Program on Technology Innovation: Review of the Uniper Energy Storage GmbH Power-To-Gas (P2G) Demonstration Projects at Falkenhagen and Hamburg-Reitbrook, Germany

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EPRI Project Manager

M. Pellow

ELECTRIC POWER RESEARCH INSTITUTE
3420 Hillview Avenue, Palo Alto, California 94304-1338 ▪ PO Box 10412, Palo Alto, California 94303-0813 ▪ USA
800.313.3774 ▪ 650.855.2121 ▪ askepri@epri.com ▪ www.epri.com

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THE FOLLOWING ORGANIZATION, UNDER CONTRACT TO EPRI, PREPARED THIS REPORT:

Evenlode Associates

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Evenlode Associates
Hillside, Albion Street, Chipping Norton
Oxfordshire, England OX7 5BH

Principal Investigators
J. Carolin
A. Jones
P. Sharman

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ABSTRACT

Uniper Energy Storage GmbH has undertaken two power-to-gas (P2G) energy storage demonstration projects in Germany. The first, at Falkenhagen, sought to demonstrate the coupling of intermittent surplus renewable energy to the storage capacity of the natural gas grid using conventional alkaline electrolysis cell (AEC) based systems to generate hydrogen which was then fed into the high-pressure transmission gas grid. The second, at Hamburg-Reitbrook, demonstrated the potential of proton exchange membrane electrolysis cell (PEMEC) technology to generate hydrogen for P2G systems.

The Falkenhagen project demonstrated that conventional AEC hydrogen production plants employ a robust technology that is ready for market deployment in P2G facilities, and that AEC systems can fulfil the technical requirements of the German secondary negative balancing power market. the overall efficiency of the AEC systems was 60-65% (based on the higher heating value of hydrogen). The AEC systems were able to consistently meet all the gas grid entry control requirements.

The Hamburg-Reitbrook P2G project demonstrated the ability to produce hydrogen using PEMEC technology at the scale required for this application. This technology was better able to respond effectively to a variable source of excess electricity, such as wind power, than was the conventional AEC technology. The overall efficiency of the PEMEC system was 70-75% (based on the higher heating value of hydrogen). The PEMEC facility was also able to consistently meet all the gas grid entry control requirements.

Based on the experience of these two projects, PEMEC technology, with its smaller footprint, higher efficiency, superior dynamics and more opportunity for future cost reduction, appears to be the clear leader over AEC technology for future P2G facilities. However, under current market conditions, the simple arbitrage model implemented by these projects (purchasing electricity under normal commercial terms) is not a viable economic model. Other market mechanisms are required for viable P2G projects that address the opportunities of integrating the electricity, heat, transportation, and chemical sectors.

Keywords

Power-to-gas (P2G)
Renewable energy
Alkaline electrolysis cell (AEC)
Proton exchange membrane (PEM) electrolysis cell
Hydrogen

GLOSSARY OF TERMS AND ACRONYMS

AEC	alkaline electrolysis cell
ATEX	ATmosphéres EXplosibles - EU Directives for protecting employees from explosion risks
bar(g)	gauge pressure in bars above ambient or atmospheric
cm	centimeter
cm^2	square centimeter
CNG	compressed natural gas
DC	direct current (electricity)
DLR	German Aerospace Center (Deutsches Zentrum für Luft- und Raumfahrt e.V)
DVGW	German Technical and Scientific Association for Gas and Water (Deutscher Verein des Gas- und Wasserfaches)
EU	European Union
h	hour
HGC	Hamburg Gas Consult GmbH
Hz	hertz
ISE	(German) Institute for Solar Energy
ISO	International Organization for Standardization
km	kilometer
kV	kilovolt
kW	kilowatt
kWh	kilowatt hour
M	million
mg	milligram
mm	millimeter
MW	megawatt
MWh	megawatt hour
m^3	cubic meter
Nm^3	cubic metre, measured at Normal temperature (15°C) and pressure (1 bar)

P2G	power-to-gas
PEM	proton exchange membrane
PEMEC	proton exchange membrane electrolysis cell
ppm	parts per million
SNG	synthetic natural gas
V	volt
€	euro (currency)
%	percentage
°C	degree centigrade
μS	micro Siemens

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1 SUMMARY

Uniper Energy Storage GmbH has undertaken two power-to-gas (P2G) energy storage demonstration projects in Germany. The first, at Falkenhagen, sought to demonstrate the coupling of intermittent surplus renewable energy to the storage capacity of the natural gas grid using conventional alkaline electrolysis cell (AEC) based systems to generate hydrogen which was then fed into the high-pressure transmission gas grid. The second, at Hamburg-Reitbrook, sought to demonstrate the potential of using proton exchange membrane electrolysis cell (PEMEC) technology to generate hydrogen for P2G systems. The scale of this demonstration represents prototype hydrogen generation technology, with a number of potential benefits compared with AEC technology. A further project has begun at Falkenhagen to add a methanation unit to this facility as part of the European Union (EU) funded STORE&GO project. This project is still early in its engineering and specification phase. The methanation unit will use an innovative catalytic thermal conversion process to produce synthetic natural gas (SNG) from the hydrogen by combining it with carbon dioxide from a biogenic source. Injecting SNG avoids the limitations of the currently low allowable levels of hydrogen in the German natural gas grid.

The Falkenhagen project has demonstrated that conventional AEC hydrogen production plants employ a robust technology that is ready for market deployment in P2G facilities, and that AEC systems can fulfil the technical requirements of the German secondary negative balancing power market. At 60-65%, based on the higher heating value of hydrogen, the overall efficiency of the AEC systems was better than expected in this application. The AEC systems were also able to consistently meet all the gas grid entry control requirements. However, AEC systems have low power densities and therefore have a large footprint. Further, as a mature technology there is relatively less opportunity for future cost reduction, other than as a result of increased sales volume into the P2G application and other new energy applications.

The Hamburg-Reitbrook P2G project has demonstrated the ability to produce hydrogen using PEMEC technology at the scale required for this application. This new technology was better able to respond effectively to a variable source of excess electricity, such as wind power, than was the conventional AEC technology. The overall efficiency of the PEMEC system, in the region of 70-75%, based on the higher heating value of hydrogen, was both better than expected and better than the AEC systems by approximately 10 percentage points. The PEMEC facility was also able to consistently meet all the gas grid entry control requirements. Based on the experience of these two projects, PEMEC technology, with its smaller footprint, higher efficiency, superior dynamics and more opportunity for future cost reduction, appears to be the clear leader over AEC technology for future P2G facilities.

Both projects purchased power on normal commercial terms in Germany. This meant that the energy stored as hydrogen in the grid was at least a factor of 10 times more expensive than natural gas. Under the current market conditions such a value can only be realised for a few hours each year. This simple arbitrage is not a viable economic model for P2G today and other market mechanisms are required. Those mechanisms for P2G need to address the opportunities

and challenges of coupling different sectors; electricity, heat, transportation, and chemical feedstocks. In Uniper's view, P2G should be able to make a major contribution to the further economic development of renewable power and a low-carbon energy system. Existing market mechanisms for natural gas storage, where storage companies are paid for providing a storage service and do not own the energy, might show the way forward for wider application of energy storage.

2

BACKGROUND AND CONTEXT FOR THE FALKENHAGEN AND HAMBURG-REITBROOK P2G DEMONSTRATION PROJECTS

Developments in energy storage are crucial elements towards a more sustainable energy future. In large part, this is due to the need to balance variable demand for energy with intermittent and unpredictable sources of renewable energy. One area of development is widely referred to as power-to-gas. This approach seeks to convert electrical energy to gas, either hydrogen or methane, and then to use existing natural gas distribution infrastructure to store, transport, and deliver the gas. P2G offers the opportunity to store very large quantities of energy over long time periods, but it also offers the opportunity to couple different energy sectors. Generated from excess renewable electricity production, the stored gas can be used as an industrial feedstock (in the chemical industry and in refineries), for heat, for transport (compressed natural gas (CNG) or fuel cells) and for conversion back to electricity.

A number of P2G demonstration projects have been undertaken in order to obtain real-world experience. Two such projects were initiated by collaborative teams originally led by E.ON SE at Falkenhagen and at Hamburg-Reitbrook, in Germany. The site locations are shown in Figure 2-1, below. Both facilities are now owned by Uniper Energy Storage GmbH, a subsidiary of Uniper SE. Uniper was formed when E.ON spun-off its conventional power generation and energy trading businesses in Germany, Europe and Russia in early 2016 and the company was listed on the Frankfurt Stock Exchange in September 2016. Uniper Energy Storage[1] is one of the leading European gas storage operators with some 9 billion m^3 of working capacity at different locations in Germany, Austria, and the UK.

[1] https://www.uniper.energy/storage/en.html

Figure 2-1
Location of the Uniper P2G demonstration projects

The Falkenhagen project sought simply to demonstrate that surplus variable renewable electricity could be coupled to the storage capacity of the natural gas grid. It used conventional AEC systems to generate hydrogen which was then fed into the high-pressure transmission gas grid. The facility was commissioned in August 2013. Later, it was decided that a methanation unit would be added to this facility as part of the STORE&GO project[2] under the EU's Horizon 2020 research and innovation program. This methanation unit will use an innovative catalytic thermal conversion process to produce SNG from the hydrogen by combining it with carbon dioxide from a biogenic source. Injecting SNG avoids the limitations of the low allowable levels of hydrogen in the natural gas grid.

The Hamburg-Reitbrook project sought to demonstrate the potential of using PEMEC technology to generate hydrogen for P2G. The scale of this demonstration represents prototype hydrogen generation technology, with a number of potential benefits compared with AEC technology. The Hamburg-Reitbrook facility was commissioned in October 2015.

[2] http://www.storeandgo.info/about-the-project/

At the time when both the Falkenhagen and Hamburg-Reitbrook projects were conceived, there were concerns about using AEC technology in P2G applications, including that AEC systems:

- were not ideal for following variable loads (because the technology was developed for relatively constant load applications in process industries);
- had limited ability to run in overload condition (i.e. above its rated power) for long periods;
- had cold-start issues;
- had a very large footprint due to low power density;
- generally, needed a product compressor for high-pressure grid injection; and
- had potential operational concerns due to the use of a corrosive electrolyte (potassium hydroxide).

By comparison, some of the questions regarding using PEMEC technology in P2G applications were that PEMEC systems:

- were more expensive than AEC systems, but with much more scope for future cost reductions;
- had a shorter lifetime, particularly in transient operation;
- were no more efficient than the best AEC systems; and
- were not commercially available at utility-scale; but
- had high power density and therefore can be very compact facilities;
- were well-suited to following variable loads;
- had good stop-start dynamics;
- could be run at high levels of overload for relatively long periods; and
- could operate at high pressures and do not need a product compressor for high-pressure grid injection.

Employing the two different electrolysis technologies, the Falkenhagen and Hamburg-Reitbrook projects provided the opportunity to explore these contrasting issues. These projects could also illuminate potential challenges regarding market mechanisms for incorporating such storage approaches into an integrated energy system.

3

THE FALKENHAGEN PROJECT

3.1 Objectives for the Falkenhagen Project

The aim of the first phase of the Falkenhagen project was to demonstrate that energy derived from a renewable energy source can be stored in the natural gas grid, as a way of decoupling consumption from generation, and making it available to other energy- and gas-consuming sectors including transport, industry, and heating. A specific objective at Falkenhagen was to demonstrate hydrogen injection into the high-pressure transmission grid, operated by ONTRAS Gastransport GmbH. The project also aimed to understand the technical and regulatory challenges involved in the development and operation of such plants. The project would allow Uniper to gain experience of costs and of trading, enabling it to define sound business models and, in due course, expand its energy storage business. Market testing would include the supply of a premium gas proposition called WindGas, with a certified 10% hydrogen content. Also, an arrangement would be in place for off-take by the Swiss natural gas procurement and transmission company Swissgas, which would also market a WindGas proposition. Finally, a market test of using WindGas for CNG vehicles in the Czech Republic would be undertaken. Figure 3-1, below, shows the Falkenhagen facility after the completion of the first phase.

The aim of the second phase of the Falkenhagen project, under the EU-funded STORE&GO project, was to demonstrate the conversion of hydrogen into SNG using carbon dioxide from a biogenic source, and subsequent injection into the high-pressure gas grid. Waste heat from the exothermic methanation process would be used in a nearby manufacturing facility.

Figure 3-1
The Falkenhagen P2G facility

3.2 Design of the Falkenhagen Facility

The Falkenhagen facility used six HySTAT 60[3] systems supplied by Hydrogenics GmbH, the German subsidiary of Hydrogenics Corporation[4] of Canada. These were conventional AEC hydrogen production plants. Each of the systems was packaged in a 20-foot ISO container suitable for outdoor installation in Northern Europe and meeting the applicable EU ATEX Directives (designed to protect employees from explosion risks). The design output of each system was nominally 60 Nm^3/h and the datasheet power consumption at the design output was 4.9 kWh/Nm^3. Total power to the facility was 2 MW, supplied via a 20 kV, 50 Hz grid connection. The electrical grid operator was E.DIS AG, a subsidiary of E.ON. Power was transformed down to 400 V, and rectified to DC for supply to the AEC systems. The electrolyte was water with 30% by weight potassium hydroxide (KOH). Feed water treatment was a reverse osmosis system. The systems included chillers which send the process water through gas heat exchangers, significantly improving the gas purification efficiency, and dry coolers to cool down the electrolyte to maintain the appropriate temperature of the system.

On the outlet side of the AEC systems, oxygen came out in the process water stream and was separated and vented to atmosphere. The process water was re-circulated. The wet hydrogen went through a system comprising a twin-bed silica drying unit and a catalytic combustion unit to control oxygen levels in the product hydrogen. Finally, the hydrogen went through a chiller unit.

The grid injection module monitored water content, oxygen and nitrogen – using gas chromatography. For injection into the grid, the hydrogen had to have a water content below 50 mg/m^3 and a temperature between 5 °C and 40 °C. Off-specification hydrogen was vented to atmosphere. Uniper's central dispatch system controlled the AEC system – to follow the required electrical loading and turning down or switching off the plant if the local grid was unable to accept hydrogen because of low flow. The local gas grid operator could only stop injection if the hydrogen was off-specification.

Hydrogen delivery pressure from the AEC systems was 10 bar(g). The standard purity of the hydrogen was 99.9%, with oxygen less than 800 ppm. Two hydrogen compressors, both housed in a single 40-foot ISO container, could take the hydrogen pressure up to 55 bar(g) for injection into the high-pressure transmission grid. Each compressor had a capacity of 250 Nm^3/h, providing some system redundancy. One hydrogen compressor was a piston compressor supplied by Idro Meccanica[5] of a type used in vehicle refueling applications. The other one was a 2-stage diaphragm compressor supplied by Hofer[6]. Finally, a 1.6 km hydrogen pipeline connected the facility to the point of injection into the high-pressure gas grid.

A number of factors determine the allowable level of hydrogen in a natural gas pipeline. Historically, networks to distribute town gas (a mixture of hydrogen, carbon monoxide, and methane) were commonplace, but these have largely been replaced by grids designed solely for

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[3] Details of this system can be found at: http://www.hydrogenics.com/hydrogen-products-solutions/industrial-hydrogen-generators-by-electrolysis/outdoor-installation/hystat-trade-60/

[4] http://www.hydrogenics.com/

[5] http://www.idromeccanica.it/company/

[6] http://www.andreas-hofer.de/en/products/diaphragm-compressors/

natural gas which is almost pure methane. Consequently, when injecting hydrogen into a gas grid today, a number of constraints need to be addressed. These include: the integrity and safe use of the pipelines and network equipment; the efficient use of the grid capacity; and the sensitivity of end-use appliances to hydrogen content. The SBC Energy Institute's Hydrogen-Based Energy Conversion Fact Book[7] contains a useful introduction to these issues.

At Falkenhagen the hydrogen injection rate was controlled so that the hydrogen content in the natural gas pipeline could not exceed 2%. This was a result of the applicable DVGW (German Technical and Scientific Association for Gas and Water[8]) code of practice G262 covering the injection of gases from non-conventional sources such as biogas and hydrogen into the gas grid. In summary, this code generally allows for hydrogen injection of up to 10%, but in each case the operator must check for three conditions. Firstly, if there is CNG refueling downstream of the grid injection point then the limit is 2%. This is because of the materials used in the construction of CNG vehicle fuel tanks, particularly older steel ones. Secondly, if there are combustion turbines operating downstream then the limit is 1-5% depending on the specific combustion turbine equipment being used. Thirdly, if there is underground gas storage downstream which uses aquifers, hydrogen injection is not allowed at all, unless the storage is in salt caverns. In both Falkenhagen and Hamburg-Reitbrook the result of applying this code of practice was a limit of 2%.

In the Falkenhagen project, change of system ownership occurred at the flange from the hydrogen pipeline into the gas grid. In the absence of applicable regulations at the time, this was the arrangement agreed between the operators. Now the applicable regulations have been amended to include hydrogen and the responsibilities are essentially the same as for biogas, which is to say that the grid control unit is the responsibility of the gas grid operator. Figure 3-2, below, shows a simple process flow diagram for the first phase of the Falkenhagen facility.

[7] See pages 102-113 of the SBC Energy Institute's Hydrogen-Based Energy Conversion Fact Book at: http://www.sbcenergyinstitute.com/_/media/Files/SBC%20Energy%20Institute/SBC%20Energy%20Institute_Hydrogen-based%20energy%20conversion_FactBook-vf.pdf

[8] https://www.dvgw.de/english-pages/?L=0

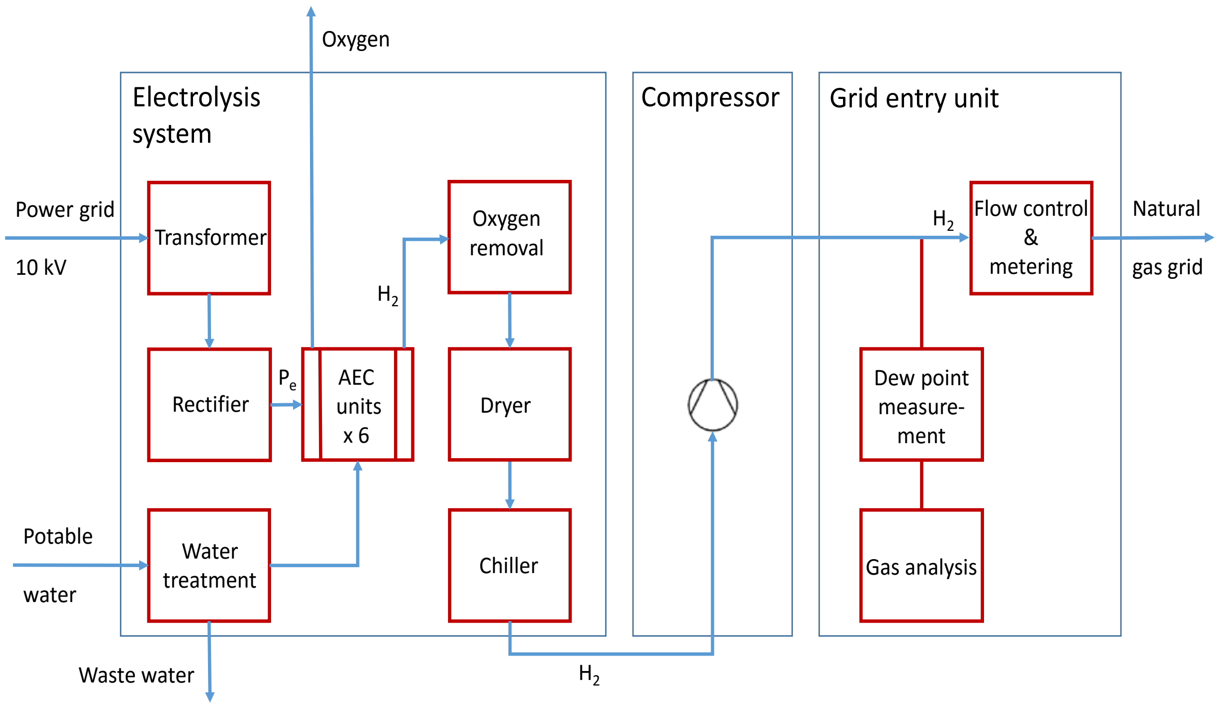

Figure 3-2
Falkenhagen process diagram (not including methanation project)

During a second four-year phase in the development of the Falkenhagen facility, a methanation unit will be added. This unit will be an innovative isothermal catalytic honeycomb-structured wall reactor supplied by ThyssenKrupp Industrial Solutions[9]. The methanation unit will have the capacity to convert approximately 280 Nm^3/h of hydrogen into SNG. Carbon dioxide will be delivered to the site in tube-trailers from a biogenic source. The opportunity for heat integration is being investigated with the heat from the exothermic methanation reaction potentially being used in a local manufacturing process.

Within the STORE&GO project framework, the Karlsruhe Institute of Technology[10] is responsible for engineering services and scientific evaluation and DVGW is responsible for overall program coordination.

3.3 Operator Experience at Falkenhagen

Total system capital costs were over €5M at Falkenhagen. On top of this amount there was also extensive development engineering and other costs, typical of any such demonstration project. Also, it was administratively complex. There were 32 contracts, both external and between E.ON/Uniper business units, to comply with all the technical, regulatory, and commercial requirements. The pure hydrogen spur pipeline was subject to different regulations than natural

[9] https://www.thyssenkrupp-industrial-solutions.com/en/
[10] http://www.kit.edu/english/

gas pipelines, for example requiring a leak detection system. Project engineering was provided by Hamburg Gas Consult GmbH[11] (HGC).

Construction of the Falkenhagen facility started in August 2012 and commissioning was completed in August 2013. This was followed by three years of operation. By July 2014 the facility had operated for 7,000 hours during which 2 million kWh of hydrogen, based on its higher heating value, were injected into the natural gas grid. By August 2015 this figure had risen to 10,000 hours and 4.5 million kWh of hydrogen into the grid, with 700 system starts-stops. While the maximum operating pressure of the grid was 55 bar(g), grid injection pressure was typically in the range 43-51 bar(g).

Based on a review of the then current literature, the original specification for the Falkenhagen project was to achieve an overall efficiency in excess of 50%. Actual performance was better than expected, with AEC system efficiency in the range 60-65% or 5.45-5.90 kWh/Nm^3 of hydrogen, based on the higher heating value of hydrogen[12]. This was largely because the AEC systems available from Hydrogenics had better efficiency than suggested in the literature. The dynamic load-following performance was also good and fully met the requirements of the German secondary negative balancing power market. The graph below, Figure 3-3, was part of the pre-qualification package for participation in this market. It shows that the system was easily able to meet the five-minute response requirement of the secondary control reserve. In practise, the system was also able to meet the 30-seconds requirement of the German primary control reserve.

[11] http://hgc-hamburg.de/en/

[12] Efficiency is calculated using a higher heating value for hydrogen of 3.54 kWh/Nm^3 (source: HyWeb, Ludwig-Bölkow-Systemtechnik GmbH at http://www.h2data.de/)

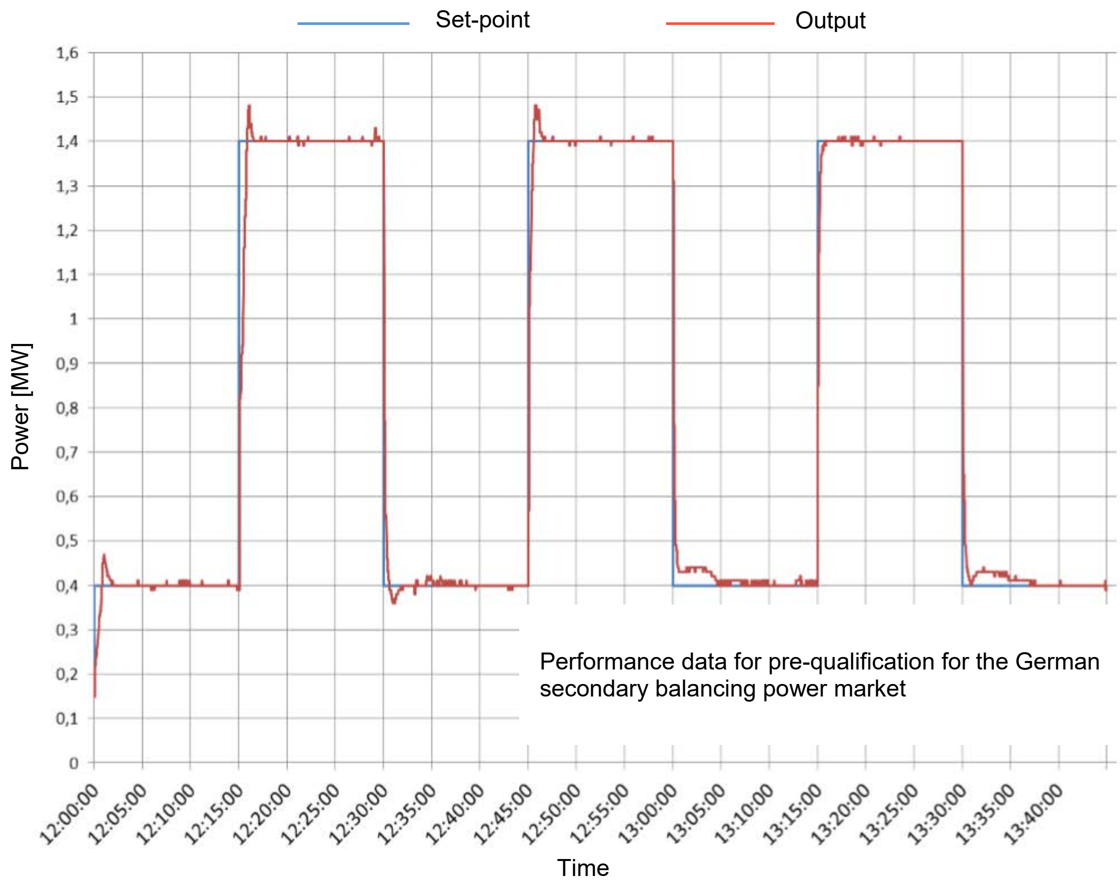

Figure 3-3
Load-following performance of the Falkenhagen P2G facility

AEC systems can only achieve this responsiveness from standby, not from a cold start, because following the start-up procedure given by the system supplier it can take anything up to two hours to become fully operational from a true cold start. However, the project demonstrated that it is quite feasible to run loaded or in standby for long periods of time and in standby the power consumed is only 40 kW. Standby in this context means that the system is maintained at its full operating pressure and that the water purification system is running.

There were no periods when the system was unable to inject hydrogen into the gas grid because of the 2% concentration limit. This was a benefit of injecting into the high-pressure grid, which typically maintains significant flows even in periods of low demand, but this benefit needs to be considered in light of the cost and energy penalty of having to raise the product hydrogen pressure. Product compression reduced the net efficiency of the complete facility by 2-3 percentage points.

The start date for the overall STORE&GO project was March 2016. The Falkenhagen methanation project is now in the engineering and specification phase and it is expected that commissioning of the system will be complete by the end of 2017 or early in 2018. Having completed its three-year program in September 2016, the AEC systems at Falkenhagen are now temporarily shut-down until the methanation system is ready.

3.4 Key Lessons Learned at Falkenhagen

The Falkenhagen project has demonstrated that conventional AEC hydrogen production plants employ a robust technology that is ready for market deployment in P2G facilities injecting hydrogen into the high-pressure gas transmission grid. The AEC units themselves cost approximately €2.2M or 1,125 €/kW. Despite the maturity of the technology, there remains further potential for cost reduction and performance improvement, but this would largely be due to P2G providing a volume market for the AEC systems suppliers who have hitherto only sold into relatively small volume applications. The Falkenhagen project showed that AEC systems can fulfill the technical requirements of the German secondary negative balancing power market. In addition to the five-minute response requirement the system must be capable of direct and automatic activation by the affected transmission system operator. Participation in the market also requires a minimum capacity of 5 MW, so small facilities such as Falkenhagen participate in pooling arrangements.

The results of the three areas of market testing were disappointing but, nevