EnergieAgentur.NRW

Hydrogen – the key to the energy transition

Examples from North Rhine-Westphalia
from production to end use

EnergieRegion.NRW
Cluster Nordrhein-Westfalen

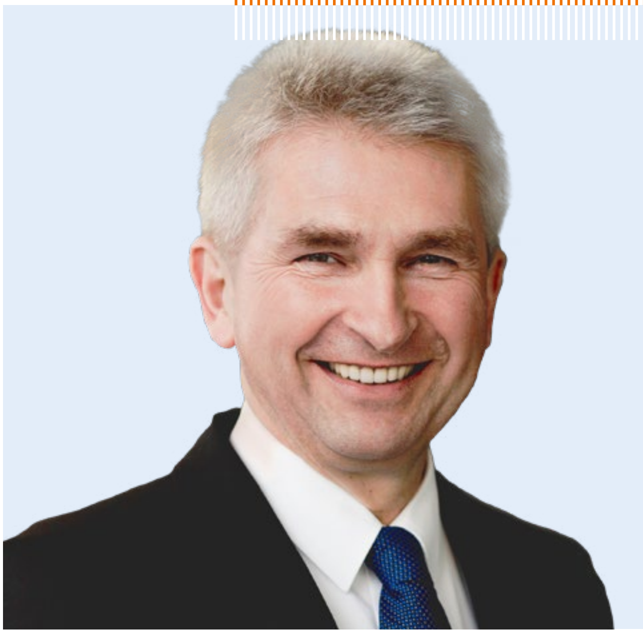
Contents

Foreword

Hydrogen is so much more than the substance water is made up of. In the mid-18th century, the British scientist Henry Cavendish discovered a previously unknown gas while experimenting with mercury and acids. He called it "combustible air". Today it is known as hydrogen. Anyone who remembers the oxyhydrogen experiments in chemistry lessons will understand why Henry Cavendish chose this term. Even today, "combustible air" would not be a bad name for the smallest of all elements; after all, at a time when we are urgently seeking low-emission and climate-friendly energy supplies, hydrogen may become the key to the energy transition.

One of the major advantages of hydrogen is that it is a versatile all-rounder for a host of applications. It can be used in stationary CHP fuel cells that generate both heat and electricity at the same time, it can contribute to low-emission mobility in the transport sector, and it is an important raw material for industry, for example in fertiliser production.

Hydrogen therefore plays a decisive role in the energy system of tomorrow. The generation of electricity from wind and solar energy is steadily increasing, yet we have no control over when and how strongly the wind blows or whether the sun shines all day long. This is why wind and solar-based energy systems require a large number of very different storage devices. Battery and pumped storage systems can store energy for several hours, yet their capacities do not allow large amounts of energy to be stored over longer periods of time. This is where



hydrogen comes in: Power-to-gas plants can react flexibly to fluctuating wind and solar power generation by breaking water down into its constituent parts – hydrogen and oxygen. This way, hydrogen-based synthetic energy sources or even pure hydrogen can be stored over long periods of time for use in various sectors, including industry or transport. Existing infrastructures such as gas pipelines or underground storage facilities can also be used.

Apart from providing a storage option for the energy transition, hydrogen offers a great opportunity for sustainable and low-emission transport involving fuel cell vehicles. Fuel cells are much more efficient than conventional combustion engines and provide pollution-free mobility – the only emission from the exhaust pipe being water vapour or steam. Fuel cell vehicles have ranges of several hundred kilometres and can be refuelled in less than five minutes. They are therefore an attractive solution that is also becoming increasingly popular in the corporate world.

The hydrogen industry is working with great dedication on innovative solutions for a sustainable future. This brochure is intended to give you a brief insight into activities here in North Rhine-Westphalia while also providing information on selected projects in other federal states. I wish you an enjoyable and informative read!

Prof. Dr. Andreas Pinkwart
Minister for Economic Affairs, Innovation, Digitisation and Energy
of the State of North Rhine-Westphalia

Foreword

New energy and transport system technologies that offer greater efficiency and fewer emissions often have to compete against established state-of-the-art systems. They tend to require more capital expenditure and operating costs and, in some cases, new infrastructure. If the advantages outweigh the disadvantages in the long term, it is society's task to help push these technologies into the market by providing appropriate funding, exchange of information and advice. Exchange between researchers, developers, manufacturers, funding agencies, potential investors and first-time users helps to foster alliances and can be useful for discussing potential opportunities, developing market entry strategies, identifying promising approaches and detecting undesirable developments through objective discussion.

The Fuel Cell and Hydrogen, Electromobility Network set up by EnergyAgency.NRW is designed to facilitate precisely this exchange. It brings together a mix of experienced and new players in the field of fuel cell and hydrogen technology, as well as electromobility, in order to jointly foster their development and market launch. The aim is to establish a new industry and support emissions reduction and climate protection at a time when the energy and transport sectors are undergoing profound change.

The network's current activities focus on investigating the possible contribution of hydrogen as an energy storage medium to the expansion of renewable energies, i.e. hydrogen production via electrolysis, decentralised and centralised storage of hydrogen, and the subsequent options for its use. These options include re-conversion to electricity, e.g. in fuel cells, use as a

material in (petro)chemical processes or the steel industry, direct injection into the natural gas grid, and conversion into synthetic energy sources. However, the use of hydrogen as an innovative fuel in the transport sector in combination with fuel cell-based vehicles (cars, commercial vehicles, buses, trucks, trains, ships) seems to be particularly interesting, not least because of the potential contribution to climate and environmental protection.

An important objective in all areas is to increase the number of market-ready systems through the acquisition of additional users and thus reduce costs. In parallel, it is necessary to conduct further research and development activities as well as demonstration projects to improve technology, increase reliability and extend asset life cycles and thus reduce costs. The Fuel Cell and Hydrogen, Electromobility Network will continue to provide its members with comprehensive support through a variety of services.

This brochure presents recent developments in hydrogen and fuel cell technology for a number of applications across the entire innovation process from research through to market launch. Most examples are from North Rhine-Westphalia (NRW), but there are also a number of national showcase projects. We would like to take this opportunity to thank the numerous co-authors for their contributions and wish you, our readers, an exciting read.

Dr. Thomas Kattenstein
Head of the Fuel Cell and Hydrogen, Electromobility Network
of the State of North Rhine-Westphalia

H_2 properties at a glance

Hydrogen is the lightest of all gases with a density of 0.0899 kilograms per normal cubic metre (under standard conditions). It was discovered by H. Cavendish in 1766. According to a proposal by J. Dalton (1803), the mass of the hydrogen atom (valid until 1899) was used as the basis for the system of chemical atomic weights. With the atomic number 1, the hydrogen atom is the first atom in the periodic table. The Earth's atmosphere contains only traces of hydrogen, but chemically bound hydrogen is found everywhere as water and in organic compounds: Hydrogen makes up about 1% of the Earth's crust. The boiling point of hydrogen is -253 °C.

Compared to other sources of energy, hydrogen has the highest mass-specific, but at the same time the lowest volume-specific energy content which, depending on the application, impacts the choice of storage in different ways.

Hydrogen has the following properties:

- Non-toxic and non-corrosive
- Not radioactive
- Not hazardous to water
- Not carcinogenic
- Lighter than air
- Easily diluted by air

In addition, there are a number of safety aspects to be observed:

- Not visible during combustion
- Wide ignition range in air and highly flammable with low ignition energy
- High combustion rate
- Tendency to cause material problems (embrittlement, low temperature)

Characteristics		Hydrogen	Methane	Petrol	Methanol
Lower calorific value	kWh/kg MJ/kg	33 120	13,9 50	12 43	5,5 20
Density (15 °C, 1 bar)	kg/m³	0.09	0.72	748	791
Ignition range in air	Vol.-%	4 - 75	5 - 15	1 - 8	6 - 44
Minimum ignition energy (= 1)	mWs	0.02	0.29	0.24	0.14
Combustion velocity in air (= 1)	cm/s	265	43	40	48
Diffusion coefficient in air	cm²/s	0.61	0.16	0.05	0.12
Toxicity		non-toxic	non-toxic	benzene TRK** 1 ppm	TLV* 200 ppm
Specific CO_2 emissions	g/MJ	0	58	74	69

The new role of hydrogen in a future energy supply system

Today, hydrogen is an important raw material for the chemical and petrochemical industry. It is mainly used for the production of ammonia (including derivatives such as fertilisers and plastics) and for the processing of crude oil into fuels and high-quality chemical products. Hydrogen is also required for reduction processes in metallurgy, as a coolant in electric generators, as a shielding gas in electronics, for welding and cutting in mechanical engineering, and for fat hardening in the food industry.

Funding of renewable energies has substantially increased their share in the energy mix, while series production and innovation have helped bring down costs. Germany was a pioneer in the growth phase of renewable energy and is still struggling with the "teething problems". There is a growing realisation that the key to a sustainable energy future lies in the flexible direct and indirect use of electricity from wind and solar, especially in sectors which to date have relied mainly on fossil energy: mobility, heat and industry.

These days everyone is talking about "sector coupling". However, "linking electricity, heat, mobility and industrial processes as well as the associated infrastructures" (BDEW definition) will only have the desired effect if this process is aligned with renewable energy generation both in terms of time and geographic location, if it promotes or encourages the expansion and continued use of renewables, and if the available energy is used effectively in a variety of ways – e.g. through flexible conversion into renewable chemical energy sources. Only then can prolonged periods of surplus electricity be exploited to the full. At the same time, there is a need for low-cost, flexible, fuel-based power plants that can reliably and persistently meet inflexible demand when intermittent renewable sources are not available.

Both types of converters, which will increasingly be operated in line with electricity market conditions, must also make use of their waste heat where economically viable. Demand for residual heat must continue to be met reliably – be it with heat pumps that offer high CHP coefficients, with biomass or environmental heat, or even with gas-based appliances where the aforementioned options are too costly. These systems are electricity-led, while heat and cold are secondary energies, and storage facilities play a supporting role. The gas must increasingly come from renewable sources.

Energy-intensive products and business models based on abundantly available fossil fuels will have to cede market shares to materials, processes and solutions that produce much lower emissions. What is now needed, however, is an appropriate framework that allows sustainable technologies and business models to develop in their own economic area in the first place. In this situation, players often demand a level playing field that takes account of the emission-reducing effect of each technology, and the technologies then occupy the niches for which they are best suited. These conditions define the market. The more reliable the technologies are, the more likely it is that investments will follow. Quotas and gradually declining market entry subsidies may also be necessary to boost the industrialisation of new energy paths.

Hydrogen and fuel cell technologies will make a significant contribution in this wind and sun-dominated environment which – in temperate latitudes – is characterised by significant fluctuations in supply. At times of surplus electricity generation, electrolysis can be used to split water and store most of the energy in the form of hydrogen, which can then be used in a number of ways depending on local conditions:

The hydrogen can be supplied to all standard gas-burning appliances to replace fossil gas – either in limited quantities fed directly into the pipeline grid or in unlimited quantities after methanation involving carbon dioxide.

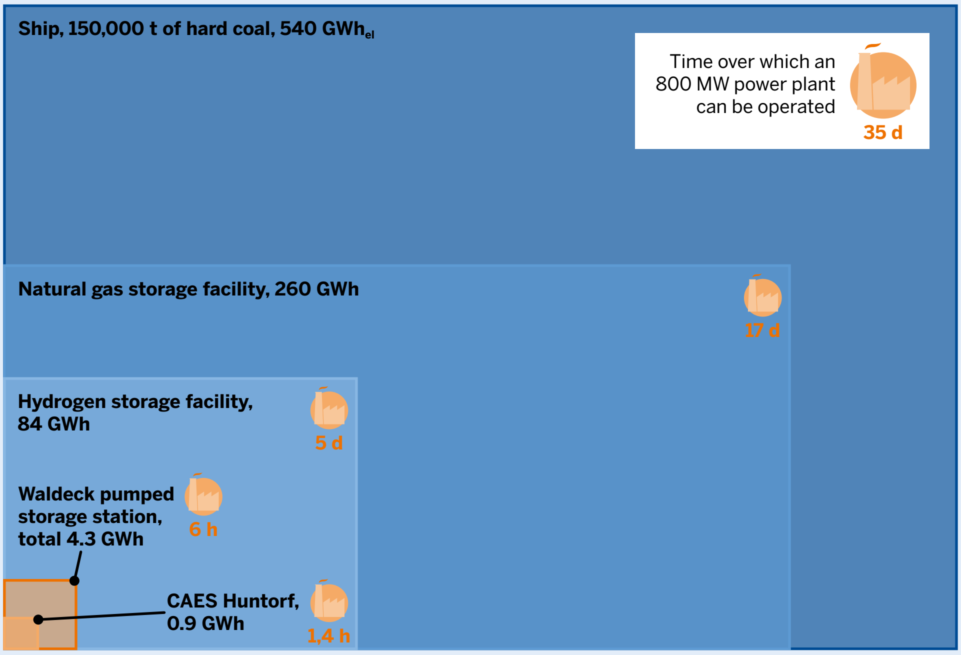
It can also be used as pure hydrogen in industry and refineries to replace hydrogen previously extracted from fossil raw materials at a loss, or in combination with unavoidable CO_2 to produce fuels or raw materials, and it can conquer new industrial terrain as a reducing agent or energy source.

Hydrogen has a high energy density and can be stored and transported in many different ways with minimal risk: physically dissolved, chemically bound, as a cryogenic or liquid gas, or under pressure. Compressed hydrogen can be stored in large quantities in salt caverns or large pipe arrays and transported efficiently in pipelines or flexibly in trailers. The largest pressurised gas trailers today hold over a tonne of hydrogen, and even larger quantities can be stored in carrier media or in liquid form. Natural gas pipelines no longer used may also be suitable under certain circumstances. Handling gaseous hydrogen outside buildings is less dangerous than handling natural gas, but hydrogen has also been safely handled inside buildings for several decades.

Finally, hydrogen in its pure form can be used as an energy carrier for power generation and, most significantly, as a fuel for fuel cell vehicles. It can thus displace carbon-rich liquid fuels and emission-producing internal combustion engines, which is why it not only has high climate-protection and emission-reduction potential, but also creates a willingness among users to pay for this alternative fuel. Hydrogen offers the flexibility motorists are used to, short refuelling times and high levels of fuel efficiency. The first series-produced passenger cars are already on the market, and some manufacturers are already offering railcars, city buses, municipal utility vehicles and vans. Demonstrators for heavy trucks, ships and short-haul aircraft are successfully in use or under construction.

Mobility with hydrogen from renewables is so important for climate protection that in the early stages where availability counts, operators may also use sources that make a smaller contribution to climate protection. Hydrogen by-products and hydrogen from natural gas are also placing developments on the right track. However, half of the hydrogen currently used by the public already comes from renewable sources.

Storage of large quantities of energy



Assumptions:
- Small cavern volume of 300,000 m^3 (= Huntorf) for hydrogen or natural gas storage
- Generation efficiency: 0.6

Source: Uniper

The development of hydrogen infrastructures, however, is a task that requires project partners to cooperate closely and be persistent. Switching fleets to other energy sources demands courage and a strategic approach – all the more so when operators have to increase vehicle numbers to make the transition affordable. In 2016/17, the economically risky business of building public refuelling stations that will not be used to full capacity for a number of years gathered momentum in Germany under the leadership of H_2 Mobility Deutschland GmbH. Without government targets, the construction of efficient supply systems, including pipelines and large storage facilities, becomes riskier economically – even if, following the conversion from L-gas to H-gas, there are potentially some gas pipelines that might be suitable for hydrogen transport. Investments for future generations therefore need political and public support. Nevertheless, they will pay off in the long term because they allow large quantities of energy to be transported more cheaply in gaseous form with fewer losses, a smaller footprint and at a lower cost than electricity.

Fuel cells supplying electricity should not go without mention. They operate quietly, do not produce any pollutant emissions, and achieve power-generating efficiencies of up to 60% and overall energy efficiencies (co-use of heat) of up to 90%. Their high efficiency, even at low output levels, makes them ideal for distributed generation. The smallest units supply portable communication devices and measuring instruments. Natural gas/biogas-based kW-scale micro-CHP units supply energy to homes and small businesses, while slightly larger ones are used for wireless communication systems, and even larger ones up to the MW range provide cogeneration for large buildings and industrial facilities or support largely maintenance-free uninterruptible power supply systems. The low-oxygen exhaust air from fuel cells can also be used for fire-fighting in warehouses and data centres.

The following chapters by our co-authors are intended to shed more light on the various aspects of the energetic use of hydrogen.

Hydrogen as a sector coupling option for the energy system of tomorrow

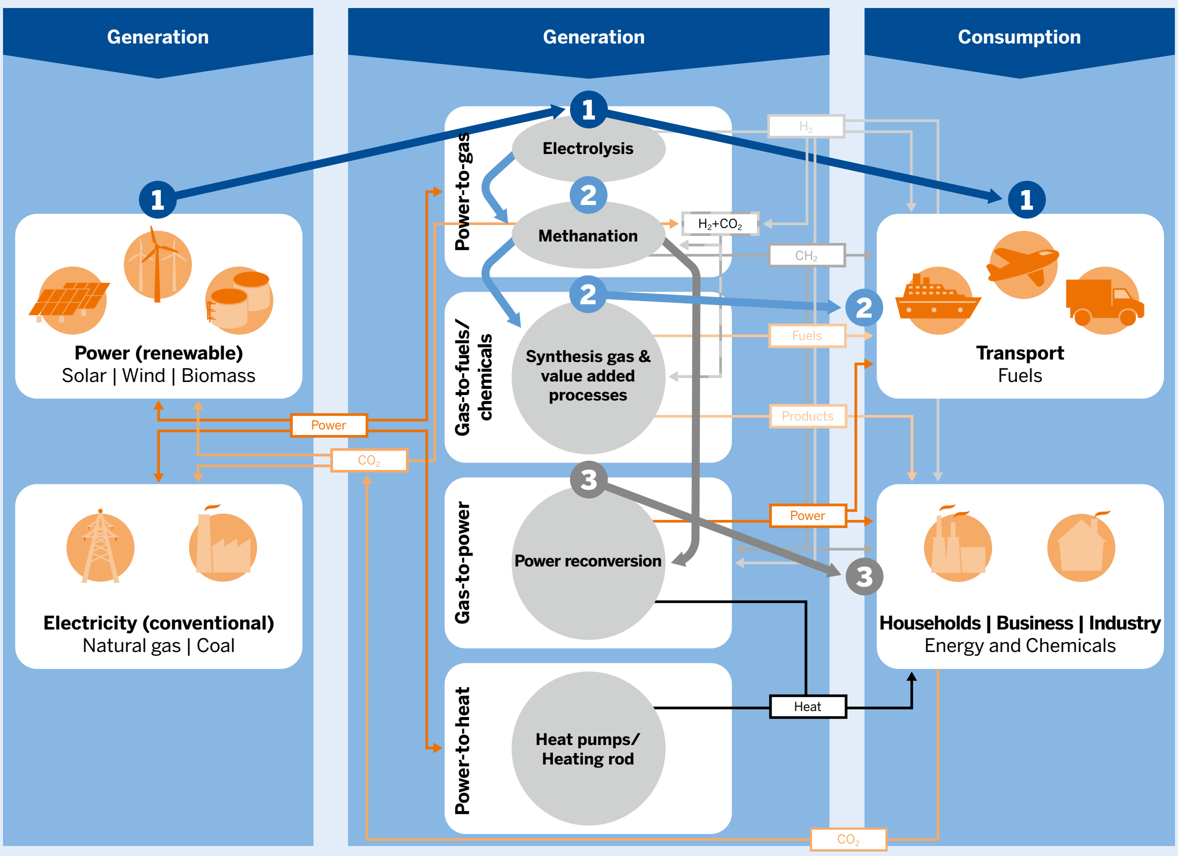
As mentioned above, sector coupling is one of the key building blocks for decarbonisation, but also facilitates more flexible energy use. One of the most important paths linking the technical and commercial aspects of both sectors is the Power-to-X path. The diagram below provides a summary of the possibilities offered by the cross-sector Power-to-X concept currently under discussion.

Apart from the use of electricity from renewables in the heating sector, for example, generating hydrogen by means of water electrolysis is also a promising option for sector coupling.

A series of alternative uses for the hydrogen produced this way are currently being discussed. They include [(1)]:

- Reconversion into electricity to compensate for fluctuating renewables fed into the grid
- Production of liquid fuels
- Use as fuel for vehicles (cars, buses and trucks) and trains with highly efficient fuel cells (FCEV)
- Production of chemical substances such as ammonia
- Direct injection into the gas grid
- Methanation for subsequent injection into the gas grid

Power-to-X paths



Source: GWI

One of the characteristic features of the third option is that it also allows the transport sector to benefit from the clean air advantages of renewable electricity, thereby replacing energy sources with higher specific GHG emissions while at the same time improving energy use through fuel cells in vehicles by a factor of two.

Status and objective of sector coupling

The table below shows current energy consumption levels and the share of fossil fuels in each sector. Increased use of sector coupling will have two effects: Firstly, the new paths will increase energy consumption in some of the sectors that use renewable electricity either directly or indirectly. However, this should not be seen as negative. The efficiency of the individual paths is no longer the sole criterion for sector coupling. Some paths that are inefficient can still be necessary and important for the overall system as they can, for example, use the peak electricity generated by renewables, which cannot be used elsewhere. Secondly, the use of this renewable electricity will then significantly reduce the share of fossil fuels in the individual sectors [2].

Sectoral energy consumption and use of fossil fuels in 2015 [3]

Sectors	Sectoral energy consumption	Share of fossil energy sources*
Industry	716 TWh	53%
Transport	728 TWh	94%
Households	636 TWh	59%
Business, trading, services	387 TWh	50%
Power generation	1,385 TWh	61%

* Note: Direct use

Apart from the German government's cross-sector targets, which include the reduction of CO_2 emissions by 80% and 95% respectively by 2050 compared to 1990 levels, there are now also sector-specific targets laid down in the German government's climate protection plan. Having achieved a comparatively low CO_2 reduction of only 1.2% between 1990 and 2014, the transport sector in particular has to make considerable strides to meet the reduction targets of 40 to 42% by 2030, as the following table shows.

