H2 international
E-JOURNAL ON HYDROGEN AND FUEL CELLS

# H2-international – e-Journal

## January 2017

**Content**

# Global Fuel Cell Market Review

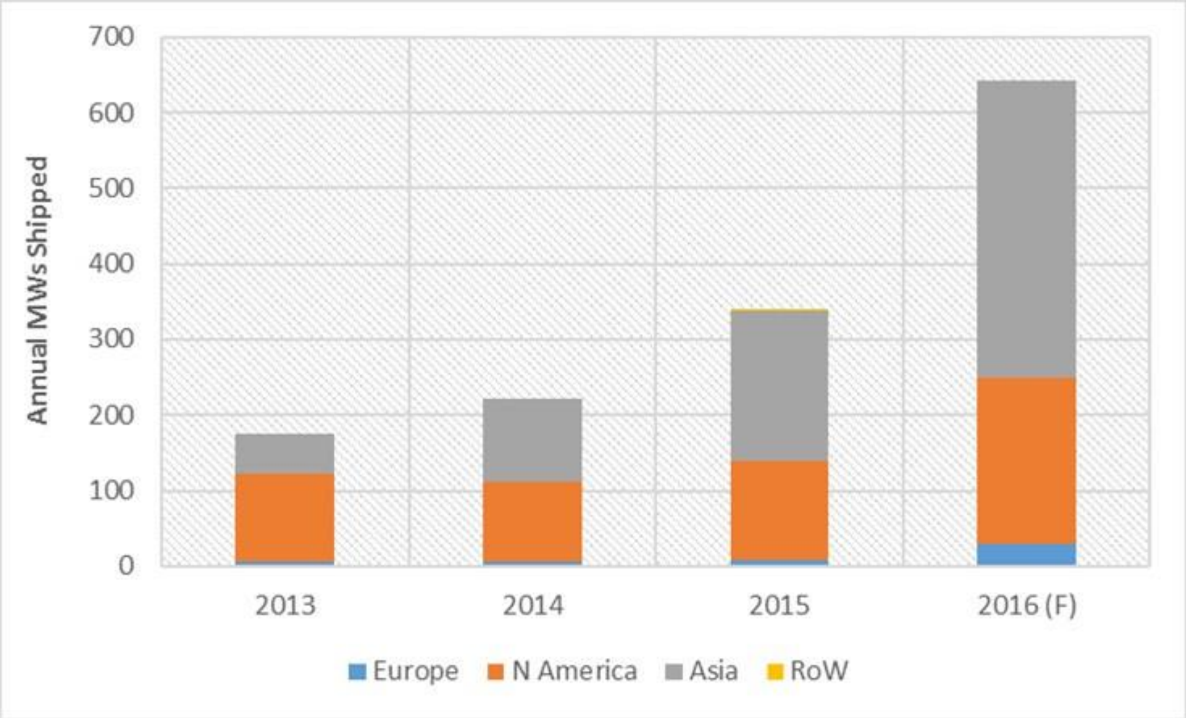


Fig. 1: *Fuel cells shipped globally, broken down by capacity and region between 2013 and 2016 (forecast)*

**Despite the fuel cell industry's recent growth spurt, the market still looks like a pyramid. At the top, you will find the stack and system manufacturers which offer commercial products and have a clear understanding of the costs involved and the wishes customers may have. These businesses are either driven by policy, as in Japan, or the forces of a free market, like FuelCell Energy. But of the worldwide more than 200 stack and system providers, fewer than 30 have made it this far.**

The second tier consists of businesses that are close to market ready or are quasi-commercial now and are drawing up the financial sections of their business plans. Similar to tier 1 companies, they are seeing investment from the private sector and are growing their customer base. This tier is populated by fewer than 60 enterprises.

The bottom of the pyramid entails the majority of stack and system companies. Focused heavily on RD&D, they are still miles away from the cost structure of stacks and systems in later stages.

What this means for the fuel cell industry is that we will see another split between tier 1 and 2 companies on one side and the rest of the industry on the other. The former will continue to contribute the biggest chunk of sales and receive the largest portion of investment, whereas the latter will be an easy target for M&A. This split became increasingly clear last year, with a rise in consolidations and buyouts.

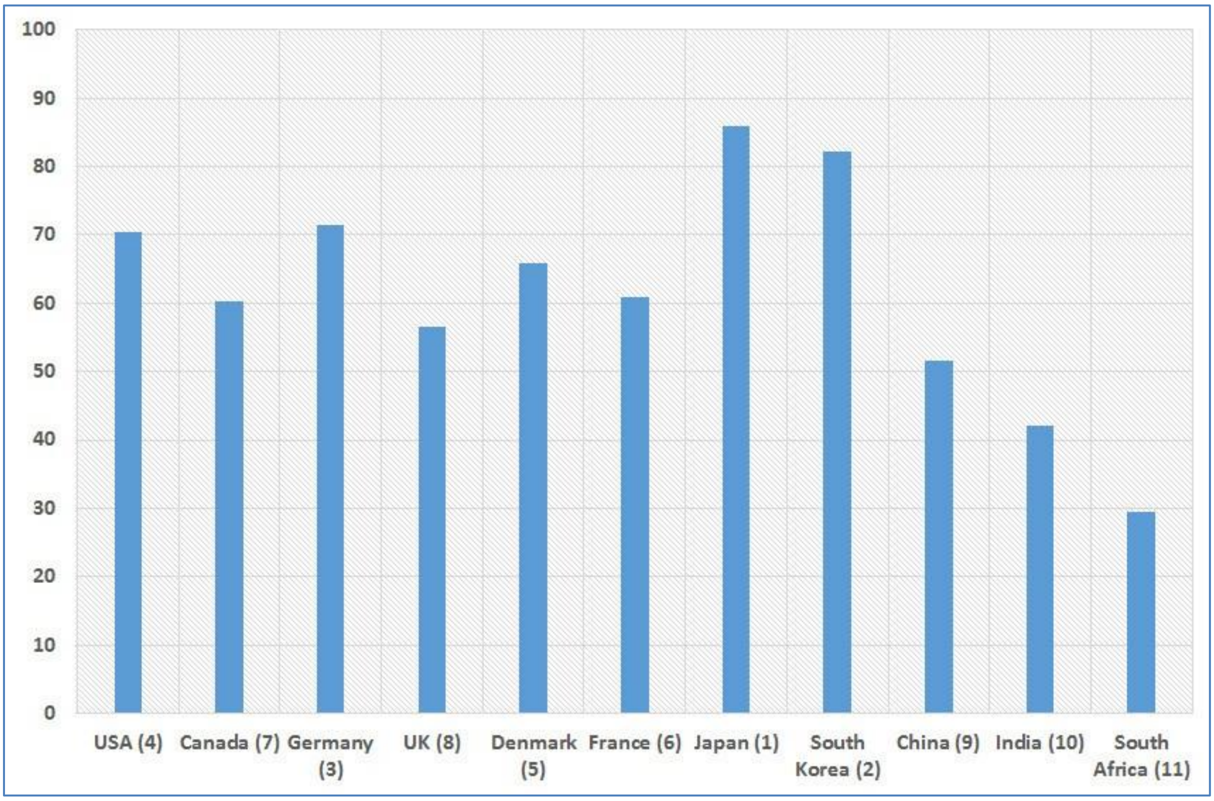


Fig. 2: *Most attractive countries in 2015*

Overall, the number of fuel cell businesses has been growing. One of the factors for this growth is a reduction in barriers to entry, especially at system level. Historically, 4th Energy Wave's rule of thumb has been that a PEM fuel cell system required around USD 1 billion for R&D and commercialization, and an SOFC unit somewhat more. But now, as we see the start of stack standardization, initial costs are falling. Obviously, there is still a long way to go, but as innovative and standardized concepts reduce financial barriers to entry, we should see an increase in the number of smaller market entrants.

**Country Attractiveness Index**

The *Country Attractiveness Index*, launched by 4th Energy Wave this year, has made it possible to clearly and unambiguously identify Japan as the leading country for fuel cells, with South Korea second and Germany third.

Government authorities in most countries are still caught up in high-level discussions about the opportunities of fuel cells and hydrogen. Often, they are not focusing on the long, complex and exceedingly detail-oriented nitty-gritty of identifying and removing local market barriers.

Japan is the only nation to steadily move forward with implementing a hydrogen society. It is known globally for a government that pursues a long-term, stable and well-coordinated approach to the development and creation of a local fuel cell industry. What has led to this country outstripping any other in developing a strong, domestic fuel cell market is the length of time of sustained investment, a clear policy direction in product development and market introduction, renewed and agreed-upon targets, as well as coordinated activities and focus.

Most fuel cells developed in Japan today are PEM-type stacks and systems. This is somewhat understandable, considering the country's policy focus on residential buildings. But as the data is replotted over the coming years, this – as 4th forecasts – is likely to change, with an increasing number of companies to work on high-temperature systems.

**Unit sales**

If we turn to shipments by region (see fig. 1), we see that in terms of megawatts, the Asian-Pacific markets have stepped up their lead, and are predicted to hold on to it in 2016.

Europe still lags far, far behind the rest of the world in terms of system manufacturing. The companies that offer commercially available products either manufacture them outside of Europe or produce small units with a capacity of up to 5 kW. The one area that Europe is very strong in is the portable fuel cell market. If we base the chart on the number of shipped systems in this field, the picture will look somewhat different.

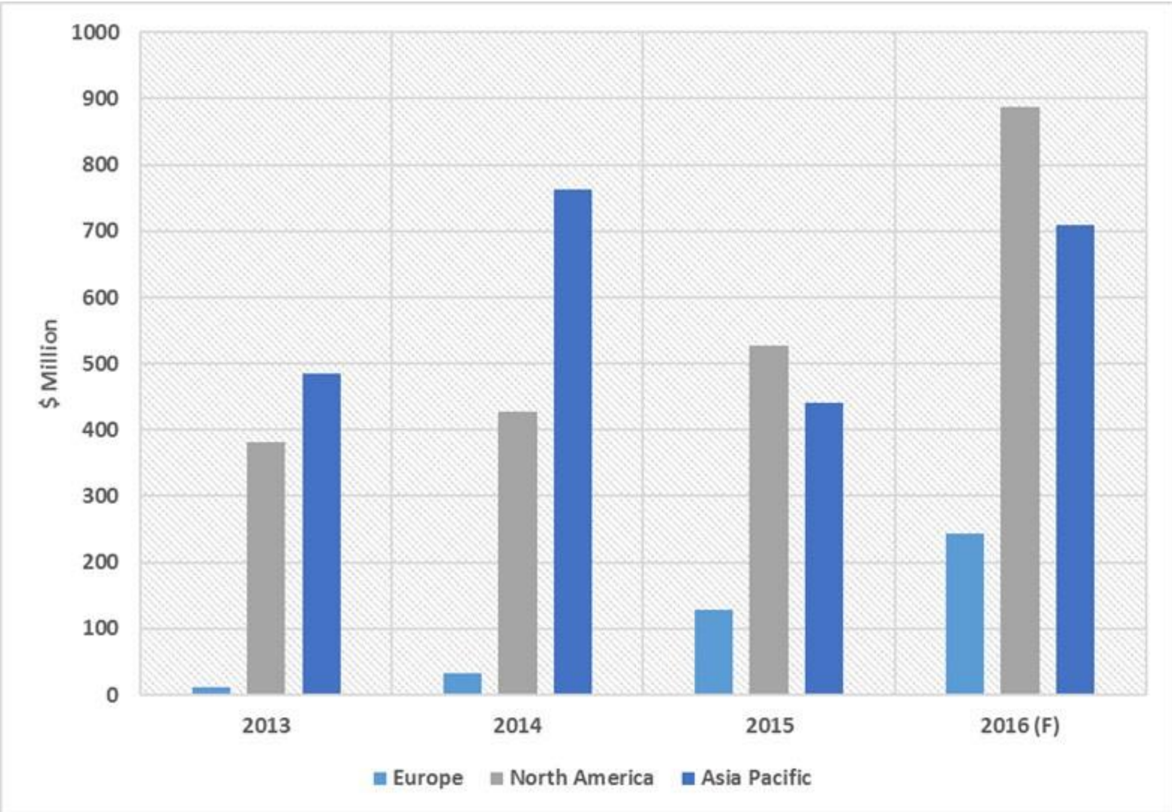


Fig. 3: *Global revenue from fuel cell systems between 2013 and 2016 (forecast)*

In terms of revenue, 4th Energy Wave focuses on money generated from the sale of complete fuel cell systems. Figure 3 shows that North America was the region with the highest revenue in this segment in 2015. It marks a shift in position from 2014, when Asia had dominated the market. Sales in North America were boosted by a number of high-profile deals, including the sale of Ballard fuel cell buses to China and the US Pepperidge Farm purchase of a 1.4 MW CHP plant by FuelCell Energy. Revenue in North America is forecast to jump again in 2016 to some USD 900 million, primarily thanks to stationary installations for which contracts were signed last year and revenue recognition is due in this one (see also FuelCell Energy: Decision on Beacon Falls).

**Conclusion**

It was a difficult 2015 for fuel cell companies. It again illustrates the challenges companies face when transitioning from an industry focused on RD&D to one of complete commercialization. Market actors will have to tear down many barriers before success can be achieved.

The "Fuel Cell and Hydrogen Annual Review" is the continuation of the Fuel Cell Today's "Fuel Cell Annual Review" report started by Kerry-Ann Adamson and her team in 2008. The dataset combines both historical data from FCT and fresh data collected and collated by 4th Energy Wave. It makes this year's review the ninth publication of its kind and the third one by 4th Energy Wave, a fully independent, distributed energy strategy, analysis and advisory firm.

Download the review (76 pages and chartbook, incl. graphics) for free on: www.4thenergywave.com

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# China's Swift and Pragmatic Approach

**Taking a look at China these days, one may wonder if we haven't already found the solution for a sustainable future in hydrogen and fuel cells. During his June business trip to the Land of the Dragon, H2-international's stock market analyst Sven Jösting took part in the two-day German-Chinese SME Conference in Jieyang as representative of German environmental organization B.A.U.M. In front of 800 attendees, he tried to answer the question: "Will water become what coal is today?" Afterward, he visited the industrial park Metal Eco City in the east of southern Chinese province Guangdong. When he came back from this trip, he sat down with Anja Barlen-Herbig from ZhongDe Metal Group, the investor and operator of the Metal Eco City, for the following interview.**

*Sven Jösting, © ZhongDe Metal Group*

*Environmental protection is pretty much at the top of the agenda of the Chinese government's 13th Five-Year Plan. Regarding research and development, the country is developing strategies to catch up to other nations' achievements in clean transport and renewable energy. Which part will hydrogen and fuel cells play in the government's plans?*

Jösting: "Green" hydrogen produced from renewable energy sources such as wind and solar could become the next big thing in China. There are many applications for which it could be used, from transportation (cars, trucks, railroad vehicles, bikes and motorbikes) to stationary systems. And fuel cell power plants can generate electricity and heat – at efficiencies above 90 percent. Additionally, power-to-gas systems can combine green hydrogen with $CO_2$ (e.g., from coal and industrial plants) to create methane. These plants can be highly effective producers of power and heat – from renewable sources, no less, since the only "waste product" is steam. Harmful emissions are converted into clean energy. It's an effective defense against heavy pollution, one that will reduce demand for coal.

*Is water the coal of the future? French author Jules Verne had already written as much in 1870 …*

Jösting: It is, indeed. I think so because the steady improvements in electrolysis will make green hydrogen production a more efficient, more cost-effective and safer process. Jules Verne will be proved right. As an idea: Wouldn't it be perfect if China were to install filling stations, supplied by locally produced $H_2$, and charging points along the Silk Road? Fuel cell buses could be refilled here, as could cars, trucks, motorbikes and even bicycles. When I think about it like that, the Chinese proverb according to which water means wealth takes on an entirely new meaning.

*A few weeks ago, you visited the Metal Eco City in Jieyang. Which opportunities do you think the city has for the use of $H_2$ and fuel cells?*

Jösting: In my opinion, the Metal Eco City is very well suited for the implementation of fuel cell technology. Jieyang's industrial facilities on the one hand and water, sun and wind resources on the other make for a good combination. You could set up a pilot project there (e.g., to install $H_2$ filling stations). I will arrange a meeting between Jieyang's authorities and hySolutions. The latter is an electric transportation company owned by the German city of Hamburg. I've already suggested this to the mayor of Jieyang, Chen Dong, and he seemed very interested in it.

