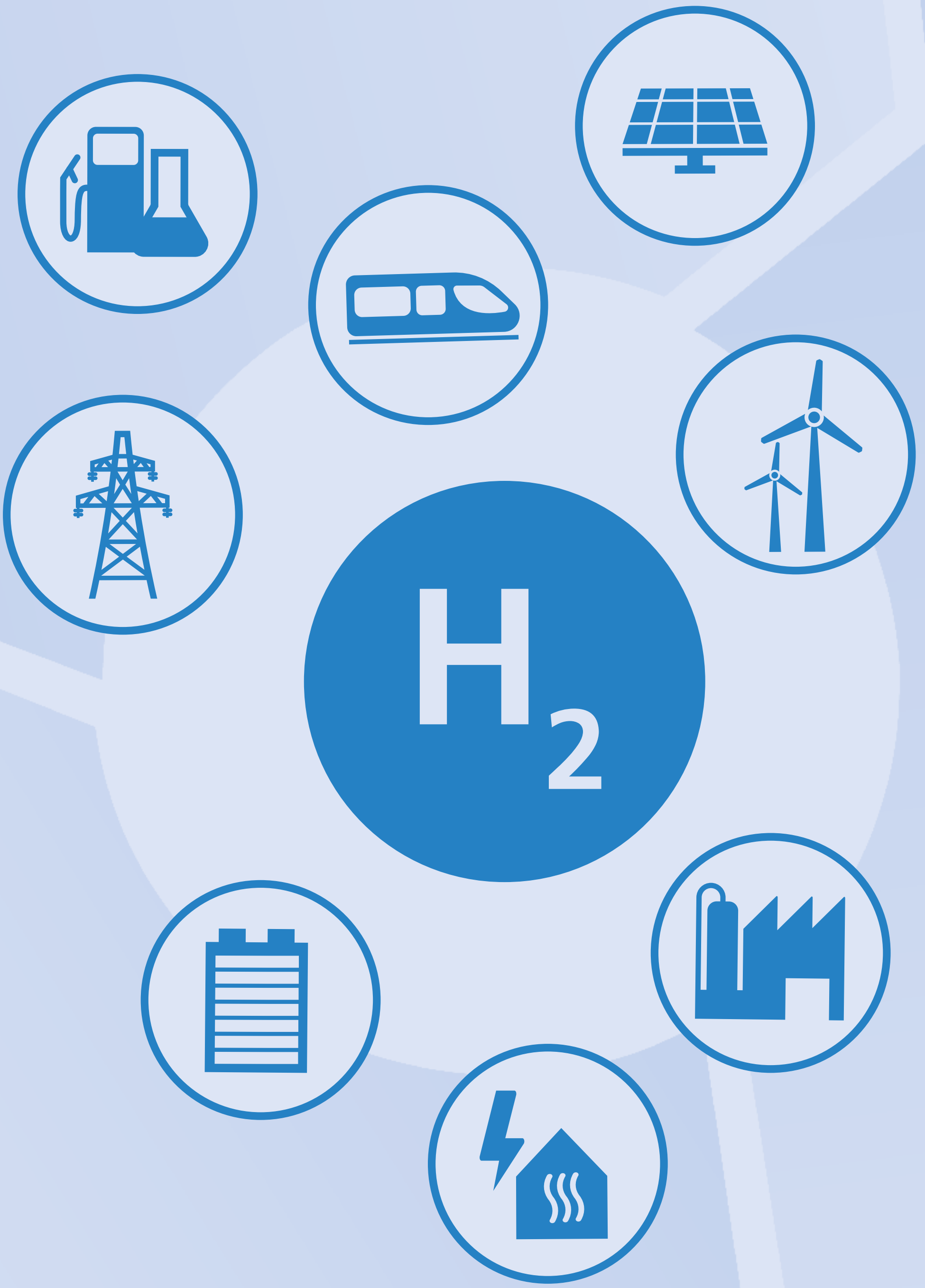
Fraunhofer

IKTS

FRAUNHOFER INSTITUTE FOR CERAMIC TECHNOLOGIES AND SYSTEMS IKTS

INDUSTRIAL SOLUTIONS

HYDROGEN TECHNOLOGIES



COVER IMAGE *Hydrogen produced with electricity from renewable energies is a key element for the successful shift away from fossil fuels.*

1 *Hydrogen is set to contribute significantly to the reduction of CO_2 in the industry and the transport sector.*
Source: petrmalinak/Shutterstock

1

HYDROGEN TECHNOLOGIES

Hydrogen is going to play a major role in our future energy and economic systems – as energy carrier and raw material. Only with hydrogen will it be possible to make industrial production, heat production and mobility climate-neutral while also reducing geostrategic dependencies.

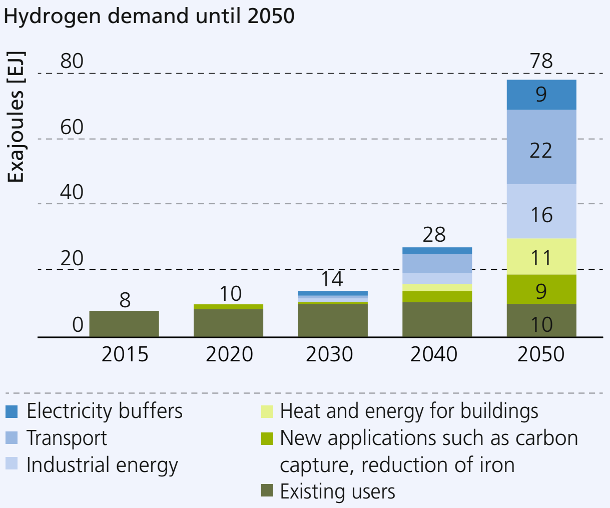
By 2050, for Germany alone a hydrogen demand of 400 TWh of hydrogen per year is expected. This would correspond to almost the entire electricity production of today. It is therefore very important that all hydrogen technologies are stable, robust, scalable and, most of all, cost-efficient. This is where Fraunhofer IKTS can contribute.

Hydrogen is only climate-friendly, i.e. green, if it is produced using renewable energies. The most important technology in this regard is electrolysis, which is ideally suited for coupling with wind power and photovoltaic electricity. Fraunhofer IKTS can look back on decades of experience in the development and construction of electrochemical reactors for the production and use of hydrogen. This makes industrial electrolysis one of our most important fields of activity.

Hydrogen is easy to store and transport in pipelines, making it very attractive for heavy mobility and industrial applications. Fraunhofer IKTS provides support in these fields with its solid know-how in materials science and its measuring and testing technology for tank and pipeline monitoring.

