMEL, however, the alkaline medium allows the use of transition metals in all components. This ensures low criticality of all the materials involved, and the scalability of the technology. The project includes the design and optimization of a novel anion exchange membrane electrolyzer (AEMEL) designed for the GW market to minimize the cost of hydrogen production. Innovations include the electrode composition, the chemical structure of the membrane, the optimized catalyst layer structure (achieved by modelling), the use of new porous transport layers and the implementation of the results in an AEMEL stack.

OffsH$_2$ore – Hydrogen production at sea using PEM electrolysis

In the OffsH$_2$ore project, a technical plant concept for offshore hydrogen production was developed in conjunction with a ship-based transportation concept for compressed hydrogen. The team, consisting of project partners[1] along the entire value chain, developed a blueprint for a 500 MW offshore hydrogen production platform and a transportation concept for compressed hydrogen. In addition, they developed a detailed technical concept and carried out a techno-economic analysis. The results showed that offshore hydrogen production using PEM electrolysis is both technically and economically feasible, and contributes to the diversification of European hydrogen production. Particularly for countries where the large-scale production of green hydrogen is already a challenge due to competition for land use, hydrogen production at sea using offshore wind energy is a valuable option.

OffsH$_2$ore project

1 Project partners: Fraunhofer Institute for Solar Energy Systems ISE, PNE AG (project coordinator), SILICA Verfahrenstechnik GmbH, KONGSTEIN GmbH, Wystrach GmbH

Hydrogen production by electrolysis and other processes

»In the foreseeable future, hydrogen will play an increasingly important role in the energy system in Germany, especially in sector coupling. On the consumption side, sustainable process routes in industry and mobility will be the biggest drivers. CO_2-free water electrolysis will become the key technology for sector coupling, and the third phase of the energy transition in Germany. Together with the corresponding political framework, research at Fraunhofer will contribute to achieving the technological maturity needed to ensure the future of hydrogen in Germany.«

Dr. Tom Smolinka
Head of the Department for Electrolysis and Hydrogen Infrastructure at the Fraunhofer Institute for Solar Energy Systems ISE

BMBF-funded project GreatSOC – Green ammonia synthesis and utilization for maritime transport using SOC technology (Haber-Bosch ammonia synthesis by electrolysis of water vapor/nitrogen mixtures)

Most of the electricity generated from wind and solar energy is not produced directly at the location where it is needed. The development of flexible energy carriers with a high capacity is therefore crucial in order to store energy and access it as and when required, regardless of location. Ammonia, which is produced in an emission-free process combining Haber-Bosch synthesis with the water electrolysis of green hydrogen, is particularly suitable for this purpose, with the advantage of high volumetric and gravimetric energy density and transportability in large tanks. Ammonia can be used directly or converted back into hydrogen. It can therefore play an important role in establishing a hydrogen economy. In the GreatSOC project, which is funded by the German Federal Ministry of Education and Research (BMBF), the Fraunhofer Institute for Ceramic Technologies and Systems IKTS is developing and testing the technical interconnection of its own SOE stacks to produce synthesis gas for Haber-Bosch ammonia synthesis by electrolysis of water vapor/nitrogen mixtures, and is investigating the degradation phenomena that occur in the process. These solid oxide cells operate at temperatures between 500 and 850 °C.

H$_2$Meer – Efficient, selective and flexible production of hydrogen from seawater

The overarching goal of the H$_2$Meer project at the Fraunhofer Institute for Manufacturing Technology and Advanced Materials IFAM is to develop cost-effective and efficient electrolyzers for the production of green hydrogen directly from seawater or saline water. This will be achieved through new, cost-effective components such as catalysts, porous electrodes and newly developed membrane and separator materials. In addition, the optimized operation of seawater electrolyzers will be researched and tested for later application. Long-term tests with laboratory-scale cells in combination with simulated offshore power inputs will verify the robustness and suitability of the new system.

An important sub-goal is the development of stable materials and components that can ensure a long service life with high performance and selectivity. The long service life is the key to achieving an economic advantage for the technology of seawater electrolysis and its use in offshore power-to-gas plants, compared to alternative processes. This will be analyzed within the project, in a technical and economic study based on the results obtained. A particularly important aspect is the development of corrosion-resistant components for the entire stack. Extensive investigations are underway with the aim of utilizing new materials in direct seawater electrolysis.

Techno-economic assessments and life-cycle analyses

The efficient and economically viable use of green hydrogen in various sectors requires a comprehensive understanding of all the individual elements of the hydrogen supply chain. Through technical and economic analyses, scientists at the Fraunhofer Institute for Solar Energy Systems develop and evaluate customized solutions for the production of clean hydrogen from renewable energies, its efficient storage and demand-oriented distribution.

The »H_2ProSim« toolbox developed at Fraunhofer ISE is a comprehensive tool for the simulation-based, techno-economic evaluation of hydrogen plants and supply chains using the Matlab/Simulink/Stateflow simulation environment. The toolbox has a modular structure and is continuously being improved and developed further. A high level of accuracy is ensured by comprehensive data validation from research and development projects and research platforms established within Fraunhofer. An integrated cost model enables the calculation of hydrogen production costs.

From feasibility analyses and plant design and optimization through to hydrogen yield forecasts, the »H_2ProSim« toolbox will be used along the entire hydrogen value chain.

An increasingly important topic is life-cycle analysis: the assessment of energy and material flows over the entire life-cycle of products in order to advise companies and public decision-makers. At Fraunhofer ISE, an interdisciplinary team conducts sustainability assessments (in accordance with ISO 14040/44) along the entire hydrogen production chain, from production and transportation through to material or energy recovery in industry and transport.

Design of tomorrow: Development of electrolysis stacks for automated production

At present, PEM electrolysis stacks are mainly assembled by hand with a low degree of automation. The aim of this project is to further develop new stacks to enable high levels of automation and clock frequencies of a few Hertz. The research is being carried out as part of the flagship project H_2Giga, funded by the German Federal Ministry for Education and Research (BMBF). The Fraunhofer institutes IWU, IPT, IPA, ENAS, IMWS and UMSICHT work in H_2Giga alongside 130 other participating institutions. The shared objective is to bring electrolyzers into series production.

Fraunhofer UMSICHT is developing an innovative, gasket-free stack design based on welded cell assemblies. As a »design of tomorrow«, the gasket-free concept will enable highly automated production from semi-finished products. Stack production should essentially be possible at one location in order to avoid long supply chains.

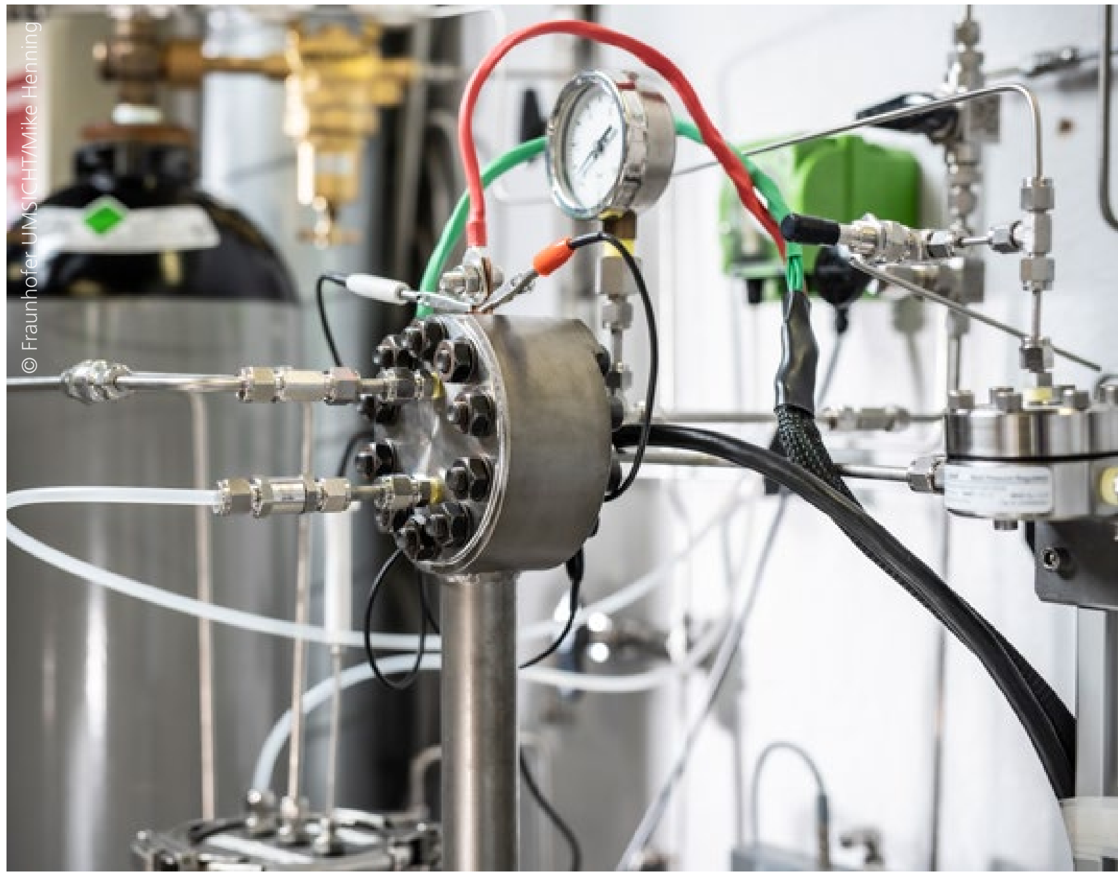
Fraunhofer ISE is supporting industrial partners in the conceptual development of a stack production line, as well as in the actual development of a large-area stack with a conventional design. This includes investigating the optimization potential of all components in the stack, qualifying and quantifying components and component properties, developing corrosion protection coatings for metallic components and integrating this process step into production, defining and validating test protocols in stack production, collaborating in the »design of tomorrow« initiative, and the development of test procedures and systems as well as operating procedures within the production flow of an automated series production of PEM stacks.

Green methanol for shipping, using co-electrolysis

Climate change necessitates a more ambitious reduction in CO_2 emissions. Germany and the EU have set binding targets for the transport sector and quotas for renewable fuels. However, sectors that are difficult to electrify, such as shipping and air transport, lack the technically established means to meet these targets without economic loss. Alternative fuels based on H_2 and CO_2 (e-fuels) offer a scalable alternative, but are not yet ready for large-scale market implementation. The aim of the project consortium[2] is therefore to develop a process chain for the production of electricity-based methanol (e-methanol) from CO_2. The CO_2 is obtained from industrial process emissions that can theoretically be classified as green in accordance with RED II.

In this project, Fraunhofer UMSICHT is developing a prototype for a new, low-temperature co-electrolysis (NTCE) process using a polymer electrolyte membrane. This produces synthesis gas with a variable composition by electrolyzing water and CO_2 at temperatures < 100 °C. In the project, the NTCE, including the electrolysis stack and balance-of-plant, is being developed for integration into the process chain, and constructed in a modular container design. Development focuses on the evaluation of suitable process control and gas purification processes, aiming for resilient operation even when the system is used under flexible loads, without negatively affecting the quality of the synthesis gas produced.

2 Project partners: Fraunhofer Institute for Environmental, Safety and Energy Technology UMSICHT, Fraunhofer Institute for Wind Energy Systems IWES, C1 Green Chemicals AG (project coordination), DBI – Gastechnologisches Institut Freiberg gGmbH, Technische Universität Berlin



Low-temperature CO_2 electrolyzer at Fraunhofer UMSICHT

»VerKEl« – Wear-resistant ceramic electrodes for electrolyzers producing hydrogen

The most advanced technologies available for the decentralized production of hydrogen in small and medium-sized plants are PEM and alkaline electrolysis. PEM electrolysis achieves higher power densities, but relies on rare and expensive catalyst materials. Alkaline electrolysis is better suited for applications on the scale required in the future, as it can be achieved using inexpensive, readily available catalyst materials.

The ISC-HTL project[3] aims to develop low-maintenance or maintenance-free electrolysis cells made of ceramic materials for use in small electrolyzers with a rated output of between 1 kW and 100 kW, that are also characterized by high environmental compatibility and a low price. The use of ceramic materials rather than the conventional nickel-steel sheets will exploit the specific advantages of carbide and nitride ceramics, and thus reduce manufacturing and operating costs.

Novel electrodes will be developed on the basis of conductive ceramics and fiber-reinforced ceramic composites as a replacement for the steel-based electrodes used to date. In particular, the electrical conductivity must be improved and the surface area of the active surfaces maximized to ensure sufficient supply and removal of the electrolyte and the breakdown products.

3 Project partners: Fraunhofer Center for High Temperature Materials and Design, FZ Jülich GmbH, Rauschert GmbH, PS-HyTech GmbH, Ostermeier Hydrogen Solutions GmbH

Methanol and ammonia as essential building blocks for the chemical industry and mobility sector

Synthetic fuels and hydrogen carrier materials

Ammonia and methanol are important basic chemicals that are essential to our economy both now and in the future. The same applies to fuels with a high energy density, which are still required for certain applications such as shipping and aviation.

However, the emissions caused by the traditional production of ammonia or methanol, and the combustion of fuels from fossil resources, contribute significantly to climate change. By using green hydrogen to manufacture these products, and, for example, recovering and utilizing the CO_2, it is possible to significantly reduce CO_2 emissions while simultaneously generating important precursor materials, for example for industry and agriculture.

In addition, solid and liquid hydrogen compounds enable the long-term storage and transportation of hydrogen in material form. Central elements of this hydrogen infrastructure are efficient production and reconversion processes and the development of technologies for the energetic and material use of these derivatives.

Methanol synthesis and reforming

Global production of methanol is currently around 90 million tonnes per year. This production relies chiefly on natural gas. The joint project »Carbon$_2$Chem«, which was coordinated by Fraunhofer UMSICHT, thyssenkrupp and the Max Planck Institute for Chemical Energy Conversion, has shown that production is also possible with CO_2/H_2 or $CO/CO_2/H_2$ mixtures.

Fraunhofer UMSICHT and Fraunhofer ISE, together with the project partners, demonstrated that gas purification and catalytic methanol production can be performed successfully even under volatile operating conditions.

Through several thousand hours of testing in their laboratory and pilot plants over the course of the project, Fraunhofer UMSICHT and ISE investigated the scaling and long-term stability of methanol synthesis, especially under volatile operating conditions, and also with real smelting gases in purified form. The capacities of the systems are between 50 ml/h and 50 l/d. The results were used in process simulations to determine the kinetics for methanol synthesis from such unconventional gases, thus enabling a detailed process design. The experimental investigations and simulations also allow the process to be transferred to other gas sources. It is also possible to simulate the synthesis process in other environments and thus to interconnect the production, chemistry and energy sectors. The co-simulation platform SimuNet, which was further developed in the project, provides support in scale-up and process optimization.

