Karlsruhe Institute of Technology

HYDROGEN

Pathways for Progress

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DEAR READER,

Hydrogen is the lightest element in the world and the most abundant chemical element in the universe, its share being about 70 percent. Will it help solve major problems of the present and future? Our answer at KIT is Yes.

To transform the energy system and reach the climate protection goals, new technological approaches are required. The energy crisis has clearly shown that a high-technology country like Germany is highly dependent on clean, safe, and affordable energy supply. KIT – The Research University in the Helmholtz Association demonstrates how the big potential of hydrogen can be used to couple the sectors of energy, industry, and mobility and to make them sustainable – by research along the pathways for progress.

Hydrogen is an energy carrier that can be stored, used flexibly, and transported easily. When produced with renewable energy, it is climate-neutral. This green hydrogen may well be the key element of sustainable energy supply. And it can also be used for the sustainable synthesis of various products by chemical industry.

At KIT, hydrogen is the subject of research of a number of disciplines in natural sciences, engineering, economics, and social sciences. The spectrum of research topics extends from production to storage to distribution to use to safety aspects to acceptance by society to the technical and economic integration of hydrogen in the energy system.

KIT researchers are involved in all three hydrogen flagship projects funded by the Federal Ministry of Education and Research (BMBF). They address the series production of electrolyzers, production of hydrogen at sea, and hydrogen transportation. KIT possesses unique infrastructures to study important aspects of innovative hydrogen technologies. At KIT's Energy Lab, Germany's future energy system can be tested, including processes relating to hydrogen. For quite a few years now, KIT has been operating a H_2-fueled shuttle bus for staff and students to gain expertise from the daily use of hydrogen.

This brochure provides an overview of KIT's wide range of hydrogen research activities as well as in-depth insights into exemplary projects. We hope that it will give you an impression of the diverse and important pathways for progress associated with hydrogen.
I wish you an interesting read.

Yours,

R. Hirth

Professor Dr. Thomas Hirth
Vice President Transfer and International Affairs

HYDROGEN IN THE FUTURE ENERGY SYSTEM

Hydrogen is the most abundant element in the world. Does it provide unlimited opportunities for tomorrow's energy supply? Hydrogen definitely is an incredibly versatile substance, but also a demanding one. On Earth, it mainly does not exist as a gas, but in bound form. Supply of molecular hydrogen (H_2) requires very much energy. When the power used for this purpose comes from renewable sources, such as the sun and wind, so-called green hydrogen results. It is climate-neutral, because no CO_2 was emitted in the course of its production and the production of its precursors, i.e. the electrical energy applied. Hydrogen is no source, but a carrier of energy. It can be compared with electrical power, but unlike the latter, it can be stored well. Electrolysis and reconversion enable a useful relationship between electrical power and hydrogen. With electrical power, hydrogen can be produced. If needed, hydrogen can be converted into electrical power or heat again. Hydrogen produced by electrolysis with green power enables power-to-X technologies to store excessive power at times when solar energy and wind power supplied exceed consumption. This will make the future energy system more flexible, more robust, and less dependent on fossil coal, oil, and gas. Hydrogen can be used to operate not only fuel cells, but also combustion engines in an efficient and climate-neutral way. Green hydrogen may also be applied for the synthesis of various substances by steel and chemical industries. Examples are methanol or ammonia that is needed for the production of nitrogen fertilizers. Using hydrogen, the CO_2 balance of various products can be optimized significantly. Hydrogen technologies also allow for the coupling of the energy, industry, and mobility sectors, thus opening up further potential for a climate-friendly future.

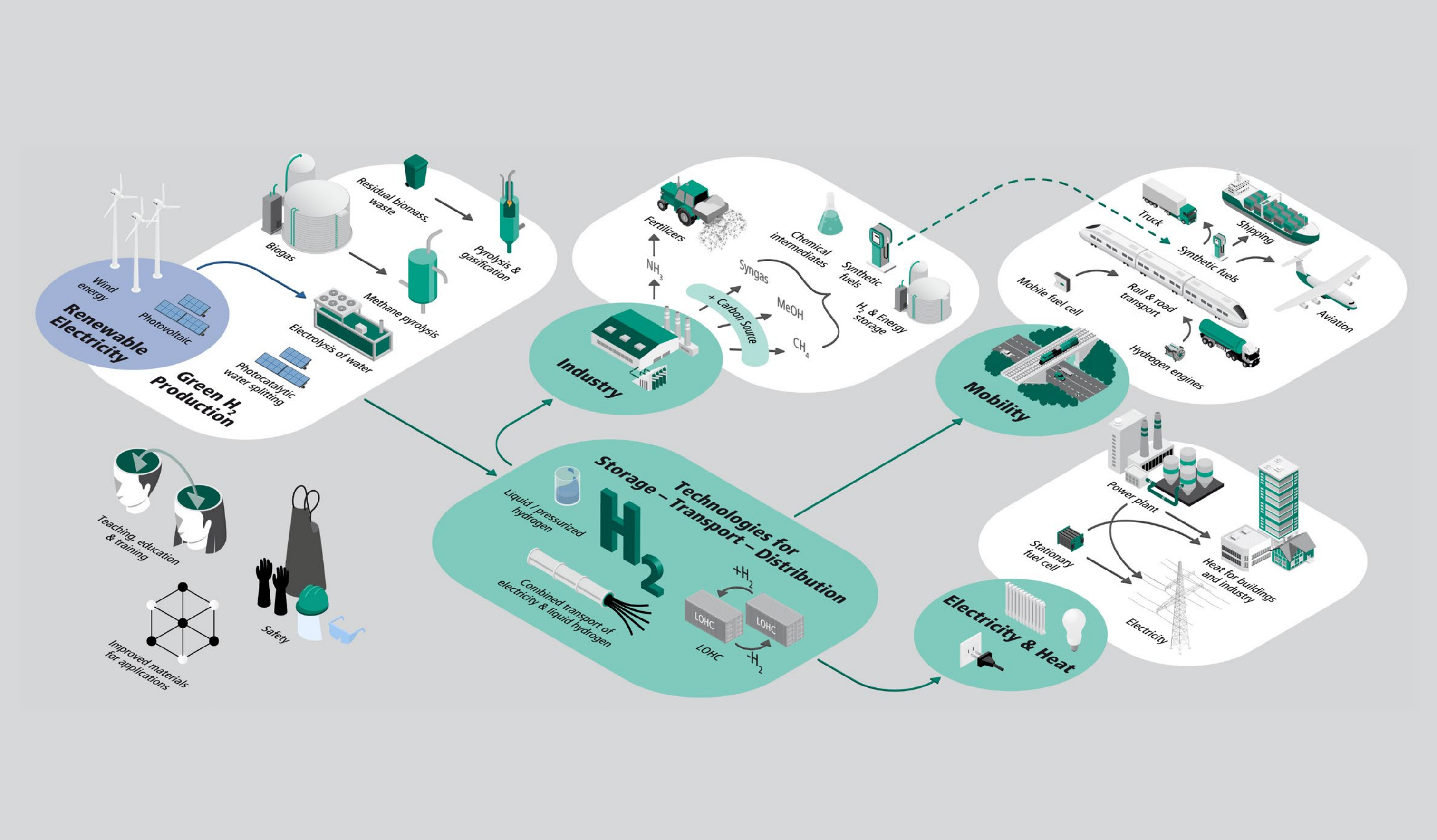
Molecular hydrogen (H_2) is an energy carrier having high potential for a climate-neutral future. Figure: iStock

