

HYDROGEN REPORT

SWITZERLAND 2010/2011

Major Achievements



Editorial

The economy in the industrialized world directly depends on the availability and consequently the price of resources. The most important resource is crude oil because it not only delivers primary energy but also represents the most important energy storage system for industrialized society. The worldwide average continuous power consumption is approximately $14 \cdot 10^9$ kW. The amount of energy stored worldwide is about $2.5 \cdot 10^{13}$ kWh which corresponds to $2.5 \cdot 10^{12}$ kg oil or $2 \cdot 10^{10}$ barrels. Furthermore, the economic benefit from fossil energy carriers during industrialization is 0.4 US\$/kWh. If we assume a 25% energy efficiency in conversion, the economic benefit is about 150 US\$/barrel. In October 2008, the price of oil reached the value of 150 US\$/barrel and this was the reason for the economic crises. Due to the reduced demand for oil upon the economic crisis, the oil price dropped and is increasing again with the growing economy. Therefore, we may anticipate the next economic crisis as soon as the oil price again reaches 150 US\$/barrel, unless we succeed to decouple economic benefit from the availability of fossil fuels.



Andreas Züttel

The future economy has to be based on closed cycles for materials and especially energy resources. The last century was dominated by an economy of mining resources, converting the resources and disposing the products in the environment. This is only sustainable as long as nature and especially the living matter is able to compensate and close the cycles. However, we have reached in the 21st century a level of materials and energy flows which approach worldwide limitations.

Switzerland has no natural materials resources and is therefore traditionally very sensitive to the use of resources. Switzerland is intensively working on the conversion of renewable energy and the hydrogen cycle: e.g. hydrogen production by electrolysis, dense hydrogen storage in solids and finally the combustion of hydrogen in fuel cells. Small and medium sized industry develops world leading technology and products for a sustainable future in Switzerland. Excellent research on the most important challenges of the future hydrogen society is performed in Swiss universities, universities of applied sciences and national research institutions.

The Swiss hydrogen association is a very appreciated platform for the exchange of knowledge and a network for project partners, especially between industry and academics. The achievements in research and industry presented in this report exhibit the great level of accomplishment in Switzerland. The Swiss hydrogen report from 2006 was devoted to the industry working in the field, the second report published in 2008 was devoted to the research activities and the current report is an overview of the major achievements.

Dübendorf, 29. April 2010

A handwritten signature in blue ink that reads "A. Züttel".

Prof. Dr. Andreas Züttel
President Hydropole

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10 Years of Hydropole

The Swiss Hydrogen Association, HYDROPOLE, is the national network for hydrogen-related matters in Switzerland. HYDROPOLE is a knowledge and information cluster focused on all aspects of past, present and future use of hydrogen. HYDROPOLE serves as a platform for research, development, industry and other public

or private organizations. HYDROPOLE fosters knowledge about hydrogen and its application in the energy sector by providing information to the general public, the educational sector, developing industry as well as for policy needs. The association maintains close links with other hydrogen associations in Europe and worldwide.

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The association was founded on 23. Nov. 2001 and is legally located in Monthey. The first president of Hydropole was Bernard Mudry, the former director of Djeva. During the last 8 years, a solid network of members in Switzerland was built up and the number of members continues to grow every year and is already greater than fifty. Approximately one third are from industry, one third from academic institutions and the remaining third are individual members. The board consists of 7 members: the president, the vice-president and 5 work group leaders.

Since 2006, Hydropole has been a member of the European Hydrogen Association (EHA). The association is represented through its board members in several political and international research organizations in order to actively connect members with key players in the field of hydrogen worldwide.

Hydropole produces a hydrogen report every other year. The first report was devoted to the industry in Switzerland and was published in 2006. This was followed by the second report which was about hydrogen research in Switzerland published in 2008. The current report presents the major achievements in the field of hydrogen science and technology in Switzerland.

Hydropole organized the "Swiss village" at the World Hydrogen Energy Conference (WHEC) in June 2006 in Lyon, France. Seven Hydropole members represented the activities in Switzerland. The exhibition was a big success and significantly increased the visibility of our members. Hydropole was represented by A. Luzzi and F. Holdener at the WHEC in Brisbane, Australia in June 2008. The WHEC 2010 will take place in May 2010 in Essen, Germany. Hydropole will

organize a “Swiss village” with 8 members from industry, research and academia.

In February 2008 and 2009, Hydropole participated in the Swiss Pavillion organized by the Swiss embassy in Japan (Dr. Felix Mösner) at the Hydrogen and Fuel Cell exhibition (FC Expo) in Tokyo, Japan. The exhibition had more than 24000 visitors and was a very impressive event.



Fig. 1: Hydropole Network

Hydropole, as a network, stimulates the collaboration between universities, institutions and industry. Numerous research and development projects have been created between the members. Examples include the light weight SAM fuel cell car with a metal hydride storage system and the research and development project on new membranes for alkaline electrolyzers.

In the first ten years of the existence of the hydrogen association Hydropole, the hydrogen community in Switzerland has been brought closer together. The personal contacts and the exchange of information within the association are of great value for the members. Furthermore, the association is well known outside Switzerland and makes a significant impact in research and industry in Europe and Asia.

Reference

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A historical technology for modern, sustainable and emission free hydrogen production

For the past few years, IHT (Industrie Haute Technologie SA) has had activities in the field of industrial electrolyser plants, mainly installing retrofits in existing plants after 30 years of operation. As a result, IHT's Board of Directors has realized that the company is ideally positioned to face the new challenges of the so-called "hydrogen economy" using their highly sophisticated high pressure electrolyser technology.

The alkaline high pressure technology, characterized by high efficiency, reliability, flexibility and short response times, is ideal for integration into renewable energy systems (RES), for pilot plants and for hydrogen mass production farms. Therefore, in order to consolidate its presence in these modern fields of application, IHT has strengthened an already ambitious research and development program and further reinforces its international position of expertise by attending the most prominent technology fairs in the world, such as the FC exhibitions in Tokyo and Hannover. In addition to employing a strong and experienced engineering team, IHT cooperates with technical schools and institutes such as HIT Lau-

sanne, Empa Dübendorf, the University of Fribourg, and the Technical University of Denmark, as well as with industry partners in Switzerland and other European countries. The current R&D projects of IHT mainly concern the improvement of efficiency in alkaline electrolysers. In addition, the European project WELTEMP in the 7th Framework Program addresses high temperature electrolysis. In the Swiss CTI project NMAE2, new types of separation membranes are being developed which aim to considerably increase electrolyser efficiency.

As part of the International Energy Agency (IEA) project, IHT also collaborates with the Aragon Hydrogen Foundation (AHF) in Spain with the objective of analyzing and optimizing the integration of alkaline high pressure electrolysis into the "RES to H₂" concept. As the first step, the IHER project was realised at "Walqa Technology Park", in the AHF headquarters [Fig. 2]. A 10 Nm³ H₂/h electrolyser and its associated plant are about to be commissioned. The IHER project was awarded the first prize as a Technology Demonstration by the International Energy Agency in 2010. IHT also develops other products, such as small electrolyser units, and designs universal testing equipment which are suitable for performing different tests on new cell types with the goal of improving the electrolysis processes with respect to cost and performance.

Presently, IHT addresses requests for large hydrogen production plants for high demand applications by clients from the refinery, gas manufacture, agrarian and food industries [Fig 5]. The gases obtained by alkaline electrolysis are free of CO, CO₂, CH₄ as well as sulphurous and chlorinated components.



Ernest Burkhalter



Fig. 1: Main production site of IHT in Monthey (VS), Switzerland.



Fig. 3: IHER 10 Nm³ electrolyser

Table of technical data:

	High Pressure Electrolysis	Atmospheric Electrolysis
Production capacity:		
Hydrogen:	110 to 760 Nm ³ /h H ₂	3 to 330 Nm ³ /h H ₂
Oxygen:	55 to 380 Nm ³ /h O ₂	1.5 to 165 Nm ³ /h O ₂
Gas purity levels:		
Hydrogen:	99.8 to 99.9 % vol.	99.8 to 99.9%
Oxygen:	99.3 to 99.6 % vol.	99.5 to 99.8%
Residual impurities:		
O ₂ in H ₂ :	0.1 to 0.2 % vol.	
H ₂ in O ₂ :	0.4 at 0.7 % vol.	
H ₂ O:	approximately 1 to 2 g/Nm ³	
KOH:	less than 0.1 mg/Nm ³	
Consumption:		
Electrical energy:	4.3 to 4.6 kWh/Nm ³ H ₂ (gas at 0°C, 1013 mbar, dry)	3.90 to 4.22 kWh/m ³ H ₂ (gas at 20°C, 1013 mbar, wet)
Feedwater:	0.85 l/Nm ³ H ₂	1 l/Nm ³ H ₂
Cooling water:	40 l/Nm ³ H ₂ (Δt = 20°C)	60 l/Nm ³ H ₂
Part-loads		
	25 to 100% of its nominal capacity	25 to 100% of its nominal capacity

History of the electrolyser

In the 1940s, the Swiss company Lonza SA, based in Visp, was faced with a growing need for hydrogen in its production activities in the field of chemistry. At that time, the management decided, for strategic reasons, to produce its own hydrogen and therefore mandated one of their engineers, Ewald A. Zdansky, to study and develop a hydrogen generator that could meet the gas requirements for the production of chemicals such as ammonia. The large availability and low price of electrical power from hydropower stations in Switzerland lead Zdansky to develop alkaline electrolysis as the most effective process for hydrogen generation. In Giovanola Frères SA (GFSA), located in Monthey [Fig. 4], he found the right partnership, equipment and large manufacturing experience for the production and testing of the first prototype electrolysers. After a few years of development, the first Zdansky-system high pressure industrial electrolysers, manufactured at GFSA, were commissioned by Lonza [Fig. 3]. The design of this electrolyser was patented by Lonza [Fig. 6, 7].



Fig. 3: First prototype of an industrial Zdansky-electrolyser (1949).

Originally, the main interest of Lonza was to produce hydrogen for own chemical plant; however, when they realized the growing interest from industry for the electrolyser, Lonza decided to sell the rights resulting from the Zdansky

design to LURGI ("Metallurgische Gesellschaft"), a large engineering company located in Butzbach, Germany. Continuing the cooperation with GFSA, LURGI began the commercialization of the high pressure electrolysers. In the meanwhile, LURGI was also committed to improving its design, particularly with respect to the electrodes [Fig. 8] and specific mechanical



Fig. 4: Facilities of the Giovanola Frères SA (GFSA), located in Monthey, Switzerland

constructions. The research and development was carried out at GFSA and managed by Jürgen Borchardt, a LURGI engineer based in Monthey. He also supervised the fabrication of more than one hundred electrolysers which were subsequently installed worldwide.

In 1996, LURGI discontinued electrolyser development and manufacturing and closed the electrolyser section. The rights to the design, developments, and customer database were acquired by the manufacturing partner, GFSA. In 2001, GFSA faced financial difficulties and soon after declared bankruptcy. Its daughter company, GTec SA, was subsequently

Fig. 5: High pressure electrolyser



created in 2002 by taking over GFSA's activities and implementing a new legal and financial structure. However, it also did not survive and later declared bankruptcy as well. In 2003, the new IHT company Industrie Haute Technologie SA (IHT) was founded to resume the manufacture of Zdansky type electrolysers. IHT manufactures the Zdansky high pressure electrolysers in the original factory in Monthey [Fig. 1].

Today, IHT is a successful electrolyser manufacturing company with engineering, manufacturing and commercial activities. Having completed contracts in Sweden, Switzerland and Argentina, the company focuses on the high demand of the world hydrogen market, where its unique large size electrolysers (up to 3.5 MW) are ideal for mass production plant applications.

Fig. 7: Cross section of a bipolar, atmospheric pressure electrolysis unit with alkaline electrolyte (Brown Boveri)

- a) First anode with pre-electrode;
- b) Diaphragm;
- c) Pre-electrode of the cathode;
- d) Cathode for the first cell compartment-bipolar middle electrode;
- e) Cell frame with insulation for the middle electrode;
- f) Distribution pipe for electrolyte;
- g) Inlet pipe for electrolyte;
- h) Take-off system for electrolyte and dissolved gases;
- i) Overflow pipe and collecting vessel for electrolyte and H₂ (an analogous system is used for O₂);
- j) Electrolyte filter;
- k) Circulation pump;
- l) End plate



Fig. 6: Patent of the Zdansky high pressure electrolyser.

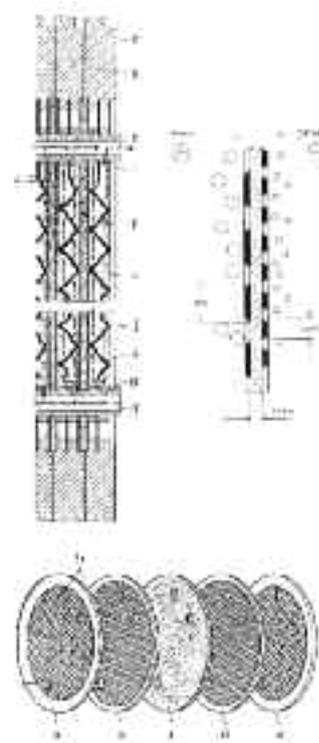
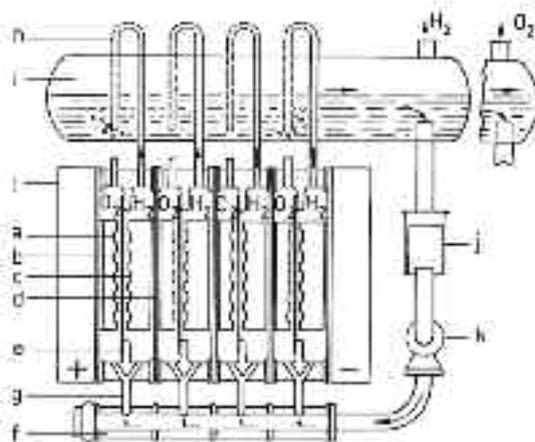


Fig. 8: Cross section and exploded view of the cells of a pressure electrolysis unit (Lurgi, Zdansky-Lonza pressure electrolysis) a) Bipolar electrodes, dimple plate cell partition; b) Pre-electrodes in the form of nets on both sides of the asbestos diaphragm (c); d) Cell frame; e) Sealing ring, sealing the electrolyte against the surroundings and insulating the bipolar sections against each other; f) Electrolyte duct; g) Bore in the electrolyte duct for supplying the electrolyte solution to both sides of the electrolyte; h) Parallel H₂ and O₂ ducts; i) Bore in the gas duct; j) Electrolyte compartment. Zero gap cell geometry. Perforated cathodes and anodes, in direct contact with the diaphragm and the membrane, respectively. The conical apertures with different diameters for O₂ and H₂, respectively, facilitate the detachment of the developing gas.

References

- [1] "Method for starting multicellular pressure electrolysers", Ewald A. Zdansky, Monthey, Switzerland, U.S. Patent 2,683,116, 30. 11. 1949.
- [2] "High-Pressure Electrolyze", E. A. Zdansky, (assigned to Lonza Elektrizitätswerke und chemische Fabriken Akt.-Ges.), Swiss Patent 330,814 (1958) August 15

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PEM Electrolyzers generating Hydrogen enriched natural gas HENG from Renewable Energy Sources

Diamond Lite S.A., a Swiss based engineering company with a European wide distribution network is providing on-site gas generation solutions mainly for industrial applications. HOGEN® PEM solid electrolyte hydrogen electrolyzers are used since a long time for many industrial applications, replacing hydrogen supply in cylinders. Proton Exchange Membrane (PEM) diaphragm technology, was developed years ago by engineers in the con-

text of the NASA space program and which was refined for military applications. In the past years, Diamond Lite has also realized projects in connection with renewable energy sources such as wind and PV. The generated hydrogen is used for fuel cell vehicles or in other cases for stationary electric power generation. This article reports about 2 projects realized in 2008 and 2009.