Sector-specific CO_2 reduction targets by 2030

Sector	1990 tCO_2 eq	2014 tCO_2 eq	2014 vs. 1990	2030 target tCO_2 eq	Target for 2030 vs. 1990
Energy industry	466	358	- 23.2%	175 - 183	62 - 61%
Buildings	209	119	- 43.1%	70 - 72	67 - 66%
Transport	162	160	- 1.2%	95 - 98	42 - 40%
Industry	283	181	- 36%	140 - 143	51 - 49%
Agriculture	88	72	- 18.2%	58 - 61	34 - 31%
Others	39	12	- 69%	5	87%
Total	1248	902	- 27.7%	543 - 562	56 - 55%

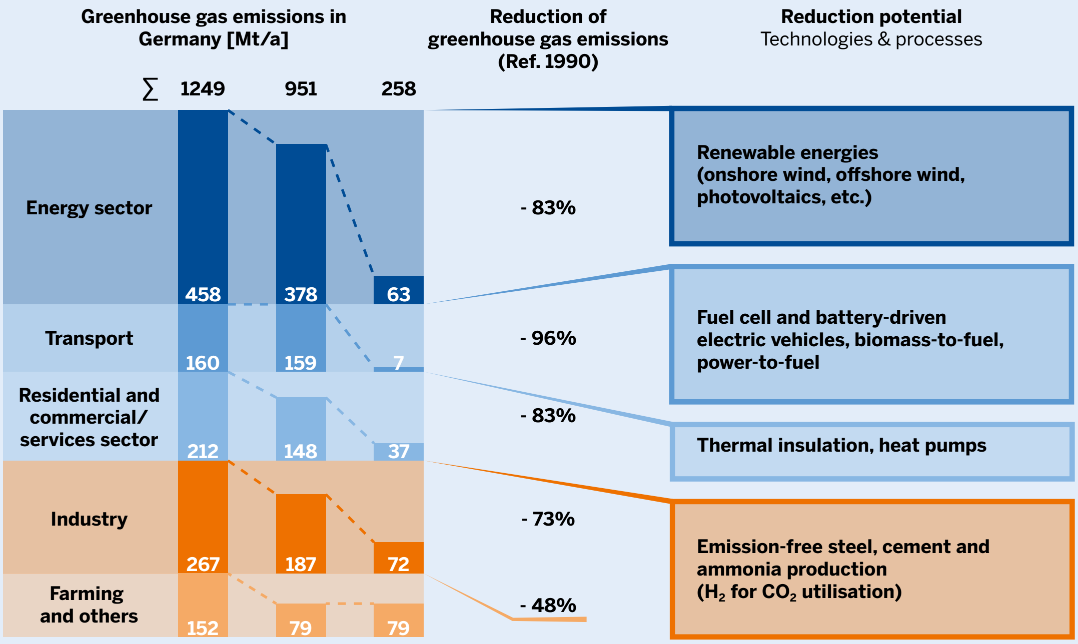
Potential contribution of hydrogen to the carbon footprint in 2050

The figure below shows that hydrogen can make a significant contribution to CO_2 reduction by 2050. There are several ways in which renewable electricity could be integrated into steel production, for example through techniques such as furnace gas recirculation, blast furnaces with carbon capture, a higher proportion of electric arc furnaces, and the use of hydrogen as a reducing agent. It has been shown that these processes could lead to greater and ultimately complete independence from coal, which opens up the possibility of making electricity and heat based on renewable sources available to the steel industry (sector coupling). An analysis for Germany has shown that these technologies could help reduce CO_2 emissions by 47 - 95% compared to 1990 levels and that 12 - 274 TWh of renewable electricity supplied to the steel industry could reduce primary energy demand by 27 - 95% compared to 2008. This would make a significant contribution to reducing carbon emissions and fuel demand in the steel industry [(4)]. Fuel cell systems (SOFC), for example, are suitable for households, but they compete with PV and heat pump systems. An economically viable example would be a self-sufficient household meeting all of its energy needs in this way [(5)]. Other hydrogen utilisation options described above are suitable for transport and industry.

Cost comparison of different hydrogen options

A comparative cost estimate based on a renewable energy concept shows that it also makes more economic sense to replace mineral oil-based fuels with hydrogen instead of natural gas. The diagram below shows the current cost of petrol at the pump (8 ct/kWh (70 ct/l) without taxes) as a benchmark for assessing the fuel option. Assuming the aforementioned consumption advantage, the "permitted" cost of hydrogen at the pump would be 16 or 22 ct/kWh, respectively, for fuel cell vehicles consuming 1 or 0.7 kg per 100 km.

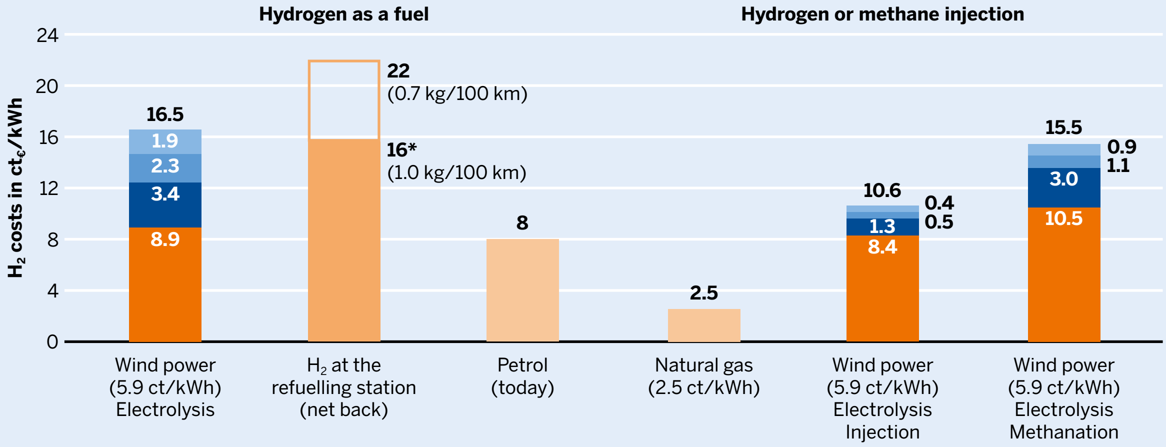
The cost comparison for the "injection into the natural gas grid" scenario shows that the specific cost of hydrogen fed directly into the system is already 4.3 times higher than the natural gas costs. With methanation, this factor even increases to 6.2. Under these circumstances the variable energy costs are already significantly higher than the cost of the energy to be substituted, which is why it is not economically justifiable at present to inject hydrogen or methane into the natural gas grid.



Examples of potential contributions of hydrogen as a sector coupling option to the reduction of CO_2 emissions in 2050

Source: FZ Jülich

Cost comparison of hydrogen options



Cost of capital: Depreciation of the investment plus interest
- 10 years for electrolysers and other production facilities
- 40 years for transmission grid
- 20 years for distribution grid and refuelling stations
- Interest rate: 5.8% p.a.

Further assumptions:
- 2,9 million t_{H_2}/a from renewables via electrolysis
- Electrolysis: $\eta = 70\%_{LHV}$, 28 GW; Specific investment 50 €/kW
- Methanation: $\eta = 80\%_{LHV}$

Whilst injection into the natural gas grid is by far too expensive, H_2 can be economically competitive as a fuel

*Net back costs for 50% lower fuel consumption compared to gasoline vehicles

- Operation
- Interest
- Amortisation
- Energy
- Net back price of H_2
- Petrol/nat.gas, before tax

Source: FZ Jülich

Compared to the aforementioned alternative uses (re-conversion of hydrogen into electricity, direct injection of hydrogen into the natural gas grid or injection of methane after methanation), this option provides the greatest CO_2 savings while also making most sense from an economic point of view, as the comparative costs in the fuel market are significantly higher than for natural gas use.

Contact:
Prof. Dr.-Ing. D. Stolten
Head of Institute
Forschungszentrum Jülich GmbH
Telephone: +49 (0)2461/61-5147
d.stolten@fz-juelich.de

Dr.-Ing. M. Robinius
Head of Process and Systems Analysis Department
Forschungszentrum Jülich GmbH
Telephone: +49 (0)2461/61-3077
m.robinius@fz-juelich.de

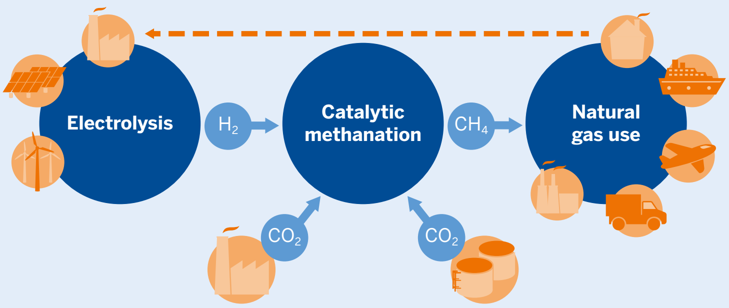
www.fz-juelich.de

Potential for injecting hydrogen into the natural gas grid

As mentioned above, a promising option for integrating renewable energies into the natural gas sector is hydrogen production including injection into the natural gas grid. The stored energy can be reused in various areas (sector coupling). This way, renewable energy is available for heating, industrial applications, the mobility sector and re-conversion into electricity, even when output from renewable sources is low (see diagram below).

The amount of hydrogen that may be fed into the grid depends directly on the quantity of natural gas consumed in a given grid. It is important to bear in mind that both the availability of renewable energies and the consumption of natural gas are subject to seasonal fluctuations.

Pathways for methane made from hydrogen



Source: GWI

Plant operators feeding gas into the pipeline network have to ensure that the quality of the gas injected is compatible with the gas network and that system interoperability is maintained (cf. Section 49 of the German Energy Industry Act – EnWG). According to the specifications the hydrogen concentration in the gas must not exceed 5% by volume. In future, H_2 levels of up to 10% will be possible as long as end users in a given service area do not operate any sensitive gas appliances.

In its "Virtual Institute – Electricity to Gas and Heat" project, the research institute Gas- und Wärme-Institut Essen e.V. (more commonly known by its initials GWI) is investigating the potential of hydrogen injection into gas distribution grids in North Rhine-Westphalia (NRW). The project not only focuses on regional renewable energy generation and conversion, but also on regional gas demand in the given distribution grids. The analysis is carried out with due consideration for seasonal and economic aspects. The annual gas offtake for NRW was determined at grid operator and municipal level. On this basis the amount of hydrogen that could potentially be injected into the grid was calculated for the 2050 scenario.

Contact:
Janina Senner
Gas- und Wärme-Institut Essen e.V.
Telephone: +49 (0)201/3618-277
senner@gwi-essen.de

www.gwi-essen.de

Hydrogen production

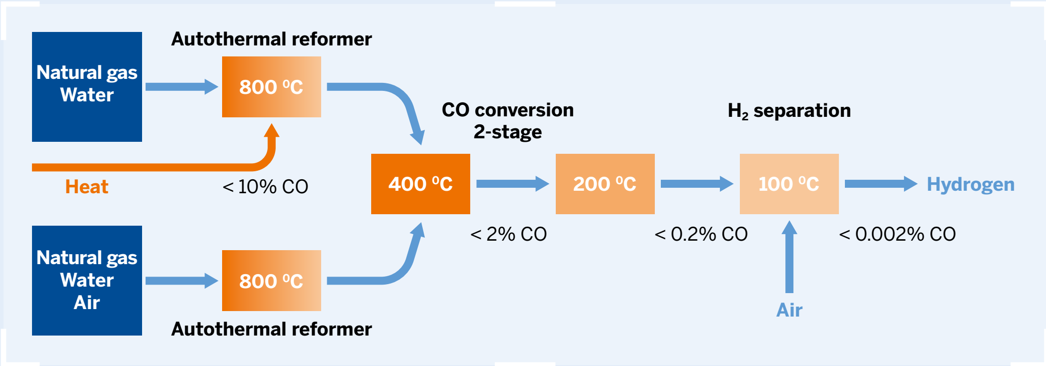
These days, hydrogen is most commonly produced by steam reforming of natural gas or naphtha. It is also a by-product of chlorine electrolysis and the reforming of carbon-rich raw materials such as acetylene and ethylene from natural gas, and a component of coke oven and steelworks gases. Water electrolysis only accounts for a small fraction of global production and usually takes place on a larger scale where cheap electricity from hydropower but no natural gas is available as a source of hydrogen for fertiliser production – and on a smaller scale where the point of use is too far away from industrial hydrogen sources.

During the transition in the energy system towards renewable energy sources, the proportion of hydrogen produced by water electrolysis will increase. Apart from classic alkaline electrolysis, PEM electrolysis and solid oxide electrolysis have seen significant growth in recent years. Further technological advances and the construction of larger units in the MW range will ensure that electrolytic hydrogen production from electricity, preferably generated from renewable sources, will become much more efficient and cost-effective, and thus more competitive compared to conventional production from natural gas.

In addition, processes are being developed that will allow hydrogen to be produced from residual materials, biomass, algae, biogas and digester gases, which could represent an additional source of hydrogen.

The following chapters describe some of these hydrogen production processes.

Hydrogen from natural gas: Steam reforming and CO conversion process steps



Steam reforming of natural gas
$CH_4 + H_2O \rightarrow CO + 3H_2$
$CO + H_2O \rightarrow CO_2 + H_2$

Shift reaction
$CO + H_2O \rightarrow CO_2 + H_2$

Residual gases

Source: DLR

Natural gas reformation

Hydrogen is still produced primarily by reforming natural gas (heterogeneously catalysed steam reforming of methane, see figure above). Natural gas reforming first produces a synthesis gas (hydrogen, carbon monoxide, carbon dioxide, steam and residual hydrocarbons), and carbon monoxide can subsequently be converted to hydrogen and carbon dioxide by a conversion reaction with water. Hydrogen is separated from the gas mixture by absorption, adsorption or by means of membranes.

Hydrogen production plant in Dormagen

In Dormagen near Cologne, Air Liquide operates an ultra-modern steam reformer. It has an annual production capacity of 22,000 tonnes of hydrogen and 120,000 tonnes of carbon monoxide.

As part of its Blue Hydrogen initiative, Air Liquide has committed itself to producing at least 50% of its hydrogen for energy applications either without releasing carbon dioxide or through carbon-neutral processes by 2020. Against this backdrop, the company has also developed strategies and concepts to increase the supply of green-certified hydrogen in Germany: Air Liquide has successfully completed the certification process for its Blue Hydrogen as a certified green product according to CEP specifications and the TÜV SÜD standard CMS 70. The Blue Hydrogen is produced centrally by reforming biomethane in a steam reformer at the Air Liquide site in Dormagen. The company uses a mass balancing system to supply its Blue Hydrogen to refuelling stations via several filling plants.

Air Liquide hydrogen production site

Contact:
Fabian Radix
Air Liquide Deutschland GmbH
Telephone: +49 (0)211/6699-4212
fabian.radix@airliquide.com

www.airliquide.com

Electrolysis of water

The electrochemical production of hydrogen by water electrolysis is a well-established technological process worldwide, dating back more than 100 years. Since it is currently more expensive to produce hydrogen through electrolysis than from fossil energy carriers (such as natural gas and coal), only about 4% of hydrogen requirements worldwide are covered by electrolysis today. However, in future energy systems, where renewable energy represents a major share of the energy mix, electrolytic hydrogen will play a major role both as a storage medium and as an energy carrier, for instance in the heating sector.

The decomposition of water by electrolysis involves two partial reactions separated by an ion-conducting electrolyte. The three relevant techniques of water electrolysis are categorised according to the choice of electrolyte. These processes are summarised in the diagrams on the next page, which show their respective sub-reactions at the anode and cathode, the typical temperature ranges and the ions for the corresponding charge transfer:

- Alkaline electrolysis with a liquid alkaline electrolyte
- Acidic PEM electrolysis with a proton-conducting polymeric solid electrolyte
- High-temperature electrolysis with a solid oxide as an electrolyte

Alkaline electrolysers

Commercial products are currently based only on alkaline electrolysis (various series of which have been available with capacities of up to approx. 750 Nm³/h of hydrogen for several decades) and PEM electrolysis (only approx. 20 years of plant development, and therefore only few commercial plants producing < 65 Nm³/h available on the market). Most alkaline electrolysers operate with an aqueous KOH solution with typical concentrations of 20 - 40%. The operating temperature is usually around 80 °C and the current densities are in the range of 0.2 - 0.4 A/cm². The voltage efficiency of the stack of commercial systems is around 62 - 82%. Alkaline electrolysis cell stacks are operated for up to 90,000 hours, so alkaline electrolysers are generally overhauled and have their electrodes and diaphragms replaced every seven to twelve years. However, only a few thousand systems have actually been manufactured since the introduction of water electrolysis more than a hundred years ago. Owing to this low level of activity, the state of the art in large-scale electrolysis plants has changed only marginally in the last forty years.

PEM electrolysers

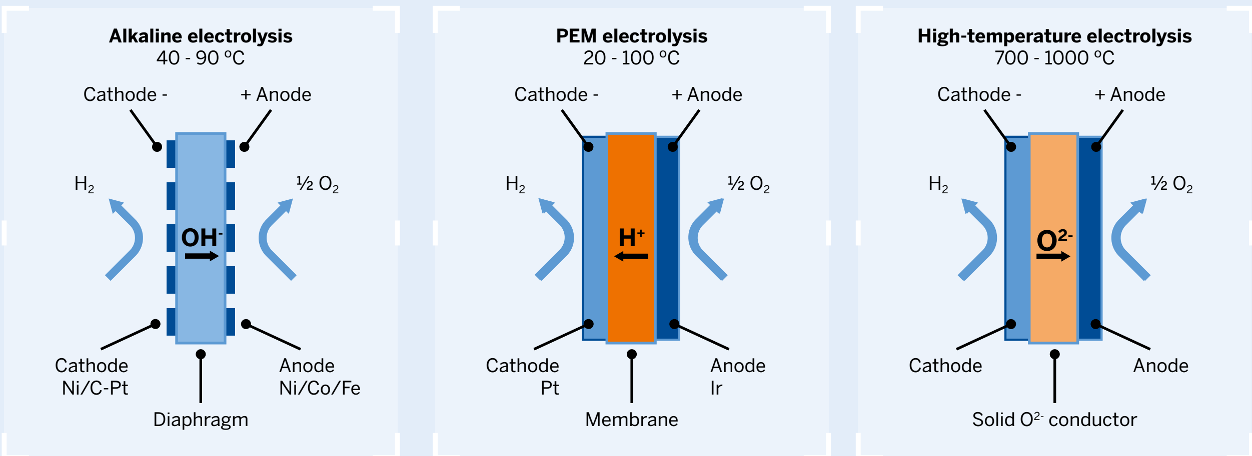
Product development for PEM electrolysis with proton-conducting membranes (see middle of diagram on next page only started about twenty years ago, so there are only a few commercial products for industrial niche applications (e.g. local production of high-purity hydrogen for semiconductor production and the glass industry) available on the market. Unlike alkaline electrolysers, PEM electrolysers use electrodes with platinum group metals. Commercial systems currently require about 4 mg/cm² of iridium or ruthenium on the anode and about 2 mg/cm² of platinum on the cathode. Under the given operating conditions, these PEM electrolysis systems operate at voltages of approx. 2 V with current densities of up to approx. 2 A/cm², and at operating pressures of up to 30 bar. This corresponds to the same voltage efficiency of approx. 67 - 82%, but compared to alkaline water electrolysis the current densities are much higher (0.6 - 2.0 A/cm²). Cell stacks in real systems are said to have a service life of up to 60,000 hours.

Hydrogenics PEM Electrolyzer (HyLYZER®-230-30), 230 Nm³/h (1.2 MW)

Water electrolysis for control reserve

The intermittent availability of renewable energies – for example in the form of wind power – represents a particular challenge to the process side of the electrolysis technology used, especially since the electrolyser is used to provide control reserve and is therefore operated with strongly fluctuating output levels and frequent interruptions when there is little or no power input. A particular problem is the partial load behaviour, especially with alkaline electrolysers, due to increasing levels of impurities in the gas. The lower partial load range of alkaline electrolysis plants, for example, is only 20 - 40% of the nominal load because the concentration of foreign gas, particularly H_2 in O_2, quickly reaches the critical range of e.g. 2%, at which the plant must be shut down for safety reasons. PEM electrolysis has a larger partial load range than alkaline electrolysis. In contrast to alkaline electrolysis, the partial load range at cell and cell stack level can be reduced to 5 - 10%. Both commercially available electrolysis technologies therefore have their advantages and disadvantages.

Operating principles of the different types of water electrolysis



$2OH^-$	→	$\frac{1}{2} O_2 + H_2O + 2e^-$	Anode	H_2O	→	$2H^+ + \frac{1}{2} O_2 + 2e^-$	Anode	O^{2-}	→	$\frac{1}{2} O_2 + 2e^-$	Anode
$2H_2O + 2e^-$	→	$H_2 + 2OH^-$	Cathode	$2H^+ + 2e^-$	→	H_2	Cathode	$H_2O + 2e^-$	→	$H_2 + O^{2-}$	Cathode
H_2O	→	**$H_2 + \frac{1}{2} O_2$**	**Total reaction**	**H_2O**	→	**$H_2 + \frac{1}{2} O_2$**	**Total reaction**	**H_2O**	→	**$H_2 + \frac{1}{2} O_2$**	**Total reaction**

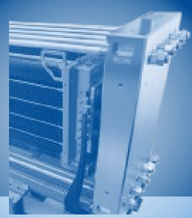
Alkaline electrolysis vs. PEM electrolysis

Alkaline electrolysis

Advantages:
- Established technology
- No noble metal catalysts
- High long-term stability
- Relatively low costs
- Modules for up to 760 Nm³/h (3.4 MW)

Challenges:
- Increased current densities
- Wider partial load range
- System size and complexity ("footprint")
- Reduction of gas cleaning costs
- Overall material use (stacks currently in tonne scale)

PEM electrolysis



Advantages:
- Higher power density
- Higher efficiency
- Simple system design
- Good partial load capability
- Ability to absorb extreme overloads (determines system size)
- Extremely fast system response for grid stabilisation
- Compact stack design for high-pressure operation

Challenges:
- Increasing the long-term stability
- Scale-up stack and peripherals in the MW range
- Cost reduction through reduction or substitution of precious metal catalysts and costly components (current collectors/separator plates)

To be able to use the two water electrolysis technologies realistically and sustainably in the mass markets of hydrogen production with renewable surplus electricity after 2020, further technological steps will be necessary to e.g. increase the low power densities, improve the inadequate stability and reduce the high costs of the technologies currently used. Important challenges in the further development of alkaline water electrolysis include, in particular, increasing the power densities of stacks, enlarging the partial load range, reducing system size and complexity, and improving the dynamics of the entire system. Apart from improving long-term stability and increasing the size of the plant to the MW range, the main priority in the field of PEM electrolysis is cost cutting by reducing and substituting the noble metal catalysts while maintaining performance values.

Contact:
Martin Müller
Forschungszentrum Jülich GmbH
IEK-3 Elektrochemische Verfahrenstechnik
Telephone: +49 (0)2461/61-1859
mar.mueller@fz-juelich.de

Marcelo Carmo
Forschungszentrum Jülich GmbH
IEK-3 Elektrochemische Verfahrenstechnik
Telephone: + 49 (0)2461/61-5590
m.carmo@fz-juelich.de

www.fz-juelich.de

Hydrogen potential from industrial production in NRW

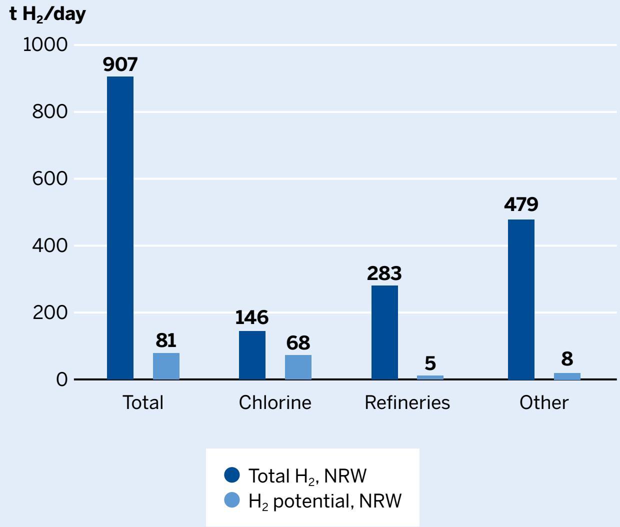
The vision of climate-friendly future energetic use of hydrogen is inextricably linked to its production from renewable sources. However, the use of hydrogen produced in industrial processes, including existing infrastructure, may be helpful for a transitional period. The Rhine-Ruhr region in North Rhine-Westphalia offers very favourable conditions and has numerous locations ideally suited for the energetic use of hydrogen.