HYDROGEN RESEARCH AT KIT

KIT's precursory institutions already studied hydrogen technologies. In the 1970s and 1980s, the then Karlsruhe Nuclear Research Center operated a test facility for nuclear fusion research and a hydrogen test vehicle driven by fuel cells, among others. Interest in the use of hydrogen for the mobility sector increased as a result of the oil crises in 1973 and 1979, but soon dwindled again, because the concepts were deemed to be too costly. In recent years, science and industry refocused on hydrogen to achieve the required transformation of the energy system and make it climate-neutral. Current research at KIT covers many aspects of hydrogen production, distribution, storage, and use and additionally addresses the overarching topics of safety and acceptance by society. KIT students are offered study courses along the entire value chain of hydrogen. Moreover, KIT researchers contribute their expertise to all three hydrogen flagship projects funded by the Federal Ministry of Education and Research (BMBF). The H2Mare flagship project focuses on offshore production of hydrogen. Thanks to the favorable wind conditions at sea and the high number of full-load hours, offshore wind parks reach a very high energy yield. Within H_2Mare, researchers explore the use of offshore wind energy without connection to the grid for the production of green hydrogen by water electrolysis, for instance. The goals are to reduce costs of green hydrogen and to increase economic efficiency. At KIT, researchers study how the green hydrogen produced on an offshore platform can be turned into products that are easy to transport and suited for use in chemical industry or fuel production, such as liquefied methane, liquid hydrocarbons, methanol, and ammonia.

The TransHyDE flagship project is aimed at developing green hydrogen transportation technologies and infrastructures. At KIT, researchers use the high energy density and cold of liquid hydrogen and combine hydrogen technologies with electrotechnical applications to develop high-temperature superconductors for energy transport and powertrains of vehicles. In addition, researchers conceive strategies to ensure safety of materials and safe handling outside of industrial facilities. At the KIT facilities, researchers can study and implement the entire chain from hydrogen liquefaction to electrical engineering applications to fuel cells.

The H_2Giga flagship project covers low-cost series production of electrolyzers for the production of green hydrogen based on renewable energy sources. KIT is involved in two collaborative sub-projects. Within "HTEL-Stacks – Ready for Gigawatt," project partners develop cell stacks for high-temperature electrolysis and associated production processes and facilities. Electrolysis at high temperatures requires less cost-intensive electrical power. The increased need for thermal energy can be covered by the waste heat produced in the cell. The "Stack Scale-up – Industrialisierung PEM Elektrolyse" sub-project aims to develop new stack technologies and methods for the series production of low-temperature electrolyzers. This electrolysis based on polymer electrolyte membrane (PEM) cells is characterized by low operation temperatures and a high power density.



KIT's hydrogen research covers a broad spectrum of technologies. Graphics: KIT

HYDROGEN PRODUCTION


A pressureless solid oxide cell water vapor electrolyzer of 150 kW, which can also be operated in the fuel cell mode, at Energy Lab on KIT's Campus North. Photo: KIT

Hydrogen can be produced by a variety of methods based on various chemical reactions. The method of choice depends on a range of criteria, including the availability of raw materials, energy source, scalability, and environmental compatibility. Industrial hydrogen production frequently takes place by steam reforming. Using steam at high temperature and a catalyst, natural gas is converted into hydrogen and carbon dioxide. This method requires very much energy. Moreover, the carbon dioxide produced adversely affects the climate, unless it is separated and stored.

By means of water electrolysis, water is split into hydrogen and oxygen with electrical power. It is an environmentally compatible hydrogen production method, provided that the power needed is supplied from renewable energy sources. Pyrolysis means that a carbon-based material, such as biomass or natural gas, is heated to very high temperatures in the absence of oxygen. This thermal decomposition gives rise to various gases, including hydrogen.

Certain microorganisms, such as bacteria, also produce hydrogen as a metabolic by-product. This process is referred to as biological hydrogen production. Among the approaches pursued is the cultivation of algae in bioreactors and the fermentation of biomass. Solar hydrogen production uses solar energy to split water into hydrogen and oxygen. This may be achieved directly by photolysis or indirectly by the use of solar cells and electrochemical methods.

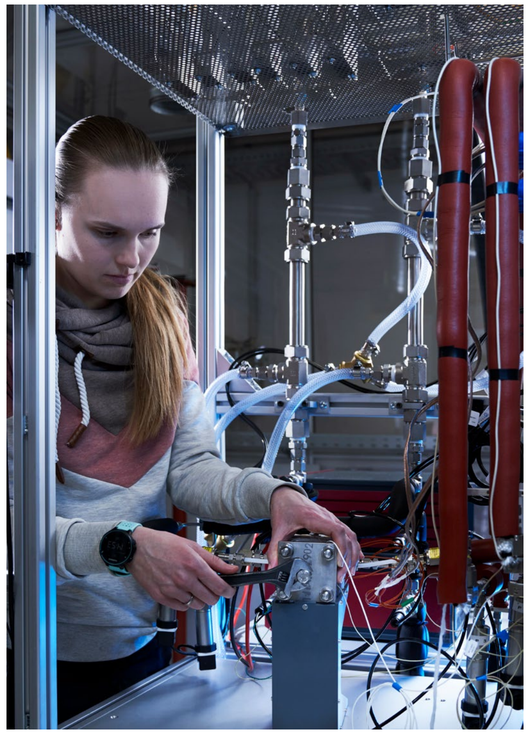
KIT explores several hydrogen production methods, some of which are presented below.

HIGH-PERFORMANCE ELECTROCATALYSTS AND ELECTROLYSIS CELLS

Water electrolysis represents an important pathway for hydrogen production: With the help of electrical energy, water is split into oxygen and hydrogen. For several years now, the Institute for Applied Materials – Electrochemical Technologies (IAM-ET) has been working on the analysis and optimization of electrocatalysts and electrolysis cells for water electrolysis.

Professor Dr.-Ing. Ulrike Krewer studies the processes at the oxygen electrode, where the electrical power is used to split water into oxygen and the electrons and hydrogen ions needed for hydrogen. The underlying reaction pathways are highly complex and responsible for most of the energy losses in electrolysis cells. Development of optimized high-performance electrocatalysts accelerates reactions by lowering the activation energy. This makes water electrolysis more efficient. The group of Dr. Philipp Röse has developed a new digital analysis method to evaluate catalyst experiments and to identify and quantify those surface processes that impede the splitting of water. This digital twin then allows for the knowledge-based development of more powerful electrocatalysts for electrolysis.

Work of the group of Dr.-Ing. André Weber focuses on the characterization and modeling of various electrolyzers. Dynamic measurements and the models derived from them provide essential information on high- and low-temperature electrolysis cells and help increase their efficiency and service life.