Hydrogen enriched natural gas

In the context of the “Sustainable Ameland”, Eneco started a project involving the blending of hydrogen in the gas network. An innovative project that examines the impact of blending hydrogen on various materials. Using a blend of natural gas and hydrogen for heating and cooking saves energy.

The project, which was supervised by KIWA/Gastec, is carried out at 14 households to gain experience with the consequences of blending for heating and cooking purposes. Hydrogen is generated using electricity from renewable sources. The PEM type HOGEN® electrolyser is in successful operation since almost 2 years.



H. Vock



Fig. 1: HOGEN® hydrogen generator in container

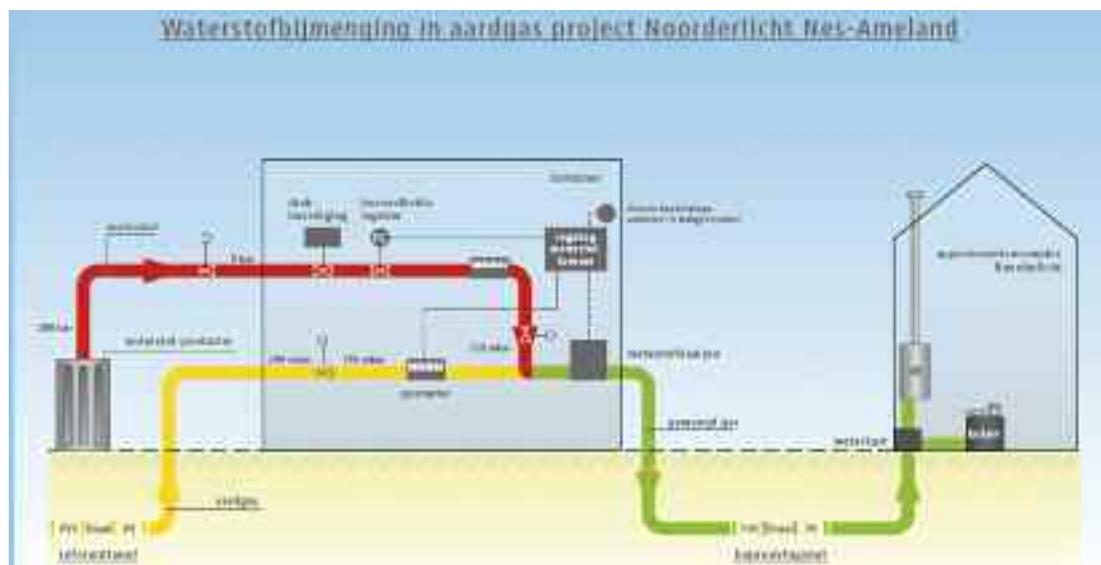


Fig. 2: Schematic diagram of the blending project

HENG Benefits

HENG enables the initial deployment of hydrogen in the energy system without the need for expensive infrastructure investments. This resolves the classic “chicken and egg” problem of hydrogen production and the dedicated storage, transmission and other equipment needed to use it directly as a fuel. The use of HENG enhances combustion and reduces CO₂ emission from natural gas. It also leads to lower emissions of pollutants such as nitrogen oxide (NO_x), carbon monoxide (CO) and unburned methane and other hydrocarbons. HENG can also improve the fuel efficiency

of gas-fired combustion in boilers, engines and turbines, using existing natural gas delivery infrastructure and end-use equipment.

HENG increases the efficiency of natural gas conversion into useful energy. Adding even small amounts of hydrogen leads to more complete combustion of the fuel, including CO, methane and other hydrocarbons in the gas stream. This can improve engine efficiency and lower emissions of harmful pollutants.

Street lights powered by fuel cells

In order to reduce the dependency on heavy fuel oil and diesel for power generation, a hydrogen generation and storage demonstration plant was installed on the island of Porto Santo.

In a first stage, electricity from a renewable energy source (wind mill farm) is used to generate hydrogen. The H₂ is generated at 30 bar without compressor and stored in a tank. At night, hydrogen is fed to

fuel cells, to generate electricity for street lights on this touristic island. It has been proven, that the generation of hydrogen from renewable sources and applying a PEM electrolyser unit is a viable solution within the overall project goal.

HOGEN[®] hydrogen generators can absorb excess power from the wind turbine in a range from 0 to 100% capacity without any problems.



Fig. 3: General overview of the installation

fuel cells, to generate electricity for street lights on this touristic island.

The installed plant is part of H₂RES (Hydrogen from Renewable Energy Source) model to be put in place for the whole island. The H₂RES concept is designed to balance on an hourly time basis the demands of water, electricity, heat and hydrogen supply from available sources like wind, solar and others.

The operation of the complete system began in No-

References

www.duurzaamameland.nl
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Fig. 4: HOGEN[®] 30 bar hydrogen generator

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Solar Production of Hydrogen

The Solar Technology Laboratory at PSI and the Professorship of Renewable Energy Carriers at ETH Zurich jointly perform research aimed at developing solar thermochemical processes for the production of hydrogen, making use of concentrated solar radiation as the energy source of high-temperature process heat [1,2]. State-of-the-art solar concentrating facilities – solar furnace and high-flux solar simulator – serve as unique experimental platforms for the development of high-temperature thermochemical reactors.



Christian Wieckert

The strategy for developing technically and economically viable solar chemical technologies for producing hydrogen (H₂) and syngas (mainly H₂ and CO) involves research on two paths (Fig. 1); (1) Long-term path via solar water-splitting thermochemical cycles, e.g. the ZnO/Zn cycle; (2) short/medium-term path via solar decarbonization of fossil fuels, e.g. cracking, reforming, and gasification processes. Benchmark is the water electrolysis using solar thermal electric power (central line).



Anton Meier

Example: solar hydrogen via carbothermic production of zinc

The so-called SOLZINC process for the solar carbothermic reduction of ZnO to Zn is shown schematically in Fig. 2. It is a near-term variant of a H₂O-splitting cycle already realized at pilot scale and now ready for further up-scaling to industrial scale and commer-

cial application: ZnO is mixed with a carbon source, e.g. biochar, coal, or other carbonaceous materials. The mixture is heated with concentrated solar energy to 1200 °C, at which the endothermic reaction $ZnO + C \rightarrow Zn + CO$ proceeds at a fast kinetic rate. Only 20% of the carbonaceous reductant consumed in the conventional production of zinc is required for the solar process. The solar-made zinc allows for storage of solar energy. The exothermic hydrolysis reaction, $Zn + H_2O \rightarrow ZnO + H_2$, is decoupled from the availability of solar energy and can then be accomplished on demand at the hydrogen consumer site. Alternatively, zinc may be used in Zn-air fuel cells/batteries for electricity generation. In either case, the chemical product is ZnO, which is recycled to the solar reactor. In the framework of an EU-funded project with partners from France, Israel, and Sweden, the SOLZINC reactor technology was successfully demonstrated in a 300 kW pilot plant at the solar tower facility of the Weizmann Institute of Science (Figs. 3 and 4), yielding 50 kg/h of 95%-purity Zn with a solar-to-fuel energy conversion efficiency (ratio of the reaction enthalpy change to the solar energy input) exceeding 30% [3].

Outlook and concluding remarks

In addition to further pursuing the SOLZINC process, PSI and ETH are jointly investigating the production of Zn without any carbon by direct thermal dissociation of ZnO [4]. Testing of a 100 kW solar pilot plant is planned for 2011. Another major solar chemical demonstration at 500 kW scale is the steam gasifi-



Aldo Steinfeld

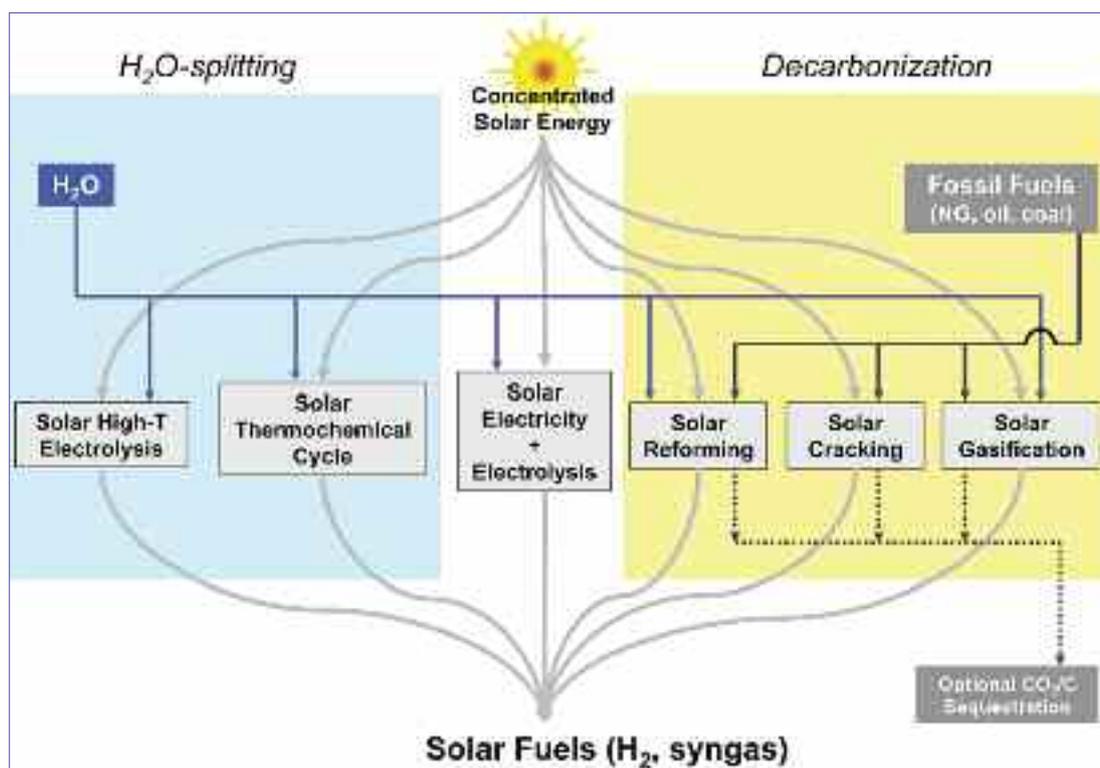


Fig. 1: Thermochemical paths for H₂ production using concentrated solar energy.

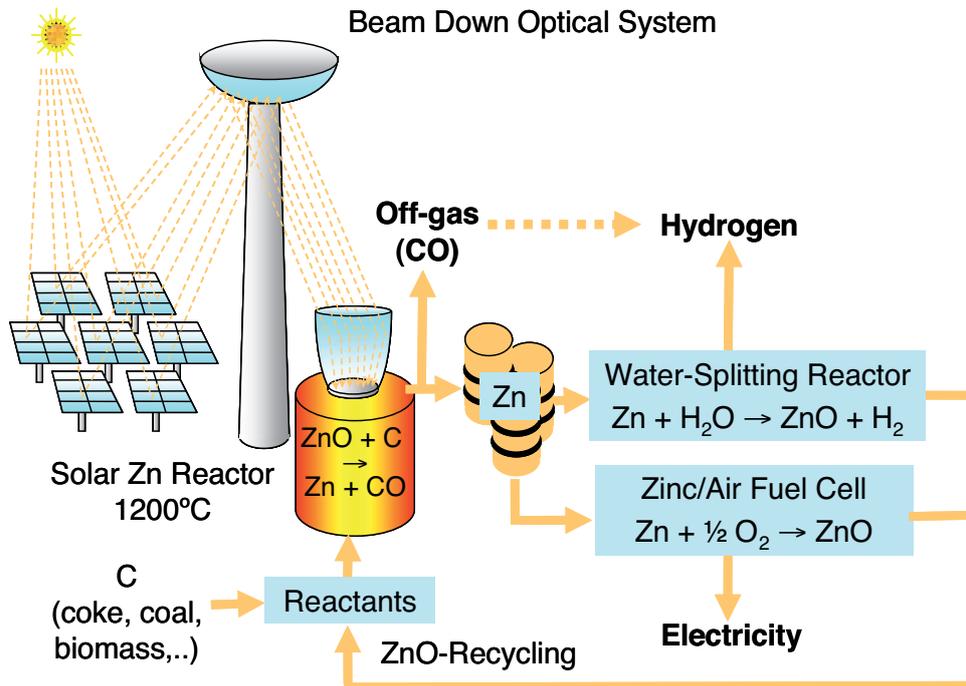


Fig. 2: SOLZINC process for the solar carbothermic reduction of ZnO and the cyclic processes for the on-demand production of solar hydrogen in a hydrolyser or solar electricity in a Zn-air fuel cell/battery.

cation of petroleum coke for the production of syngas (H₂ and CO, which can be further processed to liquid fuels), scheduled for 2010 at the solar tower of the Plataforma Solar de Almería/Spain. The solar chemistry research program at PSI/ETH is

being funded primarily by the Swiss Federal Office of Energy, Swiss National Science Foundation, Swiss Innovation Promotion Agency, European Union, and private industry.



References

- [1] A. Steinfeld, A. Meier, "Solar Fuels and Materials", *Encyclopedia of Energy*, Vol. 5 (2004), pp. 623-637.
- [2] A. Steinfeld, "Solar Thermochemical Production of Hydrogen", *Solar Energy* 78 (2005), pp. 603-615.
- [3] C. Wieckert et al., "A 300 kW Solar Chemical Pilot Plant for the Carbothermic Production of Zinc", *ASME J. Solar Energy Engineering* 129 (2007), pp. 190-196.
- [4] L. Schunk et al., "A Solar Receiver Reactor for the Thermal Dissociation of Zinc Oxide", *ASME J. Solar Energy Engineering* 130 (2008), 021009.
- [5] A. Z'Graggen, A. Steinfeld, "Hydrogen Production by Steam-Gasification of Carbonaceous Materials using Concentrated Solar Energy – V. Reactor modeling, optimization, and scale-up", *Int. J. Hydrogen Energy* 33 (2008), pp. 5484-5492.

Fig. 3: The heliostat field of the solar tower facility at the Weizmann Institute of Science (Israel) delivers concentrated solar radiation that is directed via a "beam-down" reflector to the 300 kW SOLZINC pilot plant installed on the ground.



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Fig. 4: The 300 kW SOLZINC solar reactor (left) is designed for a one batch per day operation. Zinc vapor exits the reactor to the off-gas system (right), where it rapidly condenses to zinc dust.

Hydrogen Production: New Membranes for Alkaline Electrolysis

Development of efficient hydrogen production is a high priority task for the growth of a sustainable-energy society. The classical and environmentally clean production method of hydrogen is the electrolysis of water; however, it requires high energy costs. High pressure alkaline electrolyzers are currently the most efficient and established type. One of the main components of an electrolyser is the membrane between the cathode and the anode, separating hydrogen and oxygen gases; it strongly affects the energy consumption of the electrolyser and the gas purity.