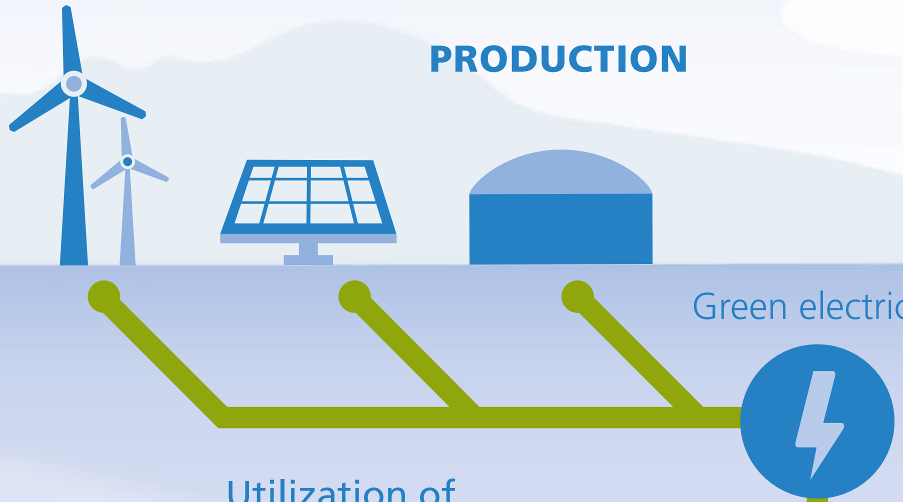
The most important contributions of Fraunhofer IKTS refer to the utilization of hydrogen: conversion of hydrogen into chemical energy carriers or basic chemicals, reconversion into electricity in fuel cells, or direct energetic use in thermal processes or the steel industry.

IKTS develops and demonstrates these technologies with its extensive system know-how as well as prototyping and testing capabilities. Fraunhofer IKTS, with its expertise and various specialized sites and technical centers, is a leading European partner for the complete value chain of current and future hydrogen technologies.



Annual demand for hydrogen could increase tenfold (Source: Hydrogen Council, Hydrogen Scaling up).

VALUE CHAIN
FOR GREEN HYDROGEN

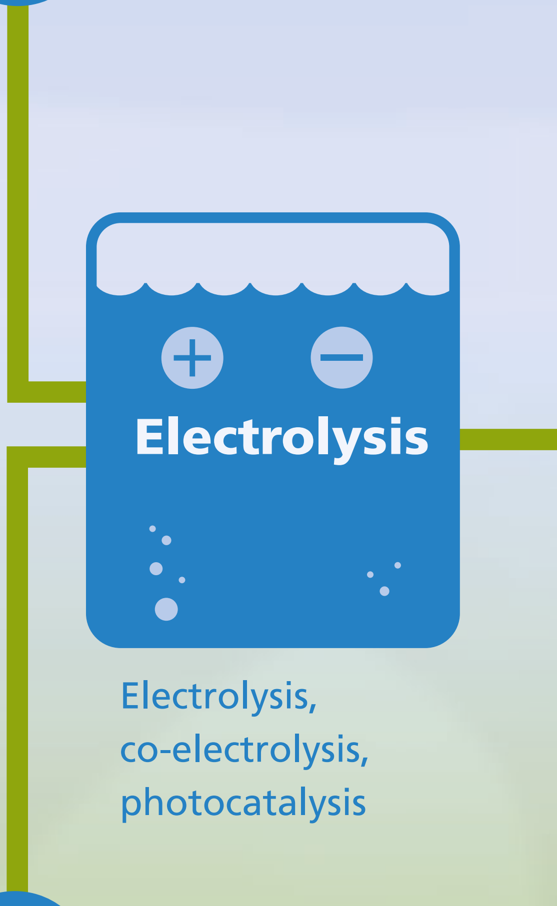


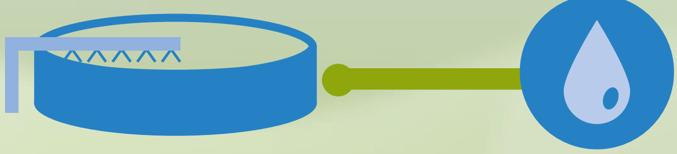
Hydrogen produced from renewable energy is a key element for the successful energy transition.

Hydrogen is ideal for sector coupling and thus contributes to the defossilization of energy supply.

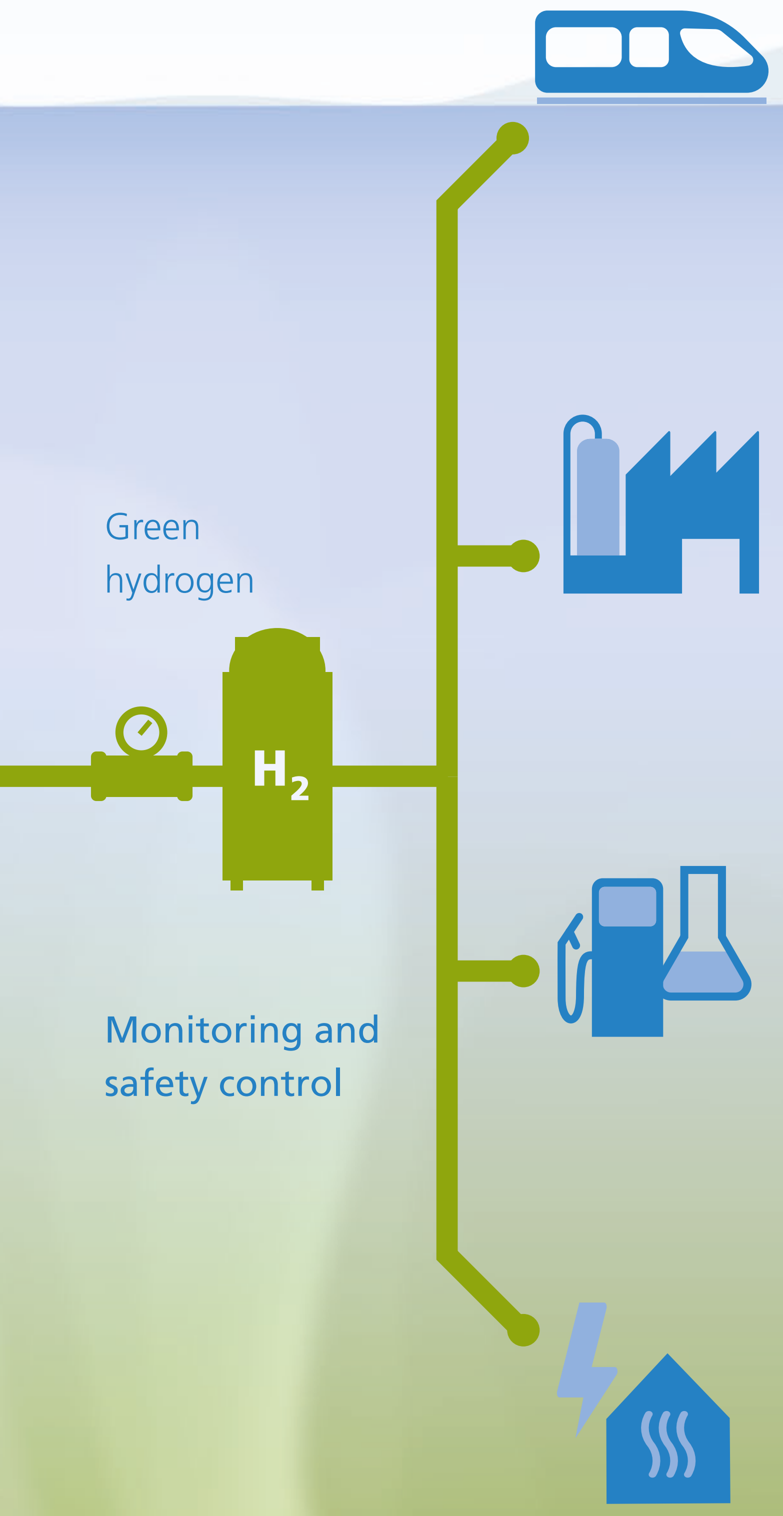
Water is becoming increasingly important as raw material for the production of hydrogen.