A study by the Federal State of North Rhine-Westphalia entitled "Options for the cost-optimised, step-by-step development of an H_2 infrastructure in North Rhine-Westphalia" (6), which was completed back in 2009, combines a survey of available hydrogen quantities in NRW with a model for the development of a hydrogen infrastructure, emphasising the favourable conditions already in place in this federal state. The idea here was to make surplus quantities of fossil hydrogen available to mobile uses for a transitional period.

Significant sources and uses of industrially-produced hydrogen in NRW can be found, in particular, in chlorine production, refineries, and the declining production of coke used for producing crude steel. In some cases, hydrogen is also produced by natural gas reforming for use as a chemical feedstock in other production processes. High-purity hydrogen is yielded as a by-product in the electrolytic production of chlorine. Advances in process engineering allow chlorine to be produced with much less energy and without hydrogen. In individual cases, hydrogen is produced as a by-product depending on its market value.

The figure below shows a summary of the results for North Rhine-Westphalia. Here, chlorine-alkaline electrolysis plants (see photo on the following page) account for only 16% of total hydrogen production, while the share held by such facilities in terms of hydrogen potential for new utilisations amounts to 80%. By contrast, refineries and other facilities account for more than 80 per cent of total hydrogen production but together contribute only 20 per cent to the potential.

Industrial hydrogen production in NRW and potential for external use



Source: Wuppertal Institut (6)

Chlorine-alkali electrolysis in Hürth-Knapsack: 310,000 t of chlorine per year, 203,000 Nm³ of hydrogen per day

Compared to the time of the study, the available volume has decreased significantly due to the economic structural change and growing interest in industrial hydrogen. At that time, the estimated industrial potential of 958,000 Nm^3/day or 350 million Nm^3/year for North Rhine-Westphalia could have been used to fuel about 260,000 fuel cell cars (12,000 km per year at a consumption of 3.5 l of petrol equivalent or about 1 kg hydrogen per 100 km) for initial projects during the market launch phase.

In addition to the possibility of zero-emission transport, hydrogen as an energy carrier also offers great potential for regional added value. So far, for example, the Cologne area has incurred annual costs of 25 – 30 million euros for diesel fuel (1.15 euros per l x 1,000 buses x 55,000 km annual mileage x 43 l of diesel per 100 km) for the operation of its 1,000 or so city buses.

Contact:
Andreas Pastowski
Wuppertal Institut für Klima, Umwelt, Energie GmbH
Telephone: +49 (0)202/2492-118
Andreas.Pastowski@wupperinst.org
www.wupperinst.org

Thomas Grube
Forschungszentrum Jülich GmbH
Telephone: +49 (0)2462/61-5398
th.grube@fz-juelich.de
www.fz-juelich.de

Boris Jermer
HyCologne – Wasserstoffregion Rheinland e.V.
Telephone: +49 (0)2233/406-123
jermer@hycologne.de
www.hycologne.de

Alternative processes for the production of hydrogen

Photobiological hydrogen production

The growing demand for environmentally friendly and sustainable energies makes hydrogen (H_2) a very attractive energy carrier. In future, photoautotrophic microorganisms could cover this demand.

Some microalgae are able to convert the sun's energy to produce hydrogen via photosynthesis. This so-called photobiological hydrogen production is carried out using the biocatalyst hydrogenase, an enzyme capable of producing up to 10,000 molecules of hydrogen per second [(7)].

The green alga Chlamydomonas reinhardtii is particularly suited for the photobiological production of H_2 because it has a highly efficient enzyme for hydrogen formation. The exact characterisation of the hydrogen metabolism of C. reinhardtii is the main field of research of the Photobiotechnology Working Group of Ruhr University of Bochum (RUB), the aim being to make biotechnological hydrogen production more efficient in the future.

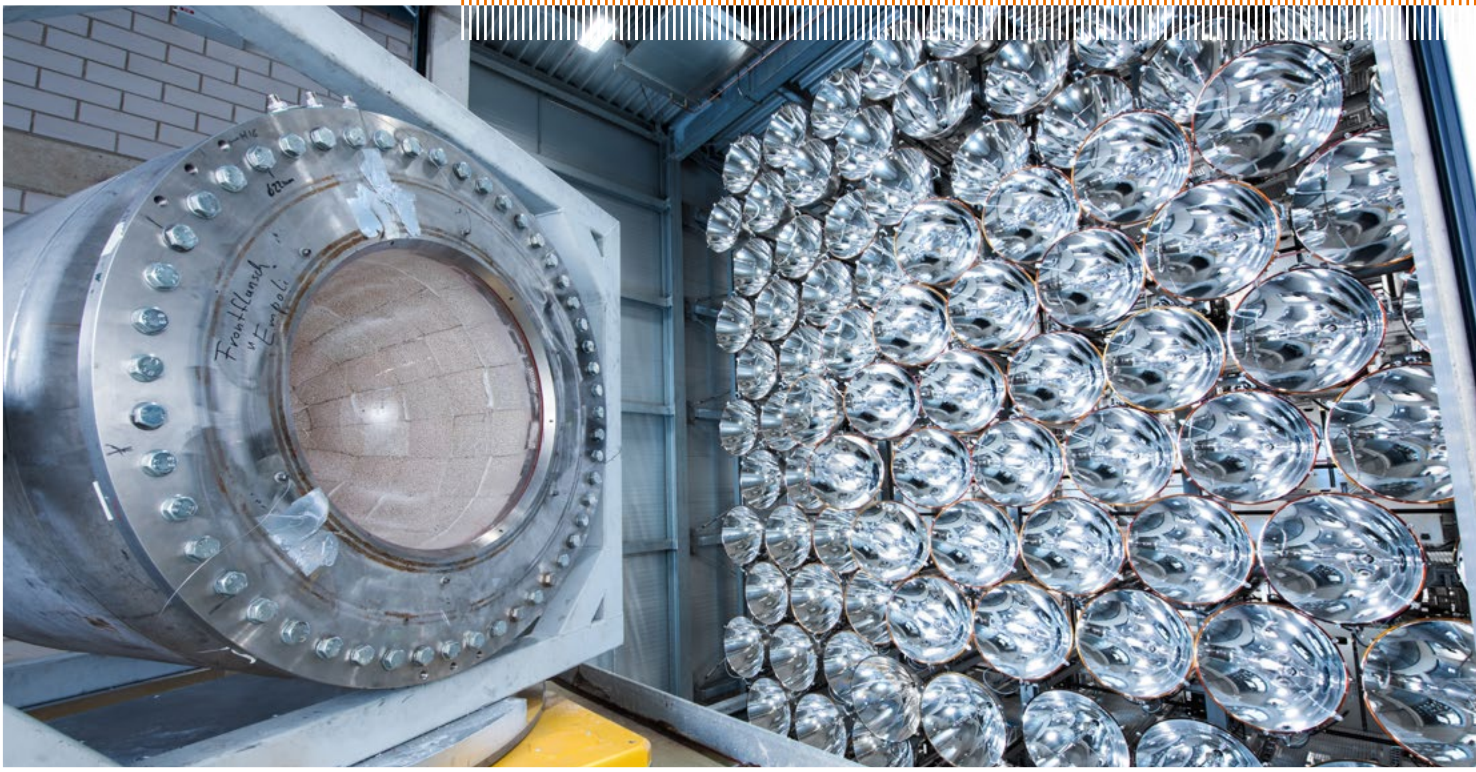
As part of the EU-funded Sun2Chem project, Professor Thomas Happe and his team developed semi-artificial chloroplasts. Chloroplasts are the structures performing photosynthesis in plant cells. With the help of synthetic biology, semi-artificial chloroplasts can contribute to increasing photosynthetic hydrogen production. A related research approach of the Photobiotechnology Working Group is dealing with the replication of the enzyme hydrogenase in the test tube. The group's initial research results have already shown that artificial hydrogenase has the same biochemical properties and is just as efficient as the natural enzyme.

The recently launched German-Sino Sigal4NRG project to set up a German-Sino laboratory for algae bioenergy has been carrying out extensive research into transferring the findings from the test tube into the algae cell. The project, funded by the Federal Ministry of Education and Research (BMBF), was initiated by the Chair of Plant Biochemistry together with the Photobiotechnology Working Group of Ruhr University of Bochum, the SolarBioproducts Ruhr project office in Herne, and the Single Cell Centre of the Institute for Bioenergy and Bioprocess Technology of the Chinese Academy of Sciences (CAS-QIBEBT) in Qingdao. The researchers want to use molecular biological methods to optimise the properties of algae strains for energy production.

Synthetic and molecular biology are valuable tools for photobiological hydrogen production. The results of the research work by the Photobiotechnology Working Group can in future contribute to the production of hydrogen from microalgae on an industrial scale, which would make it economically competitive.

Contact:
Prof. Dr. Thomas Happe
AG Photobiotechnologie
Ruhr-Universität Bochum
Telephone: +49 (0)234/3227026
thomas.happe@rub.de

www.rub.de/pbt



Receiver/reactor inside the modular high-power solar simulator (Synlight) at the German Aerospace Centre (DLR) in Jülich

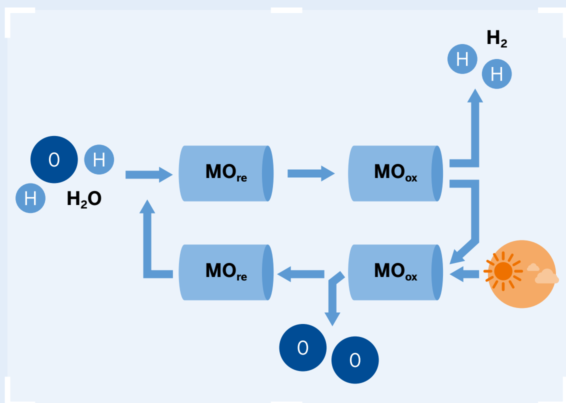
Hydrogen production via solar-thermochemical cycles: Hydrosol Plant – Synlight – ASTOR

Solar-powered thermochemical cycles are a promising pathway for the renewable production of hydrogen. If the process heat required is supplied by concentrated solar radiation in a thermochemical cycle, the process requires no fossil resources.

As part of a series of EU projects (HYDROSOL I, HYDROSOL II, HYDROSOL3D and HYDROSOL PLANT), DLR's solar research team, in collaboration with other European partners, has developed and "solarised" a two-stage thermochemical cycle in which metal oxides are used as redox material. The reactor concept is based on the use of cellular structures consisting either entirely of the redox material used or of a layered composite carrying the redox material as a surface layer on a ceramic substrate. The structures through which the water vapour flows provide the reaction surface for the splitting of water while also serving as volumetric solar absorbers. They are heated to the required process temperatures of 800 to 1,400 °C by concentrated solar radiation.

In the first of the two steps, the redox material is oxidised. The oxygen required for this step is extracted from the water vapour flowing through it, which splits the water molecules and produces hydrogen. In the second step, the metal oxide is reduced and returned to a low-oxygen state, i.e. "regenerated" so that it can be used again for the production of hydrogen.

Process diagram of a two-stage cyclic process



Source: DLR

750 kW plant for solar thermal chemical hydrogen production on a solar tower

As part of the above projects a number of solar reactors and plant technology were successively enhanced and qualified in a series of measurement campaigns. To show that the developed plant concept also works on a larger scale, a 750 kWth plant (see picture above) is currently being built, which will demonstrate the process at the Plataforma Solar de Almeria in southern Spain. This plant, which uses nickel ferrite and cerium oxide as redox materials, will further increase hydrogen sales with improved efficiency. The technology will be further introduced to the market as part of two NRW/EU-financed projects known as "Modular High Power Radiators" (MHLS) and ASTOR. The heat recovery concept will be improved and the process (partially) automated. The experiments in these projects will not be performed with concentrated solar radiation, but in an "artificial sun", i.e. the "Synlight" plant built as part of MHLS. It consists of 149 high-power light sources and offers optimum, uninterrupted test conditions with a total radiation output of approx. 200 kW.

Contact:
Dr. Martin Roeb, Dr. Thomas Fend
Deutsches Zentrum für Luft- und Raumfahrt e.V.
Telephone: +49 (0)2203/6012673
martin.roeb@dlr.de, thomas.fend@dlr.de

www.dlr.de

Hydrogen from digester gas

With its wastewater treatment plants, the water industry offers significant potential for the introduction of a sustainable hydrogen-based energy infrastructure. The digester gas produced during sludge treatment at these plants can serve as a renewable resource for the production of bio natural gas and hydrogen. This is particularly useful if there is excess energy – e.g. from other renewable energies at the site – that is to be converted into a storable form.

Emschergenossenschaft, Germany's largest wastewater treatment plant operator, decided at an early stage to test and further develop the treatment and conversion of digester gas to bio natural gas and hydrogen as part of the "EuWaK – Natural Gas and Hydrogen from Wastewater Treatment Plants" demonstration project at its Bottrop site. The project was completed in 2012. The project partners working with Emschergenossenschaft to develop and implement this project were Tuttahs & Meyer Ingenieurgesellschaft für Wasser-, Abwasser- und Abfallwirtschaft mbH (T&M), Forschungsinstitut für Wasser- und Abfallwirtschaft (Research Institute for Water and Waste Management) at RWTH Aachen University (FiW), Ingenieurbüro Redlich und Partner GmbH (IBR), and the city of Bottrop.

In this pilot project, digester gas was first processed into bio natural gas. The maximum digester gas input of the plant was 120 Nm^3/h. A side stream of the bio natural gas was diverted, compressed (max. 72 Nm^3/h) and used to fuel the company's own natural gas vehicles at an NGV refuelling station. The refuelling station was and will continue to be used for the company's vehicle fleet after completion of the project. A further side stream of the bio natural gas was converted to hydrogen in a steam reformer (max. 100 Nm^3/h). The hydrogen produced this way was piped to a nearby school via a new pipeline built as part of the project, where both electricity and heat for the school were generated in a cogeneration unit. During the project period from 2008 to 2012, this hydrogen CHP unit was operated at nominal load for between 500 and 1,500 hours per year. The hydrogen was used in cooperation with the city of Bottrop. In addition, the project explored further processing of the hydrogen for use as a vehicle fuel. For this purpose, a hydrogen refuelling station was built at the Bottrop sewage treatment plant, which was meant to be connected to hydrogen production. However, this could not be accomplished during the project period.

The research results showed that the bio natural gas production facility and the NGV refuelling station were operated in a stable and reliable way. Detailed analysis of the gas during the operation of production facility confirmed the high purity of the hydrogen (99.99 Vol.% H_2, i.e. grade 4.0, or even 99.999 Vol.% H_2, i.e. grade 5.0). The concentrations of CO and CO_2 were below the detection limit.

Under best-case conditions, the hydrogen production unit achieved an energy efficiency in the range of 40%; however, this value was not reached continuously due to issues with overall plant availability, which could still be improved. The overall assessment also needs to take account of the specific efficiencies of upstream and downstream process stages (in this case, bio natural gas production and H_2-fuelled CHP system).

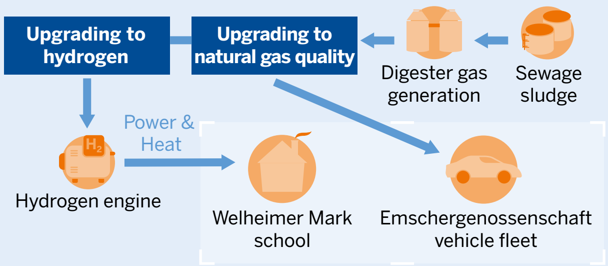
The project was implemented with financial support from the state of North Rhine-Westphalia and the European Union. Experimental operation concluded in September 2012. After completion, hydrogen production continued for a short while but has now been discontinued. The processing unit providing bio natural gas and the associated refuelling station are still in operation – partly with a view to promoting mobility in future.

Contact:
Daniel Klein
Emschergenossenschaft/Lippeverband
Telephone: +49 (0)201/1042280
klein.daniel@eglv.de

www.eglv.de

Plant components

"EuWaK – Natural Gas and Hydrogen from Sewage Treatment Plants" at the Bottrop sewage treatment plant



Source: EuWaK

Power-to-X/power-to-gas projects in NRW

The conversion of electricity into gaseous and liquid energy sources as part of a future energy system, discussed in the chapter "The new role of hydrogen in a future energy supply system" is also being trialled as part of numerous projects in North Rhine-Westphalia. While the hydrogen-based complementary energy system in Herten allows external clients to trial largely self-sufficient renewable energy supply concepts at useful loads of up to 50 kW during grid-connected parallel and standalone operation, the focus in Ibbenbüren is on system services for the electricity grid, hydrogen injection into the gas pipeline system and the use of waste heat from the electrolyser. Duisburg and Niederaußem are exploring the material use of carbon dioxide from steel and electricity generation, while in Wesseling the objective is to reduce the CO_2 intensity of classic fuels and – in future – also provide renewable hydrogen for other applications. The diversity of these and other projects is testament to the high level of expertise in North Rhine-Westphalia. The EnergyAgency.NRW brochure "Power-to-Gas in Germany and NRW" (8) also provides a comprehensive overview. Some of the locations are presented on the following pages.

Duisburg

The Carbon2Chem project investigates the use of metallurgical gases as a resource for chemical products. The utilisation of the exhaust gases provides the basis for sustainable steel products and basic chemicals from German sources. Steel mills release considerable amounts of CO_2, and the German steel industry accounts for some 6% of Germany's total CO_2 emissions, so in addition to safeguarding steel production in Germany, the aim here is to develop solutions for the sustainable use of exhaust gases that may be exported to other countries. Carbon2Chem is looking to convert metallurgical gases into chemical raw materials to replace fossil raw materials, whereby the waste gas from the blast furnaces is converted into precursors for fuels, plastics or fertilisers. Metallurgical gas contains 44% nitrogen, 23% carbon monoxide, 21% carbon dioxide, 10% hydrogen and 2% methane. The project also creates the basis for a sustainable value chain linking different industrial sectors. The electrical energy required is obtained from renewable sources under flexible load conditions. The project has the potential to become a key technology for global climate protection and can be marketed internationally, but the utilisation of metallurgical gases raises many fundamental research questions. For this reason, the project partners include leading global industrial companies as well as excellent research institutions.
www.carbon2chem.de

Essen

At the Gas and Heat Institute Essen e.V. (GWI), a 15 kW PEM (Polymer Electrolyte Membrane) electrolyser with a chemical methanation unit is being set up for research purposes as part of the Virtual Institute for Electricity for Gas and Heat project.
www.gwi-essen.de

Herten

A pilot plant for the research and development of components and configurations for renewable energy supply has been set up at the h2herten user centre with NRW/EU funding. The model plant represents a complete hydrogen-based renewable energy supply system. Its centrepiece is a complementary energy system comprising an electrolyser, a compressor, an H_2 storage system, a fuel cell and a battery. It is one of the most advanced power-to-gas plants designed for the distributed generation of renewable electricity and hydrogen. With the real-time data of the neighbouring wind power plant and the simulated energy demand of the h2herten user centre, the operator was able to ensure stable, error-free operation of a self-sufficient, industrial-scale, fully renewable energy supply system.
www.h2herten.de

Ibbenbüren

In Ibbenbüren, innogy SE operates since 2015 a PEM electrolyser with a power rating of 150 kW. The hydrogen is fed into the public gas grid downstream of a pressure regulator station. The hydrogen content by volume always remains below 1% and the concentration is monitored using state-of-the-art instrumentation. The use of waste heat from the electrolyser for preheating the natural gas prior to expansion whenever the electrolyser is in service, instead of using heat from a CHP unit, is a world first. It ensures record energy efficiency of 86%. Without waste heat utilisation, the efficiency – based on the gross calorific value – is 71% and under partial load conditions up to 75%. As part of the Designnetz project (01/2017 - 12/2020), which was started in 2017 to explore various flexibility options, the project partners are testing a solution for remote plant control by the electricity grid operator to optimise grid use.
www.designetz.de

Niederaußem

At a lignite-fired power plant operated by RWE Power AG in Niederaußem, system integrator Mitsubishi Hitachi Power Systems Europe (MHPSE) and various partners in the EU-SPIRE-funded project MefCO_2 (12/2014 - 11/2018) are building a PEM electrolyser, a unit to remove carbon dioxide from the flue gas as well as a methanol plant. Partners include Carbon Recycling International (Iceland) for the reformer, Hydrogenics Europe (Belgium) for the 1 MW PEM electrolyser, and the University of Duisburg-Essen for the CO_2 removal process.

The aim is to demonstrate the economic feasibility of upgrading captured CO_2 to a versatile raw material using hydrogen produced with excess renewable energy. The aim is to ensure flexible operation of the reformer under different load conditions. The plant will have methanol production capacity of about 1 t/d.
www.mefco2.eu

RWE's Niederaußem site is also involved in the Align-CCUS project, which was launched at the end of 2017 and is funded by the European ERA-NET Act Fund. The project is developing low-carbon solutions for five industrial regions in Europe. The project aims to reduce the cost of CO_2 capture (CC), solve various questions concerning CO_2 transportation and storage (S) in the seabed, and develop options for CO_2 conversion or carbon reuse (U=utilisation). A plant built by MHPSE in Niederaußem will explore the direct production of the methanol-based diesel substitute fuels DME and OME (dimethyl ether, oxymethylene-dimethyl ether) from the locally obtained feedstocks H_2 and CO_2 in an effort to examine the reuse of resources as one priority. RWTH Aachen University and FEV GmbH are developing an adapted injection system and will then use the substitute fuels in a vehicle to examine their usability. In addition, a 240 kW power generator is being adapted for DME. The Jülich Research Centre is performing the Life Cycle Analyses (LCA). The size of the electrolyser supplied by Asahi Kasei was not known at the time of publication.
www.alignccus.eu

Saerbeck

In the town of Saerbeck, a combined energy storage system is being built at the NRW-funded EnerPrax (12/2016 - 11/2019) bioenergy park. It includes a 12 kW PEM electrolyser with a biological methanation unit, two batteries (lead/lithium ions) with an output of 6 kW each and a 15 kW redox flow battery. Apart from four packaged cogeneration systems for biogases generating a total of 2 MW_e, the park currently has seven wind turbines each rated 3 MW and about 6 MW of photovoltaic power.
www.energiespeicher.nrw

Steinfurt

The district of Steinfurt, where Saerbeck is located, is generally exploring the use of hydrogen as an energy storage medium. As part of the Energieland 2050 strategy, the district intends to meet its energy needs entirely with local, renewable sources. Most of the energy produced locally will be used within the district. The conceptual study "Steinfurter Flexkraftwerke" from 2016 shows the role of a hydrogen economy in this process.
www.energieland2050-dialog.de

Wesseling

Shell Rheinland Raffinerie is building a hydrogen electrolysis plant with a nominal capacity of 10 MW at its refinery site in Wesseling. As one of the largest PEM electrolysers in the world, it will help the electricity grid deal with an increasing share of fluctuating renewable sources. The plant will be built as part of the Refhyne project together with ITM Power, SINTEF, thinkstep and Element Energy with funds from the European FCH 2 JU programme. The project was launched in January 2018.