Characterization of a PEM electrolysis cell under high pressure. Photo: IAM-ET/KIT

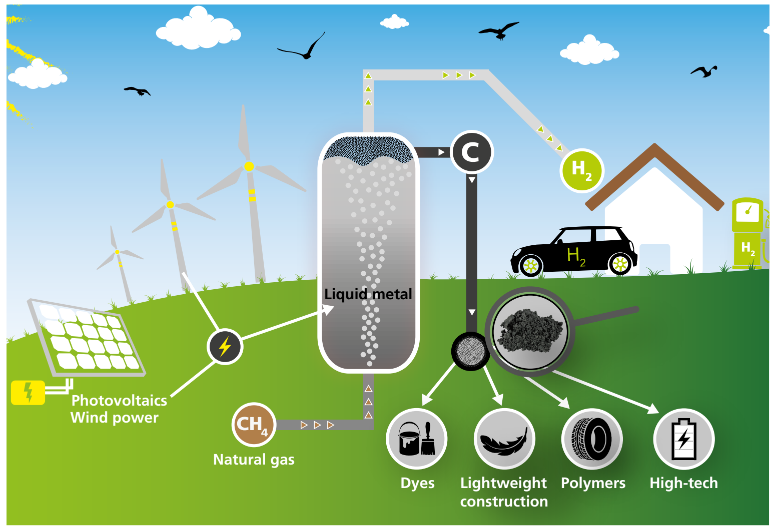
ELECTROLYSIS – HYDROGEN FROM WATER


The Silyzer 100 by Siemens Energy is a pressure-driven PEM water electrolyzer installed at KIT's Energy Lab. Photo: IMVT/KIT

At Energy Lab, KIT's Institute for Micro Process Engineering (IMVT) and industry partners study different electrolysis processes embedded in power-to-X process chains. For this, a pressure-driven proton exchange membrane (PEM) water electrolyzer of up to 50 bar and 100 kW power and a pressureless water vapor electrolyzer based on solid oxide cells (SOC) of 150 kW power are available. It is planned to soon install an SOC-based pressureless water vapor and carbon dioxide electrolyzer for the direct supply of synthesis gas by parallel electrolytic splitting of water vapor and carbon dioxide. The Energy Lab's system for hydrogen and synthesis gas production also includes a compressor for the two pressureless electrolyzers. It compresses hydrogen or synthesis gas to pressures of up to 50 bar. Energy Lab also accommodates a 50 bar hydrogen pressure tank of 50 cubic meters capacity and a unit to remove humidity and trace amounts of oxygen before hydrogen is fed into the pressure tank needed in case of PEM. Presently, an anion exchange membrane (AEM) water electrolyzer is being installed. It comprises eight modules of 2.4 kW power each.

Studies of hydrogen and synthesis gas production focus on technologies to use the substances and heat produced by electrolysis in downstream synthesis or upstream carbon dioxide production processes. Research is aimed at characterizing load-flexible operation of electrolyzers in different power-to-X process chains and at identifying optimum dimensions of interim storage systems of hydrogen or synthesis gas.

PYROLYSIS – HYDROGEN FROM NATURAL GAS



In a bubble column reactor with hot tin, methane is split into gaseous hydrogen and solid carbon. Graphics: Leon Kühner/KIT

At the KArlsruhe Liquid-metal LAboratory (KALLA) of KIT's Institute for Thermal Energy Technology and Safety (ITES), researchers use liquid metals for chemical processes at temperatures above 1000 °C. Such processes also include CO2-free production of hydrogen by thermochemical splitting of methane gas in liquid tin. Methane is split into gaseous hydrogen and solid carbon. Hydrogen can be used as a clean energy carrier, carbon is a valuable material for use in industry. KALLA has developed the pyrolysis of methane in a liquid-metal bubble column reactor. Methane gas enters the reactor via a nozzle at the bottom and is released in the form of bubbles. Due to the difference in density, these bubbles then ascend and form a type of microreactor chamber for splitting during pyrolysis. Thanks to the hot tin, methane rapidly reaches the required reaction temperature, such that it is split while the bubbles are ascending. The bubble surface acts as a wall on which carbon deposits. When the bubbles reach the top of the reactor, they burst and release a mix of hydrogen, carbon, and residual methane. The latter is fed back into the pyrolysis process again.

Within the framework of an ongoing project, ITES and its industry partner Wintershall Dea study how this method can be implemented efficiently on the industrial scale. Apart from pyrolysis experiments with pure methane and natural gas, work also covers investigations of various reactor materials. To keep thermal pyrolysis CO_2-free, researchers study possibilities to use heat from a renewable source, i.e. solar energy, within the "Solar Hydrogen – Highly Pure and Compressed" project funded by the Helmholtz Association. They assess the advantages and limits of different solar-heated reactors and study the use of concentrating solarthermal power (CSP) for heat supply.

STORAGE AND TRANSPORT

Hydrogen can be distributed by pipelines, filling stations, and tank trucks. Efforts are being made to establish a hydrogen pipeline system for transporting hydrogen over longer distances. The existing natural gas grid might also be used for hydrogen in principle. This would reduce investments in new infrastructures. Stepwise blending of natural gas with hydrogen is possible.

Hydrogen tanks at KIT. Photo: KIT

Hydrogen can be compressed to high pressures and stored in pressure vessels, such as gas cylinders or high-pressure tanks. Compressed hydrogen has a high energy density, but requires special tanks and safe handling. Moreover, hydrogen can be stored in liquid form when it is cooled to very low temperatures. Liquid hydrogen has an even higher energy density than compressed hydrogen, but requires special, well-insulated, and cooled tanks in order to maintain the low temperatures.

Hydrogen can also be stored in chemically bound form. An example is hydrogen storage in the form of methanol or ammonia. These compounds can be converted into hydrogen again by either thermal or catalytic processes.

It is also possible to store hydrogen in metal hydrides that chemically bind hydrogen. Hydrogen is stored at interstitial sites of the metal and released again, if needed. Metal hydrides represent a safe and compact means to store hydrogen, but require special materials and temperatures for storage and release.

The method of choice will depend on various criteria, such as the amount of hydrogen, infrastructure, and safety requirements.

HYBRID PIPELINES FOR LIQUID HYDROGEN AND ELECTRICAL ENERGY

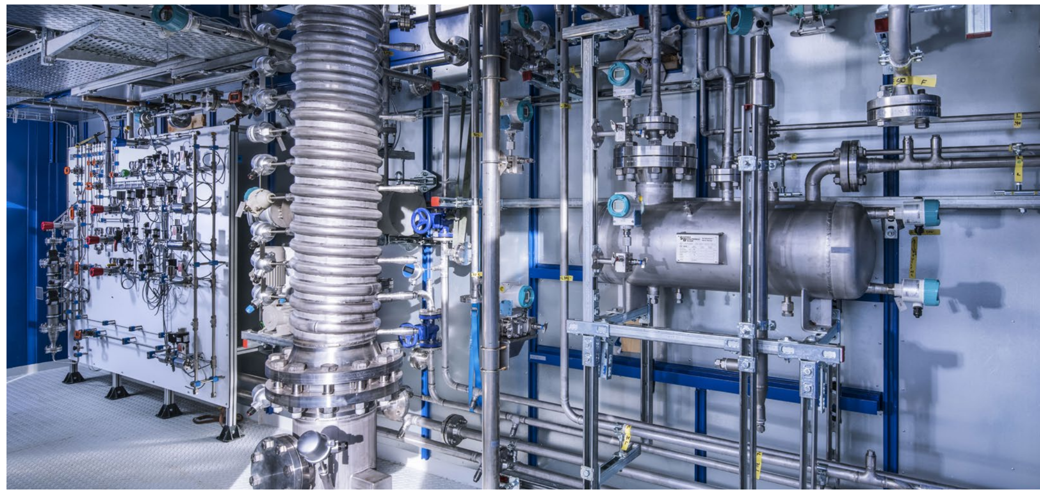
Hydrogen has a high mass-related energy density. Volume-related density of gaseous hydrogen, however, is small, even under pressure. Liquid hydrogen (LH_2) therefore is advantageous for many applications and some transport options. When transported by ship, hydrogen already arrives in liquefied form. Hence, it is reasonable to also transport it in the form of LH_2 to industry and mobility centers. The Institute of Technical Physics (ITEP) combines LH_2 pipelines and high-temperature superconductor cables in highly efficient hybrid pipelines. Superconductors are materials that have zero electrical resistance below the so-called transition temperature. Cooling of the hybrid pipeline below the transition temperature is achieved by means of the liquid hydrogen. No additional expenditure is required.