Fuel cells and electrolysis technologies can create local value chains in structurally weak regions.





UTILIZATION



Mobility

Hydrogen is the suitable fuel for freight transport and passenger traffic – the ideal complement for e-mobility.

Railway traffic • Heavy vehicle traffic • Shipping • Air traffic • Agriculture • Suburban public transportation

Low-CO_2 production

In CO_2-intensive industry sectors, hydrogen technologies can help to almost fully avoid CO_2 emissions.

Steel industry • Lime and cement industry • Chemical industry

Value-added products

The utilization of CO_2 from industrial processes together with green hydrogen allows for value-added products.

Synthetic fuels • Higher alcohols and valuable organic substances • Waxes

Electricity and heat

Like natural gas, hydrogen will be an important energy carrier. Based on fuel cell technology, it can be used to efficiently produce heat and electricity.

Fuel cell CHP units • Prime-power applications • Process sensors

"[...] HYDROGEN WILL PLAY A KEY ROLE IN ENHANCING AND COMPLETING THE ENERGY TRANSITION."

National Hydrogen Strategy of the German Federal Government

HYDROGEN PRODUCTION

Hydrogen production technologies

Today, most hydrogen is produced by steam reforming of natural gas and called 'grey hydrogen'. It is currently the production technology with the lowest associated costs. However, huge amounts of CO_2 are released. If the CO_2 is separated during reforming and stored in the earth (carbon capture and storage, CCS), one speaks of 'blue hydrogen'. The challenge consists in ensuring safe long-term storage for the CO_2. 'Turquoise' hydrogen is also produced from natural gas, with methane being split into carbon and hydrogen by applying heat or electricity. This process does not release CO_2, but the emissions from upstream processes in the production chain are significant, as it is the case for all natural gas-based production processes. This also includes diffuse methane emissions occurring during natural gas extraction, which cause an even greater specific greenhouse gas effect than CO_2. Also, it is still not clear how long-term storage of solidified carbon can be achieved. Alternatively, biogas can be used in all these processes instead of natural gas. Specifically, the use of biogenic residuals has advantages with regard to sustainability. However, the production costs would be much higher due to smaller plant sizes. Furthermore, the process chain and the associated emissions have to be taken into account as well, depending on the residual waste used.

In contrast, producing hydrogen via water electrolysis is largely emission-free, provided the electricity used comes from renewable energy sources. Hydrogen produced this way is called 'green hydrogen'. In this regard Fraunhofer IKTS is working to develop various electrolysis technologies (see 'Electrolysis'). High-temperature electrolysis is of particular interest in that context.

Biotechnological processes or concepts for producing solar hydrogen by means of photocatalysis are other options. Photocatalytic water splitting offers some clear cost advantages thanks to lower system complexity and the use of large-scale, proven technologies from the PV industry. A major disadvantage, however, is the currently lower overall efficiency. For this reason, Fraunhofer IKTS is working on new materials, advanced coating techniques and integrated overall systems to increase efficiency in the future.

Hydrogen market

Today, most of the hydrogen produced is needed in refineries and for ammonia synthesis, for the large-scale production of fuels and basic chemicals. Furthermore, large quantities of grey hydrogen are used for methanol synthesis or Fischer-Tropsch synthesis. The hydrogen is produced in large production plants using steam reforming. Almost the complete volume of the hydrogen produced this way is used directly on site, never reaching the market. One established route to produce hydrogen by using electricity is chlorine-alkaline electroly-

Comparison of various production processes with regard to current deficits and production costs

GREY
- Steam reforming of natural gas
- Associated with high CO_2 emissions
- Approx. 1.65 €/kg

BLUE
- Steam reforming of natural gas combined with CCS
- Risk of CO_2 release
- Approx. 3 €/kg

TURQUOISE
- Methane pyrolysis (in the electric arc)
- Energy supply via electrical and thermal energy
- Approx. 2.50 to 3.10 €/kg

GREEN
- Water electrolysis with electricity from renewables
- Currently cost-intensive as determined by electricity price (electricity tax, EEG surcharge and grid fees)
- Approx. 4.50 €/kg; in the future: 2.50 €/kg

sis during which hydrogen is produced as a byproduct, some of which is brought to market. However, this route only accounts for two percent of total hydrogen production.

FRAUNHOFER IKTS DEVELOPS TECHNOLOGIES FOR THE PRODUCTION OF GREEN HYDROGEN.

For the sustainable development of a market for green hydrogen, production costs must be reduced. This can be achieved if the efficiency and long-term stability of the electrolysis processes used are increased further and if suitable framework conditions can be created. Furthermore, a demand-oriented hydrogen infrastructure needs to be established.

In addition, decentralized hydrogen production could prove to be a useful approach. Depending on the volumes of hydrogen required, producing locally on-site can be more affordable – for instance when operating a hydrogen filling station for buses and trucks. Decentralized production may also be helpful for lime and cement industries or in biogas plants producing value-added products. It is available faster and means less dependence on distribution networks.

Water as a resource for hydrogen production

If green hydrogen is to be commercially viable, sufficient quantities of pure water need to be made available for its production. Therefore, cost-efficient water treatment processes are gaining traction, in particular for decentralized applications. Depending on the location of the electrolyzer, this may involve the desalination of seawater as well as the treatment of industrial process waters.

To support these efforts, Fraunhofer IKTS combines the more classical ceramic membrane technology with electrochemical, sonochemical and photocatalytic processes and integrates these processes in modular plant concepts. This results in decentralized water treatment solutions and helps to increase local value creation. In particular with regard to the treatment of mining waters, IKTS has been committed to many years of development work and developed unique electrochemical processes and technical equipment, both to a high degree of maturity. These make it possible to treat mining water while at the same time separating hydrogen as a byproduct which can be utilized further (see 'Membrane electrolysis'). For coal mining regions undergoing profound structural changes, this could be a very promising approach.

1 *Offshore wind energy converters coupled with electrolyzers are able to produce large amounts of hydrogen.*
2 *Solar plants supplying electricity for water electrolysis for the production of green hydrogen.*
3 *Water is becoming more important as starting material for hydrogen production.*

1

ELECTROLYSIS

High-temperature electrolysis with SOE stacks

High-temperature electrolysis has many advantages. In contrast with established alkaline or PEM electrolyzers, it does not require noble metal components. Integrating high-temperature electrolysis in processes where a lot of waste heat is produced – as in steel production – efficiency can be quite significantly increased compared to competing technologies. Additionally, high-temperature electrolysis enables the direct production of syngas.

FRAUNHOFER IKTS IS A LEADING DEVELOPER IN ELECTROLYSIS – THE PROCESS WITH THE HIGHEST POTENTIAL FOR GREEN HYDROGEN.