The provision of suitable synthesis gases (from $CO/ CO_2/ H_2$) for methanol synthesis can also be achieved by the electrolysis of CO_2, for example from contaminated process gases. To this end, Fraunhofer UMSICHT is developing processes for the direct co-electrolysis of CO_2 and H_2O at low process temperatures, for coupling with volatile energy sources such as wind or photovoltaics. Research and development tasks include scaling up the technology to the kW scale and integrating it initially into upstream processes such as amine scrubbing to provide CO_2 within the Power-to-X platform project. The CO_2-Syn project is furthermore developing novel electrode and catalyst materials for the direct use of cement plant process gases, and for coupling low-temperature co-electrolysis in a laboratory plant with a downstream alcohol synthesis process.

Within several projects, Fraunhofer IMM is developing methanol reformers for mobile and decentralized stationary applications. These produce hydrogen from methanol via steam reforming with a high level of efficiency, and can be used, for example, to supply hydrogen to fuel cells with a power range of up to several 100 kW. With the appropriate purification steps, both low-temperature and high-temperature PEM fuel cells can be supplied. In the scope of the European project »Gamma«, Fraunhofer IMM is developing a 600 kW methanol reformer and a 400 kilowatt ammonia cracker which will supply fuel cells with hydrogen as a power supply for a large maritime cargo vessel.

Ammonia – synthesis, cracking and utilization

With an annual production of 180 million tonnes, ammonia is one of the most important non-fossil raw materials. Even though there is no carbon in the molecule itself, the hydrogen it contains is mostly generated from natural gas, which is why ammonia synthesis is responsible for around 2 to 3 % of global CO_2 emissions. However, as it is also the most important component in fertilizers, it is essential to meet the needs of the growing global population. To render its production more

Methanol plant for the conversion of carbon-rich gases, developed at Fraunhofer UMSICHT as part of the Carbon2Chem® project

sustainable, the hydrogen used can be replaced by green hydrogen. The nitrogen required for its production can be obtained from the air. Research is also being carried out into new processes that could replace the established Haber-Bosch synthesis, particularly at decentralized locations. In the project »PICASO« (Process Intensification & Advanced Catalysis for an Ammonia-Sustainable Optimized Process), Fraunhofer ISE is working with partners on a novel power-to-ammonia (PtA) process for sustainable ammonia synthesis. The process could reduce CO_2 emissions by 95% compared to the conventional Haber-Bosch process. The main objective of PICASO is to develop an integrated reactor technology and dynamic operating strategies for a flexible ammonia synthesis process based on renewable, green hydrogen, that is also suitable for implementation in remote regions. In a follow-up project, the integrated reactor will be scaled up to demonstration level and tested in a pilot plant.

Ammonia is not only an important raw material, but is also potentially one of the most important carrier molecules for hydrogen. Particularly where large quantities are involved, and where long distances must be traveled by sea, the transportation of hydrogen in the form of ammonia is currently the most economical option. Ammonia offers the promising possibility of transporting energy from regions of the world where it is more cheaply available than in Germany, for example. It therefore plays a central role in the future supply of affordable energy. A crucial step toward successful implementation is the development of processes to efficiently

Methanol mini-plant at Fraunhofer ISE

produce hydrogen from ammonia. Fraunhofer is working on the development of efficient processes and catalysts for ammonia reformation. For example, within the DYNAFLEX® performance center, Fraunhofer UMSICHT has developed a process for the direct electrical heating of the carrier material, which means that the process can be operated without CO_2 emissions and without the combustion of ammonia itself, significantly increasing the efficiency of the entire process chain from hydrogen production through to transportation and use. With the ELIAS (Electrically Heated Catalysts Carriers) platform for endothermic reactions, Fraunhofer ISE has developed a valuable tool for implementing these reactions in very compact reactors. At the same time, Fraunhofer ISE and Fraunhofer UMSICHT are developing new catalyst and carrier materials to reduce the process temperature. The production of pure hydrogen is only one alternative. It can also make sense to crack at least part of the ammonia and then burn it for energy or convert it into CO_2-free electricity and heat within a fuel cell.

In the scope of several projects, Fraunhofer IMM is working on the utilization of ammonia for mobile and stationary applications, on the development of catalysts and reactors for ammonia cracking and its homogeneous combustion as well as on downstream hydrogen purification technologies (projects »Ammonpaktor«, »ShipFC«, »Spaltgas« and others). A plate heat exchanger with coated catalysts is applied for cracking, which allows to achieve a high system efficiency of up to 90 % and a reduction in plant size of 90 %.

Synthetic fuels

While the use of ammonia and methanol as fuels will play an important role in the future, for example in the shipping sector, methanol in particular offers a variety of possibilities for synthesizing other fuels. For example, DME (dimethyl ether) or OME (polyoxymethylene dimethyl ether) can be synthesized from methanol for use in diesel engines. OME can be used within the existing infrastructure, especially as an alternative or additive to diesel fuel, leading to a significant reduction in local emissions (e.g. soot and NOx). In the »NAMOSYN« project, Fraunhofer ISE worked on the development of OME production processes up to a scale of one million tonnes per year. In parallel, the use and compatibility of these OMEs with combustion engines was investigated under laboratory conditions and in practice. This study has been completed and published. The methanol-to-gasoline process can significantly increase energy density and produce a fully compatible gasoline. The so-called methanol-to-jet route also offers promising application possibilities. Methanol forms the basis for kerosene production, which is carried out by synthesizing olefins that are then oligomerized and hydrogenated. In the research project »Sustainable Aviation Fuels based on Advanced Reaction and Process Intensification« (SAFari), a consortium of research institutes and industrial partners, under the project management of Fraunhofer ISE, will work on the sustainable production of kerosene from methanol in a pilot plant, and its testing. The project aims to contribute to the full market approval of this methanol-based process route by the American Society for Testing and Materials (ASTM).

While CO_2 emissions can be largely avoided in crude steel production through the use of green hydrogen, unavoidable process-related emissions, primarily in lime and cement production, can be captured using ceramic membranes and used to produce high-quality products. In the WaTTh project, Fraunhofer IKTS is constructing a fully automated demonstration plant based on its own high-temperature co-electrolysis process, in which liquid hydrocarbons and waxes are produced from CO_2 and water using Fischer-Tropsch synthesis. These materials can be used in the chemical industry and for the production of synthetic fuels such as e-kerosene. The plant capacity is 8 liters of liquid products and waxes per day. Using tools developed for process simulation, the researchers are currently working on scaling up the processes to industrial scale.

Solid hydrogen carriers and POWERPASTE

In contrast to compressed gas or liquid hydrogen storage systems, the use of metal hydrides as solid hydrogen carriers (SHCs) is an economically promising option for safe storage of hydrogen with a very high purity (7.0) at low operating pressures (2 to 40 bar), in a confined space (up to 0.15 kg H_2/dm^3) and without evaporation losses. In SHCs, hydrogen is chemically bound to a solid carrier material, so that if the storage tank leaks, the bound hydrogen does not escape abruptly, but rather is released very slowly. SHC storage systems are therefore considered extremely safe. Hydrides have the potential for further application fields in hydrogen technology, such as the thermo-chemical compression of hydrogen

»POWERPASTE is a suspension consisting of a solid hydrogen carrier material (MgH_2), which can be stored unpressurized at room temperature under exclusion of moisture. To release the hydrogen, all that is needed is the addition of water.«

Dr.-Ing. Felix Heubner
Head of Hydrogen Technology Department,
Fraunhofer Institute for Manufacturing Technology
and Advanced Materials IFAM

and the purification of hydrogen-containing gas mixtures. In addition to reversible thermolysis, a hydrolysis reaction, i.e. decomposition of the hydride through a reaction with water, can be carried out with metal hydrides. »POWERPASTE« is a suspension consisting of magnesium hydride, a metal salt as a catalyst and an ester for fluidization. Magnesium hydride reacts exothermically with water, releasing hydrogen. The by-product is non-toxic magnesium hydroxide (see equation 1). A notable advantage of the technical application is the co-utilization of water for hydrogen production, and consequently the doubling of the amount of hydrogen produced per equivalent of metal hydride.

Equation 1: $MgH_2 + 2\ H_2O \rightarrow 2\ H_2 + Mg\ (OH)_2$

POWERPASTE can be stored unpressurized and at room temperature under exclusion of moisture. To release the hydrogen, hydrogen generators are required to combine the paste with the water. Together with partners from industry and research, Fraunhofer IFAM is developing several demonstrators and prototypes for hydrogen production for various applications (stationary, portable, mobile) in the power classes of 500 to 1,000 W. The hydrogen generators are coupled with PEM fuel cells of the corresponding power class. Current developments concern weight-related optimizations for mobile applications in order to achieve the highest possible specific energy at system level. Several technological milestones were achieved in 2022. For example, a self-sufficient, POWERPASTE-based emergency power system was presented at the Hannover Messe together with Grünland Innovations GmbH. In addition to stationary applications, mobile applications are also being developed and demonstrated in publicly funded projects (»POWERPASTE – Mobile hydrogen supply in the next generation« (funded by the German Federal Ministry for Economic Affairs and Climate Action, BMWK). Increasing the hydrolysis performance is another important focus of current projects, in order to open up new application fields. The upscaling of POWERPASTE production is ongoing at the Fraunhofer Project Center for Energy Storage and Systems ZESS in Braunschweig. The aim was to produce up to 5 tonnes of POWERPASTE at ZESS in 2023, for use in pilot applications.

Power-to-X Potential Evaluation

Power-to-X (PtX) refers to processes where electricity is converted into storable energy carriers. Synthetic fuels and energy carriers produced with green hydrogen hold great promise: they aim to replace fossil fuels in industries, transportation, and other sectors. Like many other countries, Germany places a high value on these PtX energy carriers within its climate policy framework.

Many regions worldwide offer favorable conditions for producing green hydrogen and renewable synthetic fuels and energy carriers. The specific potentials of these regions can be technically and economically calculated and evaluated.

Researcher from the Fraunhofer Institutes can analyze and quantify which regions are potential suitable for hydrogen and Power-to-X production, along with the transportation of these energy carriers to Germany. The Fraunhofer Institute for Energy Economics and Energy System Technology (IEE) developed the Global PtX Potential Atlas. This user-friendly tool provides insights into the Power-to-X potentials of coastal and inland locations globally. The analyses utilize high-resolution spatial data, long-term weather data, and time-series-based, cost-optimized plant and expansion plans for PtX technologies.

The assessment of technical and economic PtX potentials is based on extensive analyses, including land availability and weather conditions. Parameters such as peripheral, storage, and transport costs were also considered, along with variations in system design. Another crucial factor is the socio-economic conditions of the individual regions, evaluated using seventy indicators, such as those from the World Bank.

With the Atlas, interested parties can access information on the suitable areas for PtX, the achievable full-load hours and possible production quantities, the specific production costs for various PtX energy carriers, and the costs for their transport to Europe.

Hydrogen distribution networks, pipelines and innovative storage solutions

Hydrogen infrastructures

The transformation of the energy system, with the aim of achieving greenhouse gas neutrality by 2045, represents a significant challenge. Action is urgently needed in all demand sectors. The increasing share of renewable energies in electricity and heat generation means that suitable storage and sector coupling options are required for an efficient energy system design.

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The National Hydrogen Strategy of the German federal government focuses on green hydrogen as a key building block to ensure that Germany's energy requirements are met in every sector despite overall climate-neutrality. The strategy shows that the use of green hydrogen, alongside energy efficiency and the direct use of renewables, plays a central role in the transformation of industry, the transport sector and the energy industry toward sustainability and climate neutrality. As is clearly explained in the National Hydrogen Strategy, the highly ambitious targets for all sectors, to be achieved by 2030 and 2045, cannot be met unless hydrogen and its derivatives are introduced into the system in significant quantities. This means that by 2030, from domestic production alone around 30 TWh or approx. 1 million tonnes of hydrogen per year must be managed and distributed. This figure will be considerably higher after the complete defossilization of the national energy system. An appropriate transportation and distribution network for this volume of hydrogen needs to be in place by 2030.

TransHyDE – Storage and transportation solutions for green hydrogen

The hydrogen flagship project TransHyDE, with its five research and four implementation networks, is working on the optimal design for hydrogen infrastructures to create the greatest possible efficiency and resilience. The technological focus of TransHyDE is the research and development of transport and storage options for gaseous and liquid hydrogen, ammonia and liquid organic hydrogen carriers (LOHCs). The results obtained will be integrated directly into roadmapping processes for the development of a hydrogen infrastructure by 2045, and for the closing of standardization, certification and regulatory gaps. The flagship project is coordinated by Fraunhofer IEG, among others.

Within the subproject on system analysis, the Fraunhofer institutes IEE, IEG, IFF, IKTS, ISE, ISI and SCAI are working to classify the various transport technology options within the overall system. This analysis takes account of the spatial and temporal development of supply, demand and connecting transport and logistics infrastructures for green H_2 at national and EU level, as well as the resulting interactions with electricity infrastructures and other energy sources.

In the subproject on safe infrastructure, the Fraunhofer institutes IEG, IPM and IWM are developing concepts and methods for evaluating materials and components that come into contact with H_2 gas, and their suitability for accident-proof and long-term use in a real H_2 transport infrastructure. They are developing gas sensors and sensor systems to ensure the safety of H_2 infrastructures and components and to test the sensor technology under near-real conditions on the test rig.

Fraunhofer ISE is researching an application-oriented, industrially feasible, safe and cost-effective technology for reforming ammonia, within the AmmoRef consortium.

Research into hydrogen pipeline coatings, fouling protection and optimized coating and adhesive systems for LOHC storage systems is the focus of Fraunhofer IFAM 's work in the TransHyDE Helgoland network.

Storage of hydrogen as a flexible option

Hydrogen storage is a decisive prerequisite for implementing the energy transition. This is because hydrogen can only be a flexible option if the time lapse between hydrogen demand and production can be compensated. Potential options for storing hydrogen include the geological subsurface as well as physical and chemical storage technologies. The hydrocarbon industry in Germany and around the world has been using the subsurface for decades to store large quantities of natural gas in the pores within rocks (so-called »pore storage«) or in salt caverns. A total of around 24 billion cubic meters of natural gas are stored underground in Germany. This means that Germany has the fourth largest storage capacity in the world after the United States, Russia and Ukraine.

In the »H_2 research cavern« project, Fraunhofer IMWS is developing an H_2 storage research platform for the industrial-scale underground gas storage of green hydrogen, in salt caverns at the Bad Lauchstädt site. The project is part of the HYPOS research initiative.

In the H_2-Sponge project (»H_2 storage potential of geological rock formations«), the prerequisites are being created

Porous rock sample placed in Fraunhofer IEG's H_2 autoclave for tests under pressures of up to 50 MPa and temperatures of up to 200°C, as part of an experimental investigation into rock-fluid interaction within potential storage horizons for hydrogen.

for the safe underground storage of hydrogen in the pore space of rocks. Key issues are the geological requirements for storage, the prioritization of sites and the experimental investigation of rocks in contact with hydrogen. To this end, two innovative hydrogen test rigs are being developed to simulate the underground storage process. On the one hand, the long-term integrity of rocks in contact with hydrogen will be investigated in a mobile geochemical laboratory. On the other hand, experiments on transient storage and transport processes are carried out in a hydrogen permeameter and a hydrogen porosimeter. The interaction of these test rigs enables a meaningful evaluation of potential hydrogen storage rocks and the leak-tightness of storage facilities. Other aspects under investigation are the strategic planning of monitoring concepts, for the seamless monitoring of all relevant processes, and the development of analytical methods to assess the integrity of hydrogen storage wells. The aim is to develop proposals for handling hydrogen in geological underground storage facilities, as well as suitable infrastructure and safety concepts.

KuWaTa – Spherical hydrogen tanks

In the KuWaTa project at Fraunhofer HTL, spherical hydrogen tanks were developed from carbon-fiber-reinforced plastics (CFRPs) using isotensoid winding technology. The high-pressure storage tanks for gaseous hydrogen, with a diameter of 1.25m, are designed to store 40 kg of hydrogen at 700 bar. The spherical shape offers clear advantages

»The development of a hydrogen economy to transform the basic materials industry, heavy goods transport and the conversion sector can only be achieved with efficient hydrogen infrastructures. To this end, we are elaborating methods for the integrated planning and operation of hydrogen, electricity and natural gas grids as part of the system development strategy. All the necessary technical components are developed and tested in the institutes and research networks with a view to upscaling them to marketable solutions.«

Prof. Dr. Mario Ragwitz
Institute Director
Fraunhofer IEG

over conventional cylindrical tanks. Due to the uniform stress distribution on the spherical surface, the wall thicknesses can be significantly reduced compared to conventional cylinder geometries. Larger quantities of hydrogen can therefore be stored with the same tank weight. The use of special, diffusion-inhibiting matrices and liners further reduces the mass and achieves additional weight savings. The ratio of tank weight to stored hydrogen is currently 15:1 in the automotive sector. With the spherical tank, a weight ratio of 5:1 is the target.

The use of isotensoid fiber placement ensures that all fibers providing the reinforcement are placed almost equatorially in the direction of the circumference. As a result, the compressive load is optimally transferred to the fibers, enabling maximum exploitation of the high fiber strengths. The KuWaTa project developed a special winding algorithm for a 5-axis robot system. The uniform load on the tank surface was successfully demonstrated in burst tests.

Production of an isotensoid spherical tank in the KuWaTa project

Support for transformation processes

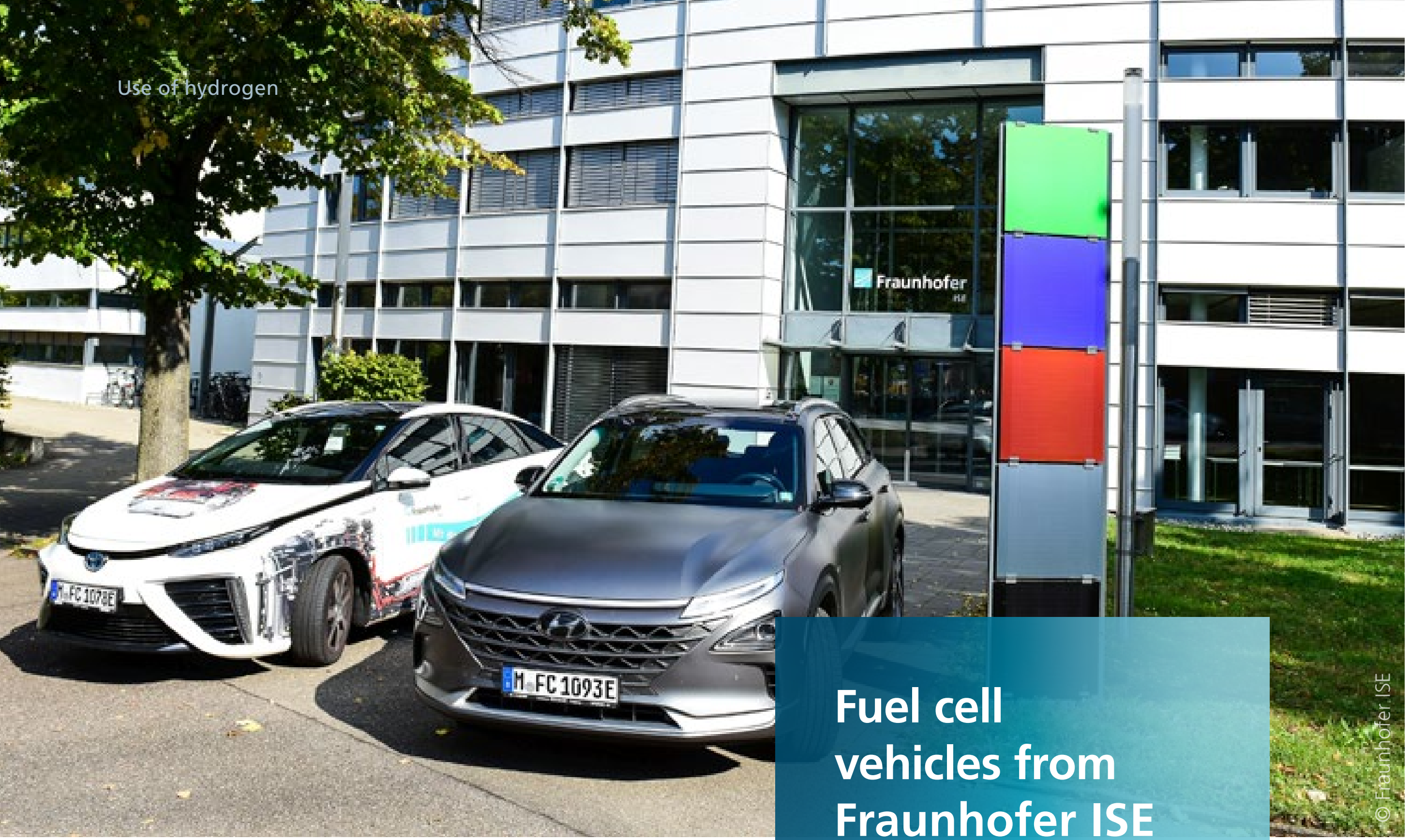
What will the transformation process toward a largely greenhouse-gas-neutral energy system in Germany look like in practical terms? On behalf of the Federal Ministry for Economic Affairs and Climate Action BMWK, experts at Fraunhofer ISI are modeling scenarios for a cost-optimized, safe and secure energy system, thus providing important guidance for discussions on the future path of the energy transition. Using the FORECAST demand model, they also investigated the demand side of the European energy system for the grid operators.

Developers, companies and investors also need more precise information on economic viability before they invest in hydrogen technology. Energy system modeling by Fraunhofer IEG and Fraunhofer ISE can provide reliable information – from hydrogen production costs, efficiency and hydrogen yield through to feasibility studies and yield assessments.

The success of innovative energy technologies depends, among other things, on social, political and economic support. Fraunhofer ISI is investigating the social acceptance of hydrogen technologies in the EU project HYACINTH. The H_2-Chancendialog project at Fraunhofer IAO's Center for Responsible Research and Innovation aims to identify the innovation potential of social perspectives, in order to develop new hydrogen solutions collaboratively, with the involvement of different stakeholders.

From import to regional distribution

In order to meet its demand, Germany will need to import a large proportion of green hydrogen, including synthesis products, because renewable energy sources are only available to a limited extent in Germany. Under the leadership of Fraunhofer ISI, Fraunhofer IEG and ISE are developing a global hydrogen potential atlas as part of the HYPAT project. To this end, they are creating a comprehensive list of possible export and import countries, the associated hydrogen export costs and, for the first time, deriving the prices at which hydrogen could be traded globally. Emphasis is placed on export partnerships between equals – for secure, economical and ecologically sustainable production and supply. In addition to a detailed survey of the global techno-economic potential and analysis of the hydrogen chains, the study includes the sustainable coverage of the partner countries' own energy demand, the achievement of their climate targets and compliance with specific sustainability criteria for the hydrogen economy. Besides identifying suitable source countries and import routes for the international supply of hydrogen, the development of the national hydrogen infrastructure is of key importance in bringing together regional producers and consumers of hydrogen. Together with Fraunhofer ISI, Fraunhofer IEG was commissioned by the Brandenburg Ministry for Economic Affairs, Labor and Energy (MWAE) to develop the foundations for a hydrogen transport network in the state of Brandenburg. The aim of the feasibility study was to develop an overarching hydrogen network that connects regional hydrogen producers, storage facilities and end users, and that is integrated into a nationwide hydrogen infrastructure. Where possible, the focus was on retrofitting existing natural gas pipelines. The study is making a significant contribution to the practical implementation of the hydrogen strategy of the state of Brandenburg.



Fuel cell vehicles from Fraunhofer ISE

Use of hydrogen technologies in industry, electricity and heat generation, and mobility

The climate targets for Germany, and for Europe as a whole, cannot be achieved without hydrogen technologies. This is particularly true for industry. Companies are therefore making considerable efforts to convert established production processes to hydrogen, and to work toward a hydrogen economy. The focus is on steel, lime and cement production as well as green chemistry. Power generation to supplement volatile, renewable energies such as solar and wind is also attracting increasing interest. In the generation of high-temperature heat, hydrogen technologies are considered particularly promising. Last but not least, drive systems based on fuel cells or renewable fuels are relevant for climate-neutral mobility.

Use of hydrogen

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The yield of renewable power plants in globally favorable locations, which is two to three times higher than the corresponding yield in Germany, often compensates for the lower efficiency of the material conversion in hydrogen technologies compared to end-to-end electrical process chains. In addition, hydrogen technologies enable energy storage and thus ensure the availability of energy regardless of where and when electricity is generated. Finally, material energy carriers enable global energy transportation and trade. Our cradle-to-grave life-cycle analyses show that all hydrogen technologies meet the requirements for sustainability with a comparable ecological footprint to fully electrified processes. The prerequisite is that green technologies are used to generate electricity or fuel, and that the advantages of a global supply chain are exploited. Our techno-economic assessments also show that the economic efficiency of hydrogen technologies is analogous to that of electrical processes. The context here is that hydrogen technologies can be used to develop the world's most economical locations for renewable energies. Fraunhofer offers comprehensive analyses of global production and supply chains as well as technology, economic and ecological evaluations.

Climate-neutral industrial processes

The majority of greenhouse gas emissions from industrial processes are generated in the raw materials industry. This includes metal production, the manufacture of mineral products and the production of basic chemicals. The strategy for achieving climate-neutral production differs depending on the industry.

In the steel industry, the use of hydrogen in a direct reduction process can decrease CO_2 emissions in crude steel production by up to 95% compared to the conventional blast furnace method. This has already been demonstrated by Fraunhofer IKTS as part of the MACOR project (funded by the German Federal Ministry for Education and Research (BMBF) in cooperation with the ISI and UMSICHT institutes and Salzgitter AG.

This emission reduction is possible if renewable energies are used to provide both the required hydrogen (via electrolysis)

Test rigs to characterize fuel cell short stacks for mobility applications, at Fraunhofer ISE.

Test rigs for the electrochemical characterization of membrane electrode units for PEM fuel cells at Fraunhofer ISE.

and the electrical energy for the electric arc furnaces. The high-temperature electrolysis process is particularly promising for hydrogen production. Demonstrators for this technology are already in use on a scale of 100 kilowatts. Transfer to the gigawatt scale is now planned.

In the BMBF-funded follow-up project BeWiSer, the above-mentioned Fraunhofer institutes are working with Salzgitter AG on the question of how hydrogen-based crude steel production can be successfully implemented in the ongoing operation of the steelworks. Here, both the experimental principles of iron ore reduction and the material and energy balances at the steelworks are considered holistically, as well as the question of acceptance of structural change at the site.

Residual emissions in steel production can be avoided through the use of carbon dioxide capture and utilization (CCU) processes, as can the emission of process-related CO_2 in lime and cement production and thermal waste treatment. The CO_2 is captured using processes such as amine scrubbing or ceramic membranes. Together with »green« hydrogen, a synthesis gas is produced that can be used in the chemical industry to produce key basic chemicals such as methanol. The implementation of this process chain is being demonstrated by Fraunhofer UMSICHT and its project partners in the BMBF-funded project Carbon2Chem®.

In the WaTTh project, Fraunhofer IKTS is constructing a fully automated demonstration plant based on its own high-temperature co-electrolysis process, in which liquid hydrocarbons and waxes are produced from CO_2 and water using Fischer-Tropsch synthesis. These materials can be used in the chemical industry and in the production of synthetic fuels such as e-kerosene. The plant capacity is 8 liters of liquid products and waxes per day. Using tools developed for process simulation, the researchers are currently working to scale up the processes to industrial scale.

Emission-free power and heat generation

Due to the volatility of sun and wind, dynamically controllable power plants will be needed in the future: hydrogen-gas-fired power plants are ideal for large outputs in the range of megawatts to gigawatts. Hydrogen-compatible turbines are already being installed today.

Beside technology and market studies, Fraunhofer offers material developments, testing and production technologies.

»Fuel cell electric drive systems can supplement battery electric systems, particularly in heavy goods vehicles, buses, trains, ships and airplanes. Our techno-economic and ecological life-cycle analyses document the significant potential of hydrogen technologies.«

Dipl.-Ing. Ulf Groos
Head of Fuel Cell Department, Fraunhofer ISE

For lower outputs, combined heat and power plants based on fuel cells or hydrogen combustion engines are a promising option, as high overall efficiencies for electricity and heat can be achieved.

In this field, Fraunhofer can provide support with system simulations and tests from the material through to the system level.

In the field of industrial process heat supply, the use of hydrogen can be an option especially for higher temperature requirements and for processes that are difficult to electrify directly. Fraunhofer UMSICHT has carried out bottom-up analyses to compare electrification and the use of hydrogen for industrial process heat in various sectors, for example in the short study »Decarbonization of industrial process heat in energy-intensive SMEs« for the Gelsenkirchen climate port.

Sustainable traffic and transport

Future mobility must be made possible without fossil fuels. Hydrogen technologies can complement battery-electric drive concepts in many areas: fuel cells supply the electricity for electric powertrains, while renewable fuels minimize vehicle emissions from combustion engines. One thing all hydrogen technologies have in common is high energy densities in the tanks, enabling long ranges with the short refueling times we are accustomed to today. In addition, the vehicles are refueled at standard public filling stations, regardless of where and when the electricity is generated.

The Fraunhofer institutes offer comprehensive R&D services for material, component and system development, experimental characterization, modeling and simulation, techno-economic studies for fuel cells, electric drive systems and combustion engines, e-fuel production, filling stations and vehicles.

Fraunhofer UMSICHT develops film-based composite bipolar plates for fuel cells as well as gasket-free cell and stack concepts. In the projects »BiFoilStack – Development of stack designs for NT-PEM fuel cells with novel compound bipolar films« and »H2GO – national fuel cell production action plan«, Fraunhofer UMSICHT is researching this new and potentially disruptive technology along the entire production chain. The focus is on the development of semi-finished products and system components as well as innovative, weldable cell and stack concepts.