Model of a cable for hybrid pipelines. Photo: Mira Wehr, ITEP/KIT

Within the framework of the AppLHy! project, ITEP, other institutes of KIT, and external partners work on the development and setup of a test environment for such hybrid pipelines. In future, they might help cover not only the increasing hydrogen need, but also the increasing power demand due to electrification of all sectors. Hybrid pipelines will reduce the need for redispatch in the power grid and the associated costs. Combined transport of liquid hydrogen and electrical power is reasonable in case of longer distances, high distribution needs, densely populated regions, and if both forms of energy are needed.

Wires made of high-temperature superconductors have a layered structure. The superconducting layer has a thickness of a few thousandths of a millimeter only and is made of several elements. The wires contain very small fractions of rare earths. As regards pipeline technology, ITEP possesses vast know-how of the handling of liquid gases. Components, such as pumps or heat exchangers, are adapted to the requirements of LH_2.

METHANATION – GREEN HYDROGEN AS A BASIS


View into the three-phase methanation container. Photo: Amadeus Bramsiepe/KIT

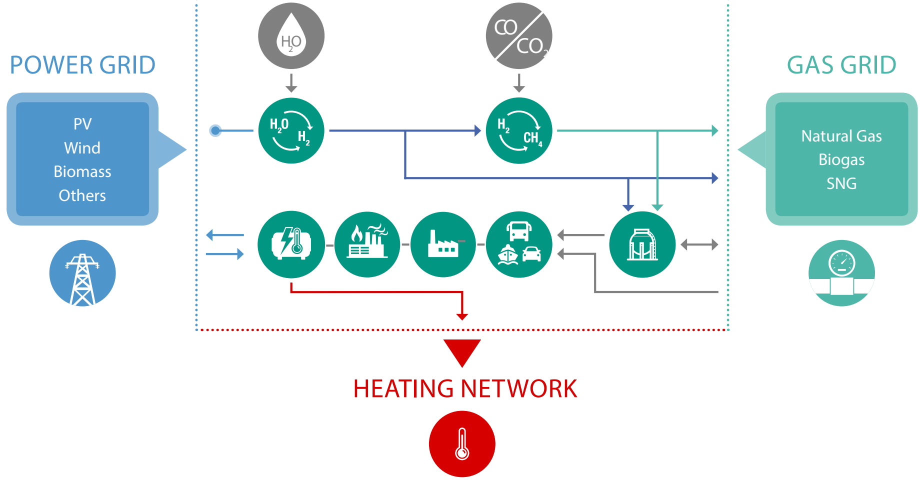
Green hydrogen produced with power from regenerative sources is the basis of methanation, a promising process to store volatile renewable energy in the form of chemical energy carriers. Green hydrogen and carbon dioxide from the air or a synthesis gas produced by biomass gasification are converted into methane. It can be fed into the existing gas grid and distributed, stored, and used easily. Methane can also be applied as a fuel or liquefied to biogenous LNG (liquefied natural gas). At Energy Lab, KIT's Engler-Bunte Institute (EBI) operates container facilities for two self-developed processes: Three-phase methanation and honeycomb methanation. Both processes convert synthesis gas into methane and water using a suitable catalyst. The product yields and efficiencies of both processes are very high. No by-products are formed.

In three-phase methanation, the catalyst is suspended in a liquid heat carrier. Both are contained in a bubble column reactor that is passed by the feed gases in the form of ascending bubbles. Three-phase methanation is highly load-flexible and ideal for coupling to volatile electricity production. The waste heat produced can be removed efficiently and used for other processes.

Honeycomb methanation uses catalytically coated metallic honeycombs as catalysts. The honeycombs are passed by synthesis gas that reacts to methane. Honeycomb methanation is highly robust. Its simple modular design facilitates upscaling to the desired plant size. Under the EU-funded STORE&GO project, this concept was implemented on the 1 MW scale in 2019. Since then, it has been further developed.

HYDROGEN TRANSPORT IN PIPELINES

KIT's Engler-Bunte Institute (EBI) and the associated DVGW Research Center (DVGW-EBI) study the production, storage, and distribution of hydrogen in a holistic approach. The GET H_2 collaboration of the BMBF-funded TransHyDE flagship project focuses on future H_2 transport pipelines. The idea is to use the existing efficient natural gas infrastructure for transporting hydrogen in future. For this, hydrogen compatibility of materials and components must be ensured and the capacity of storage systems and pipelines as well as safety aspects have to be considered. Researchers from EBI and DVGW-EBI develop regulations and inspection guidelines for the certification of materials and components. They carry out field tests to gather practical experience for the use of hydrogen. In smaller pipeline sections, up to 30 volume percent of hydrogen are added to the gas. Other pipelines are operated with pure hydrogen.



Energy system models are used to represent future developments on the basis of today's infrastructure.
Graphics: DVGW-EBI

Systemic assessments are made with the help of energy system models that model future developments based on today's infrastructure. The models are designed as co-simulations of specific heat, power, and gas grid models and of users, producers, and storage systems for integral energy planning. Gas grid modeling represents real grids or creates generic grids. Studies focus on required infrastructural measures as well as on operation concepts to support strategic decision-making by the operators of gas distribution grids. Scenarios for the development of consumption in different sectors are combined with simulation models and mathematical evaluation routines for real gas distribution grids or generic distribution grid topologies.

OVERVIEW OF THE RESEARCH ACTIVITIES AT KIT

THEMEN		INSTITUTE
H_2-PRODUCTION	**Electrochemical Production**	
	Basics	IPC
	Solid oxide electrolyzer cell (SOEC)	IAM-ET, IMVT
	Polymer electrolyte membrane electrolysis (PEMEL)	IAM-ET, IMVT, ITCP, ISTM
	Anion exchanger membrane electrolysis (AEMEL)	IAM-ET, ITEP, ITES, ITAS
	Photoelectrochemical cell (PEC)	IPS
	Catalytic Production	
	CH_4 reforming (reactor development)	IMVT
	LOHC dehydration (reactor development)	IMVT
	Thermochemical Production	
	Basics	ITT
	Methane pyrolysis	ITES, EBI ceb, ITC
	Gasification	ITC, EBI ceb
	Hydrothermal gasification	IKFT
	Biological Production	TEBI
	General Topics	
	Materials	IAM-WK
	Energy system modeling	IIP
	Chemistry modeling	ITC
H_2 STORAGE AND H_2 TRANSPORT	**Compressed Hydrogen (CGH_2)**	
	Pipline	EBI-DVGW
	Liquid Hydrogen (LH_2)	
	Basics	ITES, ETI, IAM-WK, ITEP
	Superconducting cables with LH_2 cooling	ITEP
	Compression	
	Innovative technologies	ITES
	Liquefaction	
	Process control	ITEP
	Heat exchanger	ITK
	Cryopressure	ITES
	Measurement technology	ITEP
	Solid-state Storage	
	Basics	IAM-WK
	Metal hydrides	IAM-WK
	Metal-organic frameworks (MOFs)	IFG
	Chemical Storage	
	Liquid organic hydrogen carriers (LOHC)	IMVT
	Ammonia	IMVT
	Methanol/dimethyl ether	IKFT, IMVT, ITCP
	Geological Storage	AGW