The conversion processes in high-temperature electrolysis, also called solid oxide electrolysis (SOE), take place at temperatures of more than 750 °C. The key components are SOE stacks, which are able to work in electrolysis mode or in fuel cell mode. Applying a voltage across an oxygen ion-conducting electrolyte separates water vapor into hydrogen and oxygen. Furthermore, the so-called co-electrolysis mode makes it possible to use unavoidable, climate-damaging CO_2 for the production of climate-neutral products. In this process, water and CO_2 are split into oxygen, hydrogen and carbon monoxide. At its end, electricity allows for the production of syngas which can be stored or converted into higher-value products (see 'Hydrogen utilization').

Fraunhofer IKTS has been working with SOE for more than 25 years and possesses extensive know-how across the complete value chain, from material to system, including analyses of economic viability. In recent years, developments at the institute have culminated in the incorporation of very successful new companies. Fraunhofer IKTS produces stacks and modules for integration in electrolysis plants on a pilot scale and optimizes them with regard to their long-term stability and performance (e.g. by increasing the current density up to 0.75 A/cm^2). The main focus is now on developing and testing industrial-scale automated stack production and modularization concepts for higher performance classes.

High-temperature electrolysis with proton-conducting electrolysis cells

In addition to oxygen-conducting electrolytes as used in SOE stacks, Fraunhofer IKTS also develops proton-conducting materials for electrolyzers used at temperatures between 550 to 600 °C. They provide hydrogen in a highly pure, water-free form, without any further treatment steps. If this process is combined with exothermal synthesis processes, the reaction heat can be used directly to supply the electrolysis with energy. This significantly increases the efficiency of the chemical conversion processes.

The main parameters for the use of proton conductors are proton conductivity, chemical stability and the polarization resistance between electrode and electrolyte. For this purpose, Fraunhofer IKTS develops electrolyte and electrode materials and converts them into planar stacks, in analogy with SOE technology.

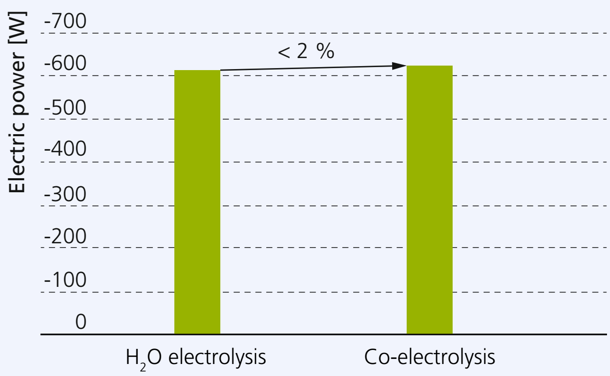
"HIGH-TEMPERATURE ELECTROLYSIS IS A KEY TECHNOLOGY FOR EFFICIENT HYDROGEN AND SYNGAS PRODUCTION."

Dr. Matthias Jahn, Head of Chemical Engineering, Fraunhofer IKTS

Alkaline large-scale electrolysis

Alkaline electrolysis (AEL) is an established industrial process for the production of hydrogen and oxygen. It uses an OH^--conducting liquid electrolyte and is operated at a temperature of approx. 80 °C. Thanks to its high maturity and low specific investment cost compared with other electrolysis technologies, it is currently the most widely applied process worldwide. However, alkaline electrolysis has not yet truly penetrated the market and automated production processes have not been established to date. This is why IKTS is optimizing stack and system components with regard to their energy density (current energy densities below 0.5 A/cm²) and ecological as well as design aspects (reducing the use of noble metal catalysts, increasing the active electrode area). Through long years of experience in SOE and MCFC stack construction, it is possible to make major steps toward improving ecological and economic parameters.

Energy consumption for water electrolysis and co-electrolysis in an SOE stack



High-temperature electrolysis enables the direct production of syngas for roughly the same amount of energy used. The electrolysis stacks of Fraunhofer IKTS have already proven their long-term stability on the lab scale, with a performance-related degradation rate of less than 0.5 %/1000 h.

Membrane electrolysis

Using low-temperature membrane electrolysis, it is possible to extract hydrogen efficiently from industrial and mining waters. Fraunhofer IKTS has developed its RODODAN® process for this purpose. In this process, the electrochemical treatment of sulfuric and sulfate-rich waters also produces, in addition to sulfate and iron, hydrogen as a usable byproduct. This process takes place in a membrane electrolysis cell whose electrode spaces are separated from each other by an anion exchange membrane. While a current is flowing, hydrogen ions are discharged at the cathode and hydrogen is removed as gas. Fraunhofer IKTS uses the findings obtained from the use of anion exchange membranes in this process for the further development of modern alkaline membrane electrolyzers (AEMEL).

1 *Long-term stable SOE stacks for use in electrolysis and fuel cell mode.*

2 *Test center for testing SOE stacks in co-electrolysis mode.*

1

HYDROGEN UTILIZATION

Hydrogen for climate protection

The use of hydrogen is aimed at reducing greenhouse gas emissions, like CO_2 and other climate-damaging gases, such as methane. Efforts focus primarily on applications which to date are using fossil energy carriers to provide electricity (e.g. coal and natural gas in power plants) or driving power (e.g. diesel or gasoline in vehicles).

However, a major share of CO_2 emissions in Germany – roughly 21 % – stems from complex industrial processes. The use of green hydrogen enables climate neutrality for processes in industry which today still result in high greenhouse gas emissions. This leads to two possible strategies: the use of CO_2 while employing hydrogen to produce valuable chemical products (carbon capture and utilization, CCU), and the complete avoidance of emissions by substituting carbon in the process chain (carbon direct avoidance, CDA).

Hydrogen as process gas

CO_2-free production processes

Ammonia and steel production are two particularly relevant areas with potential for reducing emissions where hydrogen-based concepts for direct CO_2 avoidance can be used very effectively. In steel production, coke is used in the established blast furnace process as reducing agent to convert iron ore into pig iron. To avoid the CO_2 typically released in this process, it is necessary to convert this reduction process from a coal-based one to a hydrogen- or syngas-based one. So-called direct reduction processes are already technically proven for operation with natural gas, but they can also be operated with hydrogen. The use of large-scale electrolyzers allows to significantly reduce emissions in steelmaking.

In particular, high-temperature electrolysis is an exceedingly promising technological approach in this regard, since available waste heat can be used to increase efficiency. Additionally, syngas can be produced within the electrolyzer. Fraunhofer IKTS develops process concepts based on its own solid oxide cells and stacks. These have a modular design to flexibly integrate renewable energy. This makes it possible to provide balancing power from the steel mill to the grid and support the renewable energy system.

FRAUNHOFER IKTS FOCUSES ON THE USE OF HYDROGEN AS RAW MATERIAL AND ENERGY CARRIER IN INDUSTRY.

Ammonia, a basic material for fertilizers, has become a key component for feeding the world population. In addition to nitrogen, the synthesis of ammonia also requires hydrogen. Hydrogen is currently produced from natural gas via steam reforming, with large amounts of CO_2 being released. Electrolysis represents an alternative approach. Since the established reforming process also yields the required nitrogen, this nitrogen needs to be made available other means, e.g. via air separation. This requires new and efficient processes, which especially need to be economically viable. Techno-economic

1 *Plant coupling co-electrolysis with Fischer-Tropsch synthesis to produce value-added products.*
2 *Long-chain alcohols from CO_2 and hydrogen.*

"UNAVOIDABLE CO_2 EMISSIONS COULD BE USED TO PRODUCE 10 TO 15 MILLION TONS OF CHEMICAL PRODUCTS PER YEAR."