*In Guangdong province, construction work is underway on production facilities for fuel cell stacks that will later be used in hydrogen-driven buses in several Chinese cities. During your visit to Jieyang, you also met with Hu Chunhua, the party secretary of Guangdong province, with whom you talked about the experiences you and he have made with fuel cell technology. Have you gained any new insights into the market?*

Jösting: The technological leader in fuel cells, Canadian Ballard Power, has partnered in Guangdong with Chinese businesses that will produce a great many fuel cell systems for buses. And at the beginning of this year, Mr. Hu visited the headquarters of Ballard in Vancouver. This underlines the importance China places on fuel cells. Additionally, 48 cities have taken part in a new Chinese-wide program to purchase a variety of systems for 1,000 electric buses each, including fuel cell-hydrogen and diesel hybrid vehicles, but also battery-only ones and gas-run buses. The recently passed investment plan, which has a three-year budget of more than USD 770 billion, is heading into the same direction. And Ballard is collaborating with the bigger rolling stock manufacturers in China to get hydrogen-run trains and streetcars on the tracks. This will eliminate the need for power lines.


*The share of renewable energies in primary energy supply is said to increase to 15 percent in China by 2020. The same action plan specified 20 key fields for innovative developments. Hydrogen and fuel cell technologies received an explicit mention. What opportunities do you think German businesses will have here?*

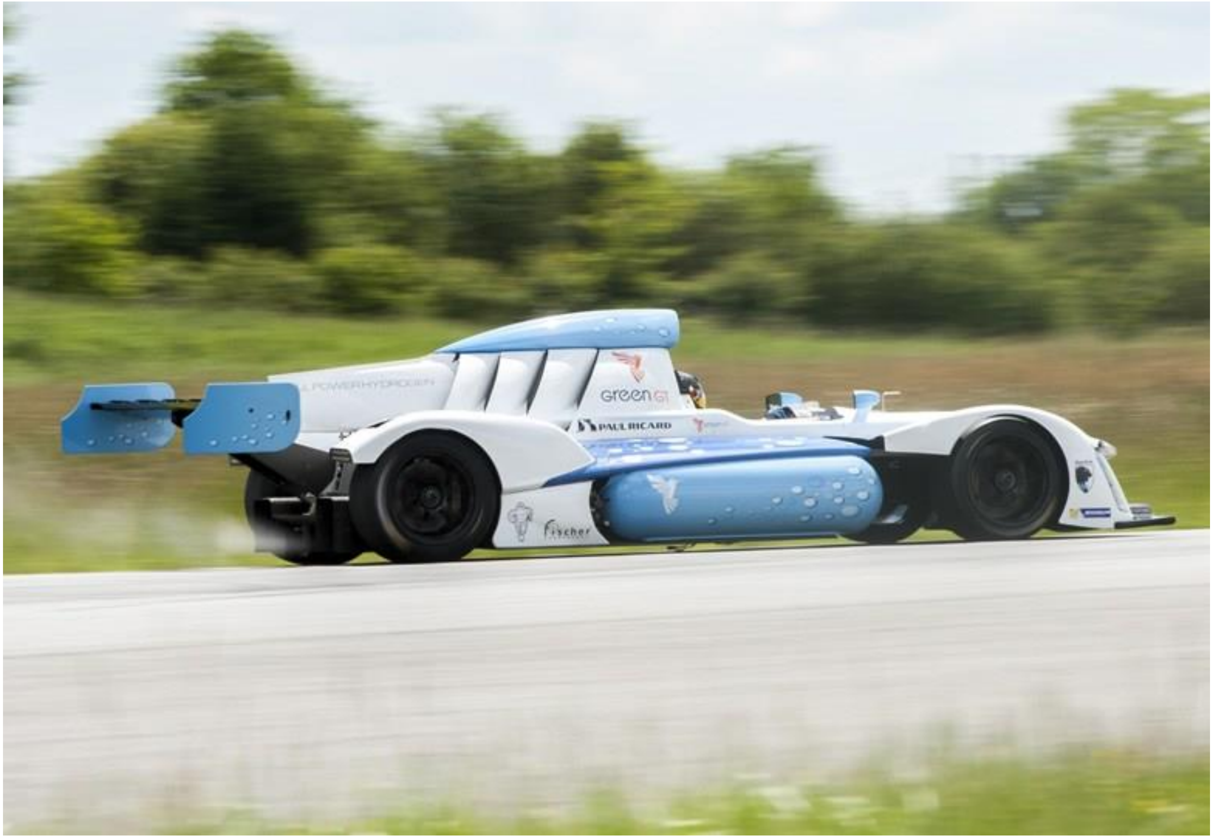
Jösting: I think it will be primarily the carmakers' turn. Daimler has already gotten involved, VW is about to, although it is Audi which is spearheading the corporate effort. Wan Gang, the Chinese minister for science and technology, used to work as an engineer at Audi. He considers the fuel cell to be a key solution for meeting demand in the energy and transportation sector. He explained this in more detail in Berlin in April, during the H2Mobility Conference, which I also attended (see Connected – Autonomous – Emission-Free). Companies like Siemens are pioneers of water conversion through electrolysis. But they're not alone: Businesses that design systems have come a long way technologically; Linde is the pioneer of $H_2$ filling stations.


*Could China become a leader in fuel cell transportation? What is your vision for the future?*

Jösting: Clearly, it can. The country is executing many projects in less time and with a more pragmatic approach. While Germany will have 400 $H_2$ filling stations by 2023 if all goes as planned, China could decide to set up 10,000 stations in five years. There is also a growing number of applications and products that can use $H_2$. The number of fuel cell hybrids (e.g., Toyota's Mirai) will go up. Ships will be powered by fuel cells and $H_2$ (see HDW submarines) – and forklift trucks. In the long term, I see hydrogen being used in aircraft as well. The battery will be replaced by a fuel cell. Refueling can be done in three minutes. On a side note, Japan wants to show the world what the country can accomplish: The government has big fuel cell plans, plans it intends to reveal during the 2020 Olympics in Tokyo.

*Interviewer: Anja Barlen-Herbig, ZhongDe Metal Group, Stuttgart*

# Green GT Vision to Become Reality



© *Green GT*

The time may have come to turn a years-old vision into reality: On Aug. 30, 2016, Pininfarina announced that it would use the Green GT powertrain design in its small-batch race car H2 Speed. The Italian car designer, which was bought by the Mahindra conglomerate for USD 28 million last December, had unveiled a concept study of the powerful, high-performance and hydrogen-run Le Mans Prototype at the Geneva International Motor Show in early 2016. Swiss Green GT began to develop the car's powertrain in 2012 and after a 2013 presentation was postponed, the drive system was first tested on the race track in 2015 and 2016 at the French Circuit Paul Ricard (with Formula 1 driver Olivier Panis behind the wheel) and in Le Mans, respectively. The prototype uses two electric motors supplied by a 210 kW SymbioFCell PEM system. Pininfarina plans to manufacture between ten and one hundred units for affluent racing fans – priced at USD 2.5 million each. A functional prototype is said to be available in early 2017. The small-batch version is scheduled for late next year.

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# More Windgas, Fewer Climate Troubles

*Sönke Tangermann, © Enver Hirsch*

**Scientific studies have shown that if we want to succeed in transforming the energy market, our priority needs to be long-term storage solutions and an integration of relevant sectors. One technology with much promise for the future is Windgas. But although P2G remains crucial to Germany's success in meeting the COP21 targets agreed to in Paris, the federal government all but ignores it. The most recent example of the lack of awareness among policy-makers is the 2017 amendment to the EEG, Germany's renewable energy law, from which gas produced by wind and solar is virtually absent.**

Limit global warming until 2050 to 1.5 °C compared to pre-industrial levels – that was the groundbreaking as well as ambitious target set during the Paris Climate Conference last December. The federal government did sign the internationally binding agreement. A laudable step in the right direction. But now, deeds must follow words.

If Chancellor Merkel, economic minister Gabriel and environment minister Hendricks intend to take the global climate deal seriously, the government needs to drastically increase the speed at which to transform the energy sector. We can no longer wait until 2050 for an emission-free economy, as shown in the "Sector Integration Study" published by HTW University of Applied Sciences, Berlin, in June 2016. We can no longer limit ourselves to an 80 to 95 percent reduction in GHG emissions, especially $CO_2$, as intended by the federal government. Quite the opposite: The emission targets set in Paris mean we must achieve a full decarburization of all parts of our economy by 2040, based on an analysis by HTW professor Volker Quaschning.