Pilot plant at the Leuna site

Testing electrolyzers on an industrial scale

Fraunhofer IWES is currently operating or building three hydrogen laboratories, which for the first time offer a digitally networked infrastructure, including test and qualification capacities for the necessary electrolysis and fuel cell systems with an output of over 25 megawatts (MW). These labs fulfill the same basic demands, but also offer specialized services. This creates a globally unique range of pilot plants along the entire value chain of the hydrogen economy.

Certification and standardization

Numerous national and international standardization activities (e.g. ISO 22734, VDI 4635) are already underway, involving Fraunhofer institutes with expertise in the standardization of hydrogen technologies and, in particular, electrolyzers. A prerequisite for the accelerated and sustainable expansion of electrolyzer capacities for (green) hydrogen production is a broad trust in this technology and its reliability by market players on the application side (project developers, investors and end-users). This can be achieved through widely recognized or standardized test protocols and procedures to evaluate the performance and durability of electrolyzers under representative conditions for current and future applications.

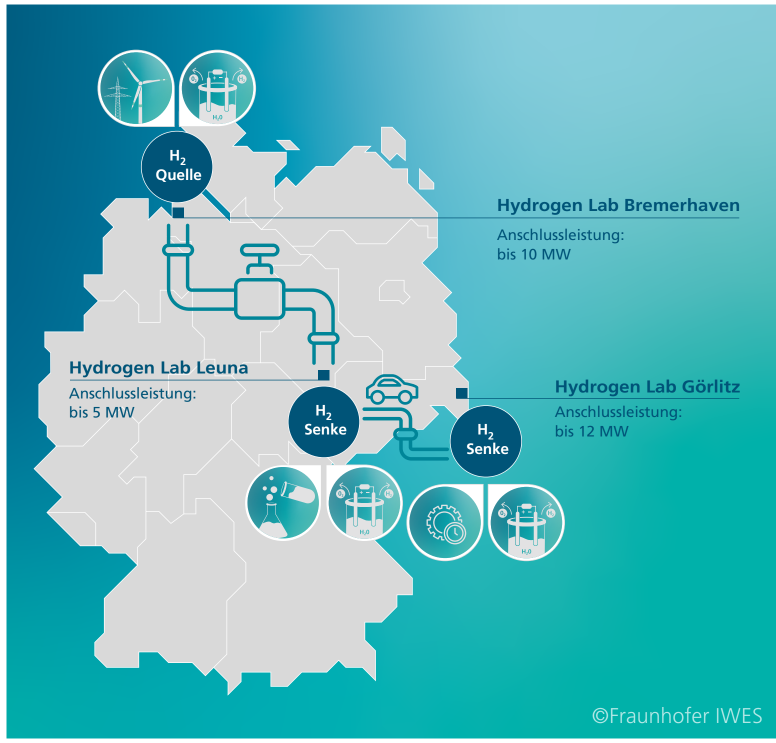
Testing electrolyzers on an industrial scale

Development of standardized testing processes and validation of product performance data

The integrated system test environments in the Hydrogen Lab Bremerhaven, Hydrogen Lab Leuna and Hydrogen Lab Görlitz, in which performance and stress tests for electrolyzers can be carried out under realistic, dynamic operating conditions, enable both the development of standardized test processes and the validation of product performance data based on these standards. System tests are supplemented by tests at cell, (short) stack and subsystem level, to support both electrolyzer OEMs and the supplier industry. Fraunhofer IWES combines unique knowledge of the characteristics of energy generation from wind turbines with insights into the demands that will be placed on large-scale electrolyzers in the future. While a path toward standardization is slowly emerging, no consistent process has yet been established for system certification of hydrogen technologies at the product level. Fraunhofer IWES is drawing on its many years of proven experience in the field of wind turbine technology as a form of blueprint for hydrogen technologies. Of course, a system certification (e.g. for electrolyzers) will ideally reference existing and established technology and product standards in its defined process descriptions.

Hydrogen Lab Leuna – Direct connection to the chemical industry

In the Hydrogen Lab Leuna (HLL), every type of industrial-scale electrolyzer – PEM, AEL, AEM or SOEC – can be tested in continuous operation 24/7. In these tests, dynamic load profiles can be simulated for operation with electricity from photovoltaic and wind energy systems, in order to investigate performance, economic efficiency and long-term behavior in real operation and in accelerated aging tests. This data will provide the basis for future certification. The HLL is one of the few existing large test facilities in which electrolysis systems in the megawatt range can be operated in test mode for periods of weeks and months. A unique feature is that the hydrogen produced is fed into the Leuna Chemical Park's hydrogen pipeline. The hydrogen can also be used in collaboration with Fraunhofer CBP and other research partners on site for the sustainable synthesis of chemical precursors and fuels. The integration of the HLL into the Leuna chemical site and its network means that innovative sector coupling processes can be demonstrated on a pilot scale directly at the chemical industrial site, and tested under realistic conditions. The laboratory is funded by the state of Saxony-Anhalt and by the EU.



The Hydrogen Lab Leuna is already in operation.

Hydrogen Lab Görlitz – Test infrastructure along the entire H_2 value chain

Fraunhofer IWES and IWU are jointly constructing the Hydrogen Lab Görlitz (HLG) in order to develop holistic solutions for a decarbonized economy. The HLG is funded by the State of Saxony and the Federal Ministry for Economic Affairs and Climate Action (BMWK).

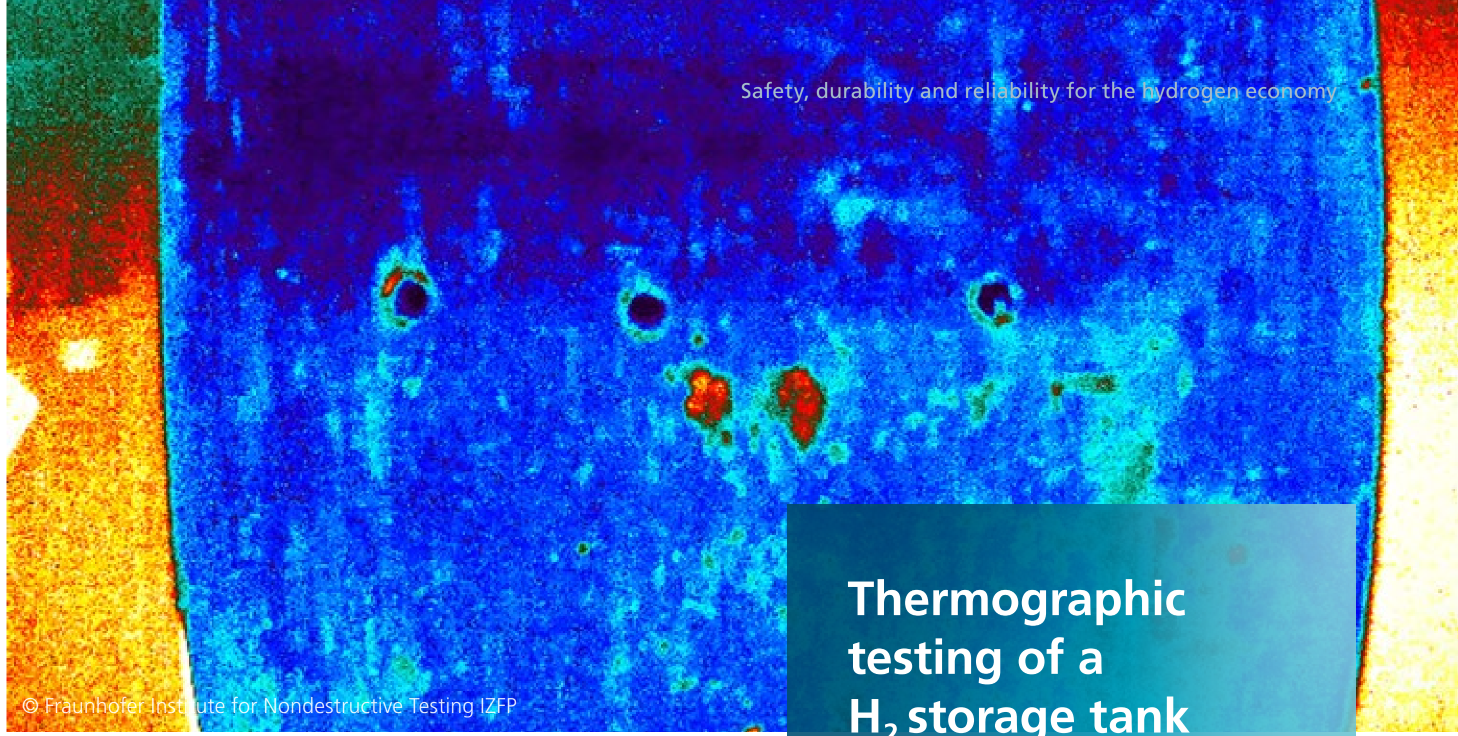
> **»Our contribution to establishing a sustainable hydrogen economy: trust and acceptance through safety and efficiency, thanks to a long service life and high reliability.«**
>
> **Prof. Dr.-Ing. Jan Wenske**
> **Deputy Institute Director and Technical Director**
> **Fraunhofer IWES**

In close cooperation with Siemens Energy, the HLG is creating a research and development platform for the power-to-H_2-to-power value chain, which is crucial for the industrial sector. Beside testing hydrogen components and developing large-scale production technologies for electrolyzers, research activities focus on the digitalization of hydrogen technology.

Hydrogen Lab Bremerhaven – Meeting the challenges of offshore production

The increasing decentralization of electricity generation through the integration of renewable energy sources places high demands on electricity grids, which until now were designed for the parallel operation of centralized, large-scale generators. Research at the Hydrogen Lab Bremerhaven (HLB) provides insights into how electrolyzers and their power electronics must be designed in order to stabilize future electricity grids, ensuring their reliability and flexibility. Work at the HLB focuses in particular on the interaction between wind turbines and various electrolyzer technologies on a real-life scale, the deep cross-sectoral integration of electrolysis (e.g. through the use of by-products), and the use of reconversion technologies for stand-alone grids and grid-supporting applications. The HLB, which is funded by the state of Bremen and the EU, is scheduled for completion in 2023 and will offer up to twelve test areas with a total output of up to 10 MW. The operation of the three hydrogen laboratories under the direction of Fraunhofer IWES means that the reservation and utilization of the test capacities can be centrally managed, enabling supra-regional, tailor-made offers for customers within optimized timeframes. Synergies with existing infrastructure and established partner structures (IMWS, IWU and IGB) are being developed. Experience in the long-term operation of electrolyzers is currently lacking anywhere, but the hydrogen labs can deliver the equivalent data within just a few months. This allows manufacturers to plan and accelerate the market launch of new system and component designs. Fraunhofer IWES thus offers unique opportunities for testing prototypes and further developing customer products, particularly in the megawatt range. This involves a team of highly qualified specialists, professional project management and the highest safety and security standards – both physically and with regard to intellectual property.

Construction of the Hydrogen Lab Bremerhaven in the immediate vicinity of the 8 MW offshore turbine.



Thermographic testing of a H_2 storage tank

Safety, durability and reliability for the hydrogen economy

Hydrogen is a promising energy source, and safety is the top priority when using it. Comprehensive procedures to qualify materials and components for hydrogen applications are therefore essential. These procedures must cover applications ranging from electrolysis and storage through to the mobility, heat/energy and industrial sectors. The question of service life is closely linked to that of safety. The Fraunhofer institutes contribute their expertise to a wide range of industrial and publicly funded projects addressing both these aspects, and also provide the corresponding testing facilities.

The safe and sure path to more hydrogen!

The transformation to a climate-neutral society requires broad acceptance of the hydrogen economy. In particular, this means a high level of trust in the operational safety of hydrogen systems. Safety and accident risks must be excluded or minimized as far as possible. The operators of plants for the production, storage, distribution and use of hydrogen must ensure a long service life and high reliability of the plants. This can be achieved through adapted service life models, the selection of qualified materials and the control and systematic monitoring of relevant status and process data. The good reputation of innovative hydrogen technology »made in Germany« is therefore not based solely on the technology itself: safety, durability and reliability are also required at the highest level in order to be considered an international benchmark. This guiding principle applies to all technical systems that must provide

Particulate sensors make hydrogen visible. Hydrogen leaks, for example, can be detected immediately.

added value for the customer and end-user while at the same time offering a long service life and high reliability. Further important factors are lightweight construction and high material efficiency without cost increases for the users. Technologies developed specifically for the hydrogen economy as part of the energy transition also need to be analyzed in terms of their availability, safety, reliability and service life. Besides electrolysis systems and fuel cells for mobile applications, this includes the analysis of systems and infrastructure components, for example when hydrogen is distributed via the former natural gas network. The planned use of the energy carrier in the processing industry – which, like the steel industry, has had no previous contact with this reducing agent – is also relevant. Developers, manufacturers and users are faced with numerous questions regarding the appropriate service life model, the right choice of materials, system monitoring and safety assessment. However, there is also a need for methods to assess system reliability and resilience.

If the weak points are not identified, the safety, functionality, reliability and service life of components and systems will continually be compromised by hydrogen-specific material damage resulting from mechanical, thermal, chemical and electromagnetic loads during operation. This can be countered by adapted service life models, the selection of materials with high H_2 corrosion resistance and systematic and planned monitoring.

Hydrogen all the way – but safely, reliably and for the long-term!

Nine Fraunhofer institutes from the Fraunhofer Hydrogen Network, with expertise in system analysis, safety, service life and reliability, are working intensively together on precisely these issues. They have pooled their expertise in a working group so that they can reach out to specific customers and address the challenges they face. In the context of the hydrogen economy, the members work on issues relating to hydrogen-specific service life models, material damage and damage detection, the monitoring of hydrogen-carrying components, the recording of status and process data, the modeling and simulation of safety and reliability scenarios and their experimental evaluation. The working group deliberately focuses on the safety, design and optimization of systems, processes and components such as H_2 electrolyzers, infrastructure components, fuel cells and storage systems. This work is supplemented by research and development activities based in the hydrogen test fields, which arise from the results of the investigations. Methods are being developed that enable effective, holistic system evaluation and monitoring, examining system behavior down to the material level using digital sensors and sensor materials. These methods ensure a continued high availability of systems, processes and mobility applications through the early detection and assessment of damage processes relevant to safety and service life, which in turn

»Safety, durability and reliability are key to the success of a hydrogen economy. These three building blocks must be given equal consideration with cost reduction, raw material availability and resilience for the transformation to succeed.«

Prof. Dr. Karsten Pinkwart
Deputy Director of Applied Electrochemistry
Fraunhofer Institute for Chemical Technology ICT

enables timely maintenance work. It is particularly important to ensure that the methods and concepts developed by the research institutes are both safe and relevant for the application. The working group also participates in scientific and standardization committees to develop standards, guidelines and implementation recommendations relating to hydrogen.

Safety through visibility – making hydrogen visible

Hydrogen is already an important source of energy, and its significance will continue to grow in the coming years in both the industrial and the private sectors. Hydrogen cannot be seen, smelled or directly perceived with other human senses. Measures must therefore be taken to make hydrogen perceptible – quickly, cost-effectively, safely and comprehensibly. This is the only way ensure the safe use of hydrogen in households and industry. Fraunhofer ISC, together with a university partner[1] has developed a concept for the simple detection of hydrogen using a novel, particle-based powder indicator. Like a traffic light system, this indicator can show the presence of hydrogen via a two-stage color change. The key feature of this flexible powder indicator is the structure of the individual particles. These are so-called supraparticles, which are produced by spray drying and consist of thousands of smaller nanoparticles. Various components (carrier particles, catalyst particles, dye) are used in these hydrogen indicator supraparticles, all of which have a specific function in the detection of hydrogen gas. The supraparticular structure allows a microenvironment to be created in the smallest of spaces, in which a sensitive dye can change its molecular structure and thus its color. If the superparticle comes into contact with hydrogen, the gas can penetrate its pore system and dissociate on the reactive surfaces of its catalyst particles. The activated hydrogen atoms then react with the dye molecules and first reduce them irreversibly, resulting in an initial color change from violet to pink. On further exposure to hydrogen, the dye molecule is further reduced and a second color change from pink to colorless occurs. As soon as the hydrogen is removed, the dye molecule releases the bound hydrogen and returns to the pink-colored state. This creates a traffic light system that indicates the presence of hydrogen in the ambient air by means of a simple color change. The chief advantage of this newly developed supraparticulate powder is its wide range of potential applications and its simple and cost-effective production on a large scale. Defective sealing in pipes can be detected when the powder is integrated into gloves or leak detection sprays. Incorporated into the coating for example of hydrogen filling stations, cars or heating systems, the color change can quickly and easily draw attention to a hazard. No electronic devices or specialist personnel are required to detect the results, as the color change can be seen by anyone with the naked eye.

1 Friedrich-Alexander-Universität Erlangen-Nürnberg)

Digital platforms create networks

The digital world of hydrogen

Hydrogen is considered a promising energy carrier that can have a major impact on the transition to a climate-friendly energy supply, thus contributing to the decarbonization of industry and the transport sector. Digital solutions play a decisive role in making the production, distribution and use of hydrogen safer, more efficient, and more cost-effective. Digital solutions can facilitate the integration of renewable energy sources into hydrogen production, and enable improved interconnectivity between production and consumption. In this context, digital solutions are becoming increasingly important in hydrogen production and will play an important future role in the energy transition. In addition, digital options are an important growth driver that can pave the way for new business models. Since 2021, Fraunhofer IMW has been working together with various research partners to digitally support the market development of the hydrogen sector in Germany. The group evaluates the obstacles and challenges faced by the digital H_2 ramp-up and discusses the measures needed.

Discovery Day and workshops

The Discovery Days are aimed at companies that are (or would like to be) intensively involved with digital technologies and their role in establishing a sustainable hydrogen economy. The workshops cover various aspects, including the digitalization of hydrogen production plants, the integration of hydrogen into existing energy infrastructures, the role of digital technologies in the optimization of hydrogen networks and the development of digital business models in the hydrogen sector.

The aim of the Discovery Days is to convey an understanding of the key role played by digital solutions in implementing a sustainable hydrogen economy, and to situate these solutions within an individual hydrogen strategy, including initial ideas for implementation. So far, three such Discovery Days have been held in various formats.

HyTrust – Data exchange in the hydrogen economy

The HyTrust research project focuses on the issue of data exchange in the emerging hydrogen economy. This sector plays a crucial role in tackling socially relevant problems such as the energy transition. The development of digital solutions and the promotion of innovation and competition depend heavily on the ability to share data effectively. Despite the increasing availability of data, cross-organizational data exchange has so far been implemented only sparingly. This is due to various obstacles, including lack of trust, fear of losing know-how, fear of competitive disadvantages, and the lack of a secure organizational framework and clear business models.

In this context, data trust models (DTMs) are a promising approach for promoting cross-organizational data exchange and commercial date use. A key objective is to strengthen individual control over data traffic. Nevertheless, the introduction of data trust models is associated with numerous questions that need to be examined in various subject areas.

The HyTrust project, which is being carried out by Fraunhofer IEE in Kassel and Fraunhofer IMW in Leipzig, aims to research the implementation of data trust systems in the emerging hydrogen economy for different application contexts. The project focuses on two use cases: a hydrogen industrial park and the corresponding hydrogen networks, and capacity marketing.

The HyTrust project is therefore an important step toward tackling the challenges of data exchange and commercial data use in the hydrogen economy, thus contributing to the successful implementation of the energy transition.

»The dual transformation of decarbonization and digitalization means that we need to expand not only the physical infrastructure but also the digital world of hydrogen in order to ramp up the hydrogen economy.«

Prof. Dr. Heiko Gebauer
Senior Expert, Data and Platform-Based Value Creation Unit
Fraunhofer Center for International Management and Knowledge Economy IMW

Cluster of Excellence »Integrated Energy Systems« (CINES)

The Energy Systems Analysis Division of the Fraunhofer Cluster of Excellence »Integrated Energy Systems« CINES is coordinated by Fraunhofer ISI. CINES addresses the central technological and economic challenges resulting from the system and market integration of high shares of variable renewable energies into the energy system, and focuses on hydrogen production via electrolysis as a central element of this transition. Its services are primarily aimed at policy makers and decision-makers at national and EU level, but also at stakeholders in the energy industry (TSOs, energy suppliers, federal network agencies, etc.). They include:

- Modeling of the overall energy systems in high resolution.
- Development of tools to visualize the status of the German energy transition and the transformation of the German energy system.
- Path analysis to climate neutrality. To this end, CINES tackles issues surrounding the integration of renewable energies and the role of hydrogen in the future energy system.
- Development of a comprehensive database on the German and European energy system.
- Pooling of expertise from various Fraunhofer institutes and the combined use of different models.

Long-term scenarios

The project »Long-term scenarios for the transformation of the energy system in Germany« (long-term scenarios 3), funded by the Federal Ministry for Economic Affairs and Climate Action, is modeling scenarios for the future development of the energy system, which will enable energy and climate policy goals to be achieved. The modeling covers the entire energy system, i.e. the generation of electricity, heat and hydrogen as well as the demand for energy in the industrial and transport sectors, and from buildings and appliances. The energy infrastructures (electricity and gases) are also modeled. The focus of the analysis is not to develop an individual »lead scenario«, but rather the investigation of different scenario worlds, performing comparative analyses to gain insights into the advantages and disadvantages of alternative paths to transforming the energy system. The project provides detailed results, data sets and content in the form of a scenario explorer and a large number of topic-specific webinars for science, industry and politics.

HYPAT – Global H_2 Potential Atlas

The HYPAT project is developing a global hydrogen potential atlas. For the first time, it is creating a comprehensive list of potential partner countries with which Germany could jointly develop a green hydrogen economy, taking particular account of the significance of the production regions for a secure, economical and ecologically sustainable supply. The project is based on the objectives of the German National Hydrogen Strategy, the international agreement on climate protection and the Sustainable Development Goals (SDGs). In addition to a detailed survey of global techno-economic potential and an analysis of the hydrogen chains, the study also considers the symmetrical needs of the partner countries. This includes their need to sustainably meet their own energy demand, achieve their own climate targets and comply with specific sustainability criteria for the hydrogen economy. The ability of the partner countries to build such capital- and technology-intensive plants is also evaluated. Opportunities arising for these countries are identified, and acceptance and stakeholder analyses are carried out. The resulting supply of hydrogen and synthesis products is then compared with the global demand from importing countries. The analysis centers on how hydrogen markets will establish themselves, and what market prices can be expected for hydrogen in the future. Finally, policy recommendations are being prepared for the development of a sustainable import strategy for Germany.

TransHyDE-Sys

The flagship project TransHyDE is one of three hydrogen flagship projects of the Federal Ministry for Education and Research (BMBF), and is concerned with the development of a hydrogen transport infrastructure. To this end, several hydrogen infrastructure technologies will be developed, evaluated and demonstrated. In order to overcome the challenges inherent in establishing a hydrogen economy, the TransHyDE flagship project comprises both demonstration projects and research alliances. In the TransHyDE-Sys research network – »System analysis of transport solutions for green hydrogen« – the cross-sectional project of system analysis will play a particular role: on the one hand, essential system knowledge will be generated for the time-sequenced construction and coupling of energy infrastructures, drawing on in-house modeling and simulation work as well as ecological analyses. On the other hand, observations, analyses and requirements from the implementation and research projects will be compiled, compared with existing knowledge and classified in a comprehensive manner. The results will be incorporated in a continuously evolving roadmap. This will provide ongoing support for the research and implementation projects, identify potential research and development topics for the next project phases, and provide important recommendations for external stakeholders.

Modeling and simulation of fuel cell systems in hybrid applications

Simulation plays an increasingly central role in modern development processes, shortening development cycles and avoiding time-consuming intermediate steps in cost-intensive prototypes. Extensive expertise is available at the Fraunhofer institutes, particularly in the area of fuel cell systems and their integration into vehicles.

One focus of work at Fraunhofer IVI is the modeling of fuel cell systems to create efficient and low-wear operating strategies for vehicles. The institute's own models of fuel cells and battery systems are applied. These include both performance and wear characteristics, and are created using test rigs for cell and system characterization. The operating strategies developed for use in hybrid powertrains with batteries and fuel cells are self-learning and predictive, and they optimize component service life and system efficiency.

The focus of the simulation and modeling is to determine and utilize component properties in various use scenarios for commercial vehicles, rail vehicles, agricultural machinery and specialized vehicles. Particular attention is paid to ensuring that the operating strategies developed can be executed in real time on vehicle control units, so that the transition from simulation to reality is as straightforward as possible. These integrative simulation tasks provide direct support to vehicle developers in the areas of vehicle dimensioning and design.

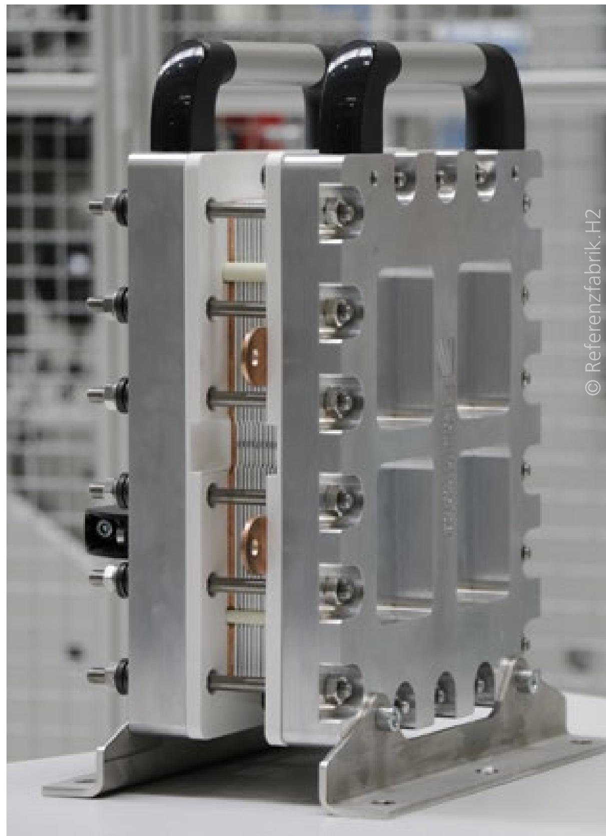
However, Fraunhofer explores the issues in yet more detail. At Fraunhofer ISE, for example, fuel cell system development and simulation is carried out at cell and stack level. This provides insights into the physico-chemical effects at micro and macro level, which are necessary to describe the performance and aging behavior in relation to component design, material selection and system management. Analytical and numerical models from 0-D to 3-D are used, alongside machine learning methods to analyze in particular the impact of different production processes.

Referenzfabrik.H2

Production of hydrogen systems: electrolyzers and fuel cells

Hydrogen technologies play a central role in achieving the German and European climate targets. The key elements are systems for converting renewable energies into hydrogen (electrolyzers) or reconverting hydrogen into electricity (fuel cells). However, the technologies required for the economical production of these key elements are still lacking. This is the impulse behind »Referenzfabrik.H2«, and the flagship projects H_2Giga/ FRHY (electrolyzers) and H_2GO (fuel cells) funded by the Federal Ministry for Education and Research (BMBF) and the Federal Ministry for Digital and Transport (BMDV).

FRHY
REFERENZFABRIK
FÜR HOCHRATENFÄHIGE
ELEKTROLYSEURPRODUKTION



FRHY stack: reference for high-rate electrolyzer production

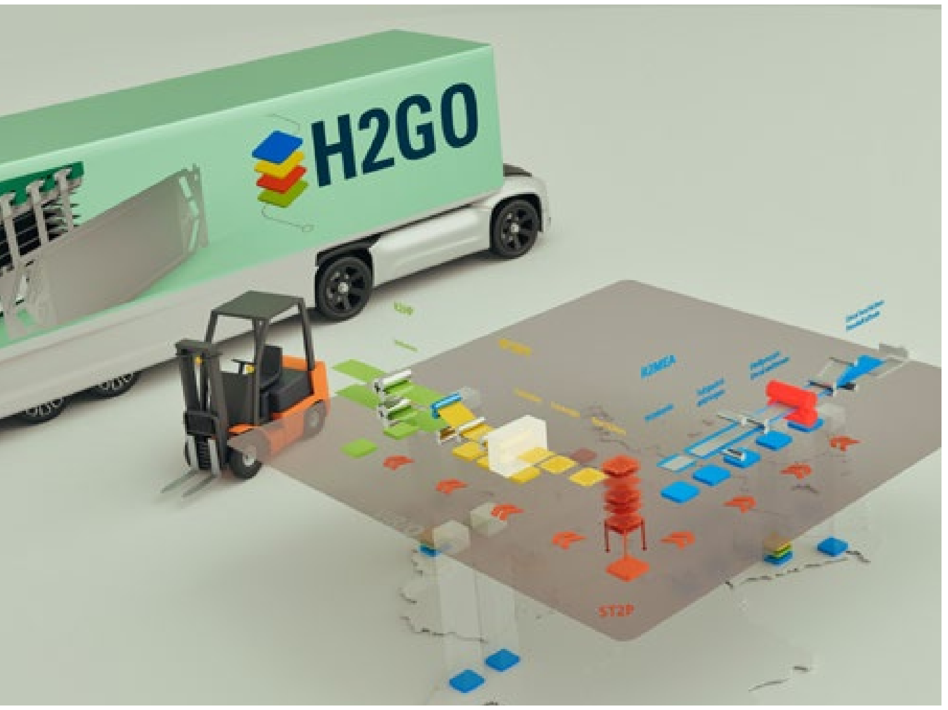
The production of essential hydrogen systems such as electrolyzers and fuel cells will create an attractive business area for numerous companies of various sizes and sectors in the near future. In Referenzfabrik.H2, numerous Fraunhofer institutes have pooled their expertise to provide customers with a technological and economic perspective for industrialized solutions.