Shell Rheinland Raffinerie uses some 180,000 tonnes of hydrogen from steam reforming for its processes every year. With plants in Cologne-Godorf and Wesseling, it is the largest German refinery. Around 17 million tonnes of crude oil are processed each year. The electrolyser, which operated with renewable electricity, will be the key to carbon-free hydrogen production at the refinery, as the hydrogen can be fully integrated into on-site processes. The site allows the technical installations to be expanded to deliver hydrogen to customers outside the refinery. It will play an important role for the integration of energy storage and grid balancing.
www.fch.europa.eu

Hydrogen logistics

Hydrogen logistics covers all aspects from well to wheel, i.e. from the primary energy source to conditioning (liquid, gaseous), storage and transport (gas cylinders, cryogenic containers, trailers, pipelines) and refuelling of vehicles. It also includes all processes at the refuelling stations: on-site hydrogen production by electrolysis, on-site natural gas reforming, evaporation of liquid hydrogen or compression for refuelling high-pressure gas storage tanks. The selection of suitable logistics strategies for hydrogen supply is based on criteria such as economic viability, efficiency and environmental impact and depends to a large extent on the following aspects:

- Primary energy used (wind, sun, biomass, natural gas)
- Technology and sizing of hydrogen production plants
- Regional and local conditions (distance between refuelling station and hydrogen production, demand situation)
- Hydrogen use (mobile, stationary, capacity)

Using conventionally produced hydrogen may make sense for a transitional period until renewable energies are available in sufficient quantities. Supply routes for specific applications need to be analysed, compared and evaluated under the above conditions. The technical prerequisites for the use of hydrogen as an energy carrier in the transport sector are there. What is still lacking, however, is comprehensive, sustainable hydrogen infrastructure.

Hydrogen storage

The storage of hydrogen is a key criterion for the commercial success of hydrogen used for energy conversion by means of fuel cells. Enormous efforts are being made worldwide to solve this problem. Partial options that are particularly appropriate include the ones shown below.

A comprehensive evaluation of the different hydrogen storage systems (in terms of tank, storage mass, periphery, loading and unloading) would have to be based on criteria such as storage efficiency, energy demand (energy efficiency), service life, loading and unloading rates, type of storage, hydrogen losses and costs. The following storage forms are of particular importance: high-pressure gas storage, liquefied gas storage, metal hydride storage, chemical hydride storage (inorganic and organic compounds), and large-scale storage in salt caverns, as discussed in connection with the energy transition.

Physical storage

High-pressure gas storage
(350 to 700 bar, 23 to 39 g of H_2 per litre)
Tank storage density, fibre composite, up to 4.5 wt.% of H_2

Liquified storage
(-253 °C, 1 bar, 71 g of H_2 per litre)
Tank storage density, steel shell, up to 6 wt.% of H_2

Adsorption storage

(Van der Waals or other sorption bonds), e.g.: zeolites, C nanostructures, metal-organic frameworks (MOF)

Chemical storage

(Chemical compounds of H_2 with metals and non-metals)

Metal-hydride storage
Classical metal hydrides: $LaNi5H_6$ <=> $LaNi_5$ + 3 H_2
Complex metal hydrides: $NaAlH_4$ <=> NaH + Al + 3/2 H_2

Chemical hydride storage
$NaBH_4$ + $2H_2O$ <=> 4 H_2 + $NaBO_2$ (H_2 charging not in car)

Covalent and liquid organic hydride storage
Ammonia, boranes, hydrocarbons (e.g. Liquid Organic Hydrogen Carriers (LOHC))

Cavern storage facilities

(Underground voids in salt domes)

Production of a CFRP pressure vessel at EMS in Jülich

Pressure vessel for the gaseous storage of hydrogen

The low volumetric energy density of hydrogen makes it necessary to highly compress the hydrogen to be able to store it in larger quantities in an appropriate space. High-pressure storage in pressure vessels has proven to be a viable solution.

Basically, there are four different gas pressure vessel designs:

- Type I = Conventional steel gas cylinders
- Type II = Steel liners with a composite fibre wrap around its circumference
- Type III = Metallic liners fully wrapped with composite fibre
- Type IV = Plastic liners fully wrapped with composite fibre

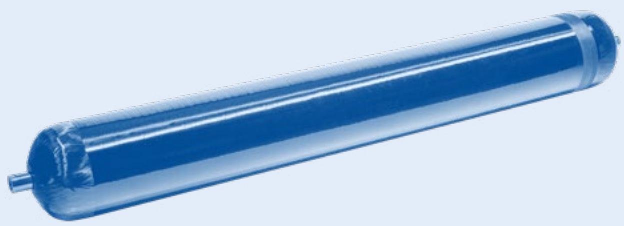
Due to their low weight, the extraordinary strength of the material and their suitability for cost-efficient series production, modern type-IV vessels are seen as the design of choice for current and future hydrogen storage.

NPROXX is a leading supplier of type-IV pressure vessels made of carbon-fibre-reinforced plastic (CFRP). A type-IV gas cylinder made entirely of CFRP was already approved for use at the Jülich site back in 1999 when steel cylinders were standard and CFRP products were virtually unknown. It was the first time such a product was approved in Europe. Today, the most sought-after products include, most significantly, CFRP pressure vessels used as tanks for mobile applications (cars, buses, trucks, trains) with operating pressures of up to 700 bar, and vessels for stationary use, e.g. at hydrogen refuelling stations. The Jülich site also benefits from its favourable location in the immediate vicinity of the Jülich Research Centre and RWTH Aachen University and from its integration into scientific research networks.

Contact:
NPROXX Jülich GmbH
Johannes Lorenz
Telephone: +49 (0)2461/657200
Johannes.lorenz@nproxx.com

www.nproxx.com

Type-IV pressure vessel for hydrogen storage



Source: NPROXX Jülich GmbH

Hydrogen logistics on the road

Until the end of the 1990s, mobile hydrogen storage systems relied entirely on type-I pressure vessels. Some designs included as many as 400 individual cylinders mounted on a trailer in large bundles. The storage volume was approx. 3,000 m^3, the pressure 200 bar.

To this day, transport solutions based on type-I pressure vessels – known as tube trailers – with storage volumes of up to 4,500 m^3 at 200 bar are still being used. The main features here are the small number of cylinders (no more than 10 per vehicle) and the inspection intervals, as these cylinders only have to be inspected every 10 years.

The use of new vessel technologies now allows more effective transport solutions. Composite vessels offer a much better kilogram/litre ratio than pure steel containers, which translates into higher loading volumes and higher pressures of up to 500 bar.

The 300-bar system is the most widely used system allowing up to 14,500 m^3 to be transported. The system is designed as a trailer vehicle or a multiple-element gas container (MEGC), although trailer designs are somewhat lighter than the container/chassis combination and have a slightly higher loading capacity. Container designs also offer the advantage of allowing the chassis to be replaced, if necessary, and this represents a considerable advantage, especially when visiting a workshop, as it considerably reduces downtimes. Container solutions can also be used in combined transport, e.g. road/rail operations. Containers from 10 to 45 ft are available on the market, but even the container version with a chassis does not reach the permissible total weight. Rather, it is the volume limit of this combination that is reached first.

Today, all systems from type I (tube trailers) to type IV still have their role to play. However, when it comes to loading volumes, the transport system with composite containers (types III & IV) has the most to offer (see picture above). High volumes have a considerable impact on logistics costs and the environment, as the use of the towing vehicle is reduced to one third compared to the old type-I solution. The first generations of the new systems still had inspection intervals of five years, so the operating costs were higher, but this has increasingly changed to ten years. This extended interval is down to positive test results over the last few years – which also represents progress in terms of safety.

Mobile hydrogen storage system

Source: Wystrach

Type IV containers allow more alternating loads and therefore have no service life limitations. Shut-off devices and safety systems ensure that the rear/side pipework does not carry any gas during the journey in case there is a rear-end collision, and further safety systems can be installed to allow controlled draining in the event of fire.

The new 300 bar systems such as those built by Wystrach in Weeze also have the advantage of allowing higher pressures during withdrawal from the container/trailer. Tanks to be filled on industrial premises are usually rated 40 bar, so the 40/300 or 40/200 bar pressure difference means that one full container/trailer can supply more customers.

Contact:
Wolfgang Wolter
Wystrach GmbH
Telephone: +49 (0)2837/913513
wolter@wystrach-gmbh.de

www.wystrach-gmbh.de

Hydrogen filling centre and hydrogen pipeline

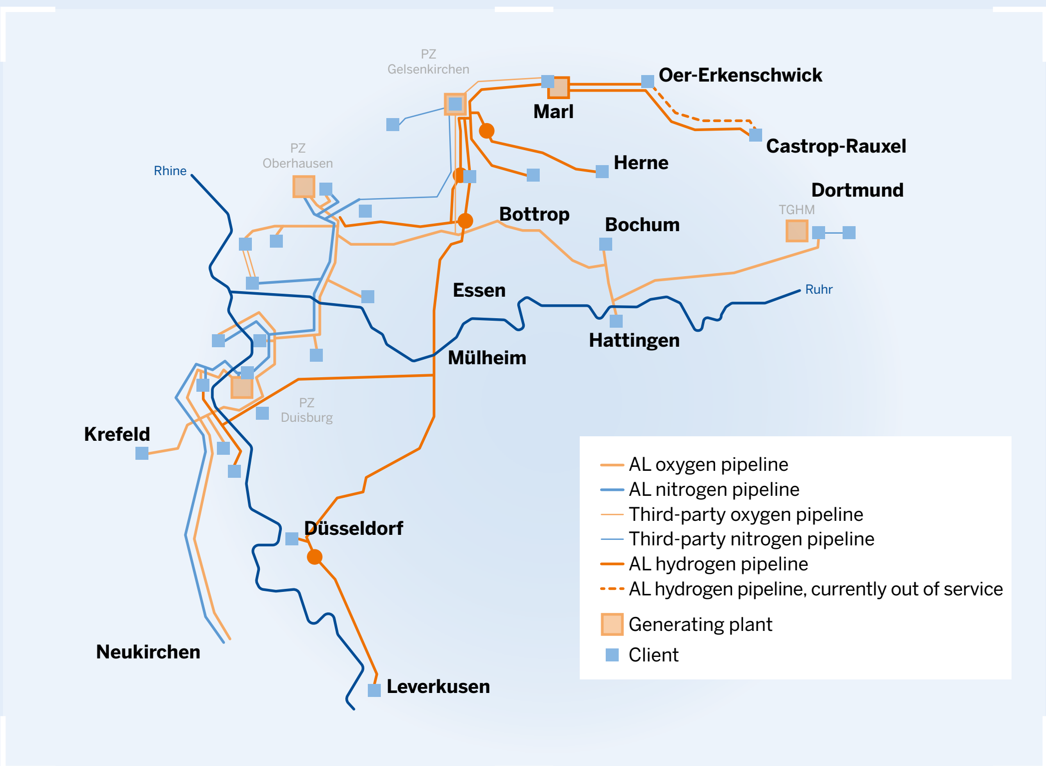
AIR LIQUIDE Deutschland GmbH operates Europe's largest hydrogen distribution centre at the Marl chemical park. The hydrogen is produced mainly by steam reformers and then compressed to as much as 300 bar. Side streams of hydrogen supply production facilities at the chemical park, the distribution centre, and the pipeline. The facility is used to fill hydrogen trailers with an operating pressure of 200 bar and a capacity of 3,500 to 7,500 m³ (290 - 625 kg) as well as steel cylinders and cylinder banks with operating pressures of 200 and 300 bar. Post-treatment allows grades of up to 99.9999 Vol.% to be achieved. Every year, approx. 15,000 trailers as well as a large number of cylinders and banks are filled in Marl.

Marl is also the starting point of Germany's longest hydrogen pipeline, which has a total length of some 240 kilometres (with terminals at Castrop-Rauxel and Leverkusen, plus connections to Krefeld and Oberhausen). Consumption peaks and troughs at individual customers can be absorbed, and industrial hydrogen can also be fed in.

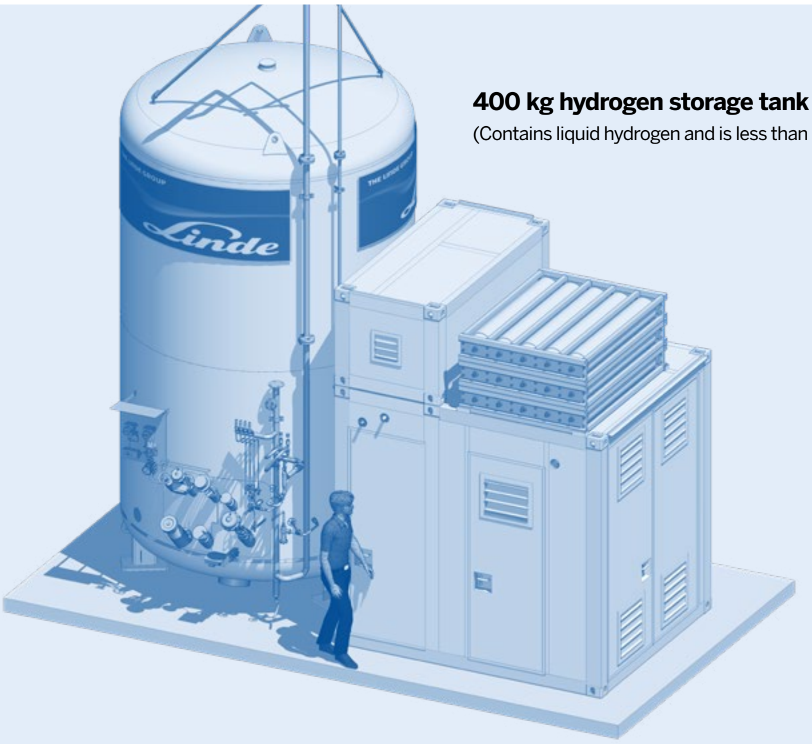
Contact:
Andrea Feige
Air Liquide Deutschland GmbH
Telephone: +49 (0)2151/3799346
andrea.feige@airliquide.com

www.airliquide.com

Hydrogen pipeline network (240 km)



Source: Air Liquide



400 kg hydrogen storage tank
(Contains liquid hydrogen and is less than 6 m high)

Source: Linde

Liquid gas storage

The storage of hydrogen in liquid form is not a new technology. It has been used in the gas industry since the beginning of the 20th century. The liquefaction process is energy-intensive because industrial plants convert electrical energy into cold energy, which is required for liquefaction, but because of the higher energy density (i.e. more hydrogen can be transported per shipment and stored per footprint) and the significantly lower energy requirement for subsequent compression, liquid hydrogen often offers an economic advantage over a supply chain based on compressed, gaseous hydrogen. This advantage is particularly noticeable where larger hydrogen quantities are needed.

The liquid hydrogen tank used for transportation and storage essentially consists of two vessels:
The outer vessel is exposed to atmospheric pressure while the inner vessel, which is under high vacuum, is subjected to internal pressure loads. Today, these vessels are almost exclusively made of austenitic stainless steel (see figure above).

One challenge in the storage of liquid hydrogen is the slow evaporation of the contents as a result of the ingress of heat from the exterior (conduction, convection, radiation). If no hydrogen is withdrawn over a longer period of time, a so-called "boil-off effect" (evaporation of the gas) can occur. The time until boil-off occurs can be significantly extended by using sophisticated insulation systems, active cooling and/or a combination of a liquid and pressurised storage mode. Moreover, the energy contained in the boiled-off hydrogen can be stored and used in a variety of ways, for example to cool piping, to provide energy via a fuel cell or to generate heat by combustion. This effect has a positive impact on the energy balance of the overall system.

Contact:
Alexander Schadowski
Linde AG, Linde Gases Division
Telephone: +49 (0)211/7481175
alexander.schadowski@linde.com

www.linde-gas.de

Solid-state storage

Solid-state storage systems (metal and non-metal hydride storage systems and carbon-based or mixed storage systems of this type) offer a third alternative for the storage of hydrogen in addition to pressurised and liquid hydrogen storage systems. Known reversible hydride systems store up to 1.5 wt.% of hydrogen at room temperature. Complex hydrides with an H_2 storage capacity of up to 5.5 wt.% have been under investigation for a number of years. They include both reversible hydride compounds (which allow recharging under hydrogen pressure, e.g. NaAlH4) and non-reversible hydrides (no recharging under hydrogen pressure, chemical conversions required for regeneration, e.g. in the case of NaBH4). For mobile systems reversible hydride systems are the preferred choice.

The use of metal hydrides as hydrogen storage media in the mobility sector is limited by the need for high-speed hydration. Recharging (refuelling) should take place under the following conditions: pressures of $p < 50$ bar, temperatures of $T < 100$ °C and times of $t < 10$ min. However, there are no known systems at present which would meet these requirements while offering a sufficiently high storage capacity.

The Max Planck Institute for Coal Research in Mülheim an der Ruhr conducts basic research in the fields of organic and organometallic chemistry, homogeneous and heterogeneous catalysis and theoretical chemistry, with the aim of developing new methods for selective and environmentally friendly conversion reactions.

New materials based on complex aluminium hydrides are being researched and further developed for the storage of hydrogen. Complex aluminium hydrides based on NaAlH4 achieve reversible storage capacities of 5 wt.% of hydrogen (1 g of storage medium releases around 600 ml of hydrogen), but materials with higher hydrogen contents are needed for mobile applications.

The rate of release and loading of hydrogen into the materials can be varied over a wide range by the selection of suitable catalysts. This way, the properties of the storage material can be adapted to the needs of fuel cells. These solid-state storage media are being developed in close cooperation with vehicle manufacturers. With the help of the Institute for Energy and Environmental Technology (IUTA), solutions for the integration of solid storage media and fuel cells into complete systems suitable for practical use in the 200 W_e range are being developed (see figure below).

Metal hydrides not only reversibly store hydrogen, but also large amounts of heat and can therefore be used as thermochemical heat storage systems. Heat can be supplied when there is a surplus of heat (releasing the hydrogen) and can then be withdrawn and used again at the same temperature, with no losses, when heat is needed. Thermochemical heat storage systems based on metal hydrides not only offer a link to hydrogen technology, but can also contribute to reducing the load on electricity grids and help absorb excess energy (power-to-heat). Materials and systems based on Mg compounds are being developed for the 300 to 600 °C temperature range.

Contact:
Dr. Michael Felderhoff
Max-Planck-Institut für Kohlenforschung
Telephone: +49 (0)208/3062368
felderhoff@mpi-muelheim.mpg.de

www.kofo.mpg.de

Lightweight steel storage tank

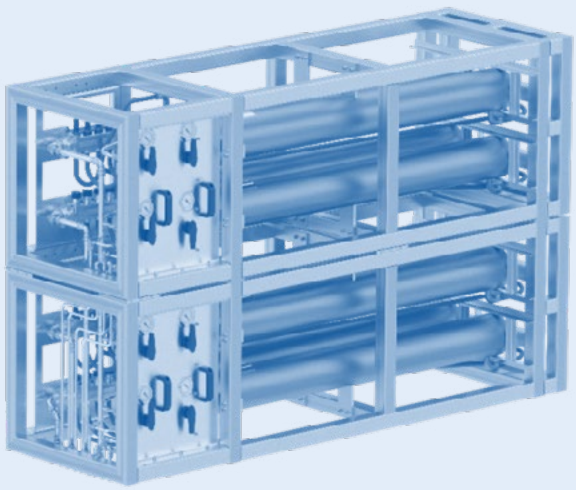
Suitable for metal hydrides with extruded aluminium profiles to facilitate optimum heat transfer for hydrogen supply to an HT-PEM fuel cell (approx. 2.0 kg Na_3AlH_6), Cooperation partners: MPI Mülheim, IUTA Duisburg, FWB Brökelmann Aluminiumwerk GmbH & Co. KG, Trimet Aluminium AG)

Source: MPI for Coal Research

Seasonal energy storage in metal hydride tanks

GKN Sinter Metals, a specialist in powder metallurgy, has been developing hydrogen storage systems based on metal hydrides for several years. At its own research centre in Radevormwald, the company not only investigated the storage capacity of various metal powders, but also explored the effects of various degrees of compaction of the material. These findings were decisive for the development of a complete metal hydride-based hydrogen energy and heat storage system.

Mobile hydrogen storage system



Source: GKN

A storage system of this kind with a capacity of 130 kWh is currently being developed for a pilot project. It can supply a four-person household with electricity for around 12 days and heat for an additional six days. This way, the GKN system achieves overall energy efficiency of as much as 90%. In the case of the pilot project in the South Tyrolean Alps, the storage system will be used in conjunction with a small water turbine. The house is not connected to the public electricity grid. Apart from allowing the short-term storage of energy to cover peak demand and providing a backup function in the event of a turbine failure, the project also focuses on the seasonal storage of energy in hydrogen.

Contact:
Dr. Nils Bornemann
Global VP Advanced Engineering
Telephone: +49 (0)228/9335140
nils.bornemann@gkn.com

www.gkn.com

Underground storage of hydrogen in geological formations

Man-made salt caverns are particularly suitable for the large-scale storage of gaseous hydrogen because salt rock has extremely low permeability to gases such as hydrogen and does not react with hydrogen. Since this form of storage – unlike porous rock storage facilities – consists of a large-volume cavity with access shaft (somewhat like a large underground tank), it is particularly suited to flexible injection and withdrawal. The suitability in principle of salt caverns for the storage of hydrogen has been demonstrated in decades of practical operation in both the UK and the USA. However, some components are still in need of development to meet the higher safety requirements in Germany. The necessary developments can be carried out as part of demonstration projects within a manageable time horizon.

The dimensions of such storage caverns typically range in capacity from 250,000 to 750,000 m³, with diameters of 50 to 80 m and heights extending from several tens of metres up to around 100 m, depending on the thickness of the salt deposit. Storage densities ranging from 8 to 11 kg per m³ of geometrical cavity are achieved for hydrogen, depending on the boundary conditions. For one complete injection/withdrawal cycle, a 500,000 m³ cavern thus provides a storage capacity of 133 to 183 GWh (based on the lower heating value (LHV) of hydrogen); see top right figure. Depending on the design of the access well, the storage facility thus has a capacity of several 100 MW (based on the LHV).

The choice of location for a hydrogen system with a cavern storage facility essentially depends on two factors: availability of suitable salt structures and the potential for the site's integration into an energy system. Germany has a very uneven distribution of suitable formations. While federal states such as Lower Saxony and Schleswig-Holstein in particular have a large number of potential storage structures, cavern storage is virtually impossible in southern Germany.