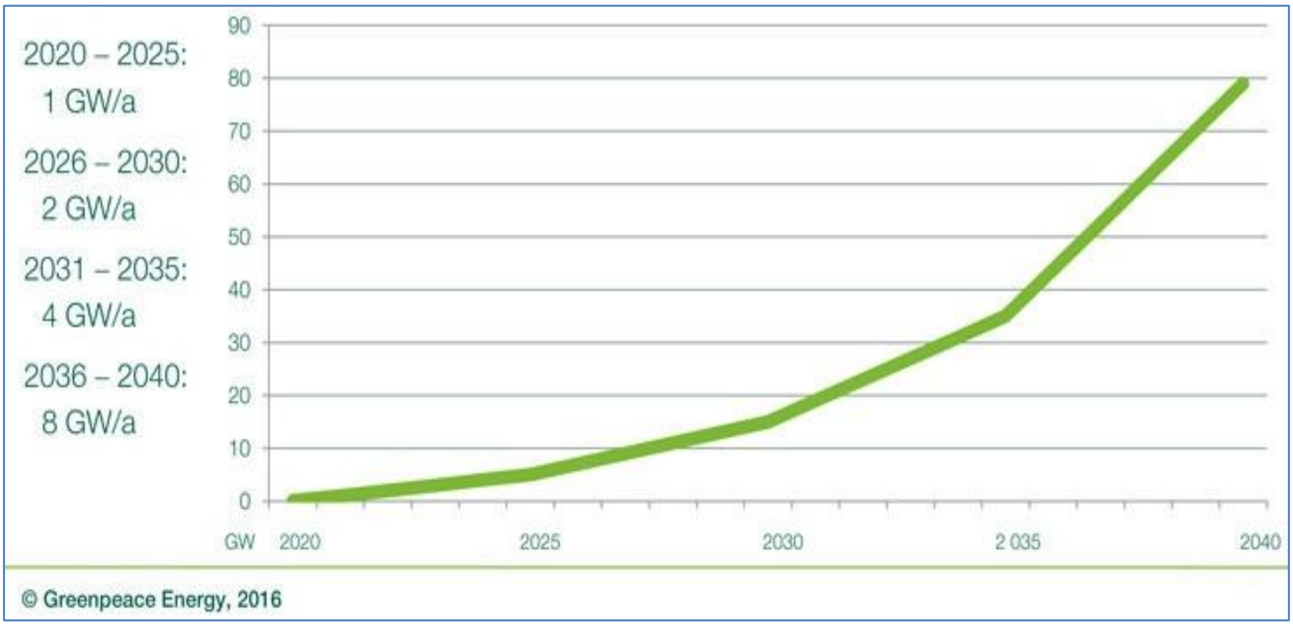
The needed change will be met with much resistance. But the transformation is possible if we draw the right conclusions from the Paris summit – and quickly. Greatly improved energy use at home and in business are only two things that the HTW researchers suggest. They have additionally identified three key requirements for effecting a successful transformation of the sector:

1) Phase out coal by 2030. But the federal government – and here, especially the chancellor's office led by the Christian Democrats and economy minister Gabriel from the Social Democrats – has just been kicking the can further down the road.

2) Grow wind and solar at a rate three times faster than planned by the government and implement comprehensive measures to improve energy efficiency. This could make it possible to meet an annual renewable energy demand of 1,320 terawatt-hours, a doubling of today's power consumption (including coal and nuclear energy), by 2040. The jump in demand will be a result of the necessary switch from fossil fuels to renewable electricity in the transportation, heat and industrial sector. At the present rate of decarburization, the suggested terawatt-hour target could only be met by around 2150 – which would be entirely irresponsible of us.

3) Add large storage capacities for renewable energy. After all, the principal requirement of an industrialized country like Germany is reliable energy supply, even if the national grid receives its electricity from renewable sources only. And if the wind does not blow or the sun hides behind the clouds – maybe even over longer periods of time – those additional capacities will prove essential.

**Minimum: 80 GW of electrolysis capacity**




The only technology that will be able to meet potential storage requirements is "power to gas." It is used to create hydrogen and methane from (ideally, excess) wind and solar energy. The amount that can be stored in the existing gas grid will secure power supply for up to three months. To cover the demand determined by Quaschning's research team, renewable storage needs to provide at least 80 gigawatts of capacity. Only then will it create enough hydrogen to meet the needs of consumers, as calculations by Greenpeace Energy show. To guarantee effective climate protection, we need to start increasing capacity immediately. The federal government, however, has chosen to ignore this important subject altogether and there are no references to it in the new EEG 2017 amendment.

And this although circumstances are favorable: Last year, Regensburg University of Applied Sciences professor Michael Sterner discovered that one consequence of the energy transformation and the switch to renewable sources, mainly to wind and PV, has been an increase in excess power. This excess amount is estimated at up to 154 terawatt-hours in 2050 or 20 percent of Germany's electricity production from 2012 – a stunning figure. Even if the power industry will initially use other, cheaper options than power to gas when dealing with fluctuations in demand, it would be economically absurd to ignore excess energy for a comprehensive transformation effort. The deployment and expansion of P2G capacities would certainly be a worry-free option.

Additionally, Windgas can be used to balance energy supply and demand anytime and anywhere. It would counter the oft-employed argument by critics of the energy transformation that a renewable power grid could not offer supply security.

**Windgas to save billions**

But that message does not seem to have gotten through to politicians. The federal government is apparently afraid that the outstanding 20 percent of renewable plant capacity will prompt a dramatic cost increase in transforming the sector.

The opposite is true, says a February 2015 analysis by Berlin-based Energy Brainpool: Starting maybe below, but certainly at a renewable share of around 75 percent (which Germany will likely achieve between 2025 and 2030, Quaschning says), a power grid using power to gas will be less expensive than one that doesn't. From that point on, the technology will save the economy billions and billions more each year thereafter, despite – or rather thanks to – fully renewable-sourced electricity supply. Conversely, a grid without power to gas would have a maximum renewable share of 86 percent, regardless of how many wind turbines or solar collectors are added to the mix. These weather-sensitive volatile sources make gaps in power production unavoidable and such gaps will have to be bridged by fossil fuels – which, in turn, produce $CO_2$ emissions.

**A plea for political leadership**

To establish the needed production capacities for Windgas, politicians and industry stakeholders need to act now. So far, unfairly designed regulations have stifled technological innovations. They have allowed the creation of only a few suppliers, such as our cooperative Greenpeace Energy, which have developed viable business models and, through the addition of hydrogen to natural gas, have been able to offer their customers a future-proof and environmentally friendly product that will help popularize the technology.

Meanwhile, the potential of Windgas has also attracted utilities, technology companies and energy corporations, and the German Energy Agency dena has established a power-to-gas platform to offer networking opportunities to market actors and recommendations to politicians. Slowly, the technology is entering the mainstream. The only people who will still have to wake up to the benefits are the ones working in the economy ministry and the chancellor's office – those who can remove the roadblocks for Windgas and pave the way for successful sector integration.

This would also make sense economically. Technology deployment may not need any subsidies in the future, considering the expected efficiency jump of electrolyzers and other transformation technologies as well as falling module prices and the ramp-up of mass production. The relevant ministries must merely remove regulatory barriers and create a balanced market environment. For example, operators of power-to-gas systems still pay above-market prices for excess power. Although they could contribute to balancing grid supply and demand, they continue to be at a disadvantage under current rules. The renewable energy heating law does not term the ecologically greatly important Windgas "renewable," and it is not on par with electric-only transportation either.

Decarburizing the entire economy – as announced with great fanfare by chancellor Angela Merkel during the G7 Summit at Elmau castle – is a task long overdue, and we cannot afford any more delays in the implementation of the binding targets Germany agreed to in Paris. The objectives are clear, the funds available. Now, the federal government needs to show it is committed to turning Germany into a renewable-only nation – through actions, not words.

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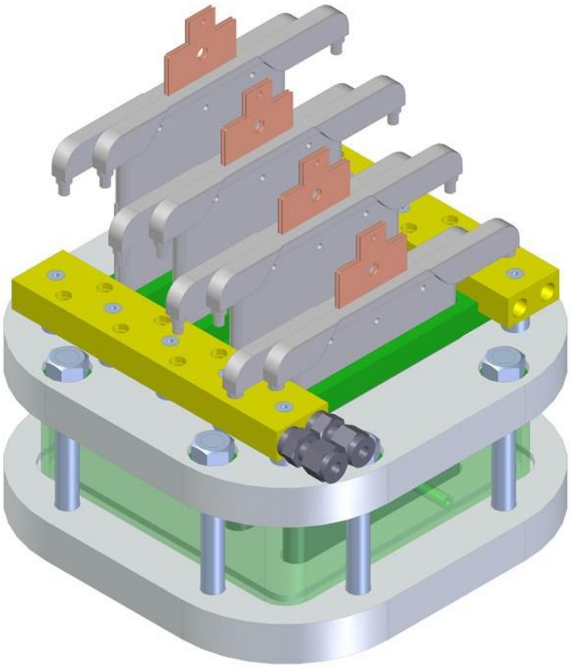
*Author: Sönke Tangermann, CEO Greenpeace Energy eG, Hamburg*

# High-Pressure Electrolyzer in Pocket Size



*Module-based PEM electrolyzer stack*

**Researchers of the Westphalian Energy Institute (WEI) at Gelsenkirchen Bocholt Recklinghausen University of Applied Sciences (WH) have developed a pocket-size PEM unit for water electrolysis. The electrolyzer stack is based on the WEI-invented method of hydraulic compression of individual cells [1] through the use of a patented control system [2]. The process allows for an alignment of hydraulic and gas pressure at the start-up of the system to achieve almost any pressure level for hydrogen production. The pressure level required to compress individual stack cells can be kept constant across the entire system, making mechanical component stability the only issue to consider.**

New water electrolysis systems should take advantage of the improved direct feed-in of mainly renewable hydrogen into the natural gas grid. By removing the need for additional mechanical compression, the novel design increases overall efficiency and eliminates a wear-prone mechanical component. The result is a reduction in overall system cost. The prototype unit was developed jointly with iGas engineering from Solingen during a publicly funded ZIM project (funding ID: KF2697002ZG3).

**WES 2016 showcase**

In April 2012, HZwei had already reported about a similar PEM fuel cell stack design that used hydraulic means to compress individual cells instead of the nowadays common mechanical connection of the bipolar cell arrangement. The design served as a good example to demonstrate the benefits of equally distributing pressure across cells and controlling their temperature. This approach has since been used to develop a PEM electrolyzer prototype to provide hydrogen or oxygen at high initial pressure, for example, for use in power-to-gas plants. It was presented at the World of Energy Solutions in Stuttgart on Oct. 10, 2016.

*Fig. 2: WEI employees (U. Rost, J. Roth and P. Podleschny; from left) put the screws into the pressure tank, © WH/MV*

The prototype includes a high-pressure storage unit with four pockets (see figure 1) and another one that encloses this structure and is used to increase pressure as described above (see figure 2). The pockets are composed of commercially available tube parts attached through wedge-shaped terminals to the top and bottom of the unit. The openings in the terminals have so far been able to incorporate up to four electrolyzer cells connected in series. Electrical contact between cells is established by gold-plated copper wires on the pockets' exterior. The anode and cathode of a cell is then supplied with water through two separate gas diffusion layers. The interface between the cell and gas diffusion layer is created by a clip system at the top of each cell [3, 4].

To validate the functionality of the PEM electrolysis unit, a test stand was specifically adapted for the requirements of hydraulically compressed electrolyzer cells. It contains three separate water circuits, whereas the pressure levels in the cell channels (at anode and cathode) and the hydraulic circuit are controlled independently. This validation system successfully proved the capabilities of the prototype unit in WEI laboratory tests up to a pressure of 5 bar [5]. The increase in pressure kept pressure levels constant throughout the device, so that the cells could operate at their maximum efficiency.

These tests have also shown that the hydraulics medium can be decoupled to transfer produced heat out of the system for use by an external heat exchanger. If future applications employ combined power and heat, the stack design can contribute to the production of ecologically sourced heat. Devices to produce hydrogen at pressure levels above 50 bar are under development. Thanks to a new grant program by the federal science ministry, a new component test stand can be used by the WEI working group next year to test new units with a pressure of up to 50 bar.

**Fully modular PEM electrolyzer with multilayer, planar pole plates**

In March 2016, a consortium of iGas engineering, ProPuls, Obitronik and WH began work on the next prototype stages of the high-pressure electrolyzer unit (Lead Market Competition in North Rhine-Westphalia, funding ID EFRE-0800099). The aim is to develop a PEM electrolyzer stack where horizontal cell segmentation can increase the voltage of each “cell” and reduce the overall amount of electricity. This will improve the conversion ratio for the intended use in power electronics and reduce power-based losses as well as increase system efficiency. You can find more information about the research project on the website of the Westphalian Energy Institute [6].

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# Green Hydrogen from Central Germany


Award ceremony, © Metropolregion Mitteldeutschland

HYPOS has been successful in making the transition from an idea on the drawing board to a big consortium that has sparked a variety of projects. Ten years ago, almost nobody knew of the combined hydrogen expertise in mid-Germany. Now, HYPOS has amassed a network of 116 partners, 75 from business and 41 from the scientific community.

HYPOS is short for Hydrogen Power Storage & Solutions East Germany (see HZwei issue from July 2013). The project was initiated by the Central German Metropolitan

Region, the Fraunhofer Institute for Microstructure of Materials and Systems, and the Chemistry/Plastics Cluster Central Germany and is part of the Entrepreneurial Regions initiative, launched by the German education ministry (BMBF) to strengthen ties between businesses.

The main office of HYPOS is in Halle, but the network partners are not all based in the middle of Germany. Organizations from Rostock and Freiburg have joined the project, although most enterprises are indeed headquartered in Saxony-Anhalt and Thuringia as well as North Rhine-Westphalia. Together, they intend to provide a big boost to the energy industry’s transformation and establish a hydrogen showcase region by 2020. The tasks range from making the chemical industry more sustainable to supplying renewable power for electric transportation.

**Twenty20**

HYPOS is part of the program Twenty20 – Partnership for Innovation, which will receive overall financial support of up to EUR 45 million from the BMBF. Its aim is to give new impetus to “cross-border” R&D efforts between the German states established pre- and post-1989.

One project sparked by HYPOS was launched as recently as July this year. The aim of the three-year, three-million-euro $H_2$ PIMS is to develop a so-called pipeline integrity management system. The system must be compatible with the existing natural gas infrastructure, so the grid can still be used when hydrogen is added. The project will ensure that pipelines meet operational safety standards for transporting hydrogen-rich gases.

One of the primary objectives of the network is the establishment of a test site for water electrolysis. Plans to set up a demonstration system are in full force. The second important aim is a feasibility study for repurposing an underground natural gas cavern at Bad Lauchstädt, Saxony-Anhalt, and turn it into hydrogen storage.

**Testing any and all electrolysis technologies**

There are yet other methods being tested to make the most of economically feasible, large-scale wind and solar-based hydrogen production through electrolysis. Spring 2017 is said to be the starting point of a new AREVA H2Gen project that seeks to develop a cost-effective and efficient 2 MW system to produce hydrogen through PEM electrolysis. The project is called MegaLyseur, has a budget of EUR 14.2 million and is reported to lead to the construction of a pilot system in Leuna (more about the project can be found in the next HZwei issue in April 2017).

But PEM-based production is not the only electrolysis method being researched: Kumatec intends to enhance a process that is already thought of as technologically mature: alkaline electrolysis. The development of a high-pressure unit with a starting pressure of 100 bar was rewarded in June 2016 with the IQ Innovation Award Central Germany, endowed with EUR 15,000 (see figure 1). The comparably efficient units could be of particular interest to hospitals, as the oxygen produced during electrolysis can easily be converted into ozone. Kumatec’s managing director, Joachim Löffler, believes that this selling point will lead to breakeven relatively quickly. For the moment, however, the business based in Neuhaus-Schierschnitz and its seven project partners from Thuringia, Saxony-Anhalt and Hesse will focus on wastewater treatment plants.

The third technology is high-temperature electrolysis, which is being tested by sunfire (see FC on board – MFC & SOFC in maritime applications). The principal research goal is cost reduction. Tapping the cost-cutting potential of different technologies (e.g., through technological advancements and economies of scale) is intended to make this type of energy conversion and storage commercially viable. And centralized solutions are said to be combined with decentralized systems to reduce the burden on power grids and hydrogen supply across the region.

Christoph Mühlhaus, chair of the eight-people HYPOS board and spokesperson of the Chemistry/Plastics Cluster Central Germany, explained: "Green hydrogen offers the chemical industry in central Germany the long-term opportunity of breaking from a complete dependence on oil and gas." But his plans go much further: "While we as HYPOS will show until 2019 that green hydrogen is all in all ready for the competition, our aim is to join a first big water electrolysis plant with a large cavern for hydrogen storage during the Power-to-X Copernicus project starting in 2020."

The biggest benefits of having the site in mid-Germany were the good infrastructure around the chemical industry triangle Halle (Saale) – Merseburg – Bitterfeld and the profound knowledge of every step of the green hydrogen value chain, from production and transport to storage and utilization.

**Funding is available**

The HYPOS board recommended a total of ten projects during the first program stage in early 2015. The first to receive grant approval by the BMBF was Local Hy. Another two were approved at the beginning of 2016. Fragrances, managed by Miltitz Aromatics, is developing an inexpensive and ecological method for creating syngas from green hydrogen and biogenic carbon dioxide. The other one, H2 MEM, focuses on carbon membranes for separating natural gas and hydrogen in shared grids.

Another eight projects for EUR 28.7 million were recommended in early 2016. Notification about approval was expected in the middle of this year, but has not been granted yet. Meanwhile, there was another application period that had started in May and accepted proposals until September.

If it fits the strategy, fund applications through HYPOS may be accepted until Dec. 31, 2019. Bernd Schumann from Jülich, which manages the project, told H2-international that there was certainly enough money available.

www.hypos-eastgermany.de

# Meta-Study: Hydrogen Is Competitive


Renewably sourced hydrogen has recently gained considerable importance in several economic sectors at once. The automotive and fuel industry sees it primarily as a way to power fuel cell vehicles, whereas its main use in the natural gas industry is for grid feed-in. The diversity of applications means that different industries will employ different technological and economic strategies for utilizing hydrogen. To compare strategies and examine the combined utilization potential, the National Organization Hydrogen and Fuel Cell Technology (NOW) and the German Technical and Scientific Association for Gas and Water (DVGW) decided to join forces and commission a study on the joint use of hydrogen as fuel and grid supply.

The “Meta-Study to Examine the Potentials of Hydrogen for the Integration of the Transportation and Energy Economy” combines the results from the two studies “Integration of Wind-Hydrogen Systems in the Energy System” by NOW [1] and “Modular Designs to Create, Store and Feed In Hydrogen and Methane Into the Natural Gas Grid” by the DVGW [2]. The NOW study examined large-scale wind-hydrogen systems and evaluated the potential of hydrogen as fuel supply for FC vehicles and the sale of electricity for grid balancing. The DVGW study focused on hydrogen feed-in into the gas grid and the fuel’s subsequent use in stationary applications. Both studies include comprehensive analyses on technological and economical aspects.

The first part (1) of the meta-study assesses and validates the core statements of the studies on which it was based and integrates those into newly devised “value chains” or the production and sales opportunities of renewable hydrogen (2). These value chains go far beyond the few options mentioned in the source papers and are its key contribution. Above all, the combination of value chains in the meta-study makes it possible to explore and quantify efficiency gains, something which had not been attempted before. The authors of the meta-study also take a look at the research and development demand that had been estimated and compare it to current and completed R&D projects (3). Based on these comparisons, they go on to suggest designs for future demonstration projects (4).

**Two studies compared**

The comparison (1) analyzes the issues examined in both papers: technological components, investment and operational cost of hydrogen supply, and market prices. In principle, there are indeed differences between individual hydrogen markets and production methods, and both studies include a number of distinct plant designs. For example, the DVGW paper examined several power-to-gas plants with an electrolysis capacity of up to 144 $MW_{el}$, whereas the NOW authors focused on only one wind-hydrogen system with a capacity of 500 $MW_{el}$. Both studies additionally explored a variety of technological and economic variants, of which merely a portion are compatible with each other. Nevertheless, the comparison has shown that there are significant agreements of technological, cost and price aspects. One of these similarities is the – crucial – specific investment cost of electrolysis. This means that we have a reliable data set available to design new value chains.

During analysis, the value chains are specified based on the production processes and sales opportunities that were suggested in the two base studies (2), Additionally, the factors that were calculated and validated in the comparison are being integrated as core elements into individual value chains. The first stage of the analysis defines stand-alone scenarios: Industry, Transportation, Gas Grid and so on. The second determines the power production cost of hydrogen and potential market prices. When we compare the cost of electricity generation to fossil fuel-based methods or with achievable market prices, renewable hydrogen displays a lack of competitive ability: The Industry scenario shows EUR 7.54 per kg of $H_2$ against a base value of EUR 2.13 per kg of $H_2$, the Transportation scenario EUR 11.65 per kg of $H_2$ against EUR 5.96 per kg, and the Gas Grid one results in EUR cent 20.98 per kWh of $H_2$ compared to EUR cent 3 to 4 per kWh of natural gas.

However, it seems reasonable to assume that the joint use of systems to meet demand in several markets will ensure economies of scale and a better utilization of a value chain’s technical components. The improvements could lead to an increase in capacity and electrolysis utilization, and costs could drop relative to sales volume. The market integration will increase demand. Whereas the cost of investment accounts for a considerable portion of overall costs in individual scenarios, combining more than one value chain by expanding the number of hydrogen applications could prompt a notable price reduction in relation to quantities. A combined approach also provides more flexibility in operational management and plant use, and it would facilitate strategies such as raising the full-load hours of electrolysis and cutting related expenses.

To determine and quantify synergy effects, the value chain analysis creates combined-use scenarios. These scenarios combine more than one individual use case to create different options, with a main value chain describing the principal market for hydrogen and other subordinate chains to complement it. For instance, the Industry scenario primarily creates hydrogen for chemical processes, but also supplies fuel cell vehicles and feed-in into the natural gas grid. Transportation's overriding aim is to supply the fuel market, but hydrogen is offered for natural gas mixtures as well. The Gas Grid scenario is used mainly for hydrogen feed-in, but includes some supply for transportation. These, however, are only the most important scenarios; there are many more shown in the study.

**Immense cost-cutting potential**

The combined-use scenario Industry cuts the cost of producing electricity from hydrogen by seven euro cents compared to the stand-alone version and brings total cost down to EUR 7.47 per kg of $H_2$; Transportation cost is reduced by EUR 3.60 to EUR 8.05 per kg of $H_2$ and the Gas Grid scenario will cut them by 1.54 euro cents to EUR cent 19.44 per kWh of $H_2$. The combination of different value chains has driven down costs in transportation by an impressive 34 percent and brought it much closer to the fossil fuel figure.

A subsequent sensitivity analysis explores additional cost-cutting potential. The – extremely influential – increase in an electrolysis system's operational availability from 2,000 to 4,000 full-load hours enables the combined-use scenario Industry to cut power production costs to EUR 4.49 per kg of $H_2$, reducing them by EUR 3.05. In Transportation, costs fall by as much as EUR 6.86 to EUR 4.79 per kg of $H_2$; the Gas Grid price drops by 9.34 euro cents to EUR cent 11.64 per kWh of $H_2$. Compared to the fossil fuel scenarios, the transport cost maximum of EUR 5.96 per kg of $H_2$ could be achieved or even underrun. Compared to the stand-alone scenario, cost was cut by 64 percent. Whereas the other two combined-use designs do not meet cost targets, the gap between fossil fuels and renewables is nevertheless getting smaller. Data collected from relevant market actors suggests that Industry scenario cost is approaching acceptable limits. The sensitivity analysis also explores the cost-cutting potential of reduced electricity supply prices and technological advancements. The potential of both of these options is enormous and could greatly improve the feasibility of the use cases outlined above.

**Need for R&D / Outlook**

The meta-study also compares the development and research demand determined in the two base studies and updates information on certain parts of it (3). For instance, important objectives of future electrolysis R&D are improvements in efficiency, more flexibility of operation and a reduction in specific investment costs. By comparing the research and development demand with the one of already realized demonstration projects, the authors develop ideas on how to design similar projects in the future (4). In light of the advantages of combined use and the additional improvement options revealed by the sensitivity analysis, it is recommended that demonstration projects be designed based on particularly promising combined-use scenarios while other opportunities for enhancement are to be sought additionally. For instance, it would be helpful to verify the statements made for the Transportation scenario during a demo project and use the opportunity to do more much-needed and important research and development.

The meta-study was conducted by research institute DBI Gas- und Umwelttechnik, with contributions by planning and consulting firm MW-quadrat. NOW and DVGW funded the study with EUR 20,000 (net value) each; the data it contains is from mid-2015.

www.now-gmbh.de

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[2] Müller-Syring, G., Henel, M., u. a., Entwicklung von modularen Konzepten zur Erzeugung, Speicherung und Einspeisung von Wasserstoff und Methan ins Erdgasnetz, Feb. 2013.