H_2Giga collaborative project: FRHY – Reference factory for high-rate electrolyzer production

FRHY is funded by the Federal Ministry for Education and Research (BMBF) as part of the hydrogen flagship project H_2Giga. Besides the project coordinator Fraunhofer IWU Chemnitz, the Fraunhofer institutes IPT Aachen, IPA Stuttgart, ENAS Chemnitz, IMWS Halle/ S. and IWES Bremerhaven are involved. FRHY is designed as a flexible, multi-directional, technology-neutral solution for the large-scale production of electrolyzers. Within this framework, novel production and testing modules are being developed. At the same time, the corresponding digital models are created and linked in a central virtual architecture. This not only creates new production solutions, but also a technology toolkit that enables far-reaching evaluations. Individual processes can be compared in terms of production qualities, scalability and costs. Production variants through to entire value chains can be assigned to the process steps in the reference architecture and calculated. This makes it possible to compare and evaluate strategies for parallelization, automation and vertical integration. As a result, not only investment costs but also return-on-investment can be calculated and validated as a function of the planned production volume. This forms the continuous basis for high-rate, reproducible production to further improve the quality and service life of electrolyzers and ensure that they can be dynamically and flexibly adapted to changing conditions.

»Hydrogen offers a unique opportunity to combine climate protection and energy transition with value creation, provided that we succeed in developing new, high-rate technologies and transferring them quickly into industrial application.«

Dr.-Ing. Ulrike Beyer
Referenzfabrik.H2



H_2GO: key research topics

H_2GO – National Action Plan for Fuel Cell Production

Fuel cell electric vehicles (FCEVs) show significant promise as a commercially viable drive system for long-distance transportation in the future. From a technological point of view, fuel cells offer a similar output per volume and weight, and similar ranges and refueling times to conventional fossil-fuel-based drive technologies. This means that haulage companies can retain the flexibility they are accustomed to in their truck operations. Compared to other emission-free drive systems, FCEVs can be economically and ecologically competitive, especially in heavy goods transportation – assuming a successful market ramp-up. Imported hydrogen can reduce the burden on the domestic electricity market, which would otherwise be constrained to produce larger quantities of hydrogen from renewable energies.

The National Action Plan for Fuel Cell Production H_2GO, funded by the Federal Ministry for Digital and Transport (BMDV), supports the establishment of the German fuel cell industry through production technology research, development and industrial implementation. This is intended to ensure national technological sovereignty in the long term, and to enhance the export capability of German truck manufacturers and the necessary mechanical and plant engineering.

At the heart of this initiative are 19 Fraunhofer institutes based in 9 federal states which, in collaboration with their local networks, draw on their research expertise and infrastructures to develop new manufacturing solutions within regional technology hubs. These will be integrated into the four technology alliances for proton exchange membranes (R2MEA), bipolar plates (R2HP, HP2BPP) and industrial dismantling and transfer to recycling and reuse (ST2P), and enhanced through targeted state and federal initiatives. The overarching NEXUS network: ViR enables synergetic integration in a virtual reference architecture for fuel cell production based on the digital images of the developed production solutions.

Due to its advanced technical maturity, the high-rate process chain gives new, previously uninvolved industries the opportunity to expand their business field through fuel cell production. Besides component manufacturers and system integrators, the mechanical and plant engineering sector therefore also benefits from the innovative production solutions resulting from the National Action Plan. The H_2GO developments also offer new economic prospects for other companies with specialized processes, as well as moldmakers, material suppliers, engineering, measurement and control technology. The approach is neutral and independent of specific companies. In particular, the concept of the Action Plan makes it possible to explore innovative future production concepts that are pre-competitive and go far beyond the technologies currently available. The Action Plan promotes comprehensive knowledge and technology transfer, and also makes the newly created infrastructure available to various industrial partners for direct cooperation, sampling, pilot production or spin-offs, and for the further development of both production processes and fuel cells as a product. Rather than merely subsidizing individual consortia, this enhances the entire value-creation ecosystem.

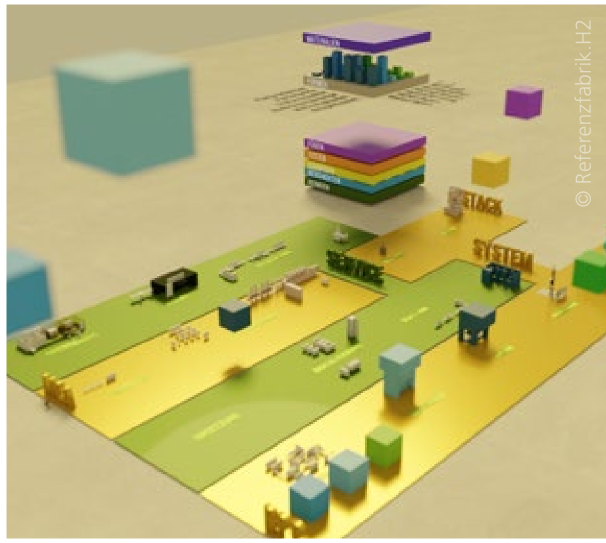
Referenzfabrik.H2 – Value-creation community for hydrogen system production

H_2GO and FRHY are the technological basis of the Referenzfabrik.H2. The factory aims to become the pacesetter for the industrial mass production of electrolyzers and fuel cells. The industrial and research sectors consider themselves as a value-creation community working together on the rapid ramp-up of efficient, scalable production processes for these hydrogen systems. In the Referenzfabrik.H2, industrial companies contribute their expertise to the value chain and develop it further through collaboration with other companies. By joining forces with the research sector they can achieve faster progress and the production of cost-effective systems for mass application.

The Referenzfabrik.H2 comprises a technology construction kit, technology services and a technology mall.

The production of electrolyzers and fuel cells for hydrogen systems is technologically very diverse. Besides various production methods, and besides the different products (alkaline, electron and proton exchange, high temperature), additional framework conditions such as geometry, service life, production quantities and costs influence the selection of processes and the need for specific process steps. The technology construction kit comprises various production technology modules in terms of process variants, equipment and pilot plants that are needed to produce hydrogen systems. It has been developed for different hydrogen system components and incorporates several levels, each representing the individual production and testing steps. Possible process variants and the investigated parameters are positioned within this structure. The aim is to enable a comparison of different process variants. Technological, economic and sustainability aspects are taken into account. A process variant can also be selected for each level or production step and then combined to form a sub-process chain. These in turn can be linked across components to form value-creating networks. The technological basis is supplied by the participating Fraunhofer institutes. Results from pre-competitive Fraunhofer projects and funded research projects are made available for transparent knowledge and technology transfer. The technology services were created specifically for companies interested in integrating their expertise and infrastructure into hydrogen system production. The thematic areas of orientation, design, development, automation, industrialization, digitalization, quality assurance and labeling are addressed. The technology mall was developed to support the transfer of technology and knowledge. The main stack components are included and the modules required for their production are specified. Possible processes are listed for each production module and described with reference to the plant technology available within the value-creation community. Individual processes can be combined into process chains with specific target corridors (e.g. high production quantities, high quality). The process chain is represented across all components based on the system developments. The service modules are represented and structured in a similar way.

Physical technology construction kit – Fraunhofer IWU



Technology mall – Fraunhofer IWU

From materials to systems: materials as drivers innovation

As an energy source and chemical raw material, green hydrogen will make a decisive contribution to achieving climate targets. However, this can only succeed if the systems for generating, storing, transporting and using H_2 become more energy-efficient, robust, safe and economical. Fraunhofer has the expertise to make a decisive contribution in this field.

Robust fuel cell and electrolysis stacks

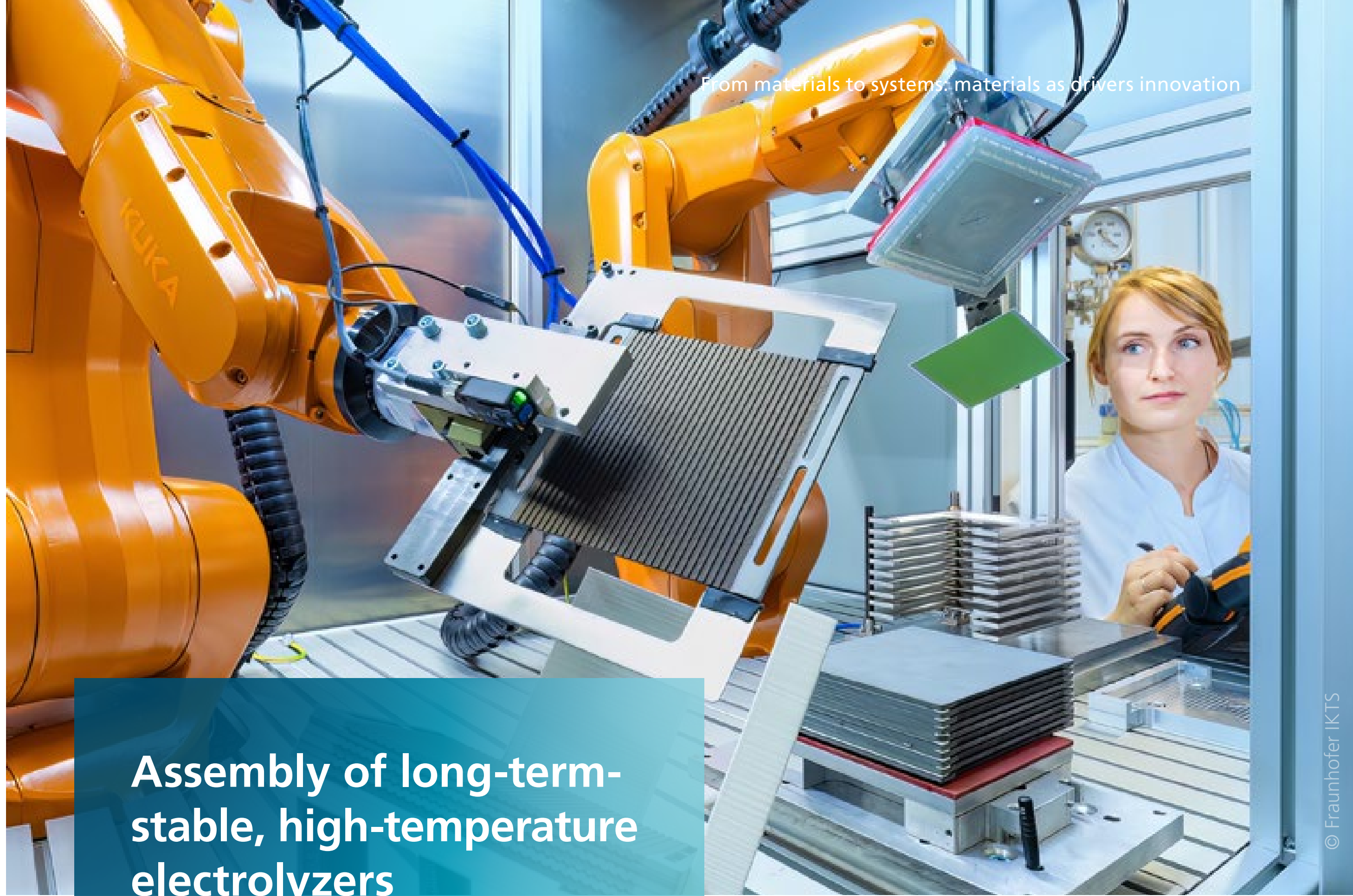
To produce green hydrogen, water is broken down into H_2 and O_2 using an electric current. Each type of electrolysis has specific advantages, so the choice of technology can vary depending on the application scenario. Fraunhofer researchers have significant expertise in all types of electrolysis, and can contribute a great deal to its further development. While aqueous alkaline electrolysis (AEL) and, to a large extent, acidic membrane electrolysis (known as PEM electrolysis) are technically quite mature, in the case of alkaline membrane electrolysis and high-temperature electrolysis some technological issues remain to be clarified.

The robust electrolyzers for AEL were previously used in power plants and chemical plants with a stationary and static load. However, a paradigm shift is now imminent: renewable energies cause significant load fluctuations, meaning that new concepts are required. Fraunhofer IFAM is investigating these dynamics on a pilot plant scale, in a system with an output of 30 kilowatts. The institute offers its partners services for analyzing the real behavior of AEL electrolyzers. In addition, Fraunhofer IFAM and Fraunhofer IMWS are optimizing the long-term stability of the electrodes. Fraunhofer IKTS is researching new materials and stack systems for the next generation of alkaline electrolyzers operating at elevated temperatures and pressures, in the AWEC++ and HHoch 2 projects with funding from the TAB and the Federal Ministry for Economic Affairs and Climate Action (BMWK). This enables an increase in power density and stable operation.

PEM electrolysis is a more recent development than AEL. While the latter has a technology readiness level of eight to nine, PEM electrolysis has a TRL of seven to eight. It also

»The electrolysis-supported direct reduction of iron ores with regeneratively produced hydrogen can become the central process step in future environmentally friendly steel production. CO_2 emissions can be reduced by up to 95 percent. In particular, high-temperature electrolysis based on ceramic technologies offers significant application potential: besides electricity, waste heat can also be used as an energy source, which leads to a considerable increase in overall efficiency«

Prof. Dr. Alexander Michaelis
Institute Director
Fraunhofer IKTS



Assembly of long-term-stable, high-temperature electrolyzers

offers various advantages: the current densities used can be very high, the design very compact, and the process can be operated dynamically. However, due to the acidic medium, the materials used must be very robust. Researchers at Fraunhofer ISE are developing new membrane materials, extending the durability of the cells with an anti-corrosion coating, carrying out service life tests, and aiming to transfer the process to a larger scale. All these measures can help to reduce costs. In the BMWK-funded project H_2GO, Fraunhofer IKTS is also working on the recycling of PEM stacks and their electrochemical characterization.

High-temperature electrolysis takes place at over 800 °C. It has particular advantages if waste heat is available: no precious metals are required to catalyze the reactions; moreover, the same systems can be used in both electrolysis and fuel cell mode. It also enables co-electrolysis, in which water is split into H_2, O_2 and CO_2 in oxygen and carbon monoxide (CO). Together with H_2, CO forms a »synthesis gas« which is the precursor for the production of numerous chemical products. Fraunhofer IKTS focuses on the long-term stability of electrolyzers as well as their efficiency and costs.

The IKTS teams optimize materials, manufacture cells and assemble them into stacks. In material tests within the BMBF-funded projects ElKoHEL and SOC Degradation 2.0, they are investigating the degradation mechanisms in stack components, including those resulting from various contaminants and concentrations. This forms a basis for reliable energy systems, for example for coupling high-temperature electrolysis and Fischer-Tropsch synthesis. In the globally unique recycling plant in Thallwitz, biological waste can be converted back into useful materials such as synthetic fuels and biowaxes (see chapter »Climate-neutral industrial processes«). Fraunhofer IKTS worked on planar cells and stacks for combined heat(/cooling) and power with hydrogen – for example for off-grid supply – and developed the technology to market maturity with the Dresden-based company Sunfire.