THEMEN		INSTITUTE
H_2 USE	**Fuel Cells**	
	Electrode	IAM-ET
	Cell	TFT
	Bipolar plates	IPEK
	Stack	IPEK, WBK
	Powertrains	IPEK
	Characterization	IAM-ET
	Simulation and modeling	IAM-ET
	LH_2	
	Cooling	ITEP
	Energy system components	ITEP
	Vehicles and aircraft	ITEP
	Simulation and modeling	ITEP
	Combustion	
	Engines	IFKM
	Ignition	ITT
	Use of Substances	
	Fuel synthesis	IKFT, ITCP, IMVT
	Methanation	IMVT, EBI ceb
	Methanol and ammonia synthesis	IKFT, IMVT
	Integrated process chain (PtX)	IKFT
	Mobility	FAST
H_2 TRANSVERSE TOPICS	**Safety**	
	Modeling and simulation of accident behavior	ITES
	Evaluation of risk potentials	ITES
	Laminar and turbulent ignition processes	ITT
	Systemic Analyses	
	Modeling of the energy system and H_2 value chain	IIP
	Evaluation of the production of H_2 and derivatives	IIP
	Sustainability analysis (LCA/LCC/SLCA)	ITAS
	Analysis of trust in the system, economy and society	ITAS
	H_2 from biomass/algae	ITAS
	Scenario-based use of H_2-based technical systems	IPEK
	Modeling of supply chain management/logistics	IFL
	Connection to the power grid	ETI
	Social Aspects	
	Acceptance research	IIP, ITAS
	Economic Aspects	
	Product profile modeling	IPEK
	Effect on exporting countries	ITAS
	Economic assessment	IIP

GREEN HYDROGEN IN THE CHEMICAL VALUE CHAIN

Synthetic fuel made of hydrogen and carbon dioxide.
Photo: IMVT/KIT

The Institute for Micro Process Engineering (IMVT) develops and studies modular, compact technologies for the conversion of ubiquitous substances, such as carbon dioxide, water, and nitrogen, with the help of renewable electrical power or solar energy into materials for chemical synthesis, fuels for transport applications that are difficult to electrify, and for longer-term storage of large amounts of energy. Green hydrogen produced by electrolysis or photocatalytic splitting of water represents an important interim product of such processes. IMVT studies efficient conversion of hydrogen into products like methanol, higher alcohols, synthetic hydrocarbons, methane, olefins, and ammonia.

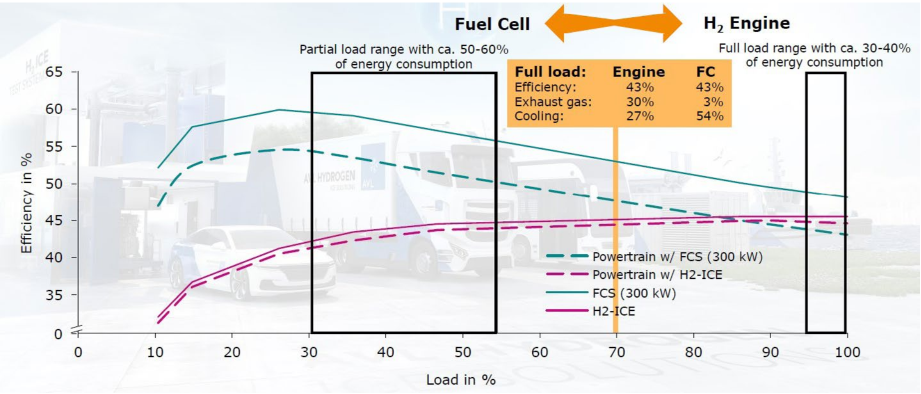
This requires power-to-X processes and process units that can be operated in a load-flexible way. Load-flexible operation allows to maximize the yield of photovoltaic systems and wind power facilities. IMVT develops, characterizes, and tests accordingly structured reactors and other process components from the lab to the industrial prototype scale. Work also covers simplified methods for processing synthetic hydrocarbons to fuels for specific uses. Researchers apply mechanical microfabrication and additive manufacturing methods to produce scalable, modular devices with outstanding heat and mass transfer coefficients and photon yields. Thanks to their small reactive inventory, they can be operated under harsher conditions without any safety losses and they can be run more dynamically than commercially available systems.

HYDROGEN ENGINE

Hydrogen has long been used as an energy carrier for fuel cell applications. Under low load, the fuel cell reaches a very good efficiency. The situation is different for the hydrogen engine: With increasing load, efficiency also tends to increase. This makes the hydrogen engine a suitable drive system for commercial vehicles.

For this to be achieved, however, some technical challenges have to be managed, including direct hydrogen injection, ignition and optimized energy conversion, exhaust gas treatment, materials-related issues, tribology, the filling system, and filling station infrastructure. Thanks to direct hydrogen injection, hydrogen concentrations in the intake duct can largely be avoided. This reduces the risk of backfiring that may damage the intake duct. Raw emissions of hydrogen engines sometimes are below those of diesel engines by an order of magnitude, although diesel engines can already be deemed emission-neutral, as exhaust gas treatment is ensured. Hydrogen engines are provided with a nearly identical exhaust gas treatment by means of an oxidation catalyst, particle filter, SCR catalyst, and an ammonia slip catalyst, all of which are individually adapted. Hydrogen diffusion is a problem that particularly affects aging of hardened steels. Moreover, selection of the basic oil and oil additives must be optimized and adapted to hydrogen operation.

Altogether, the hydrogen engine is associated with both big opportunities and technical and social challenges. While technical problems can be solved, acceptance by society will decide on the success of this technology.



Efficiencies of the fuel cell (blue) and hydrogen engine (violet). Total efficiency of the powertrain is represented by the dashed lines. Graphics: Dreisbach/AVL

USE OF HYDROGEN

Plant for e-fuel synthesis at KIT. Photo: KIT

Hydrogen is of high importance to making the energy system climate-neutral. Excessive power from renewable solar and wind power sources can be used to convert water into hydrogen by electrolysis and to store hydrogen. If needed, hydrogen can then be converted back into power with the help of either fuel cells or combustion in conventional gas turbines.

Vice versa, hydrogen can be used for power generation in fuel cell power plants. These power plants use the chemical reaction of hydrogen with oxygen to generate electrical power. Fuel cell power plants have high efficiencies. Their power generation is associated with hardly any harmful emissions. Hydrogen may also serve as a clean fuel for the production of heat in industrial processes and in heating systems of buildings and it can be combusted in gas burners or co-generation plants.

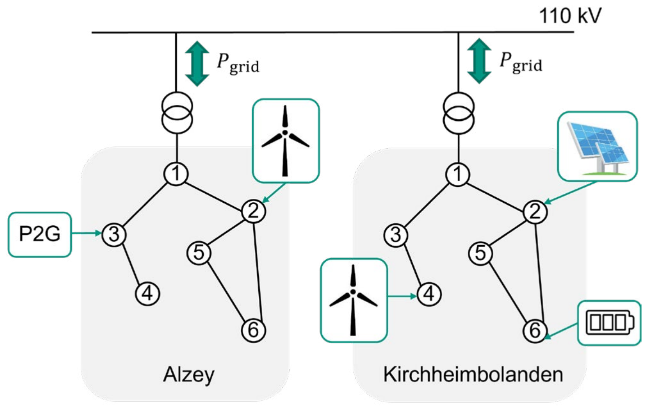
Hydrogen can also be used in vehicles. Its reaction with oxygen from air in a fuel cell generates power that drives an electric motor. Fuel cell vehicles are emission-free, as the only waste product produced by the reaction of hydrogen with oxygen is water. In addition, hydrogen can be used in combustion engines.