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# PowerPaste for Fuel Cells in Off-Grid Systems

**As a secondary energy source, hydrogen has long demonstrated some key benefits. It has a high specific energy, good efficiency and guarantees emission-free use. But market take-up has been slow in many promising areas, often because the available storage solutions have proven too costly or had technological issues. Most of the time, however, a more challenging market barrier is the lack of infrastructure or exorbitantly high logistics costs. The new PowerPaste development by Fraunhofer IFAM has the potential to change all of that.**

The production of $H_2$ through the hydrolysis of metal hydrides or other materials easily oxidizable in water (Old Greek: hýdor = water; lýsis = dissolution) has long been known as an alternative to $H_2$ storage units (high-pressure or cryogenic tanks) available on the market today. For example, calcium hydride – marketed under the trade name “Hydrolith” – has been used as a portable, commercially available hydrogen source to refuel weather balloons or even airships since 1910 [1, 2].

Calcium hydride reacts with water to form calcium hydroxide and hydrogen gas. One kilogram is enough to produce 1,070 L of hydrogen under standard conditions in an exothermic reaction:

$CaH_2$ + 2 $H_2O$ à $Ca(OH)_2$ + 2 $H_2$ $\Delta H_R$ = −186 kJ / mol

However, this kind of chemical bonding had faded into the background, mainly because of the high costs involved, a better availability of gas cylinders, heightened safety concerns and stricter regulations on hydrogen use as a propulsion gas [3]. But today's marketing of fuel cells has given a new impetus to chemical solutions generating $H_2$.

**Sodium borohydride as $H_2$ storage**

Although the use of metastable sodium borohydride solutions for off-grid $H_2$ generation had already been suggested by Herman Irving Schlesinger in 1953 [4], it was in the 1980s that the technology sparked much research and became highly recommended for fuel cell applications [5]. Sodium borohydride is similar to calcium hydride in its reaction with water. In addition to hydrogen, it creates the dangerous compound sodium meta-borohydride as a waste product (irritating to eyes, respiratory system and skin, and suspected to be reprotoxic; EU CMR category 2):

$NaBH_4$ + (2+n) $H_2O$ à $NaBO_2 \cdot$ n $H_2O$ + 4 $H_2$ (n = 2, 3 or 4) $\Delta H_R$ = −212 kJ / mol

*MgH2-based PowerPaste*

Benefits are a higher nominal storage capacity compared to calcium hydride and the somewhat better controllability of $H_2$ production through a catalyst. Some readers may still remember the history of US-based Millennium Cell: Shortly before the company went bankrupt in 2008, the main product it intended to sell was a portable power generator named HydroPak. This generator was to utilize a sodium borohydride solution prepared by the user to produce hydrogen through hydrolysis. The hydrogen would then be converted into electricity inside a PEM fuel cell to charge laptop computers or TVs [6].

Similar cartridge designs are currently being developed by myFC based on available or announced, but much smaller power generators: PowerTrekk (see HZwei issue from April 2015) and JAQ or HES. The latter uses the AEROPAK L Series for the ultra-lightweight power supply of unmanned aerial vehicles or drones through hydrolysis.

However, one of the challenges of the technology is that each solution mentioned above requires an estimate of its total energy demand in advance. The hydride continues to react with the water to form hydrogen after both elements have been mixed – regardless of whether a consumer needs energy at that time or not. The process is also limited to a relatively narrow and predefined capacity demand.

Moreover, the theoretically possible amount of hydrogen is rarely achieved under real-life conditions. What remains is a waste product rich in toxic sodium borohydride that was not allowed to react. And the excessive amount of water that the process requires greatly reduces the specific energy of the entire system. But the most severe drawback may be that the high material prices, the use of expensive catalysts and complex packaging, and broken promises in regard to recycling have driven up power generation costs to levels where the above-mentioned solutions will be attractive to niche market customers only.

Our own calculations show electricity production based on $NaBH_4$ to add up to more than EUR 20 per kWh. Even in the future, it is hard to see how power could be produced in this way for considerably less than EUR 10 per kWh.

**The better choice: magnesium hydride**

One still relatively unknown material for hydrolysis-based $H_2$ production is magnesium hydride:

$MgH_2 + 2\ H_2O$ à $Mg(OH)_2 + 2\ H_2\ \Delta H_R = -276$ kJ / mol

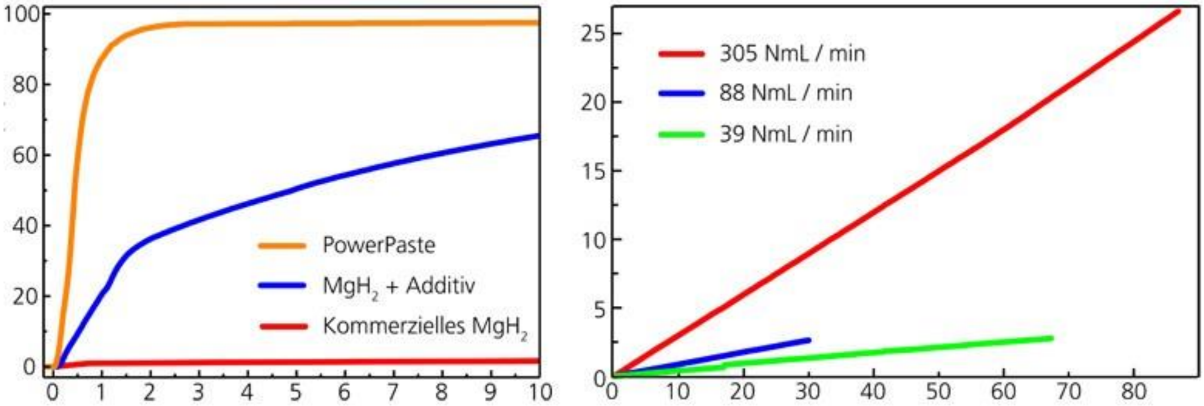


*Fig. 2: Left – uncontrolled hydrolysis of untreated magnesium hydride / magnesium hydride with Fraunhofer IFAM additive and PowerPaste; right – H2 production from PowerPaste and water; controlled reaction through metering system and microcontroller unit*

Magnesium hydride also reacts with water in an exothermic reaction to form harmless magnesium hydroxide and hydrogen gas. One kilogram equates to 1,700 L of hydrogen (= 150 grams of $H_2$ or 5 kWh). But what makes magnesium hydride so appealing is its non-toxicity, extremely high stability, abundance of a base element (magnesium) and comparably low costs for the production of the material and, subsequently, the electricity. An example of commercial implementation in a fuel cell application is Ryoden's / Biocoke Lab's tool box-size 33-watt power generator MAGPOPO, which was presented at the Hanover trade show last year.

However, the process does have one drawback: the reaction time is relatively long. The passivation layers that form when the two reactants come in contact slows down hydrolysis considerably (see figure 2 left, red curve). Adding water to a supply of magnesium provides very little control over the reaction and the potential performance density is limited as well. Additionally, $H_2$ production may be interrupted and it is not possible to start and halt the process at will.

**Paste for good measure**

These challenges have led to strong improvements in hydrolysis technology at the Dresden location of Fraunhofer IFAM. Both material and system design were enhanced. First, the magnesium hydride received non-toxic and cheap additives to prevent passivation (see figure 2 left, blue curve). [7, 8] Second, esters were added to create a paste-like material: the PowerPaste (see figure 1). This paste is extremely fast in reacting with water (see figure 2 left, orange curve), providing full control over $H_2$ production and a steady volume flow with the help of a metering system (see figure 2, right).

In contrast to known slurry-based methods using mineral oil [9], all components are non-toxic and non-volatile, resulting in high-purity grade hydrogen. It makes PowerPaste a particularly good fit for PEM fuel cell applications. Net energy density is extremely high because of a very large share of solid matter (see figure 3), whereas power production is comparably inexpensive. The price of material for electricity generation adds up to around EUR 4.50 per kWh, in-house calculations show. In the future, this amount could be lowered to somewhere between EUR 1.40

and 2.00 per kWh, which we believe gives PowerPaste the edge over other chemical hydrogen production methods.

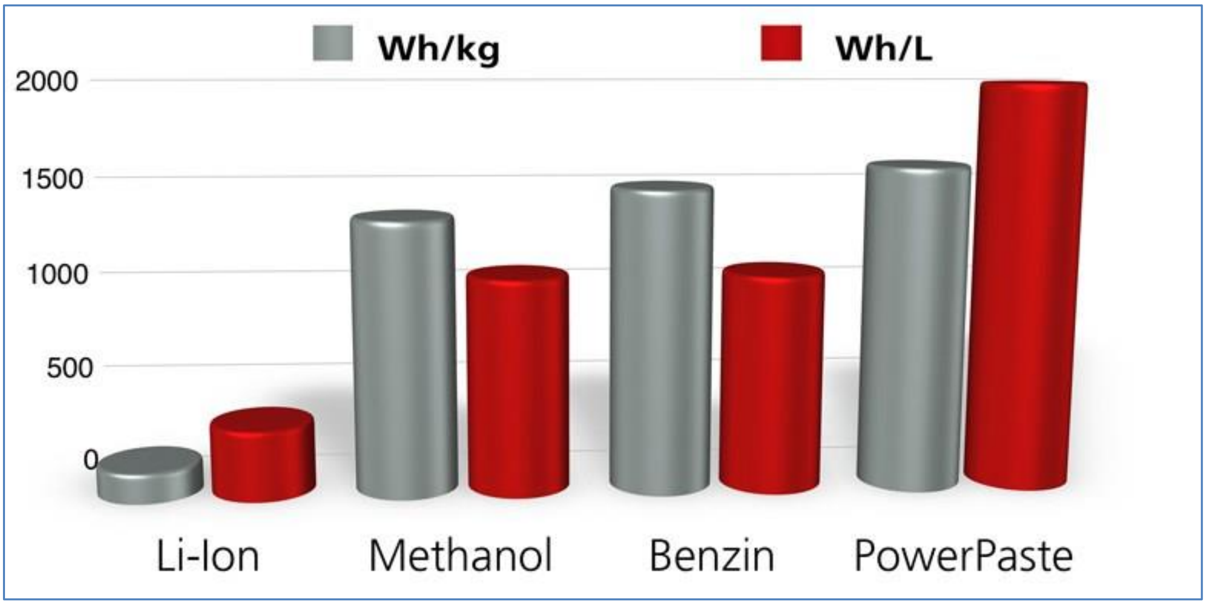


*Fig. 3: Comparison of the specific energy and energy density of lithium-ion batteries, methanol (DMFC), gas (Generator) and PowerPaste (PEMFC), including efficiency losses during energy conversion (based on 1 kW of maximum capacity)*

**50-watt and 300-watt demonstration system**

That the technology is feasible has already been proved by two stationary and operational power generators. Developed during Fraunhofer IFAM projects in less than a year, the 50-watt demonstration system of technology readiness level 4 and the movable 300-watt generator of level 5 (see figure 4) have been tested to show that hydrolysis can be used in PEM fuel cells for long-term and on-demand power generation. The generators include a microcontroller unit and a special kind of metering system to ensure the correct amount of PowerPaste is added to the water and will produce as much hydrogen as the fuel cell requires, even if demand differs considerably.

Overall, the chemical production of hydrogen through PowerPaste hydrolysis offers large economic potential. We believe that it is greatest in transportation and in the portable fuel cell market for applications that require a capacity of between 10 watts and several kilowatts and a transportable energy content of somewhere between 500 watt-hours and 100 kilowatt-hours. In many markets, these requirements meet or exceed the cost and weight limits of the average battery available today. The more energy needs to be transported and the more difficult battery charging is in an application, the cheaper and more apt will chemical generation by fuel cell be. It makes the use of the technology especially well-suited for energy-hungry use, e.g., in lightweight transportation (consumer and electric fleet bikes, etc.), logistics, drone and unmanned aerial vehicles, telecommunications (ad-hoc networks), generators (expeditions and outdoors), military devices, but also in electric wheelchairs and life-support systems.


Fig. 4: *300-watt PEM fuel cell demonstration system used for PowerPaste hydrolysis and connected to an electric cargo bike*

Transportation and portable systems, however, are not the only fields for which chemical hydrogen production could be utilized. Some stationary applications need to be grid-independent, highly reliable, greatly durable, easy to refill (resources) and have low installation and maintenance costs. Two examples are fuel cell-based emergency power supply and off-grid security and monitoring systems, all of which could greatly benefit from PowerPaste.

Comparing the price of hydrogen supply by pressure storage (gas cylinders or high-pressure tanks) and PowerPaste hydrolysis would certainly be interesting from an economic point of view. Even if a detailed analysis of these uses has not been available yet, PowerPaste is certain to have an appeal beyond mere niche markets.

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## Events

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January 31st to February 3nd, 2017, **Fundamentals & Development of Fuel Cells**, Organised by DLR, in Stuttgart, Germany
https://moreevent.meetingmasters.de

- February 7th to 9th, 2017, **E-world energy & water**, in Essen, Germany, www.e-world-essen.com

- February 16th, 2017, **Fuel Cells for Stationary**, in San Francisco, CA, USA, www.knowledgefoundation.com

- March 1st to 3rd, 2017, **European Fuel Cell Car Workshop**, EFCW2017 is an output of SMARTCat – a FCH-JU project, in Orleans, France, https://efcw2017.sciencesconf.org/

- March 1st to 3rd, 2017, **International Hydrogen and Fuel Cell Expo**, at Tokyo Big Sight, Japan, www.fcexpo.jp

- March 14th, 2017, **Hydrogen & Fuel Cells into the Mainstream**, The 13th International Hydrogen and Fuel Cell Conference #CCSHFC2017, NEC, Birmingham, United Kingdom, www.climate-change-solutions.co.uk

- March 14th to 16th, 2017, **Energy Storage Europe - IRES**, in Düsseldorf, Germany, www.energy-storage-online.de, www.eurosolar.de

- March 15th, 2017, **6th Conference Power-to-Gas**, at Messe Düsseldorf, Germany, www.otti.eu

- March 22th to 26th, 2017, **eMOBILITY WORLD**, Friedrichshafen, Germany, www.e-mobility-world.de

- April 24th to 28th, 2017, **Hydrogen + Fuel Cells + Batteries Group Exhibit**, part of HANNOVER MESSE, in Hannover, Germany, www.h2fc-fair.com

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## Companies

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- **AREVA H2Gen GmbH**, Maarweg 137, 50825 Cologne, Germany, Phone +49-(0)221-888244-88, Fax -67, www.arevah2gen.com
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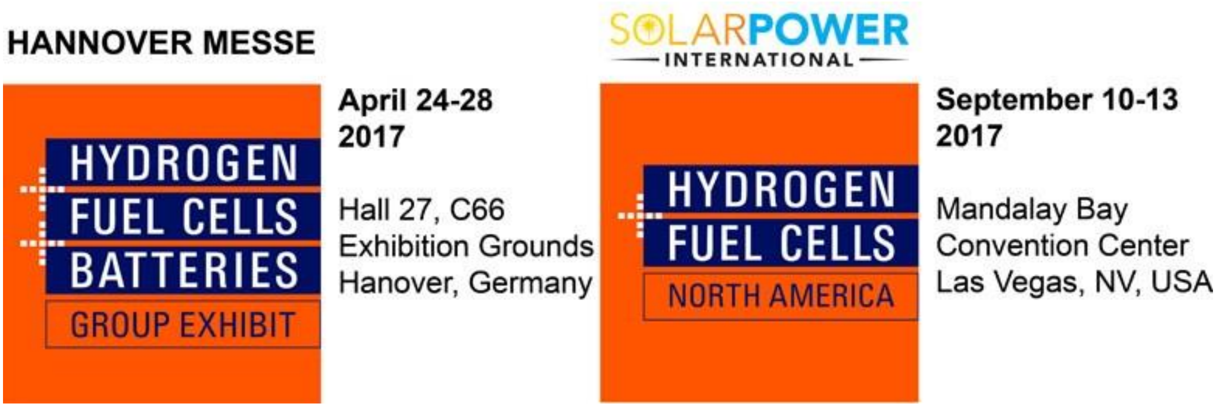


- **23rd Group Exhibit Hydrogen + Fuel Cells + Batteries**, HANNOVER MESSE 2017, April 24 – 28, Tobias Renz FAIR, Tobias Renz, tobias@h2fc-fair.com, www.h2fc-fair.com


- European Fuel Cell Forum, Obgardihalde 2, 6043 Luzern-Adligenswil, Switzerland, Phone +41-4-45865644, Fax 35080622, forum@efcf.com, www.efcf.com


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- **National Organisation Hydrogen and Fuel Cell Technology (NOW GmbH)**, Fasanenstr. 5, 10623 Berlin, Germany, Phone +49-(0)30-3116116-15, Fax -99, www.now-gmbh.de

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