High gas purity (low gas penetration) is achieved by small pore size; the pores must be smaller than the hydrogen and oxygen bubbles. High ionic conductivity in asbestos is mainly achieved through its excellent wettability, the effects related to the fibrous structure and the specific multi-scale porosity. The interplay of surface processes most likely influence the ion conductivity as well.

As one of the suitable materials, a 3-mol%-Y₂O₃-doped tetragonal-ZrO₂ powder was chosen due to its high chemical stability in hot KOH electrolyte. The first diaphragms were tested using an electrolytic cell lab setup with a current density of 200 mA/cm² at ambient conditions and revealed positive results. These data combined with impedance, X-ray photoelectric, Raman spectroscopy, and electron microscopic measurements allow the evaluation of other candidate materials for new membranes and their further development.

Further promising materials and production methods are currently undergoing the patenting procedure.

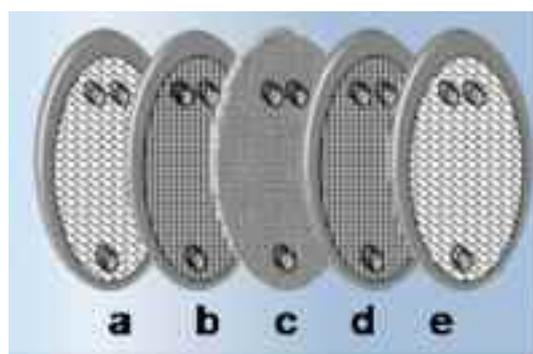


Valentina
Zakaznova-Herzog

The focus of the NMAE2 project is to study and develop new membranes integrated into high pressure alkaline electrolysis cells to improve the electrolyser's efficiency and replace membranes made from asbestos, the use of which is prohibited by recent health regulations. The new material needs to be impermeable to O₂ and H₂, ion-conductive, stable in 25% KOH at 85°C (or higher) and 32 bars, flexible, robust and affordable. Chemical stability, porosity, ion conductivity and surface properties of new and traditionally used materials were systematically investigated.



Fig. 1: High pressure alkaline electrolyser (left) and the schematic view of the electrolysis unit: bipolar electrode (a), pre-electrode (b), diaphragm (c), pre-electrode (d), bipolar electrode (e). All elements include hydrogen and oxygen ducts above and electrolyte duct below.



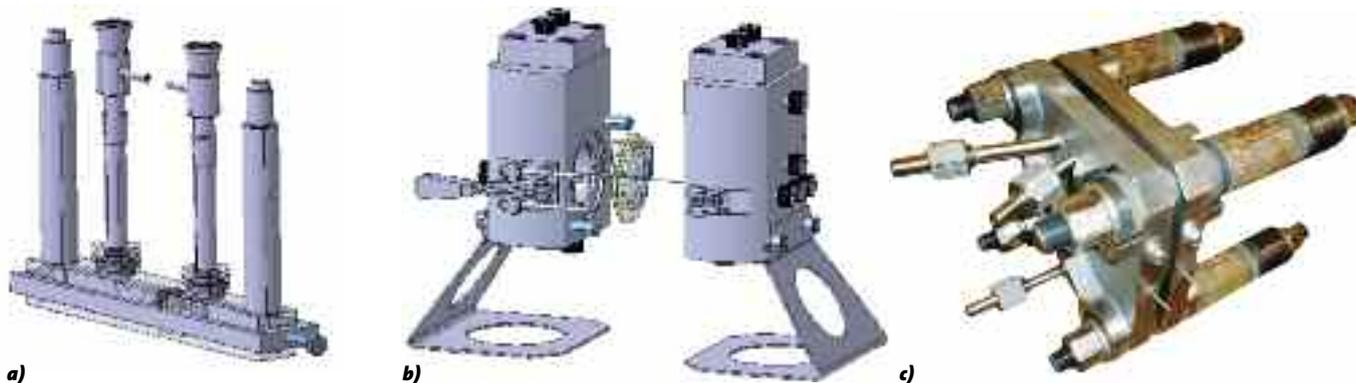


Fig.2: Electrolysis test cells: (a) cell with two reference electrodes; (b) Cell type "Electra", made from hot alkali resistant polymer, integrated in the test bench, provides testing of the membrane resistance, and corresponded oxygen and hydrogen gasses flow and purity; (c) high pressure and high temperature cell-stack, integrated in the test bench, provides testing of the membrane resistance, and corresponded oxygen and hydrogen gasses flow and purity up to 1000°C and 35 bars.

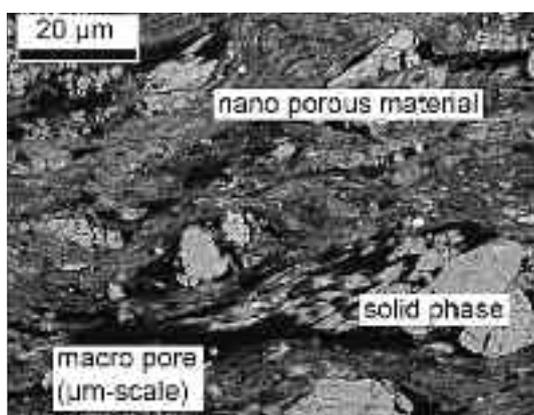
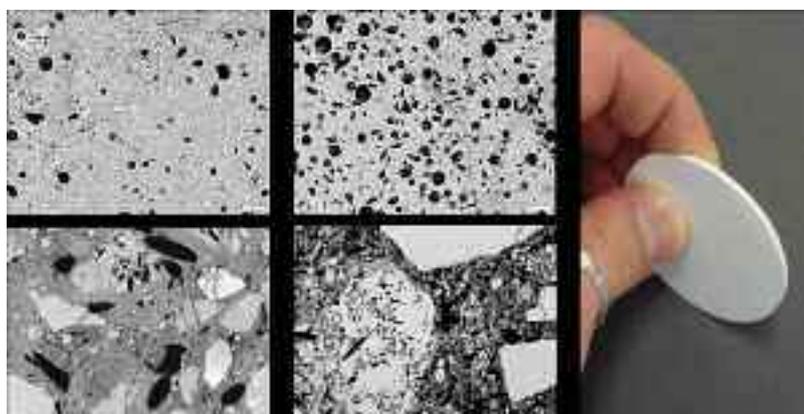


Fig.3: Scanning electron microscopy shows a heterogeneous asbestos diaphragm structure, composed of 3 phases: (1) solid silicate phase, (2) macro pores in μ -scale, and (3) a mixture of asbestos nano fibres and pores in μ -scale (nano porous material). (Wiedenmann et al., 2010)



Zakaznova-Herzog V., Stojadinovic J., Gorbar M., Wiedenmann D., Grobety B., Vogt, U., Züttel A., "Hydrogen production by alkaline electrolysis: is there a way to increase its efficiency by improving a separating membrane?" International Journal of Hydrogen Energy (to be submitted)
Zakaznova-Herzog V. et al., "Hydrogen production by alkaline electrolysis: surface and electrochemical investigations of materials for diaphragms" 4th Int. Symposium Hydrogen & Energy, Switzerland, 2010

Fig.4: ESEM images of zirconium oxide based membranes obtained by addition of graded amount of carbon powder 10, and 30 vol.%, pressed at 20 kN and subsequently sintered at 1200°C / 1 hour (top); of zircon oxide based membrane obtained by addition of graded amount of carbon fibers 10, and 30 vol.%, pressed at 50 kN and subsequently sintered at 1200°C / 1 hour (below). (Gorbar et al., 2010)



Fig.5: Experimental electrolysis test set up operated by M. Gorbar.

References

Gorbar et al., "Porosity graded ZrO_2 diaphragms for alkaline electrolysis" 4th Int. Symposium Hydrogen & Energy, Switzerland, 2010
Wiedenmann D. et al., "Impact of multi-scale pore structure on ion conductivity of asbestos gas separation diaphragms for alkaline water electrolysis". 4th Int. Symposium Hydrogen & Energy, Switzerland, 2010

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PECHouse: Creating hydrogen from sunlight and water

Using abundant and renewable natural resources to produce hydrogen in a carbon-neutral, sustainable manner is a fundamental requirement for a future hydrogen economy. This goal can be accomplished using sunlight to split water into hydrogen and oxygen in a photoelectrochemical (PEC) device. For the past two years, PECHouse, a photoelectrochemical center of excellence funded largely by the Swiss Federal Office of Energy and led by Prof. Michael Grätzel at the Ecole Polytechnique Fédérale de Lausanne (EPFL) has been leading efforts for PEC hydrogen production in Switzerland. The approach of PECHouse is to use semiconducting materials made from abundant and inexpensive elements which absorb solar light and catalyze water decomposition. Decades of previous studies have shown that it is unlikely that research will identify one material which satisfies all of the necessary requirements of stability and light absorption. Accordingly PECHouse is pursuing methods of using combinations of materials to split water into hydrogen and oxygen using sunlight in a cost effective manner. The prototypical example of this is a tandem cell approach (Figure 1) where a semitransparent photoanode made of iron oxide (hematite, an inexpensive, stable and non-toxic semiconducting mineral) absorbs light and catalyzes the oxygen evolution while the light not absorbed by the iron oxide is transmitted and absorbed

by another photoelectrochemical system, for example a dye-sensitized solar cell, which provides additional energy for the hydrogen evolution. In 2006 the laboratories of Prof. Grätzel reported benchmark performance with iron oxide by properly nano-structuring and doping the material using an inexpensive deposition method: particle assisted metal-organic chemical vapor deposition at atmospheric pressure (APCVD). [1] This breakthrough demonstrated the ability of iron oxide to convert up to 3.3 % of the sun's energy into hydrogen. Since this account, PECHouse has increased performance and the knowledge of the iron oxide APCVD system. A recent report in the *Journal of Physical Chemistry* details the advantages and limitations of the APCVD iron oxide and identifies the pathways for further improvement (see Figure 2). [2] PECHouse has ambitious goals for improving these iron oxide photoanodes, with objective performances of 7.5 % solar-to-hydrogen conversion by the end of 2011. To help accomplish this, PECHouse has gathered a team of European experts in a collaborative consortium called NanoPEC. With a budget of over 3.6 M€ over three years, NanoPEC consists of 8 academic or industrial research groups which focus on different aspects of applying nanotechnology to materials for photoelectrochemical hydrogen production. An important demonstration of one of the concepts pursued by NanoPEC, the host ab-



Michael Grätzel

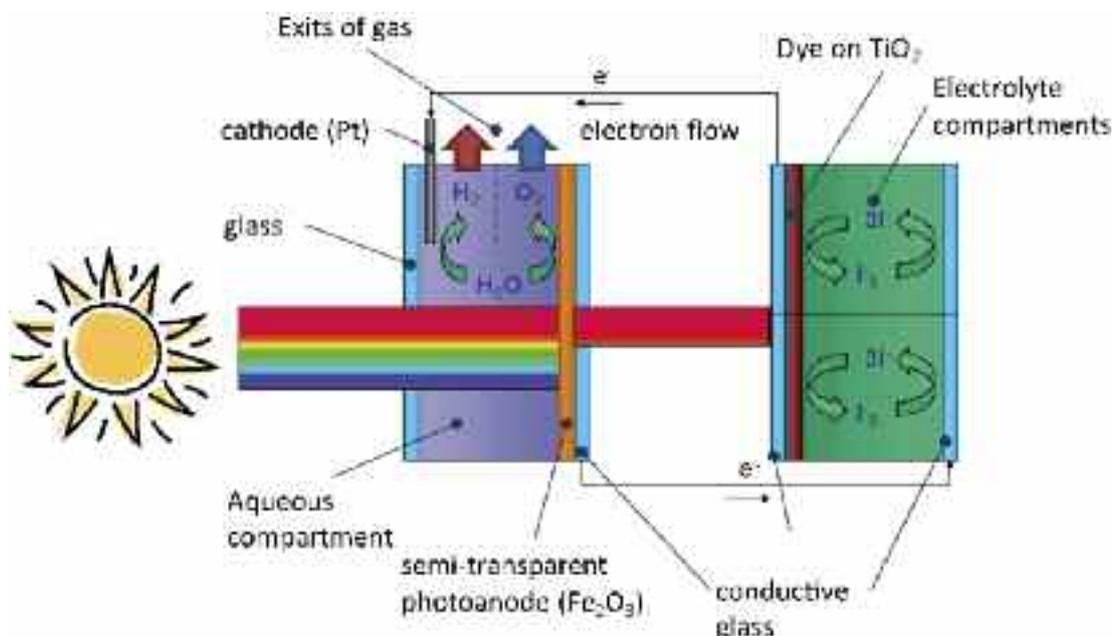


Fig. 1: Tandem cell approach for solar photoelectrochemical hydrogen production.

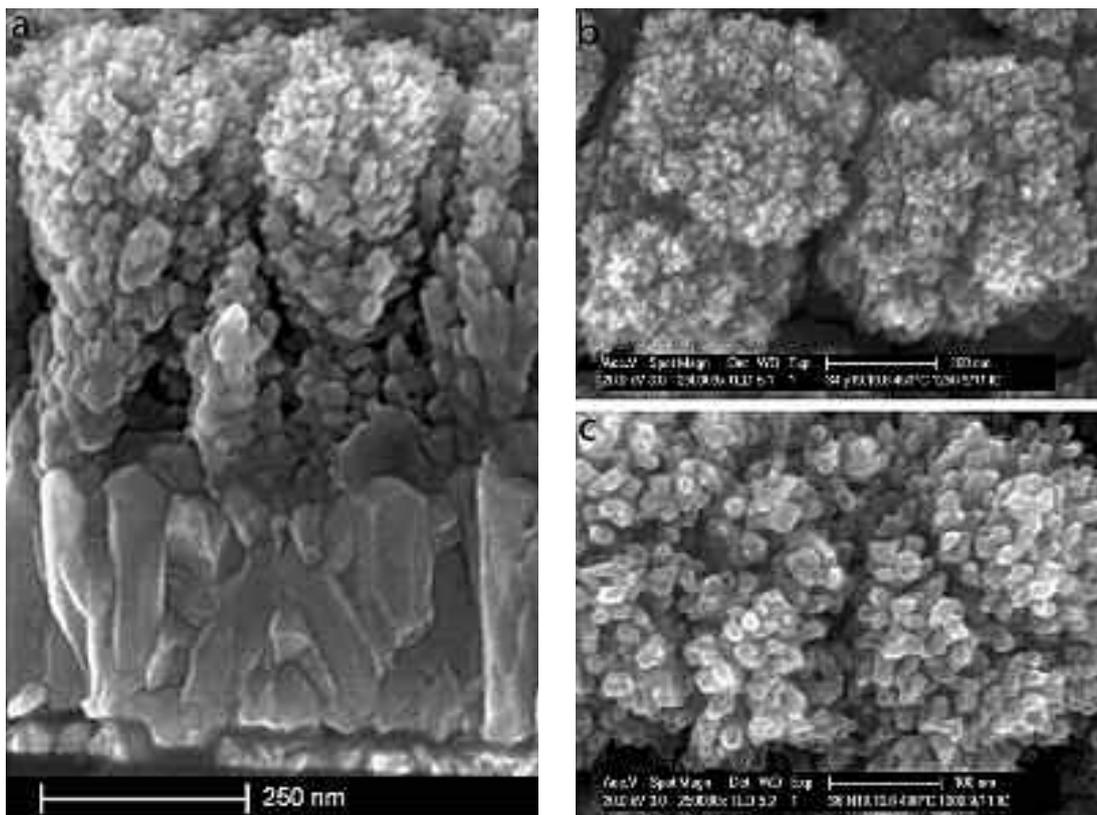


Fig. 2: Scanning electron micrograph of the nanostructured iron oxide used for watersplitting. The effect of the synthesis temperature on the feature size here is apparent. a) Cross-section at 470 °C b) 450 °C and c) 490 °C top down.

sorber/guest scaffold approach, was recently published by PECHouse members in the journal *Chemistry of Materials*. [3] Here, overcoming the poor semiconducting properties and light absorption of iron oxide is accomplished by depositing an ultra thin absorber layer on a rough scaffold material. In order to maximize the light absorption by the thin layer of absorber the scaffold must be highly nanostructured. By using a tungsten oxide scaffold coated with nanoparticles of iron oxide PECHouse was able to show a 20% increase in single light wavelength efficiency with green light (565 nm). In addition to the research on new nanostructures, NanoPEC and PECHouse are researching new inexpensive materials and catalysts that will further enhance the water splitting reaction for the goal of producing a device that can produce hydrogen from sunlight at a cost of less than 4€/kg by 2012.

References

- [1] Kay, A., Cesar, I., Gratzel, M.: New benchmark for water photooxidation by nanostructured alpha-Fe₂O₃ films. *J. Am. Chem. Soc.* 128, 15714 (2006).
- [2] Cesar, I., Sivula, K., Kay, A., Zboril, R., Graetzel, M.: Influence of Feature Size, Film Thickness, and Silicon Doping on the Performance of Nanostructured Hematite Photoanodes for Solar Water Splitting. *Journal of Physical Chemistry C* 113, 772 (2009).
- [3] Sivula, K., Le Formal, F., Gratzel, M.: WO₃-Fe₂O₃ Photoanodes for Water Splitting: A Host Scaffold, Guest Absorber Approach. *Chem. Mater.* 21, 2862 (2009).

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We all know that hydrogen is something special. Being the most abundant of all elements which exist in the universe does not automatically mean that the lightest gas is an easy task to handle. Until today, handling and storage of hydrogen requires special technologies. Thus, to find the best solution is a continuous task that is challenging research and development.

With the NOVA SWISS® trademark, Nova Werke AG develops and produces high-quality, standardized as well as customized high pressure components and systems for hydrogen in pressure ranges from 500 – 4000 bar as well as other fluid and gases in pressure ranges from 500 – 10000 bar.

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Another field of substantial research and development has been the diaphragm compressors for hydrogen. NOVA SWISS® diaphragm compressors for hydrogen are working for pressure ranges of up to 1000 bar as well as 3000 bar. They are electrically powered. The inlet pressure should be minimum 20 bar. Depending on this inlet pressure, the capacity and discharge pressure can be calculated accordingly. NOVA SWISS® diaphragm compressors also have capacities of up to 4 Nm³/hour, which is the right size for R&D centres, universities as well as laboratories.



Matthias Duvénbeck

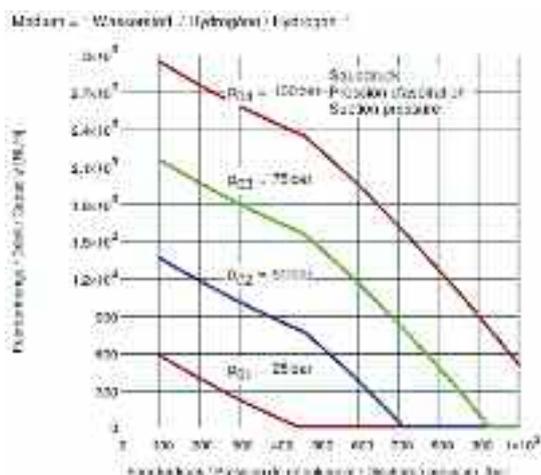
Fig. 1: Installation of 1000 bar pneumatically driven valves in hydrogen stations



Fig. 2: Hydrogen station



Fig. 3: Pneumatic driven valves



The advantage of the compact NOVA SWISS® diaphragm compressor is the cleanliness of the compressed hydrogen. There is no contact between gas and oil. In the gas chamber there are no non-metallic-elements, which means that operating with ultra-pure hydrogen is possible. Dynamic sealing problems are not possible because the piston is driven by cross head without additional gasket.

Nova Werke AG is operating from its modern state-of-the-art facilities with latest in-house material labs in Effretikon near Zürich. Well-known companies active in the hydrogen industry, e.g. R&D Centres, universities, producers of hydrogen and other industries have trusted Nova Werke for many years and rely on a careful selection of materials and precise manufacturing.

NOVA SWISS® achievements of today do not mean that the end of development is reached. As a matter of fact, the next generation of NOVA SWISS® products for the hydrogen future is already in the pipeline.



Fig. 4: A compact diaphragm compressor, max. 3000 bar

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Metal Hydride Storage for Seasonal Off-Grid Energy Storage of Renewable Energy Applications

Off-grid applications are far more complex than traditional grid-connected energy systems. They require large energy storage capacity while at the same time having highly fluctuating energy input. While batteries can in principle offer the service needed, storing large amounts of energy results in high volume, weight and capital cost. While for short time intervals these parameters are less critical, on a seasonal level they are crucial. Hydrogen is capable of performing this task. Considering the cost per energy, weight and volume stored, the technology is clearly beneficial and self discharge is not an issue.

The result is an exothermic (charging) or endothermic (discharging) reaction. Thermal flow and charge/discharge rate are inherently coupled in metal hydrides; to make it fast, one must optimize thermal flow. While in fast applications this requires a great deal of engineering and a liquid heat exchange medium, for seasonal storage (where the rate is low compared to total capacity) this parameter is met by the ambient air which removes or supplies heat at the necessary rates.

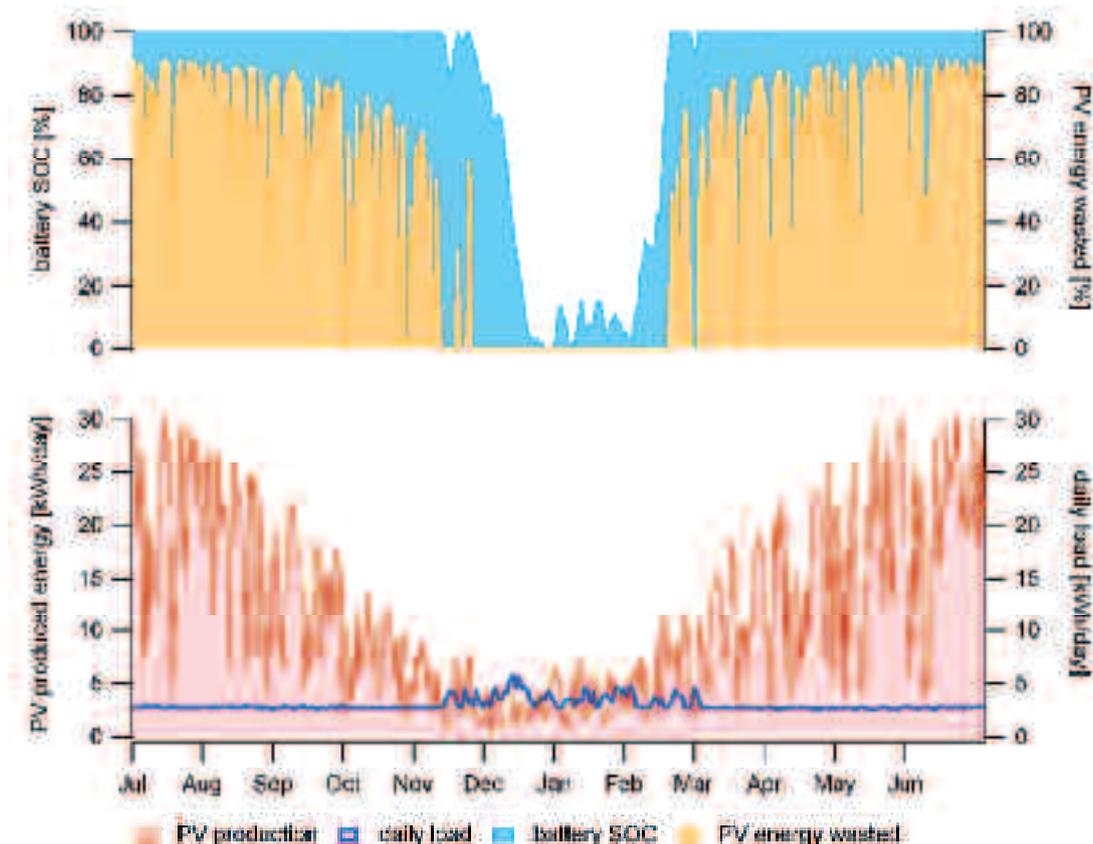
The hydrogen pressure in the hydride depends on the material used, temperature and charging state of the reservoir and is described by the pressure-concentration-isotherm which is unique to each material. Applying a higher pressure than the plateau pressure leads to charging while lowering the pressure below the plateau will lead to discharging of the container. The specifications of the individual application (minimum charging pressure, minimum discharging pressure, T_{max} , T_{min}) define the potential choice of alloy materials. Empa has developed storage units based on a multitude of alloys for a variety application fields and sizes. Currently, units are in operation for boat propulsion and units are built for seasonal energy storage: two distinctly different fields with unique requirements. Some of the units have been tested for over 1000 cycles without any loss of capacity.

For seasonal applications, pressurized storage is often ruled out by space constraints (without compression) or prohibitive cost (with compression). Metal hydrides store hydrogen in solids. A metal hydride acts, bluntly speaking, as a "hydrogen sponge"; but, in contrast to water, hydrogen is a gas and is therefore compressible. The gas is absorbed and densely packed within the material by the affinity of the alloy towards hydrogen: almost like an "internal compression". As a result, hydrogen is absorbed and stored at low pressure and at high volumetric storage density while capacity simply depends on the amount of material used. As a consequence of the condensation of hydrogen within the material, the gas undergoes a transition from a disordered to an ordered state (entropy change).



Michael Bielmann

Fig. 1: model off-grid system without hydrogen (3.6 kWp PV and 50 kWh battery) in Zurich. The load varies between 2 kWh and 6 kWh per day (excl. cooking). Almost 55% of the energy remains unused. This energy is available to produce hydrogen for later use.



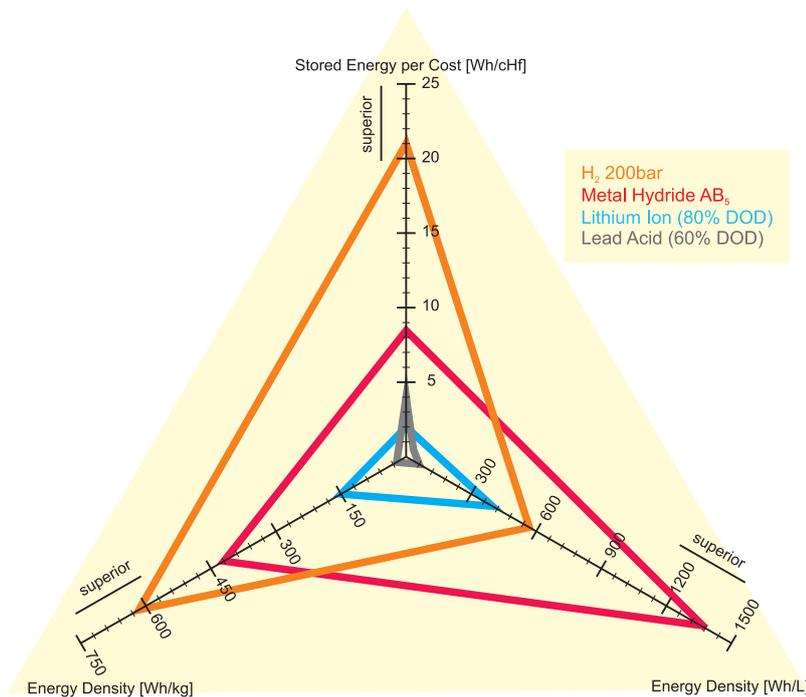


Fig. 2: Essential storage parameters: energy density per volume, energy density per mass and amount of energy stored per unit cost for batteries and hydrogen storage media. Basis: 150 Wh/kg, 400 Wh/L, 500 CHF/kWh (Lithium Ion) and 25 Wh/kg, 60 Wh/L, 150 CHF/kWh (Lead Acid). The cost for hydrogen storage reflects prototype units built at Empa and therefore offers high cost reduction potential.

Metal hydrides offer unique opportunities for storing large amounts of energy in a small package. Although their characteristics require proper engineering for the specific application, this knowledge is available. They outclass batteries in storage weight, volume and cost, by a large margin. While production of hydrogen and its reconversion to electricity or heat have an efficiency penalty and are still costly, there is a large unrealized cost-reduction potential in the technology. In most off-grid systems, the supply side must be oversized to meet production capacity needs in winter or bad weather phases. Assuming a constant load year round, almost 80% of the produced energy is wasted due to storage constraints. Producing hydrogen with the associated efficiency criteria is therefore far less critical. For long time scales, batteries are just not capable of delivering the service required: the choice is "use it or waste it".



Fig. 3: metal hydride storage unit for seasonal energy storage

p_{min} (T=40°C) (charge)	10bar
p_{min} (T=0°C) (discharge)	1.5bar
Stored amount of hydrogen	>2.7kg
Energy equivalent	106kWh
System volume	240L
Number of modules	6
Container material	Al 7000-alloy
Total System weight	300kg

Table 1: Specifications of the metal hydride storage unit for seasonal energy storage

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In the field of energy the main subjects are thermal energy systems, process optimisation, energy storages including supercapacitors and system integration.



Ulrike Trachte

Hydrogen & Fuel Cell activities

In the field of hydrogen and fuel cells (FC) the Lucerne School of Engineering and Architecture is specialised in system integration and testing of FC's in concrete applications. One project is the 'PEM Fuel-Cell Back-Up System', which is realised with two industrial partners and financial support of the Swiss federal office of energy (SFOE).

In this project, the lead-acid batteries of an uninterruptible power supply system (UPS) were replaced by a 10 kW PEM FC System. The delayed start-up behaviour of the FC is bridged with supercapacitor technology. The system is connected to an existing working base station of a telecommunication installation since January 2006.

Hydrogen is supplied by two 50 l pressure tanks which provide a stand-alone operation for about 6 hours under antenna load.

The field test is performed under real conditions with monthly grid failure simulations. Excellent results of the approximately 350 start-up's to date confirm the functionality, reliability and performance of the system.

Achievements of the FC UPS

During the project period over more than three years the market changed. An increasing number of FC

producers and UPS suppliers became aware that the application of FC's as a back-up system respond to critical market demands. They developed ready-to-market products which are suited to achieve early commercialisation success. Hence for the FC UPS application it is no longer the question of functionality but of a successful market entry.

This early market is now supported by the FC and Hydrogen Joint Undertaking (FCH JU) Program. In this program a call has been announced to demonstrate the application readiness of these back-up systems and to contribute to a widespread acceptance of this new technology.

The Lucerne School of Engineering and Architecture will continue its involvement in this segment. It will strengthen the activities in concrete FC applications, testing and demonstration of FC deployment.



Fig. 2: Hydrogen storage for telecommunications



FC System integration & Field test

Integration of Supercapacitors

Fig. 1: Energy related research subjects

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As an energy source, hydrogen can make a significant contribution towards the achievement of the ambitious objectives of European and Swiss policies for the coming decades relating to energy supply security, reduction of CO₂ emissions and industrial innovation. Within the Swiss long-term energy perspectives hydrogen continues to own a major potential as energy carrier that is absolutely needed when facing storage problems in a future energy supply based on renewable energy sources.

In Switzerland, hydrogen has been the subject of energy research for several decades. Swiss Institutions are among the world leaders in terms of expertise in research and development, both at the Federal Institutes of Technology, universities and colleges of technology, as well as in small and medium-sized companies. The research currently being carried out is to a large extent integrated into international projects. The national hydrogen research programme, which is part of Switzerland's energy research concept, is co-ordinated by the Swiss Federal Office of Energy (SFOE). In close collaboration with various federal, cantonal and municipal authorities, the programme supports research and development in the area of hydrogen, as well as efforts to bring products using hydrogen technology onto the market. The overall funding by public institutions in this field sums up to \$5 millions (2009), from which the SFOE controls roughly one quarter directly.

The general objectives of the programme are redefined every four years in the federal government energy research concept. Fostering projects in the field of hydrogen production by renewable energies and hydrogen storage in solid state systems form the long term strategy of the program. Photoelectrochemical (PEC) water splitting, a technology that was pioneered in Switzerland, is one of the main areas of focus in the area of hydrogen production. The national research activities in this field are concentrated within a competence center PEChouse at the Swiss Federal Institute of Technology in Lausanne. The overall objective is to design and develop novel semiconductor-based materials for efficiently converting solar energy into hydrogen. The area of hydrogen storage forms a second main topic in the R&D program primarily focussing on metal and complex hydrides as storage materials. Activities in this field are highly concentrated at the Swiss Federal Laboratories for Materials Science and Technology Empa.

Only a few new pilot and demonstrations projects could be realized in the past. In a recent pioneering project an air cooled PEM-fuel cell system, that has been developed at the Swiss company CEKA in col-

laboration with the University of Applied Science in Bienne and the Paul Scherrer Institute, has been integrated into a minibar which is operated on the Swiss railways. No other technical solution was available to solve the power problems encountered in this application. The Sfoe is convinced that hydrogen will start to play a more and more important role and enter our energy system via niche markets where no technological alternatives are available.



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Stefan Oberholzer

More information

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WEKA components for Hydrogen as practical energy carrier in the future

Synthetic Sapphire

Hrand Djevahirdjian was fascinated by the publication in 1902 of Prof. Auguste Verneuil's work on the creation of synthetic ruby. Verneuil had just invented a blowpipe using coal gas and oxygen, thereby opening up the way to industrial production. Hrand Djevahirdjian improved the process by replacing the coal gas with hydrogen. A combination of science and empiricism, it is still being used in the plant at Monthey. The synthesis of stones involves fusing alumina – with or without the addition of metallic oxides – using an oxyhydrogen blowpipe and producing crystal drop by drop, much like a stalagmite, at a temperature greater than 2000°C.



Katia Djevahirdjian

When Hrand Djevahirdjian moved to Monthey in 1914, he was determined to plan for the long term. There are currently 10'000 m² of buildings, housing ten departments: the production of refractory clay muffles, water electrolysis, the purification of ammonia alum, the calcination of the alum, the production of synthetic stones, quality control, and heat treatment, an applied research laboratory and the company's technical & administrative services. Djeva has been a limited company since 1924 and currently employs over 70 people. As well as manufacturing synthetic stones for both the jewellery and industrial sectors, Djeva offers a range of crystals to meet a wide variety of needs.

The real art of synthesis behind this deceptively straightforward operation resides in the accuracy of the various settings while the crystal is growing, a process that can last for several hours or even days. Fusion has to be conducted continuously in the

same area of the downwardly-applied flame so that the crystal can be built up by the superimposition of very fine layers of molten material. This means that the pedestal has to be lowered progressively and the blowpipe fed accurately and regularly.

Alumina or aluminium oxide, the raw material for corundum, is extracted from bauxite. Most of this comes from Australia and is converted into ammonia alum in Germany and France. Partially refined, it is then delivered to Djeva. Before the crystal makes its almost magical appearance, several preliminary operations have to be completed in various sections of the plant :

- the purification of ammonia alum through recrystallisation after hot-water dissolution, then filtration. This process eliminates impurities which are likely to affect the quality of the stones.
- the calcination of alum in the furnaces at temperatures over 1100°C. Purified alum, sometimes mixed with colouring agents, is distributed into quartz crucibles to undergo thermal decomposition. This operation is performed day and night. The alum is transformed into a sort of fragile meringue, which is then sieved to obtain a fine alumina powder of microscopic crystals.
- the manufacture of refractory clay muffles through pressing. Varying in diameter, these protect the crystal during its growth and its cooling.
- the production of hydrogen and oxygen through electrolysis. These gases feed the blowpipes.

Within the production area, more than 2000 blowpipes are arranged in several units. The flames are fed with a meticulously controlled supply of hydrogen and oxygen, whilst hammers, like little tap-dancers, strike the powder drums to ensure a

Fig. 1: Schematic diagram of the synthesis of sapphire with the process developed by Hrand Djevahirdjian

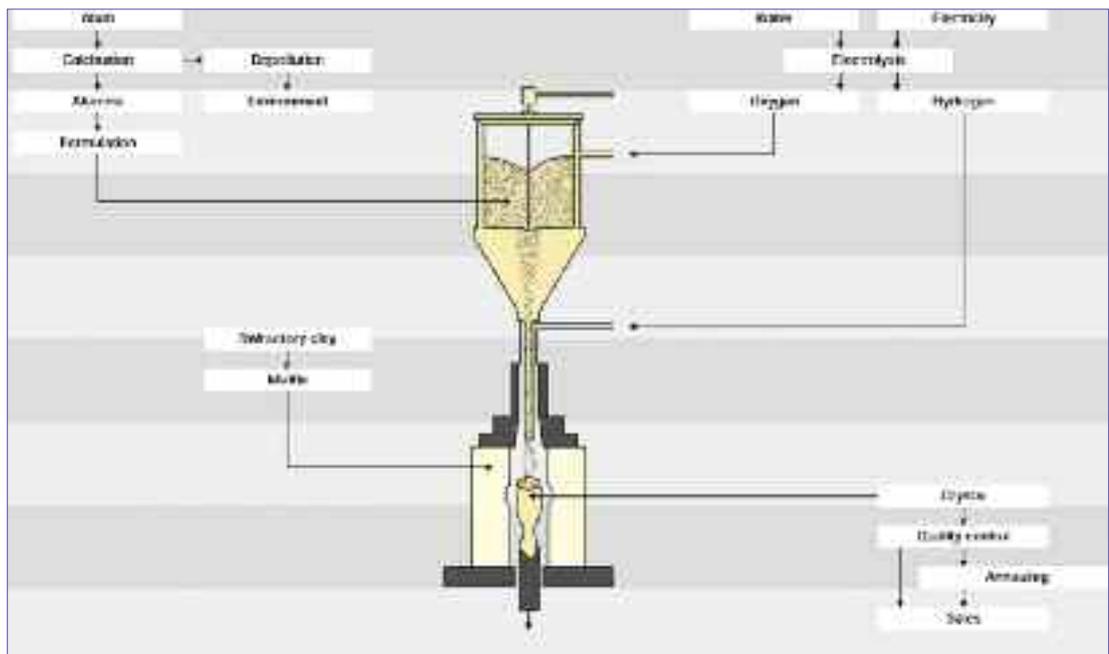




Fig. 2: A 8 MW alkaline Electrolyzer

smooth flow of small quantities of alumina powder. This melts and progressively builds up on to the seed crystal, giving the stone its crystalline direction. All that remains is to monitor the growth of the stone through an opening in the fire-proof oven and to carefully regulate the operation, which ends when the flames are extinguished.

Hydrogen and oxygen, which feed the insatiable flames of the blowpipes, are for the most part produced by water electrolysis within the company itself. But Djeva maintains close links with outside suppliers to supplement its stock. On days of peak production, daily consumption of these gases amounts to as much as 40000 m³. This varies, of course, between day and night, and sometimes from one hour to the next. Enjoying the benefits of modern technology, the plant is presently equipped with enormous pressurised buffer tanks for storing the equivalent of approximately 20000 m³ of hydrogen and oxygen. These reserves provide the necessary flexibility for production and consumption. Djeva consumes around 40 GWh of electricity a year, comparable to the needs of a village of 7500 inhabitants! This energy is mainly produced by hydroelectric plants and supplied by a nearby company.



Fig. 3: Hydrogen and oxygen storage tanks



Fig. 4: Series of hydrogen/oxygen furnace

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Ulrich Vogt

“Self” is focused on advanced building technologies (Fig. 1, 2) in combination with photovoltaics (PV), hydrogen production by water electrolysis and storage of the hydrogen via metal hydride technology. While electrical energy is provided by PV and batteries and used for the electrical systems like illumination, controlling or computer, the focus of hydrogen is to provide energy for cooking and heating purposes. This is advantageous compared to electrical cooking and heating systems since storage through batteries on the timescale of months is not possible due to low storage density, high storage volume, safety aspects and weight constrains.

Since the PV system and batteries are dimensioned for stand-alone and year round operation, excess electricity is available during summertime due to seasonal input fluctuations. This excess energy is used for producing hydrogen by water electrolysis with a PEM electrolyser, stored in hydride tanks (Fig. 3) and used for cooking and heating in wintertime. Hence, the focus is to develop a novel type of catalytic H₂ burner. Due to the catalytically active Pt coating of the porous SiC ceramics, no ignition is needed (Fig. 4). If hydrogen is present, heat is produced instantaneously and thus, no accumulation without conversion can occur. Since the combustion of hydrogen does not release harmful exhaust gases like CO₂ or



Fig. 2: Transport of SELF by truck or helicopter to arbitrary places

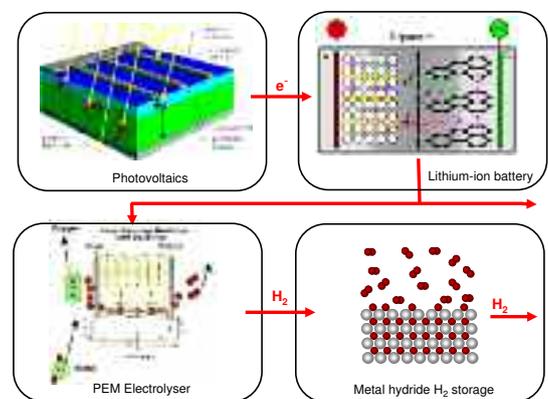


Fig. 3: Energy concept: Photovoltaic supply by PV, electricity storage in batteries, Hydrogen production by water electrolysis and storage in metal hydride tanks

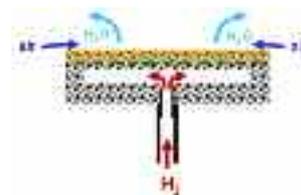


Fig. 4: Principle of the catalytic H₂ burner: $2H_2 + O_2 \rightarrow H_2O$
 The self igniting property and the fact that hydrogen and air are strictly separated, except in the catalytically active region, assures a very high passive safety aspect.



Fig. 1: the Self Sufficient Accommodation Unit can be transported to nearly any place in Europe for independent living, working or research.

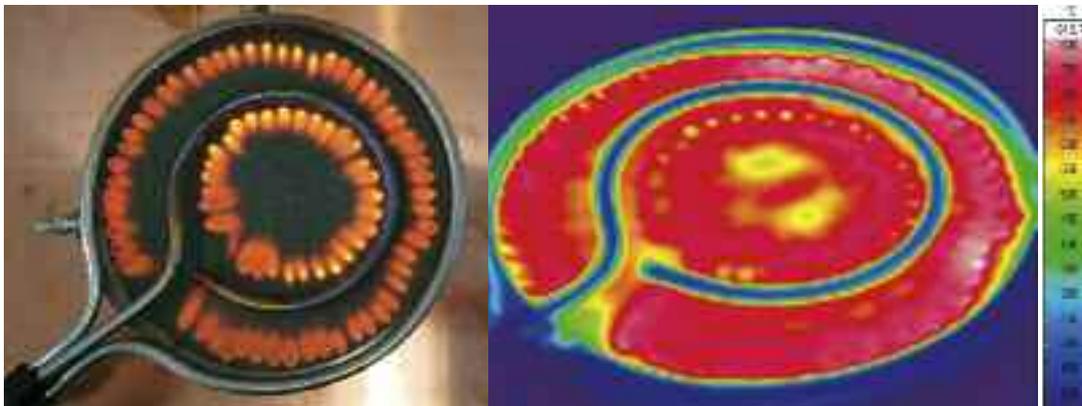


Fig. 5: (left) Hydrogen burner with air supply system. (right) Infrared image of the hydrogen burner at 800°C

NO_x, catalytic hydrogen burners can be used indoors safely and without risk (Fig. 5). The reaction product is only water, which is actually beneficial for the room climate. With this project, fundamental technical experience will be attained concerning stand-alone power systems (SAPs), the use of hydrogen as future energy carrier, the durability of PEM electrolyzers, hydride storage systems, as well as the use of hydrogen for cooking and heating purposes.

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Hydrogen sponges at home, at work, at play

Solid-state metal hydrides (“hydrogen sponges”) represent the safest and most volume efficient way of storing hydrogen. They have been studied at Geneva University for over 30 years with respect to fundamental aspects such as synthesis and properties of new materials, and practical aspects such as integration into practical devices like hydrogen storage vessels for hydrogen engines, fuel cell systems and home applications.

Notable achievements during the past years include the discovery of a wide variety of so-called “complex” transition metal hydrides of which many are capable of storing hydrogen in concentrations exceeding that of liquid hydrogen. In a quest to put these sponges to practical use the following hydrogen powered devices have been designed for home, for work, and for play.



Klaus Yvon

Hydrogen-powered lawn mower

Geneva has developed the world wide first hydrogen powered lawn mower containing hydrogen sponges as a storage medium. It was adapted from a commercial model running on gasoline and is one of the rare hydrogen powered devices still operational after 17 years of successful and uninterrupted use [1].



Fig. 1: Hydrogen powered lawn mower after 16 years of operation. Hydrogen sponges are situated in the cylindrical container.

Hydrogen-powered barbecue



Fig.2: Concentric hydrogen barbecue in use (top) and open hydrogen burners (bottom).

A commercial barbecue has been adapted by replacing the propane burner by a series of hydrogen burners connected to hydrogen sponges. A panel of evaluators confirmed that the taste of hydrogen roasted meat was undistinguishable from that of propane roasted meat.

References

- [1] K. Yvon and J.-L. Lorenzoni, "Hydrogen Powered Lawn Mower: 14 Years of Operation". *Int. J. Hydrogen Energy*, 31, 1763-1767 (2006).
- [2] P. Hollmuller, J.-M. Joubert, B. Lachal and K. Yvon. "Evaluation of a 5 kWp Photovoltaic Hydrogen Production and Storage Installation for a Residential Home in Switzerland" *Int. J. Hydrogen Energy*, 25, 97-109 (2000).

Pop music by hydrogen

Powering a music scene represents a challenge for fuel cell systems because of the rapidly varying time structure in energy demand of the various components (amplifier, light sources etc). In order to study the response to such solicitations the worldwide first TÜF certified fuel cell system (2 kWe) was successfully tested under real conditions during the festivities of the 450th anniversary of Geneva University (Nuit de l'Université, 13 June 2009).



Fig.3: Hydrogen powered fuel cell (top) powering music scene with singer Aliose (bottom) during the festivities of the 450th Anniversary of Geneva University in 2009.



Solar hydrogen house

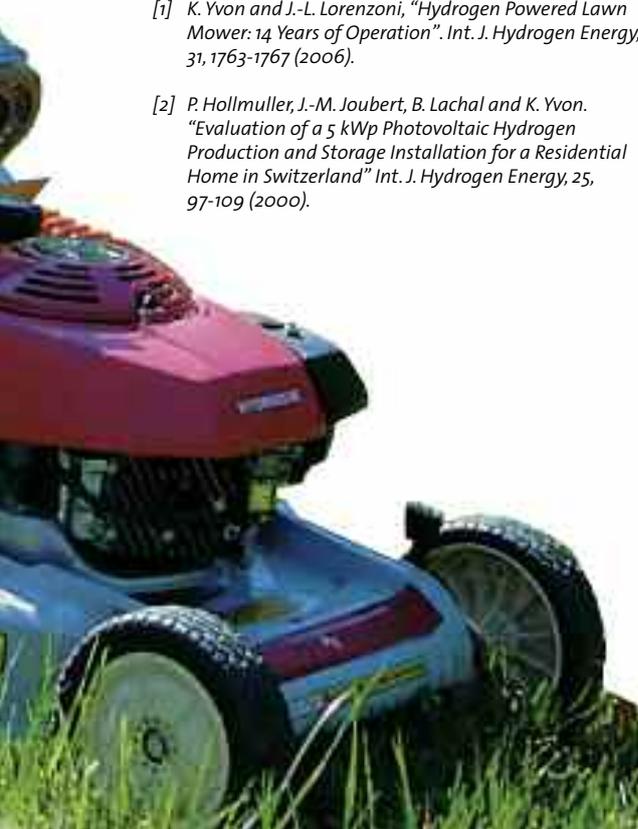
Having evaluated a photovoltaic hydrogen production and storage installation in a residential home in Switzerland some 9 years ago², scientists at Geneva University currently are assembling an updated installation for solar hydrogen production, storage and utilization (stove, lawn mower, fuel cell electricity generation), by using the latest technologies available, including the use of hydrogen sponges. Altogether, these applications aim at paving the road towards the introduction of hydrogen as a renewable energy vector in every day's life.

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Hydrogen for Efficiency in Conversion

Since the publication of the 2008-2009 hydrogen-report, significant advances have been achieved on all of the reported scales. Starting from an early demonstration of a 1 kW stand-alone system, compact and efficient fuel cell supplies for portable applications are advanced on the scales of 1000 W, 100 W, and 1–10 W. On the other hand, fuel-cell / storage hybrid systems are developed for transport applications. Functional vehicles such as municipal vehicles, standard sized cars, and light-weight family vehicles are equipped with efficient powertrains, with the aim of launching a true innovation in the market.



Philipp Dietrich

The efficient conversion of hydrogen in low-temperature polymer electrolyte fuel cells at Paul Scherrer Institut PSI dates back to 1990, when a research group was formed working on fundamentals of electrochemistry, electrocatalysis, solid polymer electrolytes, and the design of fuel cell stacks and systems. Together with long-term research in electrochemical energy storage in batteries and capacitors, this know-how formed the basis for the achievements mentioned below.

PowerPac – building block towards market introduction

Besides proven reliability and durability for the service life of the device, cost reduction of stack and system remains the main challenge for the market introduction of the fuel cell. Realizing two major opportunities for cost reduction, i.e. the manufacturing of multifunctional bipolar plates and the potential for automation of the assembly, PSI and ETH Zurich joined forces in the realization of a 1 kW

portable fuel cell generator, the PowerPac. This device was further developed at the UAS in Biel (<http://labs.hti.bfh.ch>), and found its way into fuel cell boats and a three-wheel vehicle. The company CEKA worked on developing the PowerPac into a commercial product series (<http://www.ceka.ch/Stacks.43.o.html>). The stack also was at the heart of the PacCar vehicle.

PaC-Car – challenging the limits in fuel economy

The team around Lino Guzzella at ETH Zurich attacked the challenge to break the world record in fuel economy. With a powertrain based on a PowerPac fuel cell, they designed an ultra-light weight eco-vehicle for one person. Due to advanced aerodynamic design, low rolling resistance, very low overall weight, and sophisticated controls of the fuel cell system, PaC-Car II won the prestigious trophy of the 2006 Shell EcoMarathon, demonstrating a traveled distance of more than 5000 km with the hydrogen equivalent (in energy) of one liter of gasoline. (<http://www.paccar.ethz.ch/>)

HYPOWER – technology platform for a family-sized fuel cell car

PSI has pursued a different strategy, i.e. drastically increasing the fuel efficiency of family-sized cars by the implementation of fuel cell power trains. The first demonstration of a Swiss fuel cell car, the HY.POWER, was realized together with ETH Zurich and industrial partners. This was the first fuel cell vehicle ever to master a mountain pass, by traversing the Simplon in winter of 2002. Based on a VW Bora chassis, this technology platform demonstrated that 40% reduction of fuel consumption was possible, in spite of the weight added by the fuel cell system (<http://ecl.web.psi.ch>).

Hy-Light – exploring novel design options for a fuel cell vehicle

The next development stage took full advantage of the design freedom offered by the fuel cell power train. In collaboration with CDM Michelin (Givisiez FR), a lightweight hybrid vehicle of 850 kg termed Hy-Light was developed that offered space for four passengers. Its fuel cell system, fed by structure-integrated hydrogen tank and an oxygen tank under the rear seats, combined with supercapacitors for energy recovery and peak power, excelled in 2004 by a tank-to-wheel efficiency of 60% over the driving cycle, which resulted in a consumption equivalent to 2.2 liters of diesel per 100 km. With two wheel-integrated electric motors, the car also demonstrated excellent acceleration characteristics and driving comfort by level control (Fig. 2). This concept has been further developed by the industrial partner.

Fig. 1: Test with the Hy.muve test-vehicle



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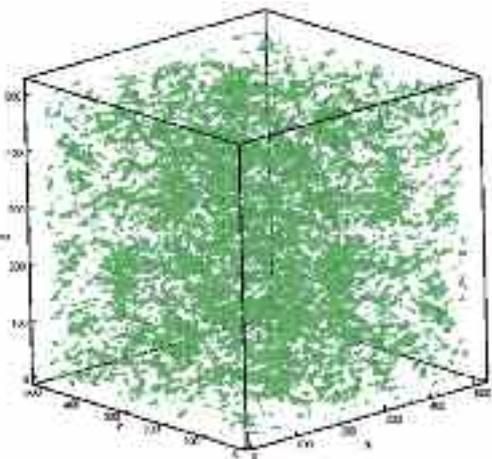


Towards portable devices

Realizing the need for efficient power supplies at the scale of 100 W, teams of ETH Zurich and the Paul Scherrer Institute have recently joined forces within the CEMTEC project, which aims at the demonstration of a highly compact and efficient converter. The fuel, butane, is converted to a hydrogen-rich feed in a partial oxidation reformer (Fig. 3). Electricity is produced in a miniaturized Solid Oxide Fuel Cell that is equipped with new types of electrodes, electrolytes, and an advanced cooling concept. This project is carried out in the framework of the Competence Center Energy and Mobility, CCEM. www.ccem.ch

ONEBAT – fuel cell for the laptop

Going one step further in miniaturization, the ONEBAT project team around Ludwig Gauckler of ETH Zurich aims at demonstrating a fuel cell system



with the size of a match box that will deliver several Watts of electric power, and will hence be suitable to power portable devices such as laptops <http://www.nonmet.mat.ethz.ch>. With a view to ubiquitous availability, liquid propane, the fuel used in today's fire-lighters, was selected, which is again converted to a hydrogen-containing mixture in a miniaturized

reformer. An innovative element is the small-scale (1 cm²) solid oxide fuel cell which, due to the very thin ceramic electrolyte of novel composition, can operate at a temperature as low as 550 °C. Excellent thermal packaging will make sure that this hot "heart" of the device will not be felt by the outside world. This project is supported by CCEM. <http://www.ccem.ch>

Outlook

In one way or the other, all of the above-mentioned projects are exploring niches where hydrogen fuel cell technology could find its way into the market. Another example is the CCEM project *hy.muve* [Fig. 1] (www.empa.ch/hy.muve) pursued by Empa and PSI together with industrial partners, in which a heavy municipal vehicle is equipped with a fuel cell power train. This project will explore the use of fuel cells under heavy-duty conditions that are very different from normal passenger car driving cycles. This project is described elsewhere in this brochure.

Innovation is often defined as an invention turned into a successful product on the market. In that sense, intense efforts are ongoing to demonstrate a fuel cell vehicle concept (including fuelling infrastructure) that could be produced in numbers reaping the first benefits of economy of scale, and would be offered at a price that is affordable to early movers. Such a product would represent an important step to secure a Swiss contribution to a potentially very important emerging market. This is targeted with the collaboration of Belenos Clean Power with PSI and other institutes of the ETH domain.

Fig. 2: *Hy-Light car being fuelled.*

Fig. 3: *Lattice-Boltzmann simulation of 3-dimensional hydro-dynamic flows*

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Applied Sciences on PEM - Fuel Cells in Biel

The main objective of the fuel cell group at the University of Applied Sciences in Biel (BFH-TI) is to bring fuel cells to the people. Ever since a small team of engineers started at the turn of the century the fuel cells activities at the BFH-TI with the installation of a test lab for PEM fuel cells up to 10 kW, an own PEM fuel cell concept and many demonstrators had been developed for mobile applications and integrated mainly in vehicles. Today the BFH-TI is able to serve an excellent infrastructure and high competence for developing and testing PEM fuel cell systems in the power range of some watts to several kW.



Michael Höckel

One of the larger projects was the development of a fuel cell - battery hybrid system and the integration in a lightweight electric vehicle called "SAM". The SAM is a three-wheel electric vehicle which offers two seats arranged in a row and has been developed in Biel for local traffic. The PEM-stack consists of 96 cells and has a maximum power of 6 kW and in combination with lithium-polymer batteries the propulsion system can be supplied by a power of 15 kW. The Hybrid SAM was tested on the roads around Biel and the results were very satisfying: low consumption of about 450g H₂/100km and a range of 130 km, which seems very interesting for an urban electric light weight vehicle.

The project is an excellent example for the fruitful collaboration of BFH-TI with industry and other research institutes. The design of the PEM-Stack, integrating a special internal humidification, had been previously developed by PSI/ETHZ for their PowerPac and was up-scaled to a larger power. The most expensive part in a PEM - fuel cell, the Membrane-Electrode-Assemblies (MEA), had been placed at disposal by Solvicore and the storage cylinders had been

developed and produced by the team of Prof. Andreas Züttel (EMPA), which contributed their high expertise in the field of hydrogen solid state storage. When designing a PEM fuel cell systems, there is still one main question: shall we use air or oxygen. To demonstrate the main differences an E-Scooter was converted at BFH-TI into a Fuel Cell Scooter. Hydrogen and Oxygen are stored in 2 litres pressure cylinders @ 200 bar. To approve the electrical dynamics, a serious of super caps is connected directly in parallel to the PEM - Stack. The performance has been proved through extensive tests on an inhouse circuit, normally used by go-carts. As soon as pressure cylinders are available which can be filled with a pressure of 700 bar, the range will be absolutely adequate for urban traffic.

Driven by the motivation to tackle the problem of high fuel cell costs an important strategic in house project was started in 2005 to develop a low-cost fuel cell based on flexible materials, which can be punched and promises cheap production costs even by small scale manufacture. Instead of the solely use of conventionally milled graphite plates the new development is based on an optimal combination of foil material, which can easily be dye cut ensuring low production time and hence cost. Further focus was set on implementing the gas humidification into the individual cells and enabling a concept of edge air cooling by providing each cell with cooling fins. Air is passed along these fins propelled by conventional axial ventilators.

Initial development steps were financed by the Swiss federal office of energy (SFOE). This development caught the interest of the Swiss company CEKA AG and further development and industrialization steps had been completed under the project

Fig. 1: Side view of the Hybrid SAM: PEM-Fuel Cell and Lithium-Ion Battery and placement of the components in the Hybrid SAM

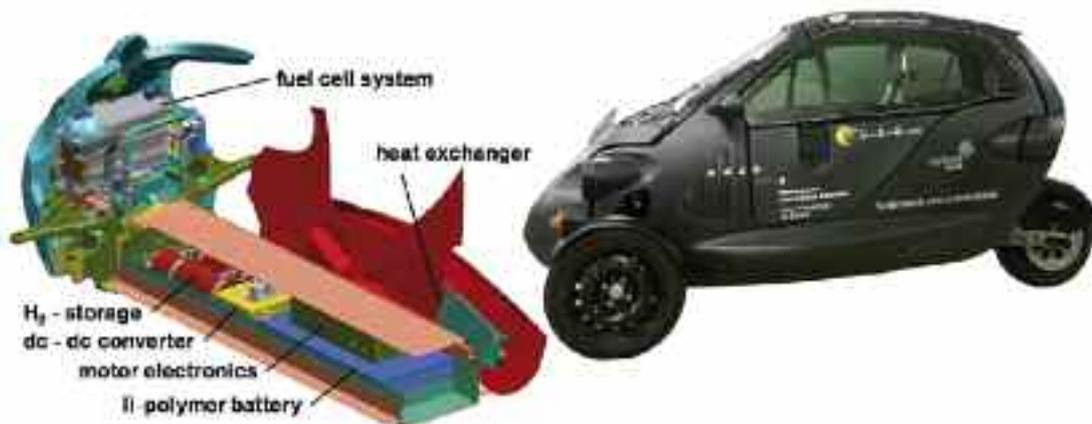




Fig. 2: Typical PEM fuel Cell demonstrator Systems at BFH-TI

name IHPOS (Independent Hydrogen Power System). The IHPOS-FC stack has been developed for use with pure hydrogen as well as reformat gas. The IHPOS development earned Swiss acknowledgment receiving the Swiss technology award 2007. The presentation of the IHPOS FC stack in the hall of innovations at the Hannover Messe, one of the biggest fair for industrial products was a big success.

CEKA AG introduced the IHPOS FC stack on the market in 2009. To demonstrate the fields of application of the IHPOS, the fuel cell team of the BFH-TI designed two different systems, the portable PemPac and the Fuel Cell Trailer with onboard generation of electricity by hydrogen. In the last month's a standardized modular IHPOS-System is developed with

the scope of a project, which brings together the main competences in hydrogen and PEM-fuel cells in Switzerland and is co-financed by CTI.

Currently the IHPOS-E prototype system is been developed to be integrated in a daily mobile application in the catering business. The goal is to introduce a first series of IHPOS-E systems on the market by the end of 2010.



Fig. 3: 500 W commercial PEM - fuel cell by BFH-TI and CEKA AG an typical applicatios



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Hydrogen driven municipal vehicle (hy.muve): from the laboratory to the street

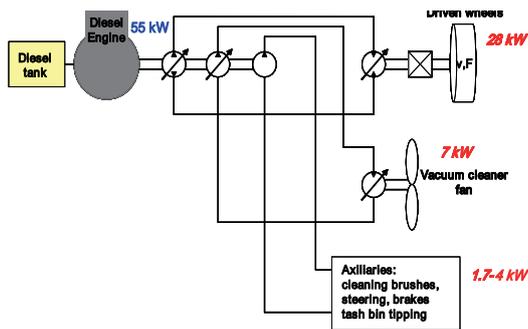
Early practical experience with fuel cell systems and hydrogen handling is essential for policy makers, vehicle manufacturer and the vehicle supply industry in view of the development of market implementation strategies, sampling of experience in real world operation and the study of socio-economic aspects in a sensible market phase.

Fuel cell powertrains are presently being tested in passenger cars and buses. In these sectors, successful market introduction faces tough challenges in view of high driving dynamics, packaging requirements in limited space and cost expectations. Marked introduction of such vehicles is expected to be after 2014. The hy.muve-project is aimed at the introduction of a fuel cell drivetrain into a municipal vehicle (road sweeper) by replacing the 55 kW diesel driven internal combustion engine and the hydraulic power distribution by a 20 kW fuel cell system, a 12 kWh lithium-polymer power battery and a 28 kW electric motor for the traction and the electrification of the vacuum ventilator (Fig 1 and 2). In view of their driving profile (operation by trained personnel, fleet operation from a fixed refuelling point, modest driving dynamics, predominantly low part-load operation, smaller relative share of powertrain in total cost, possibility to operate such vehicles in pedestrian areas and even indoor) these vehicles appear to be particularly well suited for a soon niche market introduction of fuel cells, and a possible early commercialization.



Christian Bach

Fig. 1: Conventional diesel engine driven powertrain for municipal vehicles



In a first project phase, Empa and PSI developed a prototype fuel cell municipal vehicle which is close to a pre-production series in cooperation with Bucher Schörling, the worldwide market leader in manufacturing of municipal vehicles, Brusa Elektronik AG, a Swiss electric drive manufacturer and Messer Schweiz, a hydrogen producer and hydrogen fueling station manufacturer (Fig. 3 and 4). The second and actual part of the project consist of a field testing period during 18 months in Basel, St. Gallen, Berne and Geneve. During this field testing, the vehicle will be operated by road sweeper driver in the normal field operation. Thereby, the vehicle powertrain technology will be monitored by recording several data and

signals for evaluating the property changes and the general technology behaviour under real world driving conditions.

Municipal vehicles with their hydrostatic powertrain and auxiliary drives are a new field in which fuel cell converters have not been tested in the past. As the relevant components differ in specifications from those of passenger cars, a chain of innovative component suppliers would have an opportunity to participate in the market introduction of the envisaged product. In parallel to the technical development and field testing phases in several cities, non-technical challenges for the implementation of innovations will be identified and promising strategies will be developed.

On the technical side, the questions of the powertrain layout with respect to efficiency, consumption, cost and spatial, thermal and electrical integration into a commercial vehicle represents a first challenge. These questions require fundamental knowledge with respect to modeling, development and testing of hydrogen based fuel cell powertrains.

A second challenge is the performance of aging and durability studies of the fuel cell system as well as handling and operation analysis. This part is actually one of the most important research fields in respect to the marked entry of fuel cell vehicles. It includes the identification and quantification of factors that limits PEM fuel cell durability due to contamination in the marked fuel, aspiration-air pollution and technology disaffection using property change analysis during the long-term testing.

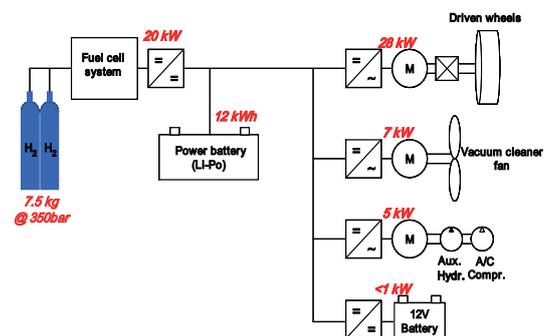


Fig. 2: Hydrogen driven hy.muve powertrain for municipal vehicles

A third challenge is the development of an innovation implementation strategy for hydrogen powered vehicles, which is based on socio-technological analysis with the evaluation of all included actors and the identification of barriers and risks. Such works have rarely been performed based on public mid-term real world testing of fuel cell vehicles but are rather based on expert's estimations or are done by industrial partners without publication. Therefore, the strategy would be of interest in other regions with hydrogen implementation plans.

Hydrogen driven municipal vehicle are a good practical exercise for certification agencies, innovative cities with visions regarding clean mobility or vehicle operators and service stations as well as energy supply companies. Practical experiences are important for the introduction of further hydrogen driven passenger vehicles like the passenger car, developed by Belenos Clean Power and PSI (see description elsewhere in this report) or hydrogen driven city busses.



Fig.3: Fuel cell system, integrated in the rear vehicle part



Fig.4: Project vehicle with hydrogen storage behind the driver cab, the fuel cell system and the power battery in the rear vehicle part beyond the waste container and the electric propulsion motor at the front axle

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The hydrogen Canal Boat in Birmingham

Over the past one and a half years, the University of Birmingham (together with contributions from alumni), British Waterways, Tempus, Less Common Metals, and EMPA (Switzerland) have invested money and materials to the value of around £100k in the design, construction, and now operation of a canal boat of the future. This boat is powered by the combination of a metal hydride solidstate hydrogen store, a proton exchange membrane (PEM) fuel cell, a lead acid battery stack and a NdFeB permanent magnet electric motor.

The boat, called the Ross Barlow, encapsulates very effectively both the hydrogen and magnetism research interests at the University of Birmingham and at Empa in Switzerland. Not only does hydrogen provide the fuel for the PEM fuel cell but it also provides the means (via the HD process) of manufacturing the NdFeB magnets.

Waterways transport is inherently efficient and the weight of the metal hydride store can be readily compensated by the removal and redistribution of the existing ballast from the twelve tonne canal boat. Thus, the use of hydrogen in this context is expected to become commercially viable at a much earlier stage than in automotive applications where the weight and volume of the hydrogen store are both critical factors and remain major challenges for the future.

The PROTIUM project began with the provision of a standard maintenance boat by British Waterways and over the past one and a half years, the craft has been converted to a passenger/display boat by replacing the standard diesel engine with an all electric propulsion system and by enclosing the middle portion of the vessel. The longer term aim is to supply the boat with “green” electricity and with “green” hydrogen so that the project will become completely sustainable and will have totally eliminated all the atmospheric, water and noise pollution associated with the boat. Perhaps the most novel aspect of the Ross Barlow is the solid state store which contains 133 kg of powdered Ti-V-Mn-Fe alloy which, when fully charged, will store around 2.5 kg of hydrogen (28 cubic metre at standard temperature and pressure). There are five storage units and in each one, the metal powder is contained within seven stainless steel tubes which are surrounded by a water jacket which provides heat when desorbing the hydrogen to the fuel cell and cooling when the store is being charged. The temperature is maintained by means of a water pump and heat exchanger. The most attractive feature of the store is that the operating pressure is less than 10 bar and the 5 units together store the equivalent of 4 fully charged standard gas cylinders (50 liters) at a pressure of 200 bar. To our knowledge, this is by far the largest solid state hydrogen store being employed in any transport application within the UK. The Protium project, therefore, will provide an excellent opportunity to assess



Ivor Rex Harris



Andreas Züttel



Fig. 1: The hydrogen powered “Ross Barlow” canal boat at the University of Birmingham.

the performance of such a store in a working environment. Why not power the boat solely by hydrogen? The reason is that there are advantages in employing a hybrid system. One of these is that, for most of the time, the fuel cell can be employed to charge the batteries at a steady rate and this avoids subjecting the fuel cell to surges in demand, hence extending its lifetime. In addition, the batteries can also be topped-up from a range of sustainable primary energy sources such as wind, hydro and solar. Practically, this is much easier and more energy efficient than generating hydrogen from these sources. There is also some possibility of regenerative charging

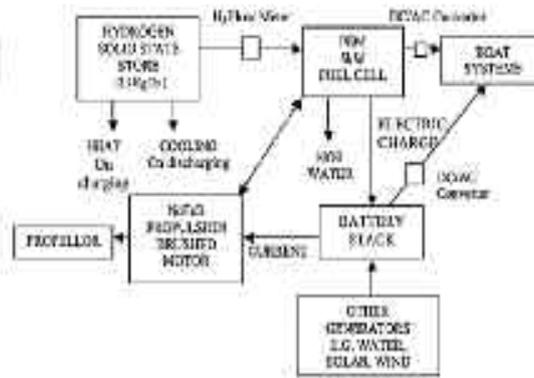


Fig.2: Schematic diagram of the energy flow on the boat.



Fig.3: Hydrogen storage tanks, holding 2.5 kg of hydrogen in a metal hydride.

ing of the batteries. The highly efficient (~90%), high torque, permanent magnet electric motor makes very effective use of the energy stored in the metal hydride and in the battery stack.

As stated earlier, the NdFeB sintered magnets have been manufactured by the Hydrogen Decrepitation (HD) process and this synergy is described in the educational material associated with the project. Another important on-board application for NdFeB magnets is in the guidance system where the conventional tiller can be substituted by a permanent magnet actuator. The complete hybrid energy system is monitored continuously and controlled by computer software designed to achieve maximum efficiency and hence maximum range between the refuelling cycles.

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Hydrides

The highest volumetric densities of hydrogen are found in metal hydrides, in some cases more than twice the density of liquid hydrogen. Many metals and alloys are capable of reversibly absorbing large amounts of hydrogen: from 1 to 3 hydrogen atoms per metal atom. The absorption takes place using molecular hydrogen gas or hydrogen atoms from an electrolyte. The group one, two and three light metals (e.g. Li, Mg, B, or Al) can combine with hydrogen to form a large variety of metal-hydrogen complexes (e.g. $\text{Na}[\text{AlH}_4]$ and $\text{Li}[\text{BH}_4]$). These are especially interesting because of their light weight and because of the number of hydrogen atoms per metal atom, which is two in many cases.



Andreas Züttel

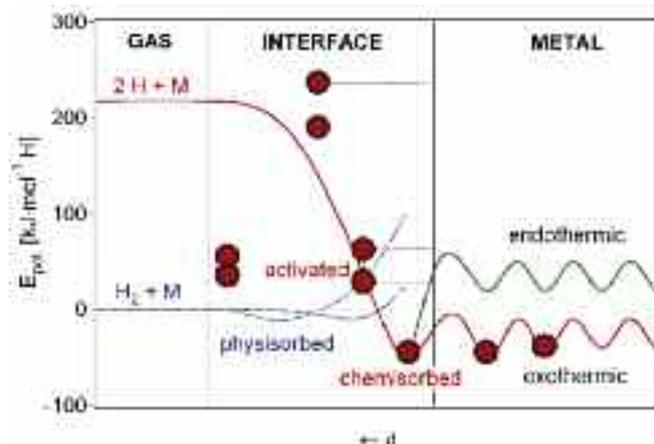
Thomas Graham, from Glasgow, Scotland, was working at the University College in London in 1968 when he exposed palladium to a hydrogen gas atmosphere. He discovered that the hydrogen was absorbed into the palladium and was able to correctly describe the absorption process.

In the 1970s, Louis Schlapbach at ETH Zürich investigated the magnetic properties of FeTi alloys and especially the effect of hydrogenation on magnetism [2]. He explained the irreversible change of the magnetic properties of FeTi upon hydrogenation, the activation process and some surface properties of FeTi by surface segregation. In a surface layer, Ti diffuses to the surface and Fe forms magnetic precipitates which probably catalyze the hydrogenation. The catalytically active surface is renewed with each cycle of hydrogenation. Later, Schlapbach developed experiments and theory of hydrogen chemisorption on clean and precovered metal surfaces and applied it to techniques for preparing metal hydrides [3]. At the surface of hydride forming intermetallics, precipitates of d metals and a metallic subsurface are produced by surface segregation and decomposition. The subsurface and the precipitates are able to

dissociate H_2 . Our recent work on the surface analysis of LaNi_5 , FeTi, Mg_2Ni and ErFe_2 is reviewed.

Complex transition metal hydrides constitute a relatively recent and somewhat exotic class of solid state compounds. Historically, the first such compound and text book example is K_2ReH_9 . It was first reported in 1964 and found to contain tricapped trigonal prismatic $[\text{Re}(\text{VII})\text{H}_9]^{2-}$ complex anions in which rhenium is fully oxidised. The second member, Sr_2RuH_6 , was reported in the 1970s and was found to contain an octahedral $[\text{Ru}(\text{II})\text{H}_6]^{4-}$ complex. Wider interest in these compounds formed in the 1980s after the discovery of transition metal hydrides (most of which are metallic), such as LaNi_5H_6 and FeTiH_2 , which have now reached commercial maturity for reversible hydrogen storage in batteries for portable electronics (mobile phones, laptops, etc.). One of these compounds, however, is non-metallic (Mg_2NiH_4) and shows a nearly fixed hydrogen content. This compound was classified as a complex transition metal hydride after its structure had been fully characterised and found to contain discrete tetrahedral $[\text{Ni}(\text{o})\text{H}_4]^{4-}$ complexes. This triggered intense activity in the field and led to the discovery of

Fig.1: Lennard-Jones potential of hydrogen at a metal surface.



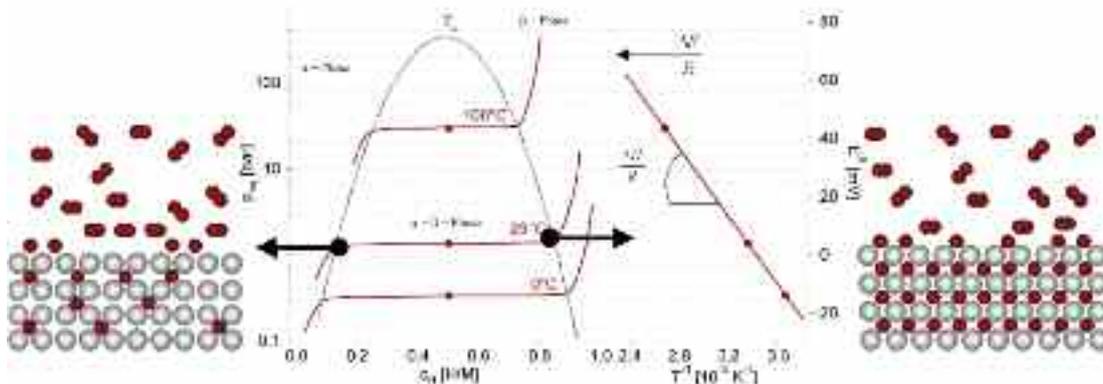


Fig. 2 Isotherm of hydride formation

many other homoleptic hydride complexes, such as octahedral $[\text{FeH}_6]^{4-}$, square-pyramidal $[\text{CoH}_5]^{4-}$, square-planar $[\text{PtH}_4]^{2-}$, and linear $[\text{PdH}_2]^{2-}$. A significant part of that work was performed by the group of Klaus Yvon [4] at the University of Geneva.

After the first report of reversible hydrogen sorption on catalyzed $\text{Na}[\text{AlH}_4]$ at temperatures of 180°C and 210°C by Bogdanovi and Swickardi in 1996, Andreas Züttel [5] at the University of Fribourg suggested the stable compound LiBH_4 as a similar alternative. It has the highest gravimetric hydrogen density at room temperature known today (18 mass%). This class of complex hydrides could be the ideal hydrogen storage material for mobile applications. LiBH_4 desorbs three out of every four hydrogen atoms in

References

[1] Thomas Graham „On the Occlusion of Hydrogen Gas by Metals“, *Proc. Royal Soc.* 16 (1868), pp. 422
 [2] L. Schlapbach, A. Seiler and F. Stucki, “Surface segregation in FeTi and its catalytic effect on the hydrogenation”, *Materials Research Bulletin*, Volume 13, Issue 7, July 1978, pp. 697-706
 [3] L. Schlapbach, A. Seiler, F. Stucki, H.C. Siegmann, “Surface effects and the formation of metal hydrides”, *Journal of the Less Common Metals*, Volume 73, Issue 1, 1 September 1980, pp. 145-160
 [4] K. Yvon, “Complex Transition Metal Hydrides”, *Chimia* 52:10 (1998), pp. 613-619
 [5] A. Züttel, P. Wenger, S. Rentsch, P. Sudan, Ph. Mauron, Ch. Emmenegger, “ LiBH_4 a new hydrogen storage material”, *Journal of Power Sources* 118 (2003), pp. 1-7

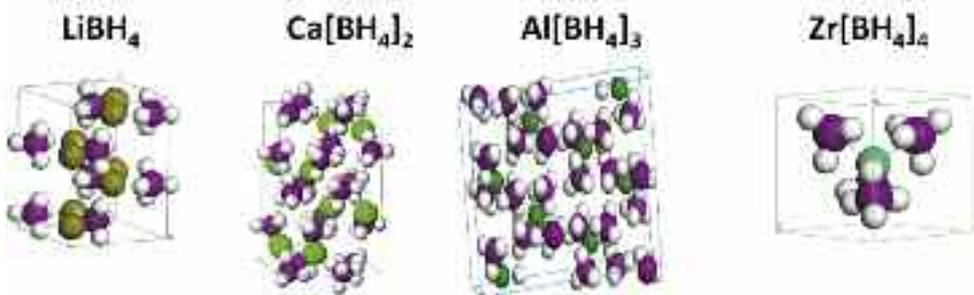


Fig. 3 Selected borohydrides

the compound upon melting at 280°C and decomposes into LiH and boron. Although there was at first a lot of doubt about the reabsorption of hydrogen in boron compounds by chemists around the world, numerous groups worldwide work intensively on borohydrides for hydrogen storage today.

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Hydrogen Facts

Hydrogen — (Gr. hydro, water, and genes, forming). Hydrogen was prepared many years before it was recognised as a distinct substance by Cavendish in 1766, it was named by Lavoisier (1). Hydrogen is the most abundant element in the universe, and it is thought that the heavier elements were, and still are, built from hydrogen and helium. It has been estimated that hydrogen makes up more than 90% of all atoms or three quarters of the mass of the universe. Hydrogen is found in the sun and most stars, and plays an important part in the proton-proton reaction and carbon-nitrogen cycle, which accounts for the energy of the sun and stars. It is thought that hydrogen is a major component of the planet Jupiter and that at some depth in the planet's interior, the pressure is so great that solid molecular hydrogen is converted into solid metallic hydrogen. In 1973, it was reported that a group of Russian researchers may have produced metallic hydrogen at a pressure of 2.8 Mbar. At the transition, the density changed from 1.08 to 1.3 g/cm³. Earlier, in 1972, a Livermore (California) group also reported a similar experiment in which they observed a pressure-volume point centered at 2 Mbar. It has been predicted that metallic hydrogen may be metastable; others have predicted it would be a superconductor at room temperature.



Andreas Züttel

On earth, hydrogen occurs chiefly in combination with oxygen in water, but it is also present in organic matter such as living plants, petroleum, coal, etc. It

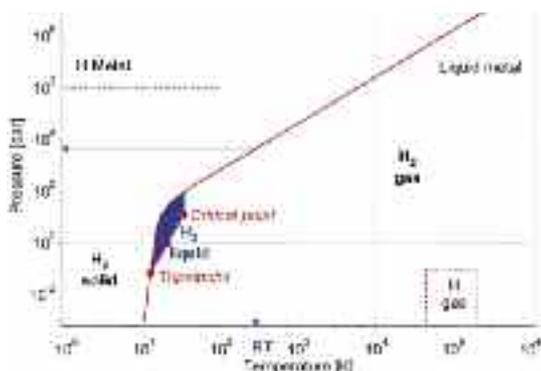


Fig. 1: Primitive phase diagram for hydrogen

is present as a free element in the atmosphere, originating from water splitting by UV-light, but only to the extent of less than 1 ppm, by volume. It is the lightest of all gases and combines with other elements, sometimes explosively, to form compounds. Great quantities of hydrogen are required commercially for the fixation of nitrogen from the air in the Haber-Bosch ammonia process and for the hydrogenation of fats and oils. It is also used in large quantities in organic chemistry e.g. in methanol production, hydrodealkylation, hydrocracking, and hydrodesulfurization. It is also used as a rocket fuel, for welding, for production of hydrochloric acid, for the

reduction of metallic ores, and for filling balloons. The lifting power of 1 m³ of hydrogen gas is about 1.16 kg at 0°C and 1 bar pressure.

Temperature [K]	Vapor pressure [kPa]	Density [kg/m ³]		
		ρ_s	ρ_L	ρ_G
1	$11 \cdot 10^{-37}$	89.024		
5	$4.76 \cdot 10^{-3}$	88.965		
10	255.6	88.136		0.006
12	1837	87.532		0.037
13.803 ^a	7.0	86.503	77.019	0.126
20	93.5		71.086	1.247
20.268 ^b	101.3		70.779	1.338
30	822.5		53.930	10.887
32.976 ^c	1293			31.43

Tab. 1: Vapor pressure and density of p-hydrogen at low temperatures, ^a Triple point, ^b101.3 kPa, ^cCritical point.

Production of hydrogen worldwide amounts 2006 to more than 50 million metric tonnes per year (2). It is prepared by the reaction of steam on heated carbon, by thermal decomposition of certain hydrocarbons, by the electrolysis of water, or by displacement from acids by certain metals. It is also produced by the reaction of sodium or potassium hydroxide with aluminum. Liquid hydrogen is important in cryogenics and in the study of superconductivity, as its melting point is only 20 K.

The ordinary isotope of hydrogen, H, is known as protium. In 1932, Urey announced the preparation of a stable isotope, deuterium (D), with an atomic weight of 2. Two years later an unstable isotope, tritium (T), with an atomic weight of 3 was discovered. Tritium has a half-life of about 12.5 years. One atom of deuterium is found in about 6.000 ordinary hydrogen atoms. Tritium atoms are also present but in much smaller proportion. Tritium is readily produced in nuclear reactors and was used in the production of the hydrogen bomb. It is also used as a radioactive agent in making luminous paints and as a tracer.

The current price of tritium, to authorised personnel, is about 2 Euro/Ci. Deuterium gas is readily available, without permit, at about 10.000 Euro/kg. Heavy water, deuterium oxide (D₂O), which is used as a moderator to slow down neutrons, is available without permit at a cost of around 500 Euro/kg, depending on quantity and purity. The price of hydrogen is directly bound to the price of electricity (0.05 Euro/kWh) and therefore around 2.5 Euro/kg.

Quite apart from isotopes, it has been shown that hydrogen gas under ordinary conditions is a mixture of two kinds of molecules, known as ortho- and para-

hydrogen, which differ from one another by the spins of their electrons and nuclei. Normal hydrogen at room temperature contains 25% of the para form and 75% of the ortho form. Consideration is being given to an entire economy based on solar- and nuclear-generated hydrogen. Located in remote regions, power plants would electrolyze sea water; the

hydrogen produced would travel to distant cities by pipelines. Pollution-free hydrogen could replace natural gas, gasoline, etc., and could serve as a reducing agent in metallurgy, chemical processing, refining, etc. It could also be used to convert organic waste into methane and ethylene.

	Hydrogen	Methane	Propane	Gasoline
Density of gas at standard conditions [kg/m ³ (STP)]	0.084	0.65	2.42	4.4 ^a
Heat of vaporisation [kWh•kg ⁻¹]	0.1237	0.1416		0.07-0.11
Lower heating value [kWh•kg ⁻¹]	33.314	13.894	12.875	12.361
Higher heating value[kWh•kg ⁻¹]	39.389	15.361	14.003	13.333
Thermal conductivity of gas at standard conditions [mW•cm ⁻¹ K ⁻¹]	1.897	0.33	0.18	0.112
Diffusion coefficient in air at standard conditions [cm ² •s ⁻¹]	0.61	0.16	0.12	0.05
Flammability limits in air [vol%]	4.0- 75	5.3-15	2.1-9.5	1-7.6
Detonability limits in air [vol%]	18.3-59	6.3-13.5		1.1-3.3
Limiting oxygen index [vol%]	512.1		11.6 ^b	
Stoichiometric composition in air [vol%]	29.53	9.48	4.03	1.76
Minimum energy for ignition in air [mJ]	0.02	0.29	0.26	0.24
Autoignition temperature [K]	858	813	760	500-744
Flame temperature in air [K]	2318	2148	2385	2470
Maximum burning velocity in air at standard conditions [m•s ⁻¹]	3.46	0.45	0.47	1.76
Detonation velocity in air at standard conditions [km•s ⁻¹]	1.48-2.15	1.4-1.64	1.85	1.4-1.7 ^c
Energy ^d of explosion, mass-related [gTNT/g]	2411	10	10	
Energy ^d of explosion, volume-related [gTNT•m ³ (STP)]	2.02	7.03	20.5	44.2

Tab. 2: Combustion and explosion properties of hydrogen, methane, propane and gasoline. ^a100 kPa and 15.5°C. ^bAverage value for a mixture of C₁-C₄ and higher hydrocarbons including benzene. ^cBased on the properties of n-pentane and benzene. ^dTheoretical explosive yields.

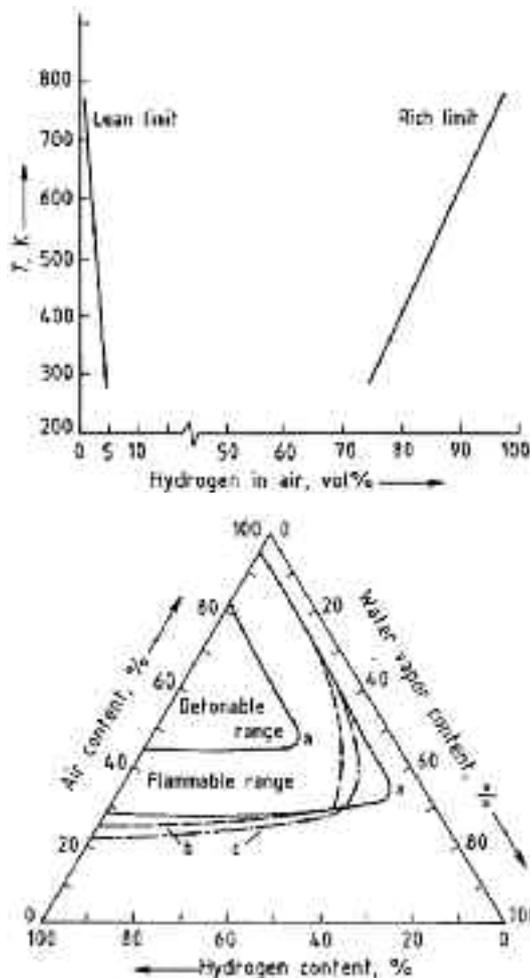


Fig. 2: Effect of temperature on flammability limits of hydrogen in air (pressure 100 kPa).

References:

- (1) Charles T. Lynch, *CRC Handbook of Materials Science: General Properties*, 1974
- (2) M. Richards, A. Shenoy, *H₂-MHR pre-conceptual design summary for hydrogen production*, *Nucl Eng Technol* 2007, 39, 1-8

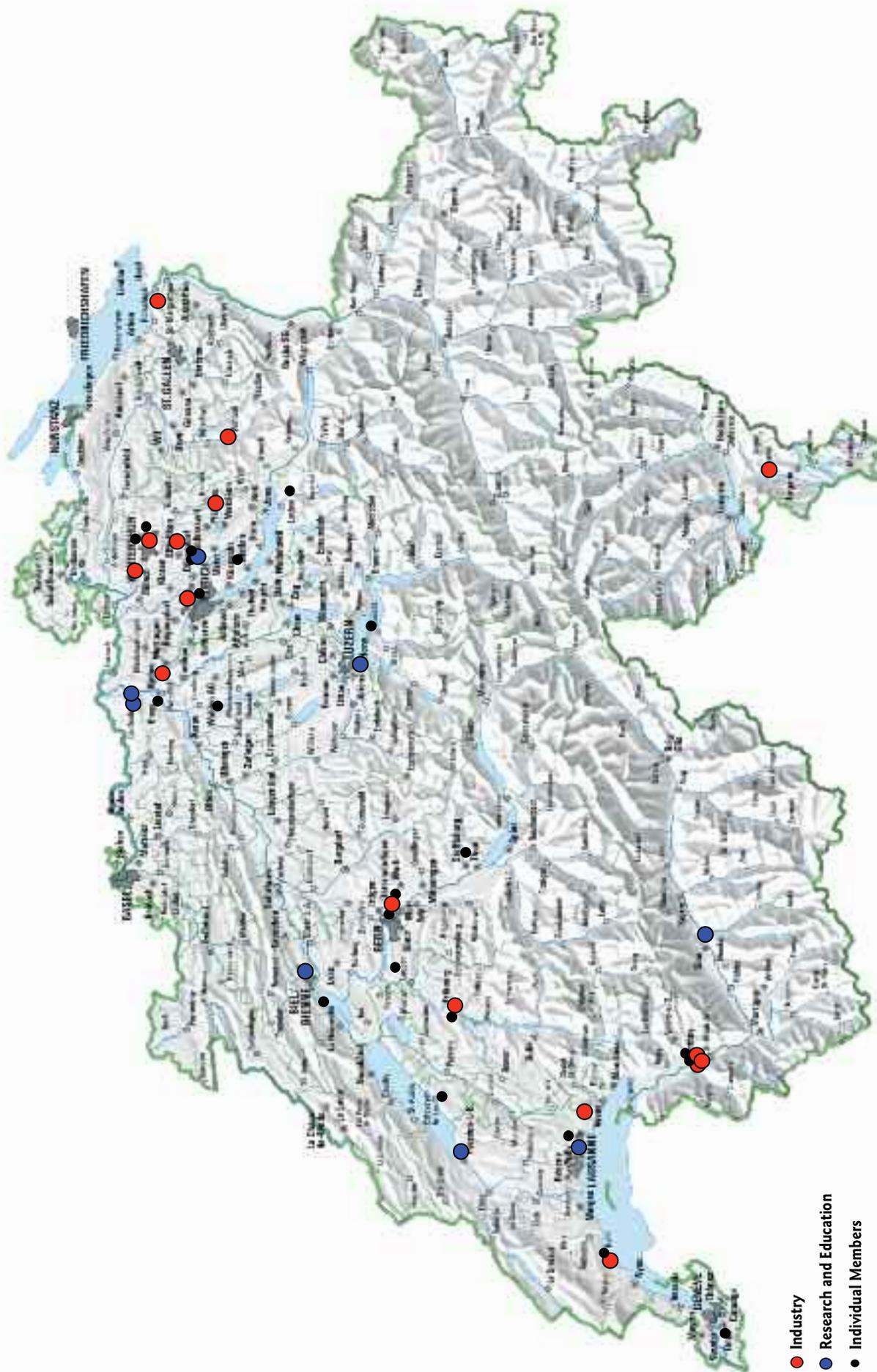
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Fig. 3: Flammability and detonability limits of the three component system hydrogen-air-water a) 42°C, 100 kPa; b) 167°C, 100 kPa, c) 167°C, 800 kPa



Industry

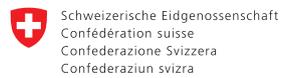
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