E-fuels are an alternative to the direct use of hydrogen. These are hydrocarbons produced by the synthesis of hydrogen and carbon dioxide. The hydrogen comes from a power-to-gas process. Carbon dioxide originates from carbon capture and utilization or direct air capture. These synthetic fuels can then be used in combustion engines or other transport and energy supply infrastructures.

In chemical industry, hydrogen can be used as a raw material for the synthesis of various substances. This improves the ecological balance of the products and enhances the sustainability of economy.

HYDROGEN IN SECTOR-COUPLED ENERGY CELLS

Power grids are facing new challenges. Electrical power is increasingly generated and fed into the grid on the distribution level. However, supply of energy from photovoltaic and wind power plants in particular varies with time and weather. In addition, new consumers, such as heat pumps and charging stations for electric cars, strain the distribution grids. These challenges were addressed by the recently completed RegEnZell project, in which several KIT institutes were involved. The project was aimed at the regional use of regionally generated power by smart coupling of the sectors of power, heat, and gas. For this, a model region in Rhineland-Palatinate with the cities of Alzey and Kirchheimbolanden was divided into so-called energy cells that were supplied self-sufficiently or exchanged energy with neighboring energy cells.



Sector-coupled energy cells were tested successfully in the cities of Alzey and Kirchheimbolanden in Rhineland-Palatinate.
Graphics: Institute for Control Systems IRS/KIT

By means of load and weather prognoses, researchers determined when and how hydrogen electrolyzers, storage systems, and other flexible components for the storage of excessive solar and wind power could be operated in an optimum way. Based on the prognoses and using high-dimensional grid models, they set up in real time operation plans for the flexible facilities. They found that the gas generated by electrolysis can be stored easily and at low cost in tanks or in the gas grid. Supraregional energy exchange can be reduced when neighboring energy cells cooperate specifically. The RegEnZell project shows that sector-coupled operation of energy cells is advantageous even for the existing energy system. Thanks to the high relevance of the research results to the energy transition, RegEnZell was chosen a highlight project to be presented in the 2023 Federal Report on Energy Research.

BIG RESEARCH INFRASTRUCTURES

KIT possesses modern research infrastructures, where scientists are given unique opportunities to carry out experiments and simulations. Central topics of high complexity, such as the integration of hydrogen in a sustainable energy supply system for Germany and Europe, require comprehensive tests of the technologies developed under various aspects, including energy efficiency, cost effectiveness, and safety. The following sections will present some infrastructures to test tomorrow's energy system components.

HYDROGEN SHUTTLE BUS

Staff and students of KIT can use shuttle buses to reach the Campuses South, East, and North. Two of them are hybrid buses driven by fuel cells. On Campus North, the buses can be refilled with hydrogen. A major funding share was provided by the Baden-Württemberg Ministry of the Environment.

The buses are Mercedes-Benz Citaro FuelCELL-Hybrid urban buses. Each bus is equipped with two 60 kW PEM FC stacks. Up to 35 kg of hydrogen are stored at 350 bar to enable a range of at least 350 km, with this figure being far higher in reality. The bus is driven electrically via two wheel hub motors on the rear axle. Energy is supplied primarily by a lithium ion battery. If needed, the battery is charged by the fuel cells. With the battery alone, the bus has a spare range of about ten kilometers. The hydrogen filling station allows 350-bar filling for buses and 700-bar filling without cooling for cars. Each day, the filling station can supply about 90 kg of hydrogen, corresponding to three bus and ten car fillings. Bus filling takes less than 20 minutes. The filling station has a storage capacity of 300 kg of hydrogen at 45 bar and 120 kg of hydrogen at 450 bar. KIT's hydrogen shuttle bus transports about 800 passengers per day. On 200 working days, this corresponds to 160,000 passengers annually. The shuttle bus demonstrates application options and everyday suitability of hydrogen technologies.

BIOLIQ®

By means of the KIT-developed bioliq® process, biomass of agricultural and forestry residues is decomposed thermochemically in several steps. The smallest chemical constituents produced are hydrogen and carbon monoxide. With the help of chemical catalysts, both are used to produce clean fuels and other basic chemical substances. At the pilot plant, researchers test the complete process chain in interaction and optimize it for use on the large industrial scale.

The bioliq® pilot plant serves to determine mass and energy balances, to train operation, and to demonstrate practical suitability and flexible use of feedstocks. It is operated for about 1000 hours per year by KIT's engineers, mechanics, and electricians.

The pilot plant demonstrates all stages of the bioliq® process: Flash pyrolysis, high-pressure entrained-flow gasification, hot gas cleaning, and synthesis. Photo: KIT

HYKA

At the HYKA Hydrogen Test Center, KIT conducts hydrogen safety research. To develop new test standards and optimize safety technology, researchers carry out hydrogen safety tests on the industrial scale. In addition, they study the behavior of hydrogen, from distribution to combustion.

The test facilities of HYKA are among the biggest of their kind in Europe. In the test chamber of 160 cubic meters in size, hydrogen engines for cars can be tested. Space is even sufficient to accommodate a complete hydrogen-driven car. Moreover, the high-performance ventilation system can be used to generate air flows similar to those of a wind tunnel or even more complex flow structures.

Two test tanks of the HYKA Hydrogen Test Center. Photo: KIT

ENERGY LAB

Europe's biggest research infrastructure for renewable energies and sector coupling is located on KIT's Campus North. Energy Lab is a project of KIT in cooperation with the German Aerospace Center (DLR) and Forschungszentrum Jülich (FZJ), which are also members of the Helmholtz Association. Energy Lab pools electrical, thermal, and chemical energy flows as well as latest information and communication technologies. It includes a solar park, various power-to-X facilities and storage units, as well as the Power Hardware in the Loop (PHIL) facility, a virtual real-time simulation environment to test newly developed technologies under variable conditions.

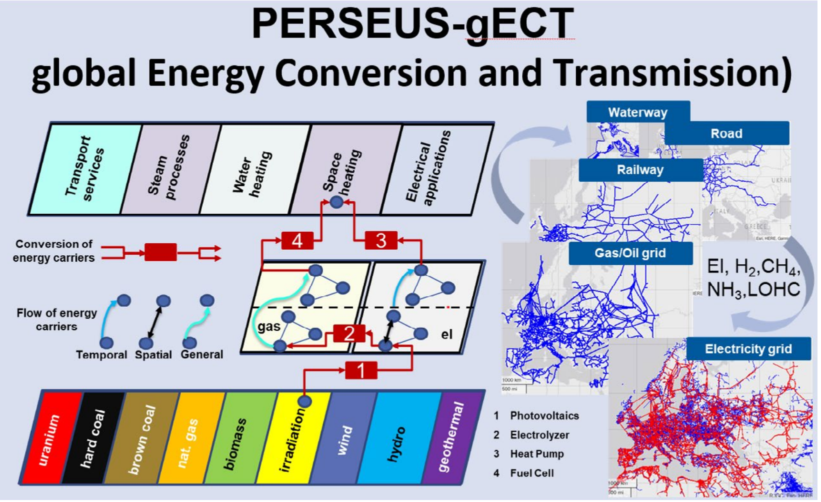
At Energy Lab, KIT researchers study the integration of hydrogen storage systems in a future climate-neutral and resilient energy system. Hydrogen allows for the longer-term chemical storage of large amounts of energy. Hydrogen can be produced by electrolysis with excessive power from fluctuating photovoltaic and wind power sources. If needed, the energy can be converted back into power again using fuel cells and fed back into the grid. The waste heat is transferred to a heating network. Energy Lab also comprises large container facilities to demonstrate various methanation processes. Unlike hydrogen, methane can be fed easily into the existing gas grid. Moreover, researchers study power-to-liquid processes for the production of e-fuels. To produce e-fuels from renewable power, water, and CO2, several processes have to be combined in a process chain. All options and combinations are studied at Energy Lab.