Hydrogen Council

2

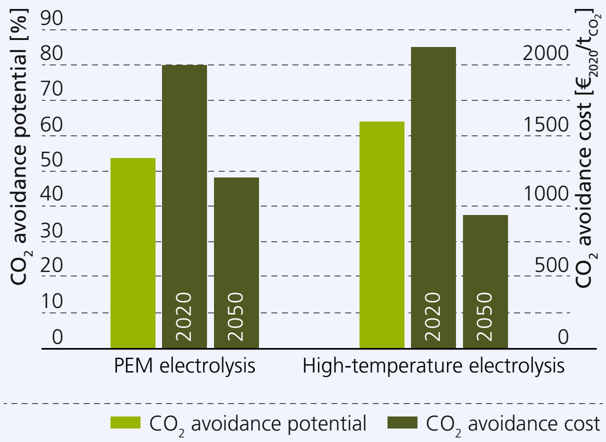
analyses conducted at Fraunhofer IKTS have shown that high-temperature electrolysis can also be used advantageously in such cases.

Low-CO_2 steelmaking or ammonia synthesis requires reconfiguring a large part of the traditional process chain. This is associated with high investment costs, but it in turn makes considerable emission reduction possible. As high-temperature electrolysis offers significant advantages with regard to operating cost, thanks to its high electric efficiency, efforts at Fraunhofer IKTS currently aim on a scale-up of the technology. In addition to the mentioned applications, the green hydrogen produced via electrolysis can also be used in the short term in existing refineries, replacing grey hydrogen from the steam reforming of natural gas.

CO_2 use for value-added products

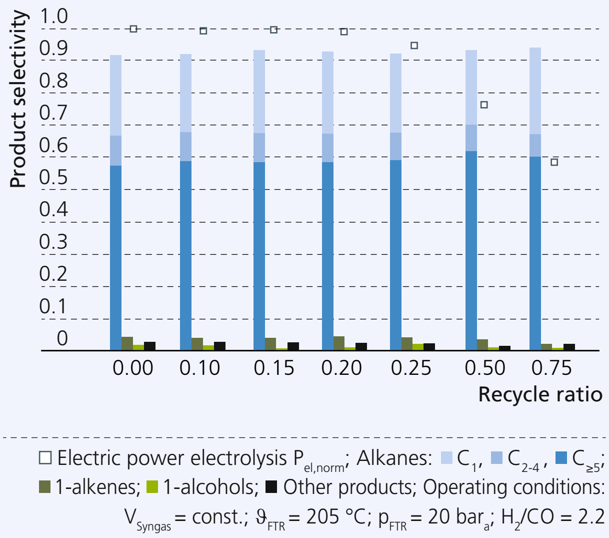
In addition to using hydrogen to avoid CO_2 emissions, it is also possible to utilize unavoidable CO_2 emissions as carbon source. This makes it possible to produce value-added products, such as fuels for air and heavy vehicle traffic or higher alcohols and waxes as starting materials for the cosmetics and chemical industries. Based on higher net profits, such value-added products are able to additionally increase the economic viability of new production routes, e.g. in the lime and cement industries. However, it is still necessary for large-scale applications to provide sufficient incentives for building and operating plants based on electrolysis.

A techno-economic look at CO_2 utilization for value-added products for the example of a lime plant



Compared with PEM electrolysis, high-temperature electrolysis offers a higher CO_2 avoidance potential and lower CO_2 avoidance cost.

Power-to-liquid process at lab scale



By combining high-temperature electrolysis with the Fischer-Tropsch synthesis a high-value product range with a large share of long-chain hydrocarbons is obtained.

Fischer-Tropsch synthesis as a technology is particularly well-suited for the production of value-added chemicals from CO_2 and hydrogen. This process yields a large number of different carbon-based products. In order to retain maximum levels of energetic efficiency and carbon utilization, the process must be coupled as closely as possible with electrolysis or co-electrolysis. Furthermore, the co-electrolysis process directly provides syngas. This will help to make the production of value-added chemical products as efficient as possible.

"UP TO 1600 KG OF CO_2 PER TON OF STEEL COULD BE SAVED WITH HYDROGEN-BASED DIRECT REDUCTION."

Deutsche Energie-Agentur GmbH

In addition to theoretical analyses of the process chain, Fraunhofer IKTS also focuses on extensive development efforts on ceramic catalyst supports and reactors for Fischer-Tropsch synthesis. A plant specifically developed and operated at IKTS was already able to demonstrate the complete process chain of the production of high-value products from CO_2 and H_2O. The know-how thus gained is currently put to the test in pilot and demonstration plants at industrial sites.

Hydrogen as energy carrier

Electricity and heat

Next to using green hydrogen to produce important base and value-added products, its use as chemical storage is another option. This makes hydrogen a key element of renewable energy systems, opening up various pathways for its direct utilization.

One option is hydrogen storage in suitable caverns and the reconversion of hydrogen into electricity as needed, using gas turbines or highly efficient high-temperature fuel cells. This provides balancing power for the power grid, helping to stabilize it even when the share of renewable energy sources is high. For this purpose, Fraunhofer IKTS has already designed and successfully applied system concepts going beyond fuel cells and stacks, for instance for the energy supply of households and for the conversion of biogas to electricity.

Also, hydrogen can in the future be used as a renewable alternative to fossil fuels in industrial firing plants in steel, lime and cement production in order to provide the high temperatures required by these industries. This is therefore another area where a reduction of CO_2 emissions can be achieved.

1 *Monitoring system for pressure tanks of vehicles running on hydrogen.*
2 *Low-CO_2 steel production through process integration of high-temperature electrolysis.*

Mobility

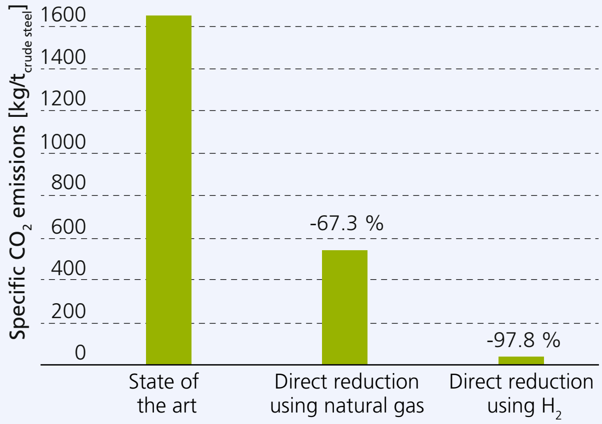
The mobility sector poses a particular challenge with urgent need for change. Over recent decades numerous initiatives failed to achieve reductions in CO_2 emissions in this field. Next to purely electric drives, trains and trucks working with hydrogen represent a potential solution in the mobility sector, in conjunction with expanding public transportation.

To make hydrogen technologies for mobility acceptable for the broader public, the available infrastructure needs to be economically efficient and, most of all, reliable. The main component for the storage of liquid hydrogen is the pressure tank, which is manufactured increasingly as a wound component made from carbon fiber reinforced plastics (CFRP).

For the permanent monitoring of hydrogen pressure tanks, Fraunhofer IKTS offers a monitoring system based on guided ultrasonic waves. If structural changes or defects in the material occur, the measured signals will deviate significantly from the original, defect-free state. By comparing the signals with entries in a defect database, we are able to localize and classify structural changes or defects. In the future it will additionally be possible to make statements on the pressure tank's remaining service life. The monitoring system can also be used to monitor hydrogen tanks in industrial settings.

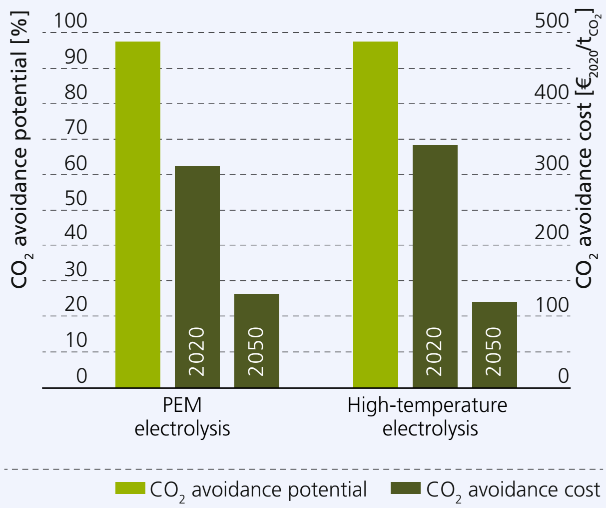
In addition to hydrogen- and battery-powered vehicles, synthetic hydrogen-based fuels are also set to gain in popularity. Next to heavy vehicle traffic, this is particularly relevant for the air traffic sector. In these areas, the processes for using CO_2 to produce synthetic jet fuel, developed by Fraunhofer IKTS, are particularly interesting.

Potential CO_2 savings in the steel industry



A hydrogen-based direct-reduction process may yield CO_2 reductions of up to 95 %.

Techno-economic look at CO_2-free production processes for the example of the steel industry



Compared with PEM electrolysis, high-temperature electrolysis offers lower CO_2 avoidance costs in the future.

1

HYDROGEN STORAGE AND TRANSPORT

Corrosion monitoring of hydrogen pipelines

In the future, large amounts of hydrogen that cannot be produced on-site will have to be transported to their consumers via pipelines. However, piping material in contact with hydrogen could become brittle and develop fast-growing cracks. To detect such corrosion early on and take appropriate measures, the pipelines will need to be reliably monitored.

Monitoring systems based on ultrasonic waves are a suitable solution. Fraunhofer IKTS has developed a concept centered around a sensor ring which is able to continuously detect defects and determine the remaining wall thickness in the case of extensive corrosion on horizontal, vertical, above-ground and underground piping. The sensor ring is permanently installed on the pipe. Installation is easy and usually does not require any modification to the piping system. Furthermore, the monitoring system can always be extended by interlinking a number of sensor rings.

"THE SUCCESSFUL SHIFT TO HYDROGEN REQUIRES A RELIABLE AND CONTINUOUS STORAGE AND TRANSPORT INFRASTRUCTURE."

Dr. Lars Schubert, Head of Condition Monitoring Group, Fraunhofer IKTS

The ring's integrated piezoceramic sensors transmit guided ultrasonic waves into the pipes. As the ultrasonic waves spread, pipe damage causes scattering and reflections. Combined with integrated signal processing, these effects are used to identify and localize defective areas.

Unnecessary digging, the removal of coating or scaffolding is avoided. Since guided ultrasonic waves travel across wide distances mostly undampened, long pipe sections can be permanently monitored from one single location. Moreover, it is possible to check hard-to-access pipes at regular intervals.

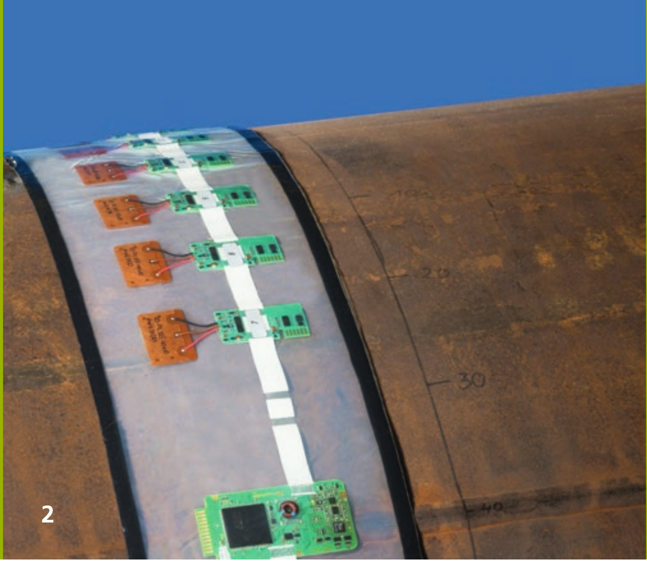
Depending on environmental conditions and requirements, various sensors of different temperature classes or custom-made versions for explosion-proof areas can also be connected. No cables are required for energy supply and to read out sensor data. This completely removes the need for plug connections on the measuring system, increasing operational reliability.

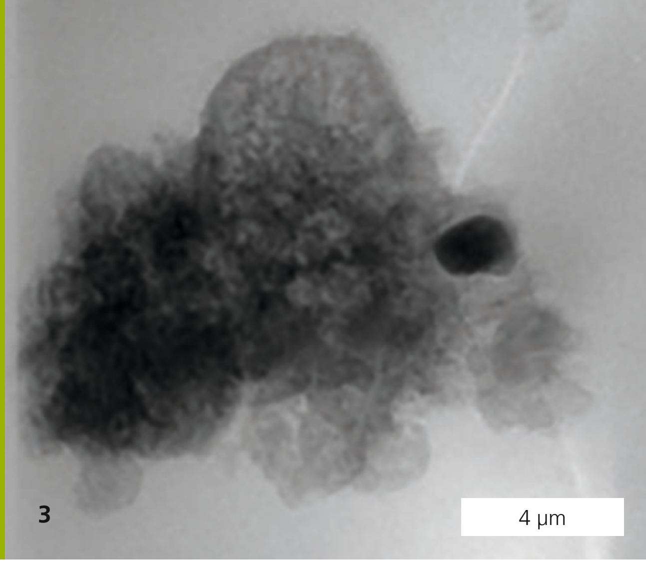
Gas sensors for leak detection

Due to the flammability of hydrogen in air, reliable sensor systems must ensure that hydrogen and methane can be detected reliably. For this purpose, Fraunhofer IKTS develops pressure, flow and temperature sensors based on LTCC technology. Compared with steel, ceramic materials provide high stability against hydrogen embrittlement, especially high sensitivity and reliable operation in hydrogen environments. Furthermore, the LTCC technology used provides very complex structuring options and enables a three-dimensional design for the sensors. This guarantees a high degree of versatility when it comes to the design and geometry of the elements integrated in the sensor, such as chambers, membranes and channels. Thus, gas sensors are easy to miniaturize and adapt to specific application scenarios.