Fuel and electrolysis cells can only be operated smoothly if the gas atmospheres are completely separated from each other. This requires solders that can be used stably up to approx. 850 °C. As part of various industrial partnerships, Fraunhofer ISC has developed crystallizing glass solders that meet all thermal, chemical and mechanical requirements. These can even be used in a fully automated manufacturing process.

Fraunhofer IWU is working with Chemnitz University of Technology and industrial partners to ensure that the stack remains tight during operation: smart seals detect changes to the preload of the stack during operation. Using shape-memory alloys, the optimum preload is then restored.

Valuable products obtained via high-temperature electrolysis and Fischer-Tropsch synthesis; Fraunhofer IKTS

Reforming systems

At present, hydrogen is usually not produced via water electrolysis, but rather via reforming of organic compounds – in the simplest case methane or methanol. This type of H_2 or synthesis gas production can also contribute to a sustainable industry if, for example, the organic compounds come from biomass, and if the resulting CO_2 is removed from the global cycle. Several Fraunhofer institutes are working on optimizing the underlying reformer systems: Fraunhofer IMM develops complete solutions for fuel processing and synthesis from laboratory through to pilot scale and series production.

Work at Fraunhofer IKTS centers on the afterburner required in a fuel cell system, or rather its core component, the foam ceramic. To ensure a long service life, this must be extremely resistant to high temperatures and thermal shock. Open-cell foam ceramics made of silicon carbide are particularly suitable for this purpose. The researchers adjust these cellular ceramics specifically to the burner or reformer type and further develop them. Fraunhofer IKTS' specialized foam ceramics have a particularly high strength in the temperature range up to 1300 °C.

Key element catalysts

High-capacity and inexpensive catalysts are essential for efficient electrolyzers or fuel cells. Several Fraunhofer institutes have built up considerable expertise in this area, aiming to reduce the use of precious metals and to increase efficiency. In the electrolyzer, completely different requirements apply for the hydrogen electrode than for the oxygen electrode. For example, in the project HyCOn (funded by the German Federal Ministry of Education and Research (BMBF)) researchers at Fraunhofer ICT have developed supported catalysts based on iridium oxide, to produce oxygen. They are also investigating the increase in activity resulting from the formation of mixed oxide or defects due to doping with halides. Based on this preliminary work, bifunctional oxygen catalysts for unitary reversible PEM fuel cells can ultimately be developed. Fraunhofer ICT is also developing electrocatalysts for different types of electrochemical cells in the low and medium temperature range (up to around 200 °C). For example, the researchers are working to improve electrodes for high-temperature PEM fuel cells. On behalf of the Federal Ministry of Defence, research is also being conducted into materials and systems that can be operated with logistical fuels in this type of fuel cell.

PEM fuel cells can play an important role in the field of heavy-duty transportation, as they offer a high power density and very high dynamics. The energy density of hydrogen gives them additional advantages for this application compared to purely battery-electric drive systems. The coatings of a membrane serve as electrodes. This is referred to as a »membrane electrode assembly«, or MEA. In the HyFab project, which is funded by the state of Baden-Württemberg, Fraunhofer ISE is investigating the functional relationships in the catalyst layer, and optimizing process technologies for the mass-production of MEAs.

From materials to systems: materials as drivers innovation

Our colleagues at Fraunhofer UMSICHT are also developing new catalysts for water and CO_2 electrolysis.

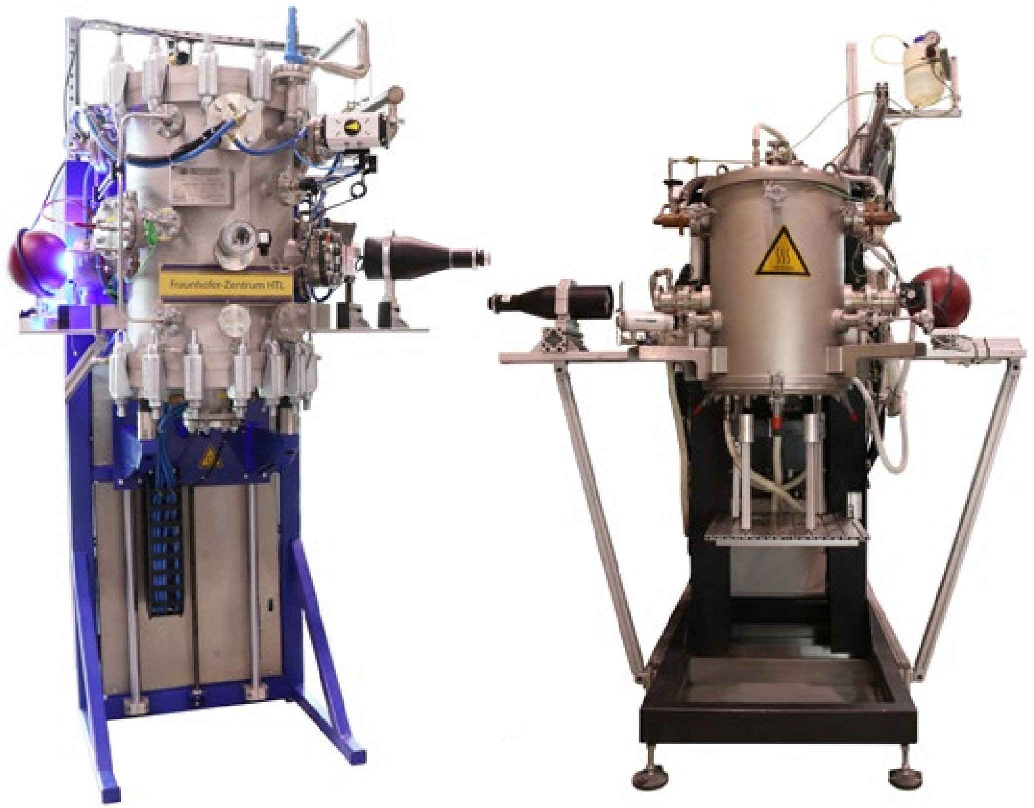
Fraunhofer ISC specializes in the upscaling of catalyst materials, and in catalysts for the use of hydrogen, for example to produce solar chemicals. Such catalytic reactions show sufficient performance and yield on a laboratory scale, but in order to upscale them for industrial application, promising catalyst materials such as the photocatalysts titanium dioxide and graphitic carbon nitride must be widely accessible. In the EU-funded project SPOTLIGHT, catalysts developed by project partners[1], are being upscaled at Fraunhofer ISC. The synthesis of various catalyst materials, which are used for example to produce methane and carbon monoxide from green hydrogen and carbon dioxide, was transferred from the 100 mg scale to the 100 g scale. The performance of these catalysts in the conversion processes is comparable to or better than the systems produced on a small scale.

Storage materials

Different applications for hydrogen require different concepts for storing and transporting the valuable gas. For distances of less than 100 kilometers, Fraunhofer IFF is developing a portable, modular H_2 storage system that weighs less than 750 kilograms and can be loaded onto »green« vans. Hydrogen can also be stored in liquid organic hydrogen carrier (LOHC) systems. To this end, H_2 is chemically bound to a carrier oil: there is no need for complex pressure accumulators or cooling systems. Researchers at Fraunhofer IAO have built Europe's first next-generation LOHC storage system, with a storage capacity of 2000 kilowatt hours. As an alternative, Fraunhofer IFAM in Dresden is developing an easy-to-handle »POWERPASTE« in which hydrogen can be chemically stored at room temperature and ambient pressure, and can be released as required by adding water.

1 TNO – Innovation for life, University of Hasselt)

100 liter synthesis reactor for the upscaling of catalyst materials to industrial pilot plant scale at Fraunhofer ISC, coupled with various in-line analysis technologies



Thermo-optical measuring systems (TOMs) for in-situ investigation of the influence of hydrogen and the hydrogen combustion atmosphere on the furnace feed and components

Influence of hydrogen and its combustion product water on thermal processes and combustibles

The use of hydrogen to reduce the CO_2 footprint of thermal processes will play an important role in achieving climate targets. This applies in particular to processes that cannot be electrified. Depending on the settings of the burners, and on the combustion conditions, the combustion of hydrogen leads to significantly higher temperatures and gas volume flows as well as increased water content in the gas atmosphere. This increased water content can affect both the product in the furnace and the furnace components. In addition to the burners, the refractory lining and furnace furniture are particularly affected. Fraunhofer ISC has special furnaces in which the influence of increased water vapor content (up to 100%) on the furnace feed and components can be investigated in-situ. In addition, a broad spectrum of analytical methods is available, including at the Center for Applied Analytics (ZAA) for the subsequent investigation of the reactions taking place within the materials. Based on these results, customized furnace programs, furnace materials and coatings can be proposed and developed using simulation tools developed in-house. Beside the influence of the water content, the influence of hydrogen or other gases can also be investigated at temperatures of up to 1800 °C.

Barrier coatings

The materials used to encapsulate sensitive components, separate gas flows or transport gases, must be gas-tight. Plastic components or films are often used for such applications, as they can be produced easily, flexibly and cost-effectively in various geometries. However, plastics are a very limited migration barrier to non-polar gases (e.g. oxygen or nitrogen). They must consequently be modified. One option that offers significant material savings and therefore increased sustainability is the use of functional layers that serve as a gas barrier. Such layers are a central component of many packaging applications, and an important subject of research, for example in the Fraunhofer POLO Alliance.

In addition to vapor deposition, sputtering and plasma coatings, functional hybrid polymer coating systems (such as ORMOCER®materials from Fraunhofer ISC) create an especially effective barrier against oxygen due to their inorganic and organic cross-linking within a single matrix. With a high network density and a suitable polarity, ORMOCER® functional layers can reduce the migration levels of plastic films from over 1300 to less than 15 cm³/m²dbar. As the layers are very flexible and only a few micrometers thick, they can also be applied to very thin films. The coating materials are produced by simple synthesis (e.g. in the synthesis reactor shown in Figure 7) and

From materials to systems: materials as drivers innovation

Use of barrier layers in industrial production facilities

can be applied to 2D and 3D surfaces using conventional methods such as spraying. A further improvement of their properties with regard to the barrier effect can be achieved by the addition of particles.

In future, hydrogen barrier layers will be developed according to similar functional principles and, for example, through the use of (layered) silicates. The use of crystalline, inorganic nanofillers significantly reduces the permeability of the polymer matrix by extending the diffusion path of the permeates. The use of hydrogen barrier layers can therefore play an important role in reducing losses during hydrogen transport, and can significantly improve the barrier properties under high pressure.

Fraunhofer Group MATERIALS integrates the expertise of 16 Fraunhofer Institutes working in the field of materials science

Fraunhofer MATERIALS research covers the entire value chain, from new material development and improvement of existing materials through manufacturing technology on a quasi-industrial scale, to the characterization of properties and assessment of service behavior. The Group covers the full spectrum of metallic, inorganic non-metallic, polymeric, and renewable raw material-based substances, as well as semiconductor materials. In recent years, hybrid materials and composites have gained significant importance. Material innovations are crucial in addressing the challenge of creating a robust, resilient, and efficient future energy system. Consequently, the group has recognized the energy sector as a key business area, with a particular focus on hydrogen. Research in materials for hydrogen technology is crucial, as hydrogen can reduce the strength and toughness of materials, leading to either immediate or delayed failure of components. This issue is particularly pertinent given the increasing importance of repurposing existing natural gas pipelines and storage facilities for hydrogen distribution and storage. At Fraunhofer MATERIALS, comprehensive evaluations, monitoring, simulations, and characterizations are conducted to develop materials that are as resistant as possible to hydrogen embrittlement.

Building expertise for the transition to hydrogen – Become a hydrogen pioneer with Fraunhofer know-how!

Based on the latest insights from applied research, the Fraunhofer institutes and Fraunhofer Academy have developed part-time training courses for a wide range of professionals.

The decarbonization of industry is one of the most significant industrial transformations ever, and it will exacerbate the existing need for specialists and managers. In addition to research, development and innovation, the qualification of skilled workers is one of the key factors for the success of the transformation. The Fraunhofer-Gesellschaft's professional education program thus makes a significant contribution through the transfer of applied knowledge into industry.

Open questions and current topics of research include: Where is my company situated in the hydrogen value chain? How strongly will I be affected by the transformation? What skills do my employees need to put my company on the path toward a sustainable future?

By 2030, it is predicted that hydrogen-related industries will need around 70,000 additional specialists and managers. They need the knowledge, skills and expertise to master the complex challenges involved. Here, Fraunhofer's training program can provide support.

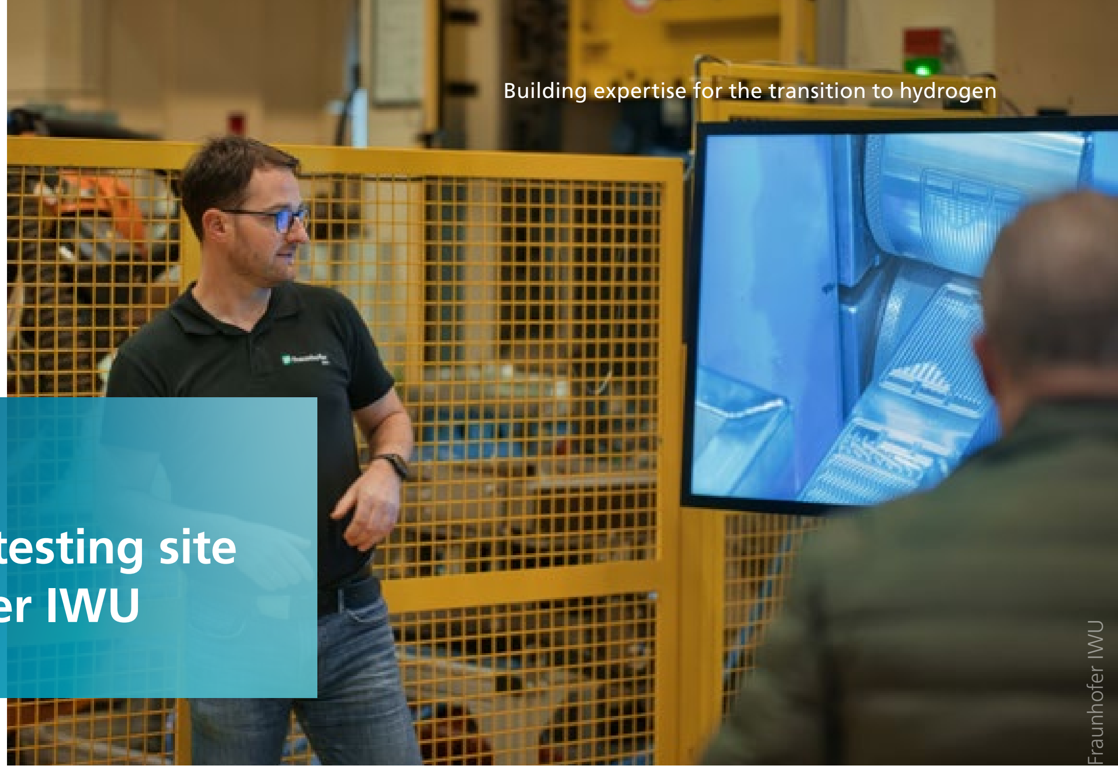
The field of hydrogen links different sectors and thus also a broad spectrum of occupational fields and profiles. Stakeholders in industry, authorities, funding institutions and public bodies will increasingly have to make decisions about hydrogen projects in the future. This requires hydrogen expertise, which must be made available in customized formats, for example also for consulting firms, banks and insurance companies.