Foto: KIT

INTEGRATION OF H_2 IN ENERGY SYSTEM MODELS

The Chair of Energy Economics of the Institute for Industrial Production (IIP) analyzes transport options for renewable energy carriers like hydrogen or synthetic gases on the global level. The goal is to identify optimum supply structures while taking into consideration techno-economic framework conditions. Work focuses on the question of which conversion and transport pathways are suited best for meeting the energy demand.

H_2 and other energy carriers are integrated as investment options in energy system models of high spatial and temporal resolution. Particular attention is paid to the geographical mapping of locations of renewable energy sources worldwide, the presentation of the national and European energy demands, and the consideration of transport restrictions in the countries of origin and the countries of demand as well as between them. Based on a global analysis of potentials of renewable energy sources, including existing and planned conversion and transport infrastructures for primary and secondary energy carriers, operation and expansion of the energy system is planned. The models focus on exchange via the power grid and on the selection of options for conversion into secondary energy carriers, such as hydrogen or water-based energy carriers, and their transport via pipeline, water, railway, and road networks which exist or remain to be constructed. Moreover, the models represent demand development in the countries of origin as well as in other regions of the world, as this is the only way to assess the dynamics of supply and its risks.

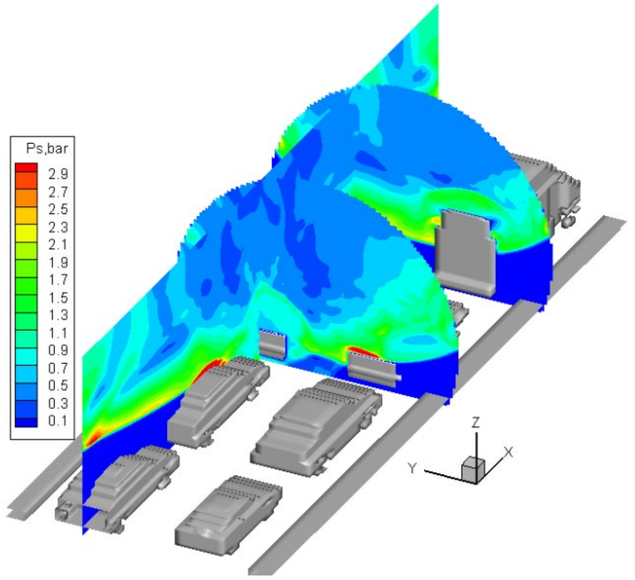


PERSEUS-gECT, an energy system model of high temporal and spatial resolution, allows for the global mapping and analysis of hydrogen integration. Graphics: IIP/KIT

HYDROGEN SAFETY

How safe is hydrogen? This question is addressed by the Hydrogen Group of the Institute for Thermal Energy Technology and Safety (ITES). Hydrogen proper is neither safer nor more dangerous than other energy carriers. Safe handling of hydrogen is essential. This requires exact knowledge of its properties. Under normal conditions, hydrogen is a very light gas with high diffusion properties. When mixed with air, it can be ignited easily over a very wide range of mixing ratios. Moreover, hydrogen burns relatively fast, which may result in pressure impacts. All this must be considered for a safe design and safe operation of hydrogen infrastructures. Use of hydrogen in vehicles requires unconventionally high storage pressures (up to 700 bar in cars) or very low temperatures (-253 degrees Celsius for LH_2 storage).

KIT was one of the founding members of the International Association for Hydrogen Safety, HySafe. Together with industry, HySafe has developed a list of research priorities that is updated periodically. Topics of highest priority presently are safety in tunnels and closed spaces, understanding of the behavior of LH_2 in case of accidents, and inexpensive and light structural materials for storage systems and pipelines. Within the HyTunnel-CS project, effectiveness of conventional safety installations was analyzed during accidents in tunnels. The GASFLOW-MPI software was applied to calculate the pressure impact of late ignition of a hydrogen-air cloud in a tunnel. The projects PRESLHY and ELVHYS focus on the behavior of liquid hydrogen in the course of accidents. The project TransHyDE-AppLHy! addresses the safety-related design of LH_2 laboratories, ignition phenomena with a high magnetic background field, and fast phase transitions with cryogenic hydrogen.



Result of a distribution and explosion simulation run for an accident scenario in a tunnel using the GASFLOW-MPI software. Graphics: ITES/KIT

TRANSVERSE TOPICS

ACADEMIC EDUCATION AND VOCATIONAL TRAINING

KIT, the only German University of Excellence with a national large-scale research center, offers excellent study conditions. Nowhere else are the opportunities to directly participate in research so manifold and promising. KIT also combines a long university tradition with interdisciplinary cutting-edge research. Researchers are directly involved in academic education and students can join thrilling research projects at an early stage of their studies already.

Natural sciences and engineering, together with studies of social aspects and cutting-edge research, represent a broad basis for academic education and vocational training in the area of hydrogen technology. KIT's lectures and courses on hydrogen technology cover the complete chain of use of hydrogen. KIT offers general lectures for all degree programs, specialized lectures, and in-depth seminars. Findings from experimental research and simulations are incorporated in lectures on production processes of hydrogen, direct use of hydrogen in fuel cells and in chemical reactions, e.g. for the development of synthetic fuels, storage systems and approaches to storing hydrogen, as well as comprehensive safety research relating to the technologies applied, including regulations, rules, and standards.

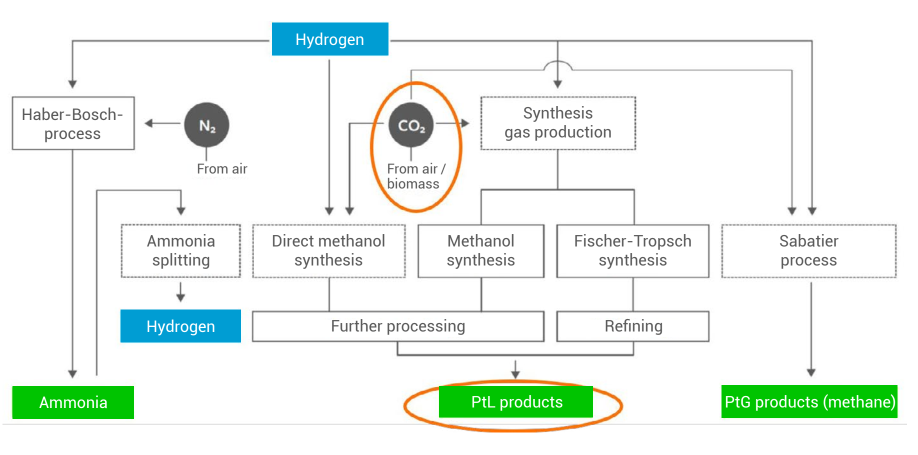
Quick transfer of scientific findings to the market is a major priority of KIT, also in the area of hydrogen technologies. For this reason, KIT supports entrepreneurship during studies already. KIT's graduates are in high demand by employers.