Hydrogen separation from hydrogen-natural gas mixtures

Some parts of the existing natural gas infrastructure, such as natural gas filling stations, are only able to cope with one or two percent by volume of hydrogen concentration. Therefore, it is necessary to separate hydrogen from natural gas before distributing it through the existing natural gas grid. Fraunhofer IKTS is developing separation processes based on carbon membranes, which compared with pressure swing adsorption or





FRAUNHOFER IKTS PROVIDES SAFETY AND MEASURING TECHNOLOGY FOR HYDROGEN INFRASTRUCTURE.

cryogenic separation processes constitute a cost-efficient option and are resistant against harsh environmental conditions and natural gas-attendant materials, such as hydrogen sulfide. Carbon membranes are chemically inert and possess a much higher permeability and selectivity than polymer membranes. A single-step membrane process can separate up to 90 percent of hydrogen from hydrogen-natural gas mixtures. Further reduction of the share of hydrogen within the natural gas down to less than two percent is possible with an enlarged membrane surface or in a two-step membrane process.

Analytics for tank, pipeline and storage materials

When selecting materials for hydrogen applications, the effect of hydrogen on material properties needs to be taken into account, whether the hydrogen exists in liquid or gaseous form.

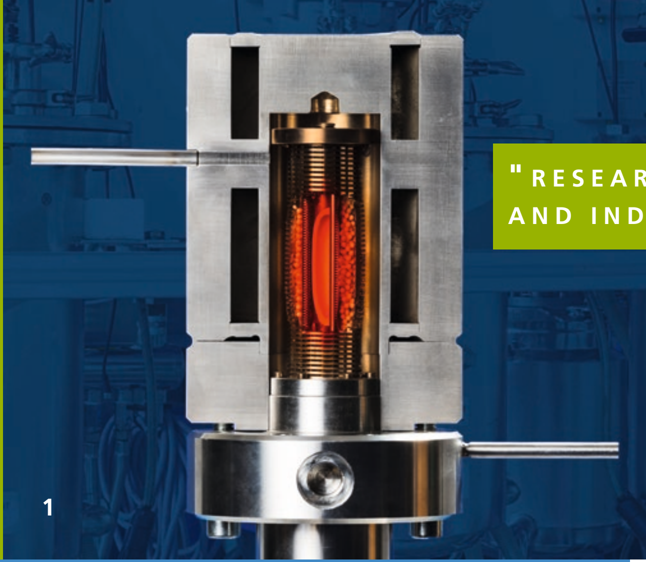
In order to examine the interactions, Fraunhofer IKTS is able to use highly modern 3D nanoanalytics to cover scales from the sub-nanometer to centimeter range. For instance, it is possible to characterize and visualize in nanometer resolution 3D structures of hierarchic materials used in electrocatalytic hydrogen production. Furthermore, we can determine information on the chemical composition, crystallographic properties, bonding states, mechanical properties and boundary surface properties.

Processes such as the hydrogen release in storage materials or the propagation of cracks in pipelines where the materials are undergoing changes can be initiated in-situ and operando in a time-dependent manner and mapped microscopically. It is thus possible to directly observe potential failure mechanisms and optimize hydrogen storage and release processes.

1 *Ceramic pressure sensors for use in hydrogen environments.*

2 *Sensor ring providing wireless communication and energy transmission for permanent monitoring of hydrogen pipelines.*

3 *In-situ nanoXCT image of hydrogen release using radiography.*



1

"RESEARCH IS A STRATEGIC ELEMENT OF ENERGY AND INDUSTRIAL POLICY."

National Hydrogen Strategy of the German Federal Government

PREPARATORY RESEARCH

Tandem solar modules for hydrogen production

Established concepts for producing solar hydrogen use a combination of photovoltaic systems and electrolyzers for water splitting. However, this is a highly complex technology, meaning investment and maintenance costs are considerable. In contrast, direct photocatalytic water splitting without electrolyzers has some clear economic advantages in operation. Furthermore, its low system complexity makes it more reliable and means it hardly requires any maintenance. At the core of this new development is a tandem solar module, where the photoanode and the photocathode are installed on opposite sides of a transparent carrier plate. When the system is irradiated with sunlight, the cathode side will release hydrogen and the anode side will release oxygen. To increase efficiency, Fraunhofer IKTS is developing novel highly pure semiconductor materials and gentle coating technologies. This will help to significantly alleviate the current problem of the defect density of materials, and thus increase the hydrogen yield. The tandem module can be scaled as needed and is therefore an attractive option for the decentralized production of green hydrogen.

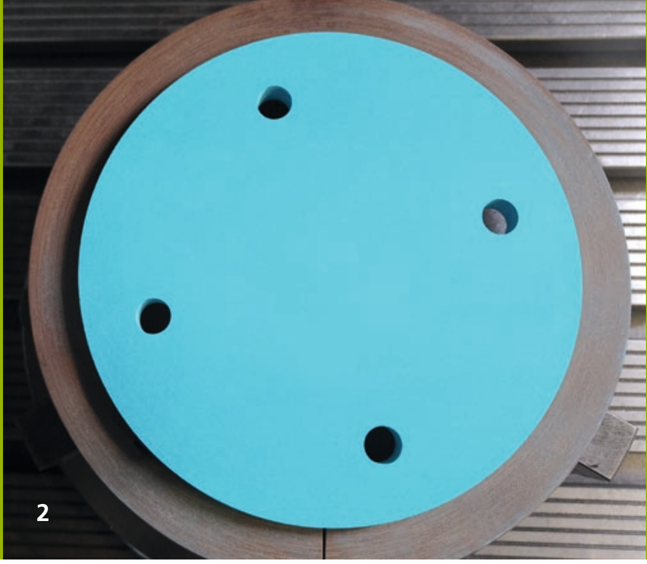
Metal-organic frameworks (MOF) for hydrogen storage

Next to compressed gas and liquefied gas storage systems, hydrogen can also be stored in porous metal-organic frameworks (MOF). These frameworks provide up to 90 % porosity and bind the hydrogen in the storage tank. Larger amounts of hydrogen can thus be stored without increasing the pressure inside the hydrogen tank. The important thing here is to fill the tank with the largest possible amount of MOFs without damaging them. Due to this, the production of MOFs is mostly about finding a compromise between sufficient mechanical stability of the body and maintaining the original MOF properties as best as possible in the molded body. Fraunhofer IKTS develops various shaping techniques to achieve this. MOFs can be used e.g. as pellets and granules in bulk or as monolithic structures, such as large-format discs or honeycombs.

FRAUNHOFER IKTS CONDUCTS PREPARATORY RESEARCH FOR FUTURE APPLICATIONS.

Membrane reactors for hydrogen production for ship propulsion

Ships transport around 90 percent of global goods. At the same time, they are among of the worst CO_2 offenders as climate-friendly propulsion for ships is still not available. In this context, Fraunhofer IKTS is conducting research in membrane reactors which enable the on-board production of hydrogen from renewables-based methane, which can then be fired in the ship's engine with almost no CO_2 emissions. Two processes take place inside the membrane reactor: Methanol and water are converted to CO_2 and hydrogen before being separated via membrane permeation. The separated CO_2 can later be re-used for on-shore methanol production, leading to a closed CO_2 cycle for ship propulsion. The carbon membranes with ceramic support used in the membrane reactor are able to withstand high reaction and hydrogen pressures and enable a high reactor throughput. Moreover, the membranes are resistant to reaction byproducts.



Micro turbine fuel cell system for reconverting hydrogen

The reconversion of hydrogen and methane into electricity is an important component of any future hydrogen economy. Fraunhofer IKTS is working on a solid oxide fuel cell that will enable effective supply for residental buildings. The fuel cell is able to use hydrogen as well as methane. To increase fuel cell efficiency, it is connected with a micro turbine to create a smart closed loop system. One advantage of this is that the turbine compresses and pre-heats the required air before the latter is used for energy production in the fuel cell. Furthermore, the exhaust gas produced in the fuel cell can be used for additional electricity production in the turbine.

Hydrogen supply for autonomous process sensors

Autonomous IIoT and IoT applications (industrial internet of things and internet of things) can benefit greatly from fuel cells running on hydrogen. Based on LTCC technology, Fraunhofer IKTS is developing versatile micro fuel cell systems with an output range of 150 mW to 5 W. The systems can be implemented both with integrated hydrolysis-based hydrogen supply and with integrated hydrogen tanks. In this context, LTCC technology offers the option of designing the fuel cell stacks and the valves as planar, thus creating a compact overall system. The ceramic valves perform two functions here. For one, they control hydrogen supply to the tank. Second, they dose the hydrogen to the fuel cell stack – according to the energy demand. Thanks to their high sensitivity, hydrogen supply can be accurately regulated.

Development of highly productive roll-to-roll manufacturing processes for fuel cell components

Electrification of the power train combined with hydrogen as a CO_2-free energy carrier is an integral part of the strategy pursued by international car manufacturers and energy suppliers. However, the manufacturing costs for fuel cells running on hydrogen are currently still very high. Fraunhofer IKTS is developing highly productive roll-to-roll techniques for the mass market, which allow to efficiently manufacture the required main components. This includes, for instance, membrane-electrode assemblies (MEA).

1 *Membrane reactor based on carbon membranes for the efficient hydrogen production for ships.*

2 *Large-format MOF molded body for gas storage.*

3 *Industrial-scale roll-to-roll manufacture of fuel cell components.*

COMPETENCIES

Manufacture of key components

Electrolysis cells and stacks

- Characterization of electrode materials
- Manufacture of electrolysis cells and stacks
- Manufacture and testing of short stacks for electrochemical water purification and accompanying hydrogen production
- Automation, upscaling of stack production
- Long-term testing of SOE components and stacks

Membranes and membrane reactors

- Development of nanoporous membranes
- Upscaling of membrane preparation up to industrial scale including production of samples
- Development of membrane reactors for the synthesis of methane, methanol and other products
- Use of membranes for hydrogen dosing, separation, purification, and for storage
- Conceptualization and equipment of pilot plants

Catalyst supports, catalysts and reactors

- Selection and development of catalysts and catalyst support structures, e.g. iron-based Fischer-Tropsch catalysts for the synthesis of higher alcohols
- Characterization of catalysts and reaction products
- Development of modular reactor concepts
- Modeling and simulation of flow processes
- Reactor testing

Development and optimization of electrolysis processes

- Modeling of the operating behavior of electrolysis stacks
- Thermomechanical analysis of stress mechanisms in electrolysis stacks
- Simulation of heat transfer and flow processes
- Development of innovative process concepts, e.g. coupling of co-electrolysis and Fischer-Tropsch synthesis
- Modeling of process steps and overall processes
- Implementation of processes at lab and pilot scale, e.g. electrochemical treatment of mining and pit water for use in power-to-X processes
- Conducting of feasibility studies, e.g. assessment of the emission reduction potential of hydrogen-based direct-reduction for steelmaking
- Testing of prototype plants, e.g. production of waxes from biogas or from CO_2 separated from lime plants

Process assessment

- Energetic analysis of process concepts
- Techno-economic assessment of power-to-X methods for the production of hydrogen, hydrocarbons and ammonia
- Sustainability assessment

Monitoring and safety control

- Consulting and development of condition-oriented maintenance concepts (simulation, measuring techniques, data processing, energy supply, integration)
- Development and provision of reliable sensors, electronics and adapted monitoring systems
- Performance of field tests, certification

Analytics

- Multiscale characterization of complex hierarchical materials using 3D nanoanalytics
- Visualization of processes (hydrogen release, crack propagation, etc.) using high-resolution analytical methods (REM, TEM, nanoXCT), combined with operando and in-situ experimental designs

COLLABORATION

Innovation and development are the cornerstones of a promising future for any company. In order to create a competitive edge, we offer tailored options for cooperation, so that small and medium-sized companies can collaborate with Fraunhofer in the best possible way. This also allows development skills to be accessed and applied at short notice and as needed.

Individual contracts

An individual contract is the classic form of collaboration. The company has become aware of a need for research or development. In accordance with the requirements of the company, Fraunhofer IKTS develops a solution that is compliant in terms of deadlines and quality.

Public-funded collaborative projects

Some problems are so complex that several partners are needed to develop a solution together. In such cases, the complete environment of the various Fraunhofer institutes is available. External partners may also be consulted.

Strategic partnerships and innovation clusters

Preliminary research, which first takes place independent of contract work, often leads to long-lasting partnerships with companies on a regional and international level.

Spin-offs

Fraunhofer employees often use new developments to become founders of company start-ups, of which the Fraunhofer group can become a shareholder. In some cases, even strategic investments and joint ventures are possible. The clients under whose contract the new development was created may also become shareholders of a new spin-off.

Licensing models

Licenses are a way to give third parties permission to use certain industrial property rights under defined terms and conditions. In this way innovations can be used where one's own further development would result in high costs, the capacities are not sufficient to achieve marketability, or where the innovation would not fit into the existing service portfolio. Fraunhofer IKTS offers flexible licensing models for company-wide use to optimize one's own portfolio or to market services to the end client.

1 *Demonstration plant for coupling co-electrolysis and Fischer-Tropsch synthesis for producing base products for the chemical industry.*

2 *Test stand for testing carbon membranes for hydrogen dosing and separation.*

FRAUNHOFER IKTS IN PROFILE

The Fraunhofer Institute for Ceramic Technologies and Systems IKTS conducts applied research on high-performance ceramics. The institute's three sites in Dresden and Hermsdorf (Thuringia), Germany, collectively represent Europe's largest R&D institute dedicated to the study of ceramics.

As a research and technology service provider, the Fraunhofer IKTS develops advanced high-performance ceramic materials, industrial manufacturing processes as well as prototype components and systems in complete production lines up to the pilot-plant scale. In addition, the research portfolio also includes materials diagnostics and testing. The test procedures in the fields of acoustics, electromagnetics, optics and microscopy contribute substantially to the quality assurance of products and plants.

The institute operates in nine market-oriented business divisions in order to demonstrate and qualify ceramic technologies and components as well as non-destructive testing methods for new industries, product concepts and markets within and beyond the established fields of application. Industries addressed include ceramic Materials and Processes, Mechanical and Automotive Engineering, Electronics and Microsystems, Energy, Environmental and Process Engineering, Bio- and Medical Technology, Non-Destructive Testing and Monitoring, Water as well as Materials and Process Analysis.

www.ikts.fraunhofer.de

202-B-21-1-15

CONTACT

Industrial solutions
Hydrogen technologies

Dr. Matthias Jahn
Fraunhofer Institute for Ceramic Technologies and Systems IKTS

Winterbergstr. 28
01277 Dresden, Germany
+49 351 2553-7535
matthias.jahn@
ikts.fraunhofer.de