Storage cavern in Zechstein salt

Capacity for hydrogen up to about 200 GWh

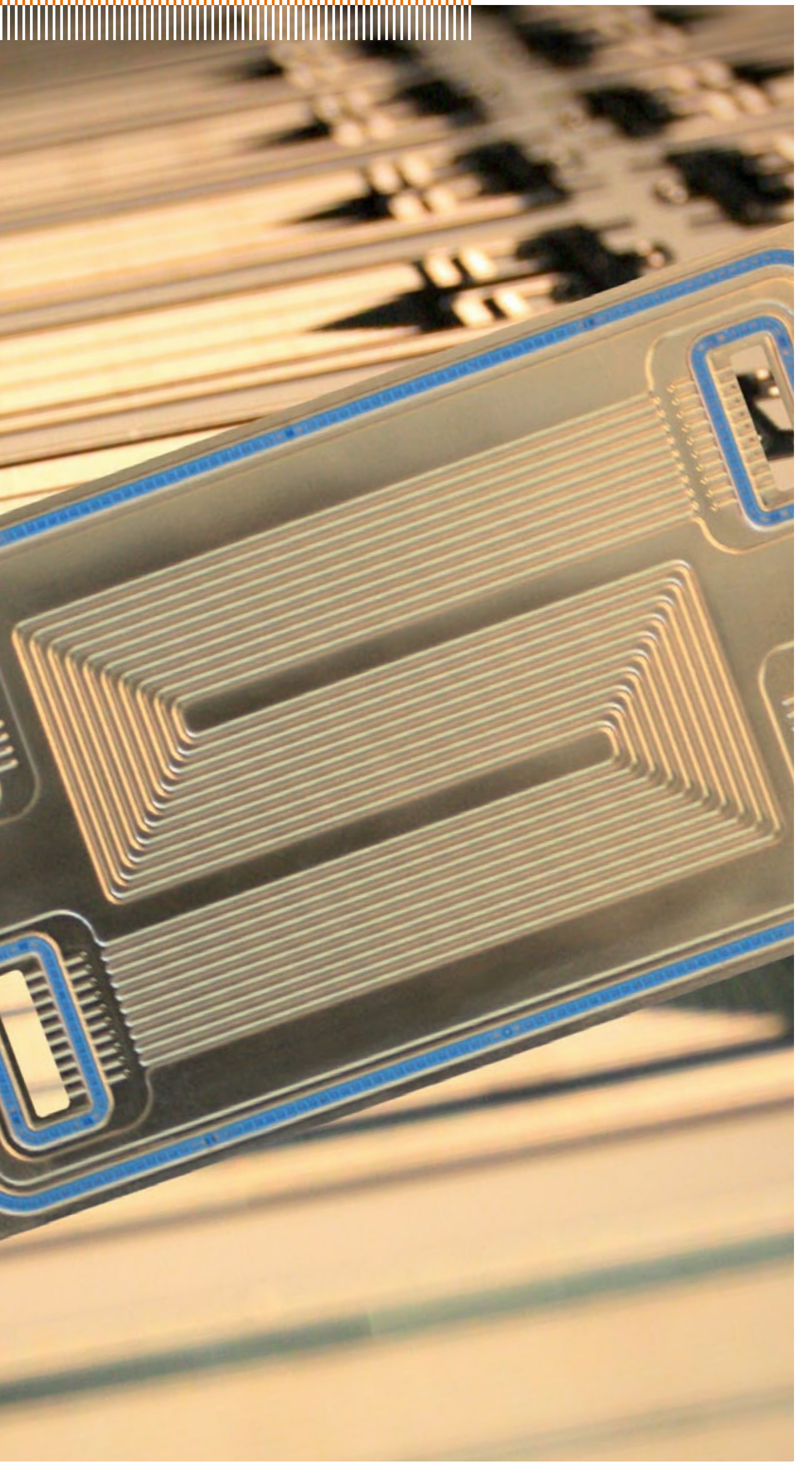
Source: KBB

In the north-west of North Rhine-Westphalia, Zechstein salt, which is ideal for leaching caverns, is located at a depth suitable for such projects. The Xanten and Epe cavern storage facilities near Gronau are located in this region, the latter being one of Germany's largest cavern gas storage facilities in a salt structure. The caverns are built by Salzgewinnungsgesellschaft Westfalen (SGW) and subsequently leased to energy companies. Part of the Federal Republic's strategic oil reserve is also stored there. Due to the existing infrastructure for solution mining and the potentials for sale of the brine produced during cavern construction, the location provides good prospects for the installation of a hydrogen storage facility. Costs and time-input would thus be significantly lower than for a new, "greenfield" location.

The development of a new storage site can take a good ten years due to the extensive planning, approval and exploration work involved. An additional positive effect in terms of integration into an energy system of the Epe site could be a possible connection to the existing hydrogen pipeline linking Marl, Castrop-Rauxel, Oberhausen, Krefeld and Leverkusen.

Contact:
Sabine Donadei
KBB Underground Technologies GmbH
Telephone: +49 (0)511/54281738
donadei@kbbnet.de

www.deep-kbb.de



Fuel cells

Hydrogen can be used in a wide range of stationary, mobile and portable energy applications. Engines, turbines and primarily fuel cells as highly efficient electrochemical energy converters are being developed for the future use of hydrogen as an energy source. The fuel cell generates electricity and heat directly from hydrogen or – after appropriate treatment – also indirectly from methane, methanol, diesel, kerosene and other energy sources.

A hydrogen membrane fuel cell is best suited for e-mobility. However, these fuel cells are also being developed for supplying off-grid applications or emergency power systems. Depending on the hydrogen supplied, emissions can be very low compared to today's systems based on conventional energy sources; however, hydrogen supply requires an appropriate infrastructure, refuelling stations or distribution of hydrogen cylinders (cartridges).

The use of synthesis gases ($H_2/CO/CO_2$ mixtures from natural gas, coal or biomass) in fuel cells has also become state-of-the-art.

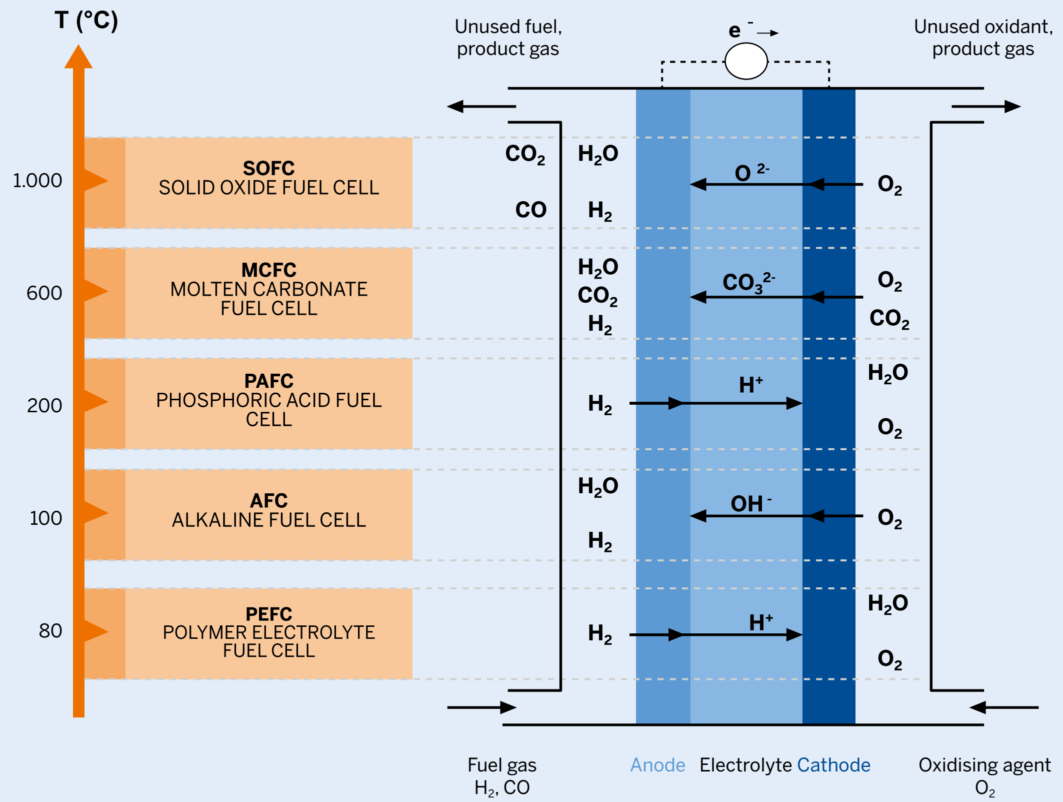
Fuel cells – an overview

Today, several fuel cell types are being developed that differ in terms of electrolyte, operating temperature and reaction gases:

- Alkaline Fuel Cell (AFC)
- Membrane Fuel Cell (PEMFC or PEFC)
- Direct Methanol Fuel Cell (DMFC)
- Phosphoric Acid Fuel Cell (PAFC)
- Molten Carbonate Fuel Cell (MCFC)
- Oxide Ceramic Fuel Cell (SOFC)

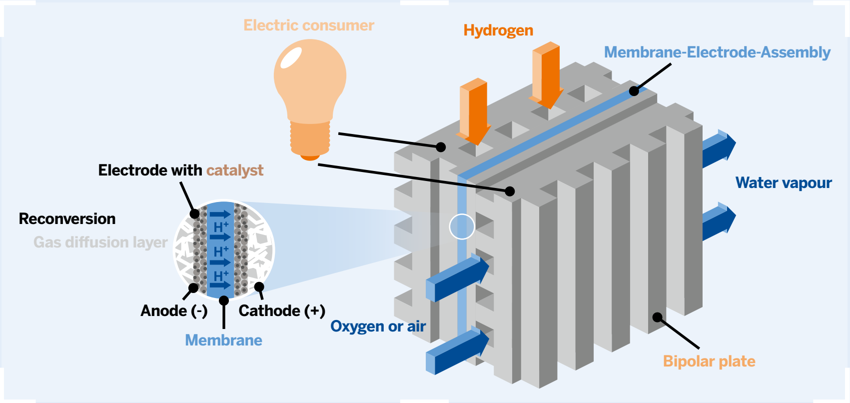
Thanks to their specific properties, fuel cells can be used in various areas. Different fuel cell types (see figure below) using different energy sources from hydrogen to liquid or gaseous hydrocarbon mixtures require very different process efforts to make the fuel gas available to the fuel cell system, and they have different overall efficiencies and CHP coefficients for the simultaneous generation of electricity and heat.

Classification of fuel cells (without DMFC)



Source: ZBT

Fuel cell configuration



Negative electrode/anode	$2H_2$	→	$4H^+ + 4e^-$
Positive electrode/cathode	$O_2 + 4e^- + 4H^+$	→	$2H_2O$
Overall reaction	$2H_2 + O_2$	→	$2H_2O$ + electricity + heat

Source: ZBT

The flow of electrons through the electric circuit generates electrical power, and the remaining energy released during the chemical process is converted into heat. The PEM operates at 60 to 80 °C as a low-temperature membrane fuel cell (LT-PEM), while high-temperature membrane fuel cells (HT-PEM) can be operated at temperatures of 120 to 200 °C. The advantages of a HT-PEM include a higher CO tolerance, no humidification of the reaction gases, and thus simplified water and heat management for the entire system.

A fuel cell system with a membrane electrode assembly (MEA), diffusion layer, bipolar plates (between the cells), end plates and gaskets needs augmentation with an electrical system, auxiliary systems, air supply and, where necessary, a fuel system. If energy sources such as methanol, diesel, kerosene or natural gas are used, an adapted hydrogen supply with a reformer and gas after-treatment is required.

Contact:
Prof. Dr. Angelika Heinzel
Zentrum für BrennstoffzellenTechnik ZBT GmbH
Telephone: +49 (0)203/75984225
a.heinzel@zbt-duisburg.de

www.zbt-duisburg.de

PEM developments

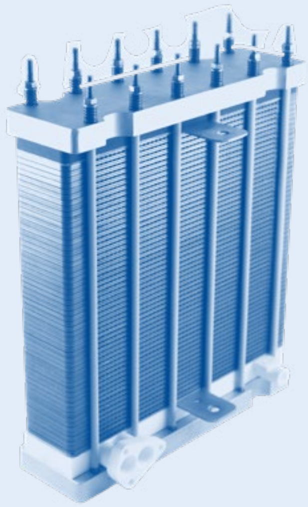
Polymer electrolyte membrane fuel cells (PEMFC or PEFC) are essential building blocks for future efficient energy conversion technology. Applications range from mobile use in motor vehicles, for example, to on-board power supplies and stationary and portable applications. Depending on the application, hydrogen or reformed hydrocarbons can be used as energy sources, which can be converted both in the classical NT-PEM and at 160 °C in the HT-PEM. Currently, NT-PEM is preferred in particular for applications with pure hydrogen, for example in mobility and emergency power supply. The high-temperature variant is used when reformed hydrocarbons such as methanol or natural gas are used.

At ZBT, for example, an important element of the fuel cell, the so-called bipolar plate, has been produced for several years using an injection moulding process on a small scale for the company's own use in the manufacture of low-temperature stacks. In a PEM fuel cell, bipolar plates, in addition to the proton-conducting polymer membrane and the two gas diffusion layers, perform a number of decisive tasks to maintain the electrochemical process – including conducting the electrical and thermal power, supplying and discharging the media, and mechanically stabilising the stack. Stacks with extremely flat metal bipolar plates are increasingly being used in automotive applications as an alternative to injection-moulded graphite-based bipolar plates.

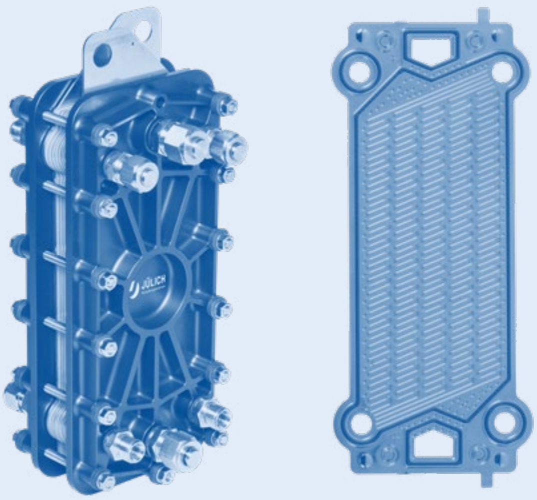
Apart from applications in the field of mobility, stationary power supply applications will be increasingly needed in the future. Fuel cell-based solutions with hydrogen or other energy sources are especially necessary in off-grid areas and regions with poor power infrastructure.

Injection-moulded bipolar plate for HT-PEFC

Fuel cell stack for emergency power supply systems



Source: ZBT



Coated metallic bipolar plate with gasket (left). 10-cell stack with metallic bipolar plates and modified end plates (right)

Source: Jülich Research Centre

System technology aspects (peripheral and control technology) and application modifications are essential part of the development work. Typical examples for the use of such systems and thus the Duisburg fuel cells include:

- On-board auxiliary power units (APU) based on hydrogen, LPG or methanol
- Uninterruptible power supply (UPS) for decentralised applications
- Lightweight transportation systems and alternative mobility concepts

The Jülich Research Centre is focusing its work in the field of PEFCs on the development and characterisation of fuel cell components and stacks rated up to 5 kW. Essential stack components include bipolar plates, which are often made of graphite composite materials. Metallic bipolar plates can be used to reduce costs, weight and volume. The IEK-3 division of the Jülich Research Centre has developed metallic bipolar plates with partner companies and demonstrated their functionality. These bipolar plates consist of embossed metal foils with a thickness of 0.1 to 0.2 mm, and their design allows liquid cooling between the welded bipolar plates on the anode and cathode side.

Contact:
Prof. Dr. Angelika Heinzel
Zentrum für BrennstoffzellenTechnik ZBT GmbH
Telephone: +49 (0)203/75984225
a.heinzel@zbt-duisburg.de

Prof. Dr. Werner Lehnert
Forschungszentrum Jülich GmbH
Telephone: +49 (0)2461/613915
w.lehnert@fz-juelich.de

Mobile applications

Major efforts are currently being made to develop new energy sources and propulsion systems for road transport applications. Objectives include:

- Reduction of greenhouse gas emissions (CO_2, N_2O, CH_4)
- Reduction of the dependence on fossil fuels (oil, gas)
- Improvement of air quality (limited emissions: CO, NO_x, particulates, C_nH_m)
- Reduction of noise emissions

To achieve these objectives, vehicle developers are focussing on:

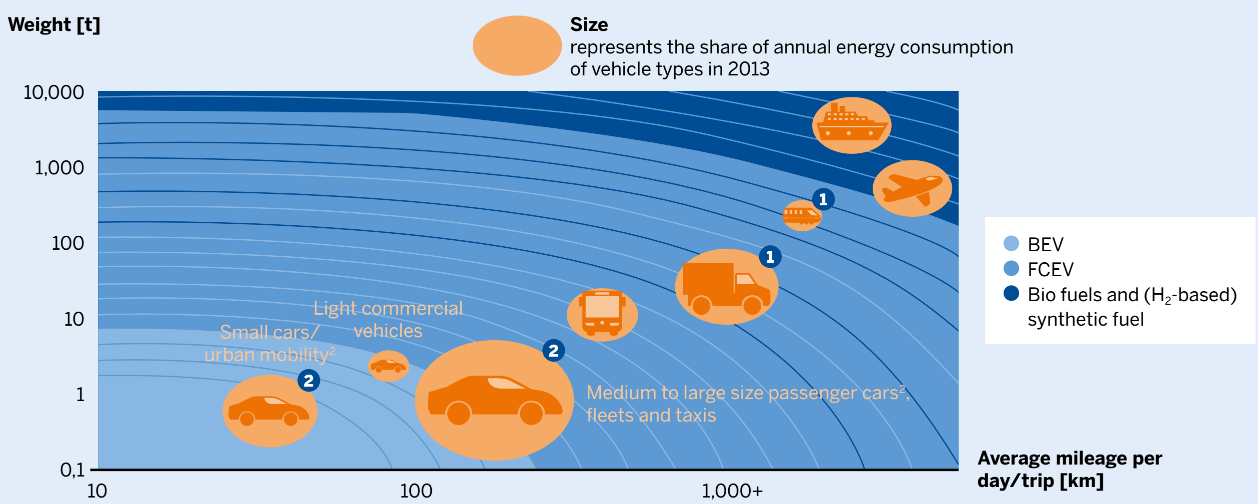
- Improving conventional propulsion systems in terms of efficiency and emissions
- Developing new propulsion systems (hybrid designs, electric systems with batteries and/or fuel cells)
- Introducing new energy sources (natural gas, biofuels, renewable fuels (e-fuels), renewable electricity, hydrogen)

Propulsion systems and energy sources

Today, most efforts are aimed at improving conventional internal combustion engines burning petrol and diesel as well as natural gas and biofuels. Increasingly, however, vehicle manufacturers are also looking into the electrification of vehicles to meet the above requirements for the mobility of tomorrow:

- Hybrid vehicles with an internal combustion engine, an electric motor and a high-performance battery in the vehicle
- Vehicles with an internal combustion engine and an electric motor whose batteries are charged with electricity from the mains (plug-in hybrids and range extenders)
- Purely electrically driven vehicles with batteries recharged using electricity from the mains
- Purely electrically driven vehicles with fuel cells and batteries, in which hydrogen is converted into electricity and the battery is partially charged from the grid

Propulsion systems for the mobility of the future



[1] Battery fuel cell hybrid for sufficient performance
[2] Split into A and B segment LDVs (small cars) and C+ segment LDVs (medium to large cars) based on a market share of 30% for A/B segment passenger cars and a 50% lower energy demand

Source: Hydrogen Council

Mercedes Benz GLC F-Cell (pre-series, 147 kW electric drive, Li-ion battery with 13.8 kWh energy content, pressurised hydrogen storage tank (700 bar) with 4.4 kg of hydrogen)

The latter two solutions, however, will only lead to significantly lower specific greenhouse gas emissions compared with conventional solutions if they are based on hydrogen produced from renewable sources or electricity and not fossil fuels – i.e. not hydrogen from coal and not electricity based on today's standard electricity mix. The well-to-wheel analysis of the hydrogen fuel cell propulsion (from the source to the wheel) shows that a significant reduction in greenhouse gas emissions (30%) is nevertheless achieved compared to the internal combustion engine when hydrogen is produced from natural gas.

Hydrogen can be stored more easily than electricity, but electricity can be stored directly from the grid in the vehicle as an energy carrier. Renewable electricity from wind, sun and water is generated discontinuously but can be easily converted into hydrogen by electrolysis and then stored. This hydrogen can be used either in fuel cell vehicles to generate electricity or directly in combustion engines, provided there is appropriate infrastructure for the supply of hydrogen. Industry has stopped pursuing hydrogen-based internal combustion engine solutions partly because of the poor energy balance of this drive.

Fuel cell systems used as electrochemical energy converters generating electricity for mobile applications are being developed and demonstrated worldwide. Some manufacturers are already offering fuel cell vehicles. The development of the necessary hydrogen infrastructure has also begun in various regions of the world, including the USA, Japan, China and the EU. In the EU, Germany has made the most progress on the infrastructure side. At the same time, electric vehicles with batteries are also being developed and launched on the market, but due to the short range, long charging times and high prices, sales have only been moderate.

Thanks to advances in battery technology (Li-ion batteries) and vehicle design, vehicle manufacturers are now offering more and more battery vehicles with a range of more than 400 km. Charging times are also becoming much shorter thanks to chargers with charging capacities of more than 100 kW. Charging times of less than 30 minutes can only be achieved with very high charging capacities of more than 200 kW. By contrast, a hydrogen tank can be refilled in just a few minutes, and the range today is already between 400 and 750 kilometres. Both vehicle concepts will therefore have a place in mobility. Depending on the size of the vehicle and their intended use, either pure battery or pure fuel cell vehicles or vehicles with a combination of battery and fuel cell make sense (see figure on page 49).