The Fraunhofer Academy offers orientation and strategic stocktaking in various learning formats such as workshops, training courses and more comprehensive further education programs involving knowledge transfer from one or multiple institutes in the hydrogen field. The courses for specialists and managers from sectors contributing to the transformation comprise both basic and highly specialized knowledge on the generation and use of green electricity, and also cover issues such as production safety, process optimization and mobility. Register today and help to shape the future!

Hydrogen | Advanced Training

How can your company benefit from hydrogen? Which path should it take in the transformation? We support you in finding the right direction.

Please note: Some QR codes lead to German websites. For more information in English, please contact info-wasserstoff-netzwerk@fraunhofer.de



Fraunhofer IWU

Fit4H$_2$-live: Tour of the testing site at Fraunhofer IWU

Fit4H$_2$: Training on the production of hydrogen systems (IWU, ENAS)

Hydrogen technologies play a key role in achieving global climate targets. The key elements are systems for converting renewable energies into hydrogen (electrolyzers) or reconverting hydrogen into electricity (fuel cells). Such systems are currently only produced in small quantities. However, to consistently reduce CO_2 emissions and build a global hydrogen-based economy and society, their availability must improve considerably, and their cost be significantly reduced. This requires industrial mass production, which in turn is inconceivable without value creation networks and the corresponding production technologies.

In the Fit4H$_2$ training workshop, the essential components of electrolyzers and fuel cells are presented, together with substantial knowledge about their production technologies.

In addition, the economic potential of production is analyzed. The aim is to provide a market overview and concrete starting points for your company's entry into the value chain for hydrogen systems production.

Training Fit4H$_2$

Production of hydrogen systems: electrolyzer and fuel cell.

Please note: Some QR codes lead to German websites. For more information in English, please contact info-wasserstoff-netzwerk@fraunhofer.de

Hydrogen production – green electricity makes green hydrogen (IWES, IKTS, IST, IMW, IMWS, CSP)

To ensure a sustainable energy supply and production processes in your company, it is essential to switch from fossil fuels to climate-neutral alternatives in the medium term. This is where the training program »Practical knowledge for hydrogen projects« comes in, aimed at project planners, engineers and industry specialists who, as decision-makers, are shaping the transformation of their company. You will learn about the technological production of green hydrogen with a focus on application. We will show you how hydrogen can serve as an energy carrier and can be used as a chemical building block in industrial processes. You will learn how to solve challenges, such as factory transformation, through real-life case studies and field trips. Using practical examples, we will show you how to significantly reduce your company's CO_2 emissions. Our experts will give you an overview of the legal, economic and safety-related framework conditions along the hydrogen value chain. This information will help you to decide where hydrogen can be used in your production process, in order to decarbonize your company more quickly. The training program consists of five learning units which can be selected individually. After passing the certification test, you will receive a personal certificate from Fraunhofer in accordance with ISO 17024.

Practical Knowledge for Hydrogen Projects

From planning to implementation to operation.

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Impressions from the »Practical energy transition« training course

»Energy transition in practice« – specialist knowledge for your transition to hydrogen (IST)

The energy transition is a very dynamic process that requires the acquisition of new skills and technologies. The »Practical energy transition« training course teaches both the individual building blocks and the interrelationships within the entire hydrogen economy value chain. Planners, management representatives, engineers, employees of municipal utility companies, foremen and -women and experts, as well as consultants from politics, public authorities and banks will learn how green hydrogen can be produced, transported and used in practice.

We share cutting-edge knowledge from research and, with the help of our partner companies, show you how hydrogen is already being used in industry. You will have the opportunity to discuss the energy cycle and factory transformation with researchers and end-users.

The training program is part-time and can be tailored precisely to your needs. Choose the basic course or a further training option to achieve the personal certificate »Hydrogen expert with TÜV Rheinland-certified qualification«.

H_2-Expertise for Your Company

Securely Enter the Future with Hydrogen – Learn everything you need to know for a safe and secure future with hydrogen.

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»Specialized, individual knowledge transfer from cutting-edge applied research and development on behalf of industry is our particular strength in the training market.«

Telsche Nielsen
Head of Knowledge Transfer & University Cooperation at the Fraunhofer Institute for Wind Energy Systems IWES

»The process of decarbonization through hydrogen technologies must not be viewed exclusively from the technology and innovation perspective. The ramp-up of the hydrogen economy depends crucially on the qualification of specialists and managers.«

Viktor Deleski
Training Manager at the Fraunhofer Academy

Hydrogen applications in mobility – how can hydrogen contribute to future mobility?

Future mobility is climate-neutral and sustainable. Fraunhofer IFAM's advanced training program »Hydrogen applications in mobility« explains the role that hydrogen can play.

The part-time training program in a blended learning format comprises five learning units. In addition to the basics of hydrogen technology, it also covers the safety of hydrogen-powered vehicles. Practical information on fuel cells, storage and infrastructure, and on hydrogen in the energy transition, round off the program.

Experts from Fraunhofer IFAM teach the majority of the learning content online using a learning platform. This allows participants to work on the content throughout the course without time pressure, when, where and as often as they wish. Face-to-face sessions are held at Fraunhofer IFAM in Bremen for selected learning content. You will gain practical insights into potential applications and the latest research findings.

Upon successful completion, participants receive the Fraunhofer personal certificate »Professional in Hydrogen Applications in Mobility«.

Hydrogen Applications in Mobility

The future of mobility is climate-neutral and sustainable – how can hydrogen contribute to this?

Please note: Some QR codes lead to German websites. For more information in English, please contact info-wasserstoff-netzwerk@fraunhofer.de

Alkaline electrolysis technology hands-on - what is the current state of the art?

The development of alkaline electrolysis technology has progressed impressively in recent years, with continuous pursuit of new process engineering approaches and the development of innovative materials. The workshop »Alkaline Electrolysis Technology Hands-On« presents the state of the art in alkaline electrolyzers (AEL) and anion exchange membrane electrolyzers (AEMEL), offering insights into the latest developments (limited to 8 participants). Participants will gain an overview of stack design and the components used (electrodes [PTL and catalyst coating], seals, separators, bipolar plates, etc.). Topics also include system cost considerations and the technology roadmap. The 1.5-day workshop concludes with a practical explanation of the electrolysis system at an industrial AEL facility. Upon request, the team also offers hands-on assembly of an electrolysis cell for integration into a testing infrastructure. At Fraunhofer IFAM, participants can literally »get hands-on« with the technology.

In addition to customized workshops for individual companies, Fraunhofer IFAM organizes an annual industrial workshop focusing on alkaline systems: »Industrial Workshop on Advanced Alkaline Electrolysis«. In 2024, the seventh workshop will take place, currently accommodating up to 100 participants. External speakers from the industry (electrolyzer manufacturers and suppliers) provide insights into the state of the art, complemented by presentations from research institutes on the latest developments.

Alkaline Electrolysis Technology Hands-On

The focused workshop on alkaline electrolysis (AEL/AEMEL) is designed for professionals and executives.

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Fraunhofer Hydrogen Network

Fraunhofer Hydrogen Network

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Freiburg, Dr. Alexander Stolz

Fraunhofer Institute for Electronic Nano Systems ENAS
Chemnitz, Dr. Andreas Willert

Fraunhofer Institute for Electron Beam and Plasma Technology FEP
Dresden, Dr. Burkhard Zimmermann

Fraunhofer Institute for Industrial Engineering IAO
Stuttgart, Dr.-Ing. Florian Herrmann

Fraunhofer Institute for Applied Polymer Research IAP
Potsdam, Dr. Christoph Gimmler

Fraunhofer Institute for Building Physics IBP
Stuttgart, Dr.-Ing. Robert Ilg

Fraunhofer Institute for Chemical Technology ICT
Pfinztal, Dipl.-Phys. Wilhelm Eckl

Fraunhofer Institute for Energy Economics and Energy System Technology IEE
Kassel, Jochen Bard

Fraunhofer Research Institution for Energy Infrastructures and Geothermal Systems IEG
Cottbus, Prof. Dr. Mario Ragwitz

Fraunhofer Institute for Manufacturing Technology and Advanced Materials IFAM
Dresden, Dr.-Ing. Felix Heubner

Fraunhofer Institute for Factory Operation and Automation IFF
Magdeburg, Prof. Dr.-Ing. Torsten Birth

Fraunhofer Institute for Interfacial Engineering and Biotechnology IGB
Stuttgart, Dr. Arne Roth

Fraunhofer Institute for Large Structures in Production Engineering IGP
Rostock, Dr.-Ing. Benjamin Illgen

Fraunhofer Institute for Integrated Circuits IIS
Erlangen, Prof. Dr. Randolf Hanke

Fraunhofer Institute for Integrated Systems and Device Technology IISB
Erlangen, Prof. Dr. Martin März

Fraunhofer Institute for Ceramic Technologies and Systems IKTS
Dresden, Priv.-Doz. Dr.-Ing. habil. Matthias Jahn

Fraunhofer Institute for Laser Technology ILT
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Fraunhofer Institute for Microengineering and Microsystems IMM
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Fraunhofer Institute for Physical Measurement Techniques IPM
Freiburg, Prof. Dr. Jürgen Wöllenstein

Fraunhofer Institute for Production Technology IPT
Aachen, Dr.-Ing. Henning Janssen

Fraunhofer Institute for Silicate Research ISC
Würzburg, Dr. Jürgen Meinhardt

Fraunhofer Institute for Solar Energy Systems ISE
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Fraunhofer Institute for Systems and Innovation Research ISI
Karlsruhe, Prof. Dr. Martin Wietschel

Fraunhofer Institute for Surface Engineering and Thin Films IST
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Fraunhofer Institute for Transportation and Infrastructure Systems IVI
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Fraunhofer Institute for Wind Energy Systems IWES
Bremerhaven, Nora Denecke

Fraunhofer Research Institution for Materials Recycling and Resource Strategies IWKS
Hanau, Dr. Benjamin Balke

Fraunhofer Institute for Mechanics of Materials IWM
Freiburg, Prof. Dr. Christian Elsässer

Fraunhofer Institute for Material and Beam Technology IWS
Dresden, Dr.-Ing. Teja Roch

Fraunhofer Institute for Material Flow and Logistics IML
Dortmund, Philipp Müller

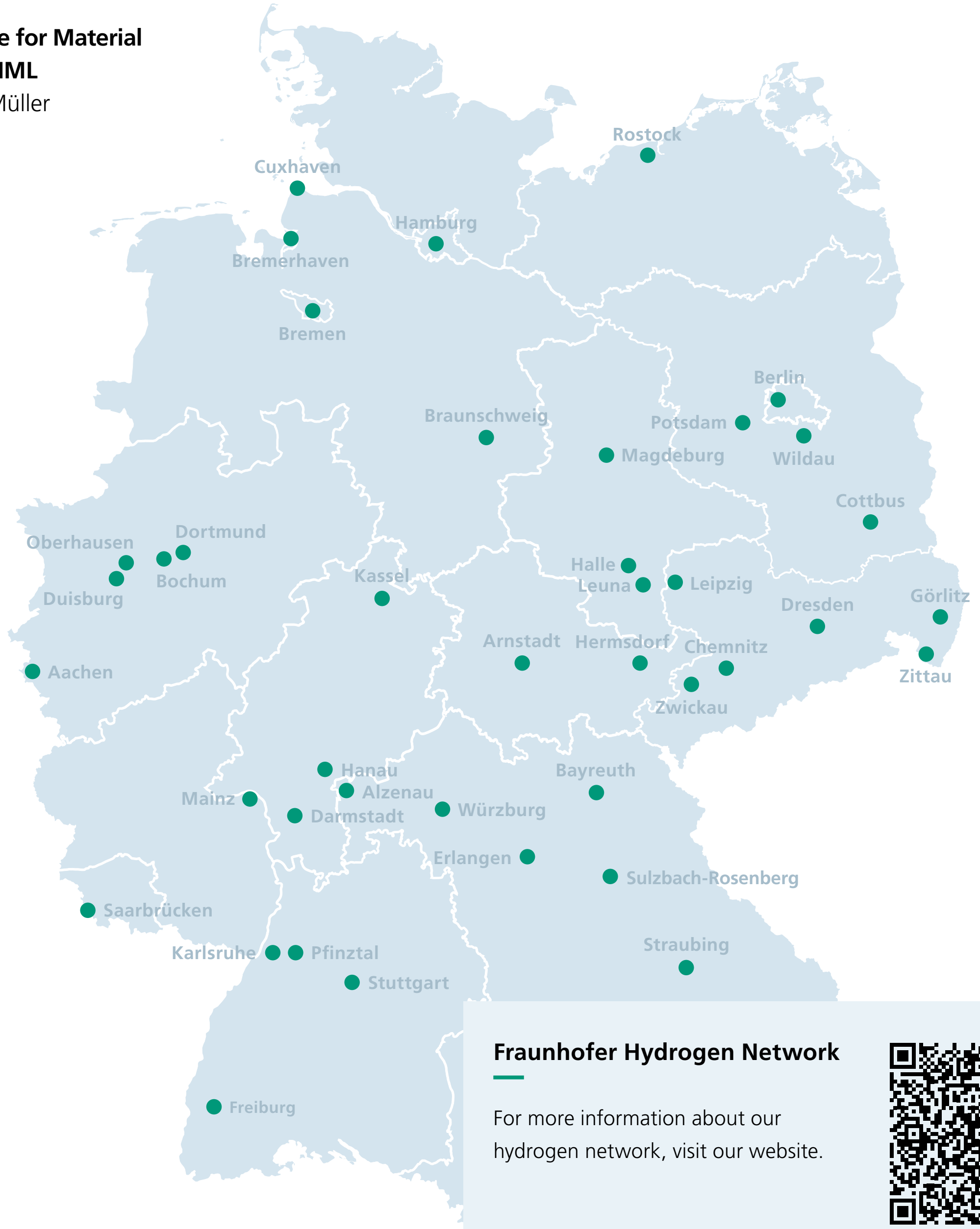
Fraunhofer Institute for Machine Tools and Forming Technology IWU
Chemnitz, Dr. Ulrike Beyer

Fraunhofer Institute for Nondestructive Testing IZFP
Saarbrücken, Prof. Dr. Hans-Georg Herrmann

Fraunhofer Institute for Structural Durability and System Reliability LBF
Darmstadt, Dr. Saskia Biehl

Fraunhofer Institute for Environmental, Safety and Energy Technology UMSICHT
Oberhausen, Prof. Dr. Christian Doetsch

Fraunhofer Chile Research
Santiago, Chile, Prof. Dr. Frank Dinter



Fraunhofer Hydrogen Network

For more information about our hydrogen network, visit our website.

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