KIT combines a long university tradition with interdisciplinary cutting-edge research. Photo: Patrick Langer/KIT

TECHNOLOGY ASSESSMENT AND ACCEPTANCE BY SOCIETY

Hydrogen gives rise to big hopes for a climate-neutral future – but what about its impacts and risks and the society's acceptance? These aspects are studied by the Institute for Technology Assessment and Systems Analysis (ITAS). To meet the expected need for hydrogen, Germany will be dependent on imports. It will be important to conclude agreements with as many countries as possible in order to reduce the risk of geopolitical dependence. Surveys reveal that Germany's society generally is positive and open-minded towards hydrogen. Problems of acceptance or conflicts refer to the systemic context, such as imports or costs, and to specific areas, such as hydrogen production using renewable energy sources. Green hydrogen in particular must be analyzed in connection with the extended use of renewable energy sources, including wind power, and the associated discussions on the local level.

Acceptance researchers recommend politicians to define standards and framework conditions for the development and funding of hydrogen technologies, which ensure that the desired positive environmental effects, such as greenhouse gas reduction and sustainability, will actually be achieved. Sustainability does not only imply ecological advantages, but also the equitable distribution of costs and benefits in economic and social respects. Acceptance studies should not only cover renewable energy sources in upstream processes, but also daughter products of hydrogen. An example are power-based synthetic fuels, which are fervently discussed as regards their role as an alternative to the hydrogen fuel cell or electric mobility.



Potential pathways of hydrogen use. Graphics: ITAS/KIT

Lectures and Courses Relating to Hydrogen at KIT

Course	Hours per Week per Semester	Lecturer/s	Institute
Hydrogen and Refuels – Energy Conversion in Engines	2	Prof. Dr. sc. techn. Thomas Koch	IFKM
CO_2-neutral Combustion Engines and Their Fuels	4	Prof. Dr. sc. techn.Thomas Koch	IFKM
Hydrogen as Energy Carrier	2	Prof. Dr. rer. Nat Helmut Ehrenberg, Aline Léon	AOC
Hydrogen Technology	2	Prof. Dr. Thomas Jordan	ITES
Electrochemical Energy Technologies	2+1	Prof. Dr.-Ing. Ulrike Krewer	IAM-ET
Batteries and Fuel Cells	2+1	Prof. Dr.-Ing. Ulrike Krewer	IAM-ET
Practical Course on Batteries and Fuel Cells	4	Dr.-Ing. André Weber	IAM-ET
Seminar on Batteries	2	Dr.-Ing. André Weber	IAM-ET
Seminar on Fuel Cells	2	Dr.-Ing. André Weber	IAM-ET
Seminar on Electrocatalysis	2	Dr. Philipp Röse	IAM-ET
Battery and Fuel Cell Systems	2	Dr.-Ing. André Weber	IAM-ET
Modeling of Electrochemical Systems	2	Dr.-Ing. André Weber	IAM-ET
Electrocatalysis	2+1	Dr. Philipp Röse	IAM-ET
Electrochemical Energy Technologies Laboratory Course	3	Dr. Philipp Röse	IAM-ET
Power-to-X – Key Technology for the Energy Transition	2+1	Prof. Dr. Dr.-Ing. Roland Dittmeyer, Dr. Alexander Navarrete Munoz, Dr. Peter Holtappels	IMVT
Hydrogen in Materials: from Energy Storage to Hydrogen Embrittlement	2+1	Prof. Dr. Astrid Pundt Dr. rer. nat. Stefan Wagner	IAM-WK
Hydrogen and Fuel Cell Technologies	2	Prof. Dr.-Ing. Dimosthenis Trimis	EBI-VBT
Basics of Combustion Technology	2+1	Prof. Dr.-Ing. Dimosthenis Trimis	EBI-VBT
Energy Technology	2	Prof. Dr.-Ing. Horst Büchner	EBI-VBT
Basics of Fuel Technology	3	Prof. Dr.-Ing. Thomas Kolb	EBI-CEB
Catalytic Gas Technology Processes	2	Dr.-Ing. Siegfried Bajohr	EBI-CEB
Refinery Technologies – Liquid Energy Carriers	3	Prof. Dr. Reinhard Rauch	EBI-CEB
Liquid Transportation Fuels	3	Prof. Dr. Reinhard Rauch	EBI-CEB
Superconducting Magnet Technology	2	Prof. Dr. Tabea Arndt	ITEP
Superconducting Power Systems	2+1	Prof. Dr.-Ing. Mathias Noe	ITEP
Cryogenic Engineering	2+1	Prof. Dr.-Ing. Steffen Grohmann	TTK-KKT
Cryogenic Engineering B	2+1	Prof. Dr.-Ing. Steffen Grohmann	TTK-KKT
Physical Foundations of Cryogenics	2+1	Prof. Dr.-Ing. Steffen Grohmann	TTK-KKT
Fundamentals of Gas Storage	2	Prof. Dr. Frank Schilling	AGW

Lectures and Courses Relating to Hydrogen at KIT

Course	Hours per Week per Semester	Lecturer/s	Institute
Design of Fuel Cell Systems	2	Dr.-Ing. Jan Haußmann	IPEK
Power Electronics for Photovoltaics and Wind Energy	2	Prof. Dr.-Ing. Bruno Burger	ETI
Production Technology for Electric Mobility	2	Prof. Dr.-Ing. Jürgen Fleischer	wbk
Chemical Hydrogen Storage	2	TT-Prof. Dr. Moritz Wolf, Prof. Jörg Sauer	IKFT
Renewable Energy – Resources, Technologies and Economics	2	PD Dr. Patrick Jochem	IIP
Smart Energy Infrastructure		Dr. Armin Ardone, Prof. Dr. Dr. Andrej Pustisek	IIP
Design of Microreactors	4	Prof. Dr.-Ing. Peter Pfeifer	IMVT

Institutes Conducting Hydrogen Research at KIT

AGW	Institute of Applied Geosciences
EBI-ceb	Engler-Bunte Institute – Chemical Energy Carriers - Fuel Technology
EBI-DVGW	Engler-Bunte Institute DVGW Research Center – German Technical and Scientific Association for Gas and Water
ETI	Institute of Electrical Engineering
FAST	Institute of Vehicle Systems Technology
IAM-ET	Institute for Applied Materials – Electrochemical Technologies
IAM-WK	Institute for Applied Materials – Materials Science and Engineering
IFG	Institute of Functional Interfaces
IFKM	Institute of Internal Combustion Engines
IFL	Institute for Materials Handling and Logistics
IIP	Institute for Industrial Production
IKFT	Institute of Catalysis Research and Technology
IMVT	Institute for Micro Process Engineering
IPC	Institute of Physical Chemistry
IPEK	Institute of Product Engineering
IPS	Institute for Photon Science and Synchrotron Radiation
ISTM	Institute of Fluid Mechanics
ITAS	Institute for Technology Assessment and Systems Analysis
ITC	Institute for Technical Chemistry
ITCP	Institute for Chemical Technology and Polymer Chemistry
ITEP	Institute of Technical Physics
ITES	Institute for Thermal Energy Technology and Safety
ITT	Institute of Technical Thermodynamics
TEBI	Chair of Technical Biology
TFT	Material Research Center for Energy Systems – Thin Film Technology
TVT	Institute of Thermal Process Engineering
WBK	Institute of Production Science

HYDROGEN

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