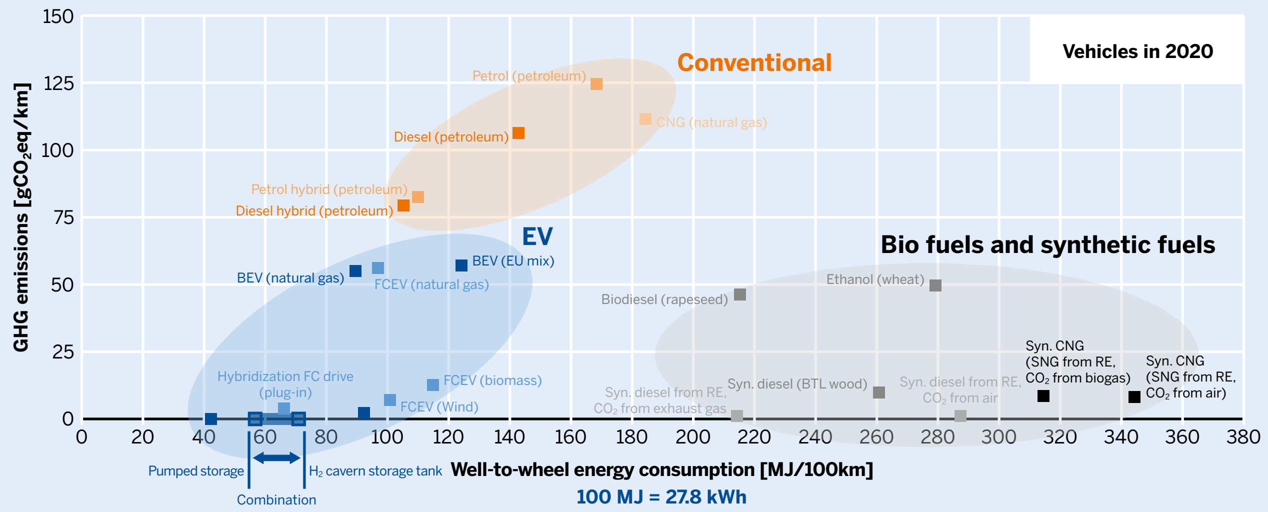
Hydrogen use in cars

Automobile manufacturers worldwide are working on the development of electric vehicles with fuel cells. The first small series of fuel cell cars and buses has been produced and tested worldwide by customers such as Daimler (left), General Motors, Toyota, Honda and Hyundai. Nevertheless, a number of aspects still need to be optimised before a broad market launch:

- Increase in fuel cell service life (not less than 5,000 h)
- Increase of gravimetric and volumetric power density
- Catalyst optimisation and minimisation of noble metal use
- Reduction of material and production costs for specific fuel cell system components
- Vehicle integration, including hydrogen storage
- Cost reduction
- Development of the necessary hydrogen infrastructure

The biggest remaining challenges are the significantly higher costs compared to internal combustion engine concepts and infrastructure development. Further progress in material development, system optimisation and series production with corresponding economies of scale will help to minimise the cost differential.

Specific GHG emissions and primary energy expenditure for passenger car vehicle drives (sustainability, ecology, optiresource)



Source: WtW Report 2014: EUCAR/CONCAWE/JRC, Version 4a

The above figure is based on an analysis according to www.optiresource.org using data from the JEC WTW study and calculations by LBST GmbH. It shows the relationships for conventional propulsion systems with combustion engines and the corresponding hybrid systems also with combustion engines and an additional battery in the top right cluster. All other results for the new energy sources and propulsion systems shown with examples can be characterised as follows:

- Electric vehicles with batteries using renewable electricity have the lowest greenhouse gas emissions and the lowest specific primary energy consumption in the overall balance.
- Electric vehicles with fuel cells also allow a considerable reduction in energy consumption and greenhouse gas emissions.
- Depending on the way electricity and hydrogen are generated, both propulsion systems allow a wide range of values for greenhouse gas emissions and primary energy consumption.
- Biofuels and synthetic fuels from renewable electricity allow a significant reduction in greenhouse gas emissions, but lead to much higher energy costs.

The big challenge in the long term will be to provide sufficient but affordable renewable electricity and hydrogen and the infrastructure required.

Contact:
Dr. Jörg Wind
Daimler AG
Telephone: +49 (0)7021/894614
joerg.wind@daimler.com

www.optiresource.org

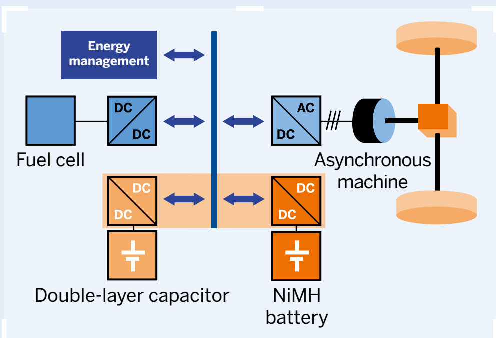
Fuel cell buses

In view of the ever-increasing levels of traffic, local public transport is set to play a more important role in the future. But here too, the same requirements regarding emission reduction (exhaust, noise) and climate protection apply as in private transport.

A major study by the EU [9] has found that buses will also have a wide range of drive trains, starting with hybrid concepts based on internal combustion engines through to battery and fuel cell buses. Yet only the latter two guarantee zero emissions in cities. The choice of the appropriate concept will therefore depend on the length of the bus routes on which the vehicle will be used and on the available infrastructure (charging stations, hydrogen refuelling stations).

A significant improvement in energy management and thus in the operating strategy for the use of fuel cells has been achieved through the redesign of the electric powertrain. In fuel cell vehicles of earlier generations, the entire power demand was met by the fuel cell. Newer vehicles are based on the "hybridisation" of the fuel cell powertrain by means of batteries and/or high-performance capacitors. The fuel cell remains in an operating state that is as constant as possible (which also extends its service life), while the electrical storage system covers peak loads during acceleration. When the vehicle is decelerated, the current generated by the motors is stored in the batteries or capacitors ("recuperation"). This concept allows the use of smaller fuel cells which helps to significantly reduce the cost of fuel cell buses.

Triple hybrid concept



Source: Cologne University of Applied Sciences

Fuel cell buses operated by Regionalverkehr Köln GmbH

Under a project jointly funded by the state of North Rhine-Westphalia and the Netherlands, work to develop the world's first ever articulated bus with a fuel cell triple hybrid drive train began in 2009. The platform used for the 18 m bus was the "Phileas" platform from APTS in Helmond. Together with batteries and supercapacitors, the 150 kW fuel cell system generated a drive power of 240 kW, which delivered a top speed of 80 km/h. The fuel cell system came from Ballard in Canada. Vossloh-Kiepe, based in Düsseldorf, was responsible for energy management, while Hoppecke Batterien GmbH from Brilon developed the storage module using NiMH batteries. Between 2011 and 2016, the buses were operated by Regionalverkehr Köln GmbH (RVK) in Hürth, in the Rhine-Erft district and in the Cologne region. Since 2014, two fuel cell buses made by Van Hool have also been in service in this region.

At present there is a trend towards so-called range extender concepts. These designs come with a relatively small fuel cell (around 60 kW) which is used to recharge the battery of the bus during the journey, thereby significantly increasing its range without the need for a larger and thus heavier battery. This way, the fuel cell is operated at a constant load point, which extends its service life. However, the fuel cell usually cannot fully recharge the main battery, so the bus may have to be recharged at a charging point at the bus depot.

In 2016, the Fuel Cells and Hydrogen Joint Undertaking (FCH JU) launched a large-scale procurement programme for fuel cell buses with the aim of significantly reducing purchase and operating costs. This resulted in the JIVE 1 and 2 projects (JIVE = Joint Initiative for Hydrogen Vehicles across Europe), through which around 300 fuel cell buses will be procured across Europe over the next few years and used by around 20 local transport operators from the end of 2019. NRW-based Regionalverkehr Köln GmbH (RVK) and WSW mobil GmbH from Wuppertal (WSW) are taking part in the programme. RVK will purchase 45 fuel cell buses as part of the JIVE projects, WSW will purchase 20 fuel cell buses. Through the EU's MEHRLIN project (under the umbrella of DG MOVE), seven bus refuelling stations will also be built in Europe, including a refuelling station in Wuppertal. Thanks to projects such as JIVE, it has been possible to reduce the purchase price of a fuel cell bus to around half the price of 2014.

Contact:
Dr. Frank Koch
Netzwerk Brennstoffzelle und Wasserstoff, Elektromobilität der EnergieAgentur.NRW
Telephone: +49 (0)209/167-2816
koch@energieagentur.nrw

www.energieagentur.nrw

JIVE Project

Great Britain (56)
- **18** FC buses at present
- **2** new FC buses in future (other projects)
- **56** new FC buses in future (JIVE project)
- **2** MEHRLIN petrol stations

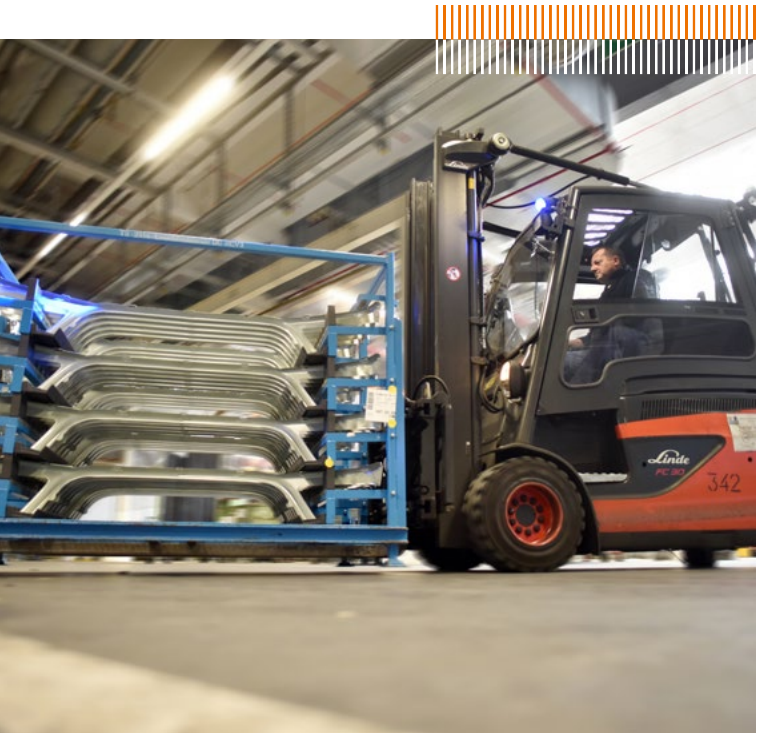
Germany (51)
- **4** FC buses at present
- **47** new FC buses in future (JIVE project)
- **4** articulated buses (JIVE project)
- **4** MEHRLIN petrol stations

Italy (12)
- **5** FC buses at present
- **10** new FC buses in future (JIVE project)
- **2** articulated buses (JIVE project)
- **1** MEHRLIN Tankstellen

Denmark (10)
- **8** FC buses in future (JIVE project)

Latvia (10)
- **8** FC buses in future (JIVE project)

Source: FCH JU [(10)]



Hydrogen-powered forklift trucks

Since December 2014, a demonstration project has been underway at the Mercedes-Benz plant in Düsseldorf involving hydrogen-powered forklift trucks used for internal logistics operations.

As part of a project funded under the umbrella of the Hydrogen and Fuel Cell Technology National Innovation Programme (NIP), two 3-tonne fuel cell forklifts and a hydrogen refuelling station were put into operation. The vehicles were converted and certified by Linde Material Handling GmbH for use with fuel cells, and the mobile refuelling station built by Air Products on the factory premises supplies the forklifts with hydrogen. The project is being scientifically monitored by the Hamm University of Applied Sciences and is supported regionally by EnergyAgency.NRW.

The aim of the project is to test the usability of forklift trucks in automotive logistics in three-shift operation and to determine whether fuel cell-driven forklifts are ecologically and economically attractive and what costs and opportunities they offer in comparison to the alternatives.

After initial reservations about the use of hydrogen, the vehicles have now been well received by drivers. In addition, the forklifts have demonstrated their robustness in the past three and a half years, as can be seen from the interim results:

- Energy consumption: 0.2 - 0.45 kg/h (0.3 on average)
- Mileage with one tank: 4 - 6 operating hours
- Total operating time to date: > 13,000 operating hours
- Refuelling: > 2,600 operating hours

Contact:
Matthias Kromm
Telephone: +49 (0)211/9532224
matthias.kromm@daimler.com

Wolfgang Radtke
Telephone: +49 (0)211/9533174
wolfgang.radtke@daimler.com

www.daimler.com

Hydrogen refuelling station at the Daimler plant in Düsseldorf

Fuel cell ship “MS innogy”

In the summer of 2017, innogy SE launched the motor ship “MS innogy” as part of a series of events celebrating Essen as the official “European Green Capital 2017”, with the aim of showcasing a solution to the range problem of e-mobility in ships. The previously diesel-powered tourist ship on Lake Baldeney in Essen was equipped with a methanol-electric propulsion system consisting of seven HT-PEM fuel cells each rated 5 kW, two lithium-ion battery packs each with a capacity of 60 kWh (net) and an electric motor. In the purely battery-powered electric mode, the 29-m ship can carry up to 160 passengers and can run for about two to three hours, while fuel cell operation with a 330-l methanol tank can extend this period to as much as 15 hours by continuously recharging the batteries. The use of green methanol produced with renewable electricity means that the operation of this ship is carbon-neutral overall. Thanks to the silent electric motor it can now also travel to the Heisinger Ruhraue bird sanctuary.

Project partners:
Lux-Werft und Schiffahrt GmbH
Moselstraße 10
53859 Niederkassel

Weisse Flotte Baldeney GmbH
Hardenbergufer 379
45239 Essen

Serenergy
Lyngvej 8
9000 Aalborg
Denmark

Contact:
Henning Joswig
innogy SE
henning.joswig@innogy.com
www.innogy.com

Railcar with fuel cell drive

Around 50% of the German rail network is not electrified, which means that only diesel-powered locomotives and railcars can be used on these lines. Operators and the public frequently show keen interest in moving from conventional diesel-powered engines to zero-emission solutions. However, the installation of overhead contact lines is very costly (from € 250,000 per km plus power), and maintenance costs are not insignificant. Overhead contact lines are therefore often not economically viable on lines with low capacity utilisation and are sometimes not at all desirable in attractive rural settings.

The use of electric multiple-unit trains with hydrogen-powered fuel cells is an interesting alternative here, which can further underline Germany's technological leadership and provide the necessary flexibility in a changing local transport sector – especially in rural areas.

The French railway manufacturer Alstom has developed the fuel cell-driven Coradia iLint at its plant in Salzgitter. The railcar has a maximum speed of 140 km/h and appropriate acceleration and braking performance. Depending on the topography, a full tank holding 180 kg of hydrogen provides a range of up to 1,000 km. The Coradia iLint is also equipped with a battery to temporarily store the electrical energy generated on board and to recover braking energy. The rail car achieves energy savings of as much as 40% when compared with diesel-powered alternatives. Even if hydrogen from fossil sources is used, CO_2 emissions can be up to 30% lower.

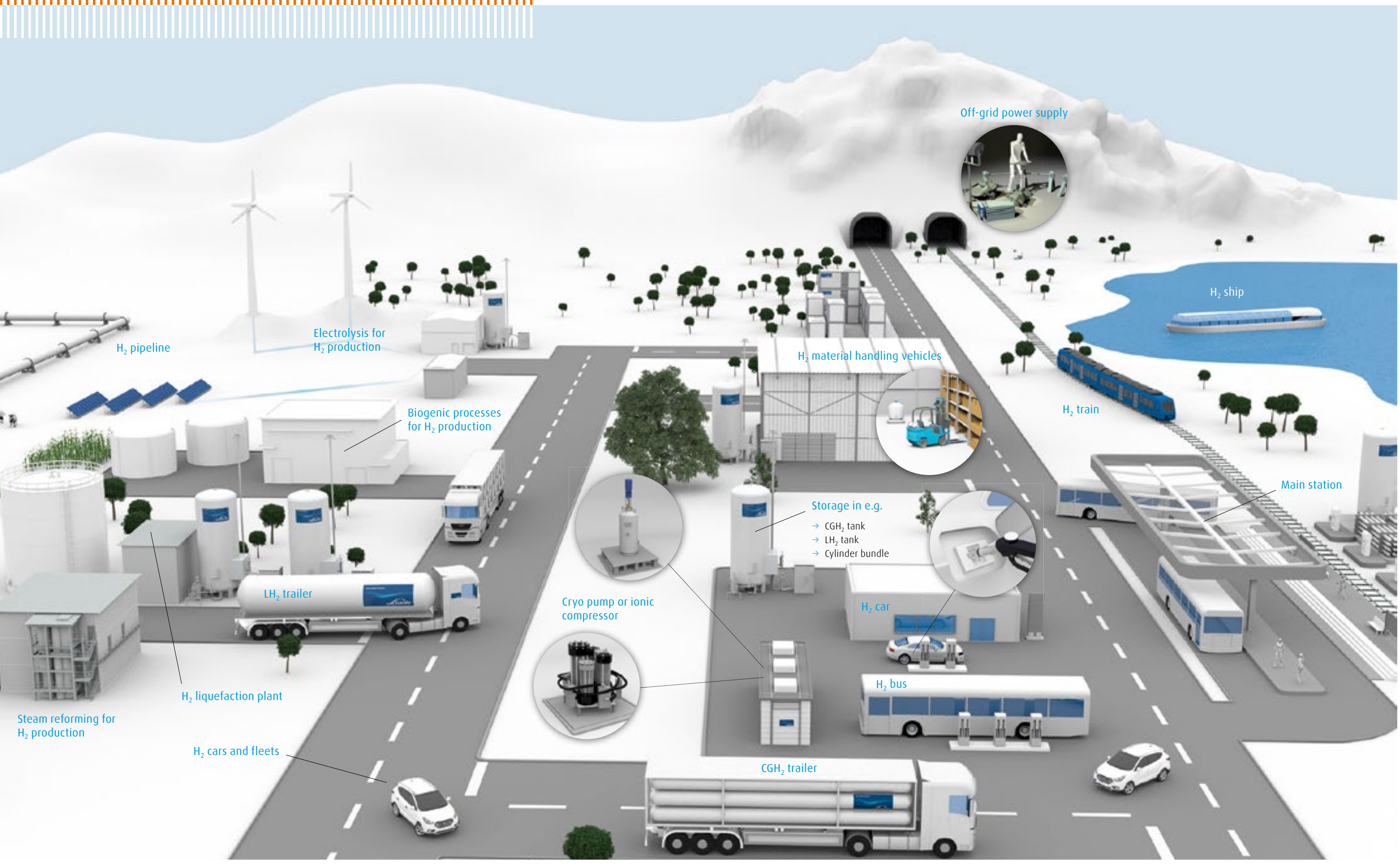
One of the technical challenges is the refuelling infrastructure. Depending on the size of the railcar fleet, several tonnes of hydrogen will be used every day, but refuelling stations of this size have not yet been built. Hydrogen provision must also be ensured and should be as efficient as possible with minimum impact on local residents. In North Rhine-Westphalia, for example, the existing hydrogen pipeline in the Ruhr area would be an ideal solution, which would avoid road transport with trailers.

A first pilot project was launched in the Hamburg area in 2018. Further projects in other federal states are to follow.

Contact:
Dr. Jens Sprotte
ALSTOM Transport Deutschland GmbH
Telephone: +49 (0)5341/9004721
jens.sprotte@alstomgroup.com

www.alstomgroup.com

Alstom Coradia iLint fuel cell railcar



Hydrogen value chain (Source: Linde)

Refuelling with hydrogen

Hydrogen is delivered to refuelling stations either in liquid form in cryogenic tanks at -253 °C (liquified hydrogen – LH_2) or in gaseous form at pressures of 200 to 500 bar (compressed gaseous hydrogen – CGH_2) and then transferred to appropriate storage tanks. It can also be produced by electrolysis or steam reforming directly on site. Since the vehicles only offer a limited space for storage, the gaseous hydrogen is compressed at the refuelling station to 700 bar for passenger cars and 350/700 bar for commercial vehicles/buses.

Compressors are the heart of hydrogen refuelling stations. There are two different methods: One method involves compressing gaseous hydrogen to as much as 900 bar, which is done using various compressors including dry compressors, diaphragm compressors or the ionic compressor developed by Linde AG specifically for this application. In Germany, there are already some 30 public hydrogen refuelling stations with ionic compressors.

The other method involves supercritical compression of liquid hydrogen to as much as 900 bar using cryopump technology. The hydrogen temperature is raised to -40 °C prior to refuelling in gaseous form. Cryopump technology is particularly suitable when there is a high demand for hydrogen, as it can be used to store much larger quantities of hydrogen per volume on site, and is therefore the most efficient technology requiring the smallest space and very little energy. This technology is also part of Linde AG's portfolio and is already being used successfully in several plants throughout Germany.

The refuelling pressure at the station is 900 bar, which provides the pressure differential required to completely fill the vehicle's tank to around 700 bar. Car tanks currently hold about 5 to 7 kg of hydrogen, which allows a range of up to 800 km, and refuelling takes about three minutes, so is equivalent to the time needed for conventional passenger cars.

The technology itself and the storage, compression and refuelling processes are now so mature that global refuelling standards are now in place for commercial applications (SAE J2601TM (TIR)). There are already standardised solutions for refuelling fuel cell vehicles and for handling the pump nozzle, which is quite similar to NGV refuelling. The only visible difference to conventional car refuelling is that the consumer no longer fills up in litres, and instead the amount is charged in kilograms. The rule of thumb for fuel consumption by cars is 1 kg/100 km.

In Germany, mobility based on liquid hydrogen can be experienced primarily in the greater Munich area: As of the beginning of 2018, six public H_2 refuelling stations are supplied with liquid hydrogen.

Contact:
Alexander Schadowski
Linde AG, Linde Gases Division
Telephone: +49 (0)211/7481175
alexander.schadowski@linde.com

www.linde-gas.com

Hydrogen refuelling station network in NRW (planning status in September 2018)

Hydrogen refuelling station infrastructure: Clean Energy Partnership and H_2 MOBILITY

Whilst hydrogen has long been regarded as one element of Germany's energy transition in the transport sector, the still fragmented and expensive hydrogen infrastructure is proving to be a major obstacle to more widespread use.

The establishment of H_2 MOBILITY Deutschland GmbH & Co. KG in 2015 has accelerated and optimised the expansion process. It all started with the Clean Energy Partnership (CEP) launched in 2002 as a joint initiative by politics and industry under the aegis of the Federal Ministry of Transport. Until 2016, this partnership was the largest demonstration project for hydrogen mobility in Europe and a lighthouse project of the Hydrogen and Fuel Cell Technology National Innovation Programme (NIP) in the transport sector. The aim was to test the suitability of hydrogen as a fuel for everyday use.

By the end of 2019, H_2 MOBILITY will plan, build and operate around 100 hydrogen refuelling stations in Germany together with its shareholders Air Liquide, Daimler, Linde, OMV, Shell and TOTAL to provide a basic supply of hydrogen. In the Rhine-Ruhr region alone, the most densely populated region with a huge traffic volume, ten stations had been put into service by the end of 2018 and another eight are under construction. In addition, there are numerous pumps along major roads and motorways. In a second phase, this number could go up to 400, depending on how vehicle numbers develop.

The hydrogen stations will preferably be integrated into existing service stations. They have a compact design that relies mainly on standardised components for the pumps, hydrogen storage and compression.

The map above shows the status of the expansion plans for the hydrogen refuelling station network in North Rhine-Westphalia in December 2018.

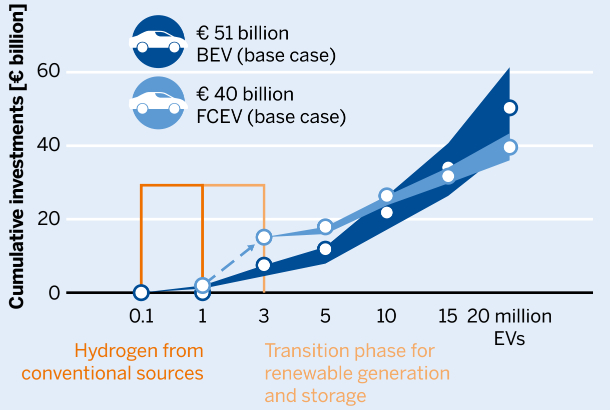
Contact:
www.h2-mobility.de
www.h2.live
www.cleanenergypartnership.de
www.now-gmbh.de

Infrastructure costs of battery and fuel cell-based electric mobility

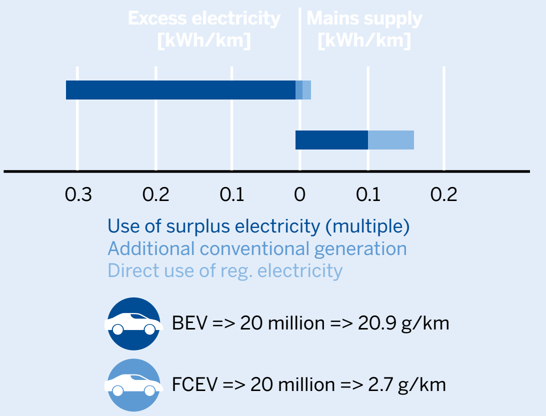
Infrastructure costs for the development of e-mobility (fuel cell and battery-powered electric vehicles) are often described as the biggest obstacle to a breakthrough. A study by IEK-3 has analysed the development of both infrastructures for even large shares of e-cars in the market [11].

The analysis of the different scenarios shows that investment in infrastructure for both technologies is almost the same for low vehicle numbers up to several hundred thousand vehicles. In the transition phase, hydrogen production will be switched to the exclusive use of renewable surplus electricity, while seasonal hydrogen storage facilities will be built to help bridge any gaps in production of up to 60 days. The concept allows for the use of green hydrogen. In the initial phase, this will require higher investments than for the battery-charging infrastructure, but for battery-powered vehicles, the study does not take into account seasonal electricity storage, which would be necessary to secure the supply of 100% renewable electricity. A comparison of the cumulative investments needed to achieve a high market penetration rate of 20 million vehicles shows that battery-charging infrastructure requires much more investment (around € 51 billion) than hydrogen infrastructure (around € 40 billion).

Comparison of cumulative investments for the necessary infrastructure



Comparison of kilometre-dependent CO_2 emissions and electricity demand of 20 million vehicles



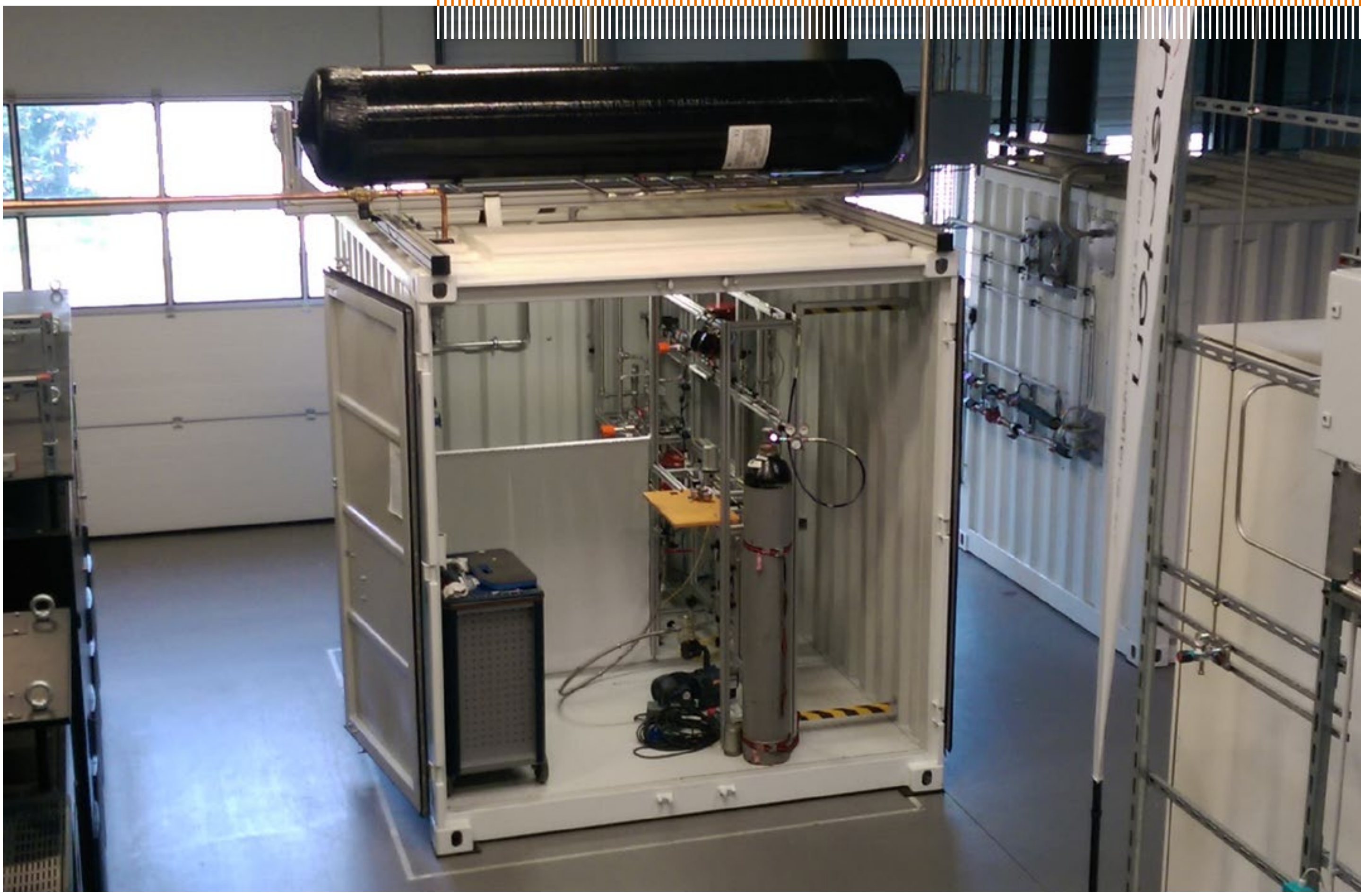
Source: FZ Jülich

The scenario with 20 million fuel cell vehicles requires 87 TWh of surplus electricity for electrolysis and an additional 6 TWh of electricity from the grid (hydrogen transportation and distribution). Charging 20 million battery-powered vehicles requires 46 TWh of electricity from the distribution grid. Whilst the charging infrastructure and the vehicles are more efficient, flexibility on the demand side is restricted to shorter periods. For both infrastructure paths, the quantity of surplus electricity in the assumed energy supply scenario with high shares of renewables exceeds the demand of the 20 million vehicles by a factor of three to six.

The use of renewable electricity surpluses and grid electricity with high shares of renewables means that CO_2 emissions per kilometre for both supply options are low compared to the use of fossil fuels. The hydrogen infrastructure, with its inherent seasonal storage capability, can integrate higher shares of surplus renewables and is therefore at an advantage in terms of CO_2 emission reduction. However, a charging strategy based on the availability of renewable electricity could further reduce the carbon footprint of battery vehicles.

Contact:
Prof. Dr.-Ing. Detlef Stolten
Head of Insitute
Forschungszentrum Jülich GmbH
Telephone: +49 (0)2461/615147
d.stolten@fz-juelich.de

Dr.-Ing. Martin Robinius
Head of Process and Systems Analysis Department
Forschungszentrum Jülich GmbH
Telephone: +49 (0)2461/613077
m.robinius@fz-juelich.de



Fiscal flow metering of compressed hydrogen

One of the challenges when refuelling vehicles is the precise fiscal measurement of the hydrogen transferred into the tank. As part of a project focussing on H_2 storage, the Energy Institute of the Westphalian University of Applied Sciences, together with a medium-sized company, is developing a high-pressure hydrogen flow meter to be used for refuelling H_2 vehicles. The Energy Institute has designed and built a test stand, known as a hydrogen weighing scale, for experimental tests on several prototypes. A special feature of the test stand is its mass flow calibration system, which is based on gravimetric measurement – i.e. weighing – and is therefore largely independent of the parameters of pressure and temperature, which strongly influence mass flow determination. This makes the test stand particularly suitable for investigating and optimising dynamic high-pressure refuelling processes. The hydrogen quantities can be measured at pressures of up to 1,000 bar.

Contact:
Prof. Dr. Karl H. Klug
Westphalian University of Applied Sciences, Gelsenkirchen Campus
Telephone: +49 (0)209/9596808
energieinstitut@w-hs.de

www.energie.w-hs.de

Stationary applications

More than a third of the final energy in Germany is used in households for space heating, hot water and electricity. Since energy losses are lowest when the energy is produced at the point of use, distributed power generation and simultaneous use of heat are particularly advantageous. Combined heat and power (CHP) systems with high power-generating efficiencies and low emissions will be the technical challenge of the future for a more efficient energy supply. Fuel cells allow the simultaneous production of electricity and heat in domestic heating systems with very low emissions. They produce a hydrogen-rich fuel gas from natural gas in a single process using atmospheric oxygen to convert the gas directly into electricity. The residual heat from the entire process is fed directly into the heating circuit and the service water storage tank. These systems have an output of between 300 W_e and about 5 kW_e.

High-temperature fuel cells offer a big advantage in that their waste heat can be used to convert gaseous and liquid hydrocarbons (natural gas, liquid gas, heating oil) into hydrogen. The remaining waste heat may also be used directly as steam or fed into a district heating network, meaning high overall efficiencies can be achieved. Fuel cells today have capacities in the range of 300 kW to 1 MW.

In principle, this also applies to solid oxide fuel cells (SOFC). For smaller domestic applications there is a clear trend from PEM to SOFC systems, but the development of larger SOFC systems will still take some time due to the high cost of the production technology for large cells.

Phosphoric acid fuel cells (PAFC) are ideally suited for the medium output range from 50 to several hundred kW. Most operating experience has been accumulated using this fuel cell type, and many systems have completed 60,000 or more operating hours. PAFCs have conquered a new market thanks to their fourfold benefits: they can provide consumers with electricity, heat, cold and oxygen-depleted air that can be used for firefighting purposes.

PEM fuel cells for larger stationary applications are also seen as having strong market potential. They are a particularly interesting option where hydrogen is available in large quantities, as is the case, for example, with overproduction in chemical plants. One such plant is the Solvay plant in Antwerp, which operates a 1 MW PEM fuel cell. It remains to be seen, however, whether high-capacity cells will be able to benefit in terms of cost from developments in the mobility sector (buses).

Now that the environmental and efficiency advantages have been demonstrated, development and demonstration projects worldwide are continuing to focus on costs, service life and fuel cell system reliability.

Contact:
Prof. Dr. Angelika Heinzel
Zentrum für BrennstoffzellenTechnik ZBT GmbH
Telephone: +49 (0)203/7598-4225
a.heinzel@zbt-duisburg.de

Stationary power generation with fuel cells

Fuel cells are among the most efficient energy conversion systems currently available on the market. Apart from PEM fuel cells, solid oxide ceramic fuel cells (SOFCs) are also suitable for stationary use, as they not only offer a high degree of flexibility with regard to the fuel used, but also very high electrical efficiencies and, at the same time, long service lives. A number of manufacturers now also offer fuel cells for stationary use in residential and commercial buildings, either as heat-led systems to replace conventional heating or as electric-led systems to generate electricity.

One such system is BlueGEN, a fuel cell-based micro-power plant developed by SOLIDpower GmbH from Heinsberg in North Rhine-Westphalia. This electric-led CHP system delivers a continuous electrical output of 1.5 kW with an electrical efficiency of more than 60%. It can be operated continuously all year round regardless of weather and heat demand, producing some 13,000 kWh of low-emission, cost-efficient electricity at the point of use. Thanks to its high electrical efficiency, carbon emissions for electricity generation are more than 50% lower than the German electricity mix, and users can roughly halve their electricity costs. More than 1,000 systems have already been installed.

Natural gas-fuelled, highly efficient micro-power plants of this type are particularly suitable for consumers with a high demand for base-load electricity, such as commercial businesses and owners of large residential properties. Base-load electricity generation is not dependent on heat demand because the CHP unit is primarily operated to supply electricity. The thermal energy produced during power generation can also be used to support hot water production or space heating, and the unit, which is designed as an add-on solution, can be integrated into almost any heating system via a hot water storage tank. SOLIDpower has no upstream reformer; rather, it uses the internal steam reforming process to harness the hydrogen contained in the natural gas and achieve very high electrical efficiencies.

Contact:
Andreas Ballhausen
SOLIDpower GmbH
Telephone: +49 (0)2452/153-763
Andreas.ballhausen@solidpower.com

www.solidpower.com

Production of the BlueGEN micro-CHP system from SOLIDpower in Heinsberg, NRW

Active fire protection by means of fuel cells

Fuel cells produce electricity, heat and optionally also cold energy in the same way as conventional (C)CHP plants. Depending on the type of fuel cell used, the energy conversion process generates low-oxygen air, which can be used as an inert gas and for firefighting purposes. This exhaust air collects continuously and at no extra cost during system operation. It can be piped across the premises into rooms requiring fire protection to create an atmosphere in which fires cannot occur in the first place, while people can still do their work.

Conventional systems for fire prevention in warehouses or data centres use electricity-intensive and expensive air separation units and compressors which entail high operating costs.

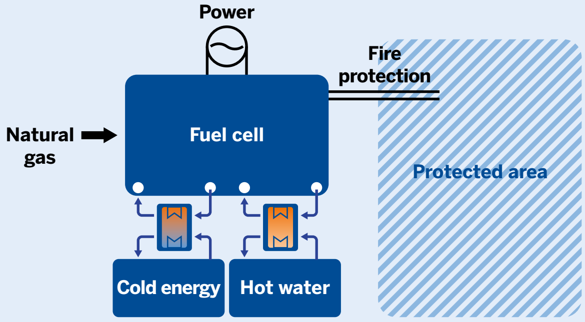
QuattroGeneration from Fuji N2telligence GmbH is a 100 kW PAFC fuel cell. This (C)CHP plant provides fire protection as a side product at zero cost. It is the first fire prevention system that generates revenues and hence a return on investment by supplying energy. For this reason, Minimax GmbH & Co. KG, one of the world's leading suppliers of fire protection systems and services, has decided to cooperate with Fuji N2telligence GmbH.

In May 2015, a plant of this type was commissioned at the Hydrogen and Fuel Cell Centre (ZBT) in Duisburg (see picture above). The electricity and heat produced are integrated into the site's energy supply system, although given the sporadic demand for cold energy, it was decided to do without this extra option. The low-oxygen air, on the other hand, is used for experimental and demonstration purposes. Plant operation to date has been largely trouble-free without any fuel cell degradation.

Contact:
Lars Frahm
Fuji N2telligence GmbH
Telephone: +49 (0)3841/7584500
Lars.Frahm@n2telligence.com

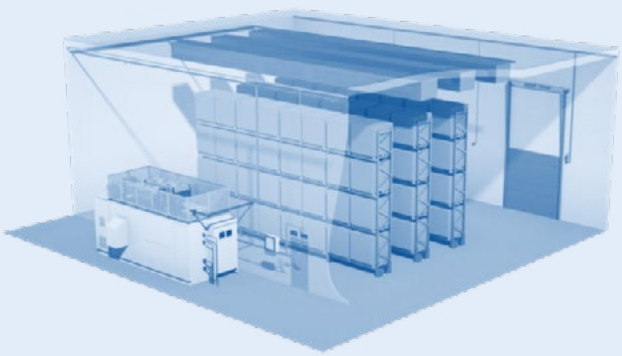
www.n2telligence.com

Fire protection with fuel cells



Source: Fuji N2telligence GmbH

Application example for fire protection



Source: Fuji N2telligence GmbH

Fuel cells supporting critical supply infrastructure

Fuel cells also offer numerous technical advantages over conventional solutions in critical power supply applications, including longer service lives, longer autonomy periods, and lower energy consumption – in other words, a way to an efficient, intelligent and resource-saving future.

Netzgesellschaft Düsseldorf mbH (NGD), a wholly-owned subsidiary of Stadtwerke Düsseldorf AG, operates the city's electricity, gas, water and district heating grids. NGD always endeavours to make use of modern technologies to meet its public service obligation under the German Energy Industry Act. The information gained from grid sensors and future smart meters used in conjunction with grid automation systems offers potential for efficient and sustainable use of resources, with the future integration of numerous e-charging systems an additional challenge for grid operators. In order to transmit this data securely and cost-efficiently, NGD has already set up a CDMA 450 MHz network.

However, this also means that the data must be available at all times. When NGD set up its new communication system, it also re-examined the emergency power supply situation, and the technology eventually chosen – thanks to its low costs over the entire life cycle – was a PEM fuel cell. In 2017, NGD put out a tender for the construction of five fuel cells with outputs of 2 kW and 8 kW, for the purpose of protecting secondary systems at CDMA network stations and antenna sites against power cuts. The focus here was also on expandability to achieve slight performance improvements. At the end of 2017, adKor GmbH successfully commissioned the modern air-cooled Jupiter PEM fuel cells at all five locations.

Contact:
Fabian Fischer
Netzgesellschaft Düsseldorf mbH
Telephone: +49 (0)211/8212508
ffischer@netz-duesseldorf.de

www.netz-duesseldorf.de

Emergency power supply system operated by Netzgesellschaft Düsseldorf at its Flingern site

Copyright: Manuel Gloger

Hydrogen and fuel cell state North Rhine-Westphalia

To date, the state government of North Rhine-Westphalia and the European Union (European Regional Development Fund – ERDF) have provided almost € 150 million for over 140 fuel cell and hydrogen projects. These projects have included the development of individual system components including compressors and sensors, as well as the development and testing of complex fuel cell applications such as buses or mobile refuelling stations. In the field of battery-based e-mobility, around 80 projects with a funding volume of € 56 million have been launched and supported since 2009 under the German government's "Model Regions Electromobility" and "Electromobility Funding Directive" funding programmes. New projects are being added continuously.

Fuel Cell and Hydrogen, Electromobility Network

The network operates as one of twelve EnergyAgency.NRW networks on behalf of the state government of North Rhine-Westphalia. Since March 2017, it has been continuing the work of the Fuel Cell and Hydrogen NRW Network, which was launched in 2000, along with the activities of the NRW Electromobility Model Region project office, which have been ongoing since 2009.

Hydrogen and fuel cell technologies and battery-based e-mobility are seen as key technologies for responding to the challenges of the energy transition, climate protection, efforts to improve energy efficiency and expanding the use of renewable energies in all areas of the energy and transport system.

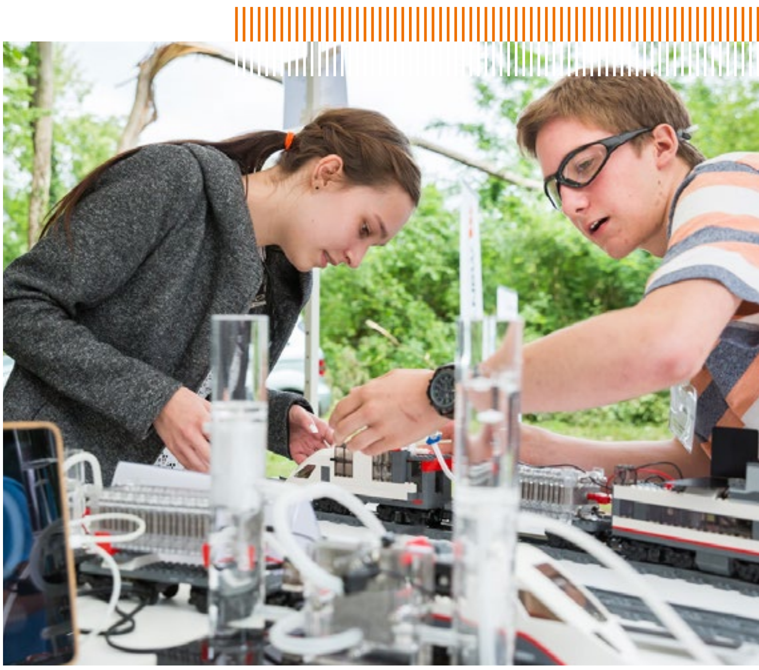
More than 470 members and over 120 project partners from industry and science in the NRW Electromobility Model Region are already actively involved in the Network and use its numerous services.

The main focus of the Network's activities is on launching and technically supporting cooperation projects. With the expansion of renewable power as part of the energy transition, hydrogen is set to play an increasingly important role as an energy storage medium. Surplus wind power can be converted into hydrogen by means of water electrolysis both centrally and locally ("Power-to-gas"). This hydrogen can be stored in various ways for conversion back to electricity as and when required through highly efficient processes including fuel cells, or used as "domestic fuel" for emission-free mobility with fuel cell vehicles. Projects to test this approach – including wind power electrolysis, expansion of the refuelling station infrastructure, and everyday testing of fuel cell vehicles – are one of the Network's current priority activities.

The Network has been testing fuel cell vehicles for several years. These vehicles (various makes) were made available as part of the Clean Energy Partnership (CEP) to demonstrate their suitability for everyday use. They have a power output of around 100 kW and consume around 1 kg of hydrogen per 100 km, which corresponds to about 5 l/100 km of diesel. By mid-2018, they had clocked up more than 100,000 km with just under one tonne of hydrogen from around 500 refuelling stations.

The Network is also actively involved in stationary fuel cell applications. Fuel cells installed in basements, for example, are used for combined heat and power generation (CHP) or to provide uninterruptible or off-grid self-sufficient power to network cell towers, for example. There are attractive funding schemes available for investments in fuel cell-based CHP systems.

To establish a professional exchange between its members, the Network has set up various expert groups on topics such as "H_2 system", "Power-to-gas", "Market launch", "H_2 for public transport" and "E-mobility". The experts meet regularly to discuss specific issues in detail.



Students taking part in the FUELCELLBOX school competition

The winners of the Hydrogen NRW Research Prize NRW 2017

To encourage young scientists, the Network has been organising the FUELCELLBOX school competition with around 200 teams from all over North Rhine-Westphalia for several years. There is also the Hydrogen.NRW Research Prize awarded together with the EnergyResearch.NRW cluster, which is intended to encourage young academics to integrate the key topics of the NRW Progress Research Strategy into their final theses and thus support the development of NRW as a research location.

The Network has helped make North Rhine-Westphalia one of the leading fuel cell locations in Europe. It is a member of the European Association for Hydrogen and Fuel Cells and Electromobility in European Regions (HyER). Major fuel cell companies such as Hydrogenics (Canada) and Ceramic Fuel Cells (Australia, now SOLIDpower) have set up business in North Rhine-Westphalia. Foreign manufacturers of fuel cell and hydrogen systems including the Japanese company Asahi Kasei have their technologies tested by NRW companies and institutes to ensure compliance with European requirements. Leading battery-based e-mobility players such as vehicle manufacturers StreetScooter and e.GO AG as well as charging infrastructure manufacturer Mennekes are also based in NRW.

Companies and institutes already working in the field of fuel cell, battery and hydrogen technology, but also specialist newcomers looking to develop new technologies are expressly invited to join the Network, as are technology users, foreign companies and institutes. Membership is free of charge.

Contact:
Stefan Garche
Netzwerk Brennstoffzelle und Wasserstoff, Elektromobilität der EnergieAgentur.NRW
Telephone: +49 (0)211/866 4223
garche@energieagentur.nrw

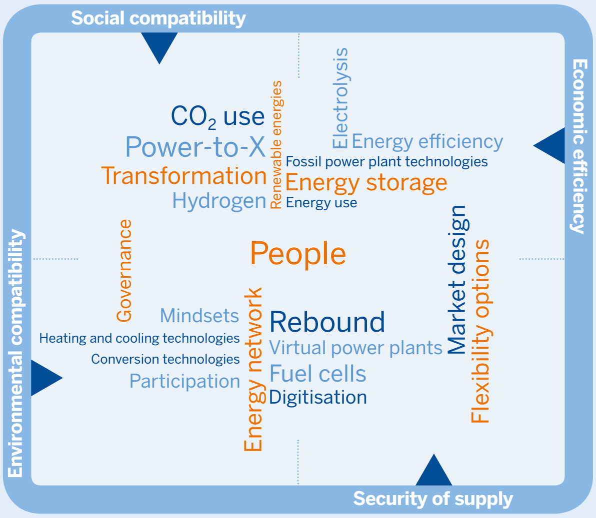
www.energieagentur.nrw
www.fuelcellbox-nrw.de

EnergyResearch.NRW Cluster (CEF.NRW)

The EnergyResearch.NRW Cluster, which is also part of EnergyAgency.NRW, works on behalf of the state government of North Rhine-Westphalia. It sees itself as the point of contact for all questions relating to energy research in NRW, and also acts as a central transfer point between energy-relevant activities by the EU and the federal government as well as initiatives by civil society. The Cluster's research priorities include:

- Renewable energies
- Fossil-based energy generation
- Networks and storage
- Digitisation
- Energy economics and socio-political aspects
- Fuel cells and CHP

Energy research in North Rhine-Westphalia: The key to energy system transformation



The work of the EnergyResearch.NRW Cluster is aimed at initiating and promoting research and development to generate sustainable energy solutions. In this way, the Cluster contributes to achieving the energy industry and climate policy objectives of the state government and to improving national and international competitiveness. The Cluster encourages coordinated cooperation between industry and scientific or research institutions, and helps to ensure that new technological and socio-economic knowledge quickly finds its way into application development, thereby making a significant contribution to the energy transition.

The aim of the EnergyResearch.NRW Cluster's work is to secure an environmentally friendly, reliable, affordable and sustainable energy supply for the future. This means putting the complex energy supply system as a whole at the centre of interdisciplinary and transdisciplinary research.

CEF.NRW is managed by EnergyAgency.NRW, so its networks and partners will continue to form the basis of its activities. This will also ensure continued close integration with the EnergyRegion.NRW Cluster, which is also managed by EnergyAgency.NRW.

Contact:
Dr. Benedikt Rösen
Cluster EnergieForschung.NRW
Telephone: +49 (0)211/21094410
info@cef.nrw.de

www.cef.nrw.de

EnergyAgency.NRW

EnergyAgency.NRW was established by the state of North Rhine-Westphalia as an operational platform with broad and varied expertise in the energy sector, from energy research, technical development, demonstration and commercial launch to energy consulting and advanced professional training. Energy efficiency and climate protection are the focus of many activities. In times of high energy prices, it is more important than ever to forge ahead with the development of innovative energy technologies in North Rhine-Westphalia and have an independent body highlight ways in which companies, municipalities and private individuals can use energy more efficiently or deploy renewable energies in a meaningful way.

EnergyAgency.NRW has around 140 employees based mainly in Düsseldorf, Gelsenkirchen and Wuppertal and is financed by the EU's (EFRE).

Cluster and network management

On behalf of NRW's Ministry of Economic Affairs, EnergyAgency.NRW manages the EnergyRegion. NRW cluster and runs 17 powerful climate protection networks under individual contracts dealing with system transformation, energy infrastructure, energy market design, business and financing models, knowledge management, biomass, fuel cell and hydrogen, energy-efficient solar-based construction concepts, geothermal energy, photovoltaics and wind energy. EnergyAgency.NRW also runs the "Energy Industry" and "Mining Industry" networks that focus on forging competitive partnerships to develop ideas for innovative projects and products, accelerate their market maturity and exploit their economic potential.

Initial consultation

EnergyAgency.NRW engineers provide information on energy system weaknesses – from technical installations in buildings to commercial production processes. The spectrum ranges from heating and heat recovery systems to thermal insulation in large workshops to protect against heat and cold and assist with leak detection and the development of energy concepts. The experts explain funding opportunities, help companies reduce their energy costs and contribute to increasing competitiveness.

Knowledge management

EnergyAgency.NRW offers a range of advanced training seminars – including for end users. These seminars, which are also available online, can be used by institutes, energy suppliers, associations, clubs, universities, municipalities and companies in NRW. The programme also includes user motivation courses such as "aktion.Efit" and "mission E" for company workforces. EnergyAgency.NRW also operates an online platform for vocational education and training.

Activities and projects

"EnergyDialog.NRW", an information platform about renewable energies in NRW, is a mediation and consultancy service for citizens, municipalities and investors run by EnergyAgency.NRW. EnergieDialog.NRW is intended to help resolve conflicts. If there is a conflict – e.g. as part of project planning and/or approval – the parties based in NRW can use the conflict mediation services.

In addition, EnergyAgency.NRW coordinates market initiatives and joint activities across Germany. Projects like the "AltBauNeu" refurbishment campaign for buildings, the "Gebäude-Check" energy audit, the "Solar-Check NRW", "50 solar housing estates in NRW", "100 climate protection housing estates in NRW", the "Wood pellet initiative" or the "Heat pump market place NRW", and the "CHP.NRW – electricity meets heat" campaign, as well as the photovoltaics market initiative provide information on environmentally friendly and innovative heat and power generation and tips on saving energy in NRW.

Contact:
EnergieAgentur.NRW
Roßstraße 92, 40476 Düsseldorf
Telephone: +49 (0)211/866420
info@energieagentur.nrw

www.energieagentur.nrw

Regional activities

HyCologne Wasserstoffregion Rheinland e.V.

HyCologne Wasserstoffregion Rheinland e.V. is a network which has teamed up with public and industrial partners to organise the provision of industrial hydrogen as an energy source for transport and other projects. The chemical industry (mainly in chlorine production) and refineries in the Cologne area produce large quantities of hydrogen as a by-product without requiring additional energy. The first hydrogen refuelling station (350 bar) in Hürth was put into service in 2010, allowing the operation of initially four fuel cell buses (since 2011). The project has demonstrated the technical and organisational feasibility of zero-emission technology in local public transport (with a range over 250 km per vehicle per day) and the strong will and financial commitment of the partners involved.

It began with two "Phileas" type fuel cell hybrid buses in 2010, and since 2014, two more Van Hool A330 FC hydrogen fuel cell buses have been in service in the cities of Brühl and Hürth. These have proven to be just as reliable as diesel buses and are now operated in Hürth, the Rhine-Erft district and the Cologne region. By mid-2018 they had clocked up more than 200,000 km.

The "Chemergy – Provision of By-Product Hydrogen for Transport Projects" initiative (2009 - 2012), which was part of the National Innovation Programme (NIP), was set up to create public access to previously closed chemical infrastructure to allow hydrogen to be used as an energy source for transport. Since the end of the funded project period, operation of the refuelling station built by Air Products has been successfully continued by the municipal utilities of Hürth and Brühl. It has a very high availability of more than 98%.

In 2018, the capacity of this refuelling station will be expanded, as more hydrogen fuel cell buses will be in service in Hürth and Brühl from 2019, and another 45 buses will be operating in the Cologne area by 2021. In addition to the refuelling station at Cologne/Bonn Airport, which has already been completed, the hydrogen infrastructure in the region will be expanded by another two refuelling stations in Meckenheim and Wermelskirchen.

Contact:
Boris Jermer
HyCologne Wasserstoffregion Rheinland e.V.
Telephone: +49 (0)2233/406123
jermer@hycologne.de

www.hycologne.de

h2-netzwerk-ruhr e.V.

Hydrogen use has a long tradition in the Ruhr area. A network of H_2 pipelines connects producers and industrial users, high-pressure trailer filling stations provide additional supplies, and excellent research facilities work on hydrogen and fuel cell technologies. This gives the metropolitan area the chance to play a leading role in zero-emission hydrogen technologies. In 2003 the Hydrogen and Fuel Cell Centre (ZBT GmbH) was founded in Duisburg. The Emschergenossenschaft (Emscher River Association) water board launched a project called EuWaK ("Natural gas and hydrogen from sewage treatment plants") to produce hydrogen from sewage gas, and this "HyChain" project demonstrated that fuel cells are a reliable technology for small vehicles despite some other vehicle issues. Hydrogenics GmbH have settled in Gladbeck, and the city of Herten now boasts the h2herten user centre with a wind power electrolysis unit (see below), which can be rented as research infrastructure, while the Westphalian University of Applied Sciences has begun system development work.

The h2-netzwerk-ruhr e.V., an association of municipalities, companies and research institutes, supports the development of fuel cell and hydrogen technology with the aim of creating jobs. Today, the association, founded in 2008, has 35 members, the newest of whom are a number of pipeline gas transmission companies. The association's work focuses on specialist events, PR and educational work, partnerships and lobbying activities, which are currently carried out jointly with HyCologne. The joint Rhine-Ruhr hydrogen workshop, supported by EnergyAgency.NRW, regularly gathers top-class experts under the motto "Think Big!"

Contact:
Dr. Michael Weber
h2-netzwerk-ruhr e.V.
Telephone: +49 (0)211/86642245
m.weber@h2-netzwerk-ruhr.de

www.h2-netzwerk-ruhr.de

h2herten user centre

The h2herten user centre features a pilot plant which is unique, at least in Europe. It was funded by the state of North Rhine-Westphalia and the EU (EFRE) and allows different plant configurations with real and fictitious renewable generation profiles and real load profiles to be run and monitored in real time using sophisticated instrumentation. Now that the first goal of the project – to demonstrate the feasibility of a permanent, self-sufficient wind power and hydrogen-storage-based energy supply for a commercial property – has been achieved, the research and development platform is open for use by industry and science.

In this intermediate stage between laboratory and grid, interested parties can now, for the first time, gain real operating experience with components, plants or systems for renewable energy supply with comparatively little effort. Apart from science, energy suppliers and operators of industrial estates, this offer is primarily aimed at component and system manufacturers as well as engineering companies.

Since all tests are run as simulations, the pilot plant can be flexibly configured for a wide variety of application scenarios. While the focus for grid-forming stand-alone operation is on operating and control concepts as well as reliability and fault management, robust grid-parallel operation is ideally suited for optimising the load capacity, efficiency and cost-effectiveness of individual plant components. Apart from complete systems, the pilot plant also allows individual components to be operated and tested so they can be characterised for later simulations, for example. Plant control and monitoring, which can be manual or automatic, is handled by a standard process control system.

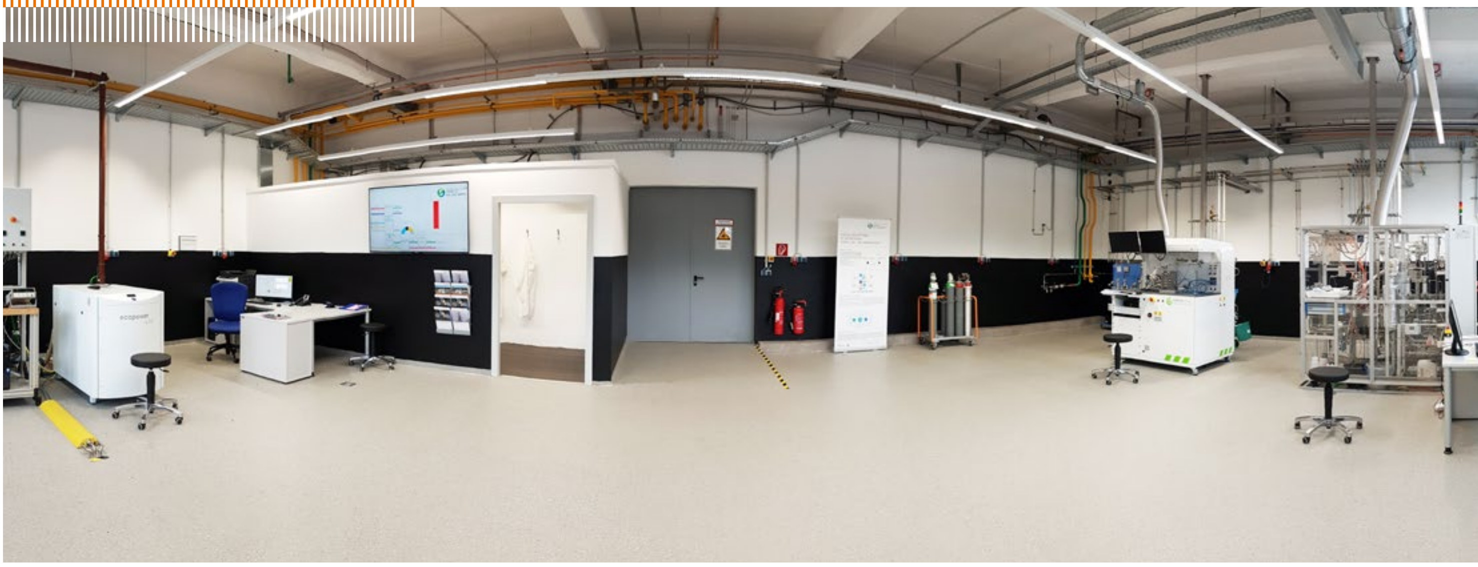
Current developments:

- Certification and market launch of an alkaline water electrolysis system, investigations into dynamic operation, cooperation partner: Asahi Kasei Europe GmbH
- Development of a gravimetric calibration system for the calibration of H_2 dispensers for high-pressure vehicle refuelling systems, cooperation partners: Energy Institute of the Westphalian University of Applied Sciences, Esters Aschaffenburg, Germany
- Construction and operation of a public 700 bar H_2 filling plant for cars and refuse collection vehicles, project management agency: H_2 MOBILITY Deutschland GmbH & Co. KG

Contact:
Dieter Kwapis
Anwenderzentrum h2herten GmbH
Telephone: +49 (0)2366/305286
info@h2herten.de

www.h2herten.de

h2herten user centre



Virtual Institute "Power to Gas and Heat"

One of the major social challenges is the transition from today's fossil-dominated energy supply system to a climate-friendly, secure and affordable energy future. This restructuring of our energy supply and the resulting expansion of intermittent renewable energies in accordance with the goals of the federal government and the state of North Rhine-Westphalia will long before create a situation where the supply of electricity in terms of time and location no longer matches demand. Accordingly, the future energy supply system must be much more flexible.

"Power to Gas and Heat" is one possible answer to the need for greater flexibility. Electricity can either be used directly to generate heat or can be converted into gaseous energy sources (e.g. hydrogen, synthetic natural gas) or liquid fuels (e.g. methanol) in various processes.

Our complex energy system offers a multitude of ways of using electricity with numerous flexibility options. The Virtual Institute "Power to Gas and Heat", founded in 2014, has the task of exploring potential utilisation options and evaluating them from a technical and economic perspective. For this purpose, the Virtual Institute identifies and pools the expertise available in NRW. The term "virtual" describes the fact that there are no structures – in terms of staff or material – but that the existing structures in NRW cooperate efficiently on selected topics. Activities are coordinated by the Essen-based Gas and Heat Institute (GWI) and the Institute of Energy Economics at the University of Cologne (ewi). Further partners are the Jülich Research Centre (FZJ) with the working groups IEK-3 and IEK-STE, the Wuppertal Institute (WI), the Hydrogen and Fuel Cell Centre GmbH (ZBT), Fraunhofer UMSICHT and the Laboratory of Industrial Chemistry at Ruhr University Bochum (RUB).

In addition to the analysis of flexibility options, a research infrastructure for power-to-X set up at GWI in Essen will allow technical processes (e.g. power-to-gas) to be studied experimentally. The data collected will be for the path analysis.

The Virtual Institute "Power to Gas and Heat" sees itself as an open platform for all players involved in sector coupling and also makes its expertise available to external project partners.

Contact:
Janina Senner
Gas- und Wärme-Institut Essen e.V.
Telephone: +49 (0)201/3618-238
senner@gwi-essen.de

www.strom-zu-gas-und-waerme.de

International Activities

HyER

HyER stands for “Hydrogen, Fuel Cells and Electro-Mobility in European Regions” and was founded in 2008 on the initiative of the European Commission. The partnership has been tasked with coordinating the activities of what are currently 20 European regions and cities from ten countries under various European initiatives and programmes. It promotes the dissemination and commercialisation of hydrogen and fuel cell technology (stationary and mobile applications), and e-mobility (battery and fuel cell-based) along with the development of the necessary infrastructures. At the same time, it acts as a point of contact for EU projects and supports the submission of project applications. HyER’s three main areas of activity are:

- Development and dissemination of recommended actions for decision-makers in member municipalities and regions on the basis of up-to-date technical information (HyER is involved in numerous EU projects)
- Analysis, evaluation and – where necessary – contribution to establishing a European funding and financial framework for municipalities and regions to facilitate the development, testing and market introduction of innovative technologies
- Compilation and development of robust development scenarios for innovative technologies in the member regions and municipalities as well as analysis and evaluation of the respective drivers and motivations

North Rhine-Westphalia is a founding member of HyER and chaired the organisation from 2008 to 2014.

Contact:
www.hyer.eu

International Members

HyER members:
- Aberdeen City Council GB
- Akershus NO
- Aragon ES
- Arnhem – Nijmegen NL
- Baden-Württemberg DE
- Berlin DE
- Bolzano IT
- Hamburg DE
- La Manche FR
- Lazio IT
- Lombardy IT
- Midi – Pyrenees FR
- NRW DE
- Piemonte IT
- Province of Groningen NL
- Riga LV
- Rogaland County Council NO
- Skane SE
- Torres Vedras PT
- Transport Scotland GB
- Trento IT

Source: HyER, Version: 6/2017

Cooperation with non-European regions

Outside Europe, the Fuel Cell and Hydrogen, Electromobility Network has been cooperating for many years with the Japanese prefectures of Fukushima, Fukuoka, Osaka and Yamanashi in particular, as well as with the Canadian province of British Columbia. Like North Rhine-Westphalia, all these regions show an extraordinary commitment to hydrogen and fuel cell technology in their respective countries.

As early as 2014, the federal state of North Rhine-Westphalia signed a memorandum of understanding with the prefecture of Fukushima on cooperation in the energy sector, including hydrogen economy/technologies. The prefecture of Fukushima wants to meet its entire primary energy demand from renewable energies by 2040. According to Prime Minister Abe, Fukushima is to become the main production site of green hydrogen in Japan, which is to be used, among other things, for public transport during the 2020 Summer Olympics.

There is a wide-ranging exchange between all regions on infrastructure concepts, the political framework and technical standards, as well as cooperation among the regions with companies and research institutes. Numerous delegations, especially from Japan, have visited hydrogen and fuel cell projects in NRW.

Contact:
www.energy-agency-fukushima.com/en
www.hysut.or.jp/en
www.chfca.ca

Bibliography

(1) Robinius, M., A. Otto, P Heuser, L. Welder, K. Syranidis, D. Ryberg, T. Grube, P. Markewitz, R. Peters, and D. Stolten, Linking the Power and Transport Sectors - Part 1: The Principle of Sector Coupling. Energies, 2017. 10(7): p. 956

(2) Markewitz, P., T. Grube, M. Robinius, T. Kannengießer, and D. Stolten, Energietransport- und Verteilung. Brennstoff-Waerme-Kraft, 2017. 69(5): pp. 45 - 53

(3) Markewitz, P., T. Grube, M. Robinius, T. Kannengießer, and D. Stolten, Energietransport- und Verteilung. Brennstoff-Waerme-Kraft, 2017. 69(5): pp. 45 - 53/BMWi, Zahlen und Fakten Energiedaten - Nationale und internationale Entwicklung, 2016

(4) Otto, A., M. Robinius, T. Grube, S. Schiebahn, A. Praktiknjo, and D. Stolten, Power-to-Steel: Reducing CO2 through the Integration of Renewable Energy and Hydrogen into the German Steel Industry. Energies, 2017. 10(4): p. 451

(5) Kotzur; L., P. Markewitz;, M. Robinius, and D. Stolten, Kostenoptimale Versorgungssysteme für ein vollautarkes Einfamilienhaus, In: Internationale Energiewirtschaftstagung "Klimaziele 2050: Chance für einen Paradigmenwechsel?" Vienna 2017

(6) www.wupperinst.org

(7) vdi nachrichten "Künstliches Grün für den Wasserstoff" (Commentary by Thomas Happe), www.vdi-nachrichten.com

(8) Power-to-Gas in Deutschland und NRW, www.energieagentur.nrw

(9) Fuel Cell Electric Buses - Potential for Sustainable Public Transport in Europe, www.fch.europa.eu

(10) www.fch.europa.eu

(11) Robinius, M., J. Linßen, T. Grube, M. Reuß, P. Stenzel, K. Syranidis, P. Kuckertz, and D. Stolten. Comparative Analysis of Infrastructures: Hydrogen Fueling and Electric Charging of Vehicles, 2018; www.fz-juelich.de

Imprint
EnergieAgentur.NRW GmbH
Roßstraße 92
40476 Düsseldorf
Germany

Telephone: +49 (0)211/837 1930
hotline@energieagentur.nrw
www.energieagentur.nrw

As of
12/2018

Contact
EnergieAgentur.NRW
Netzwerk Brennstoffzelle und Wasserstoff, Elektromobilität
Dr. Thomas Kattenstein
kattenstein@energieagentur.nrw

Picture credits
Title: RVK
Inside: p. 5: MWIDE NRW/E. Lichtenscheidt; p. 17: malp - Fotolia.com; p. 18: Air Liquide; p. 23: Wuppertal Institut; p. 24: Ruhr-Uni Bochum; p. 25/26: DLR; p. 28: Anwenderzentrum h2herten; p. 31: malp - Fotolia.com; p. 33: EMS; p. 40: Gräbener Maschinentechnik; p. 43: CBT; p. 46/49: Daimler; p. 47: malp - Fotolia.com; p. 51: RVK; p. 52: innogy; p. 53: Alstom; p. 55: malp - Fotolia.com; p. 58: Westfälische Hochschule; p. 60: SOLIDpower; p. 61: N2telligence; p. 62: Netzgesellschaft Düsseldorf; p. 65: Foto Klaus Voith; p. 66: CEF.NRW; p. 69: CEF; p. 71: GWI Essen

EUROPÄISCHE UNION
Investition in unsere Zukunft
Europäischer Fonds
für regionale Entwicklung

Ministerium für Wirtschaft, Innovation, Digitalisierung und Energie des Landes Nordrhein-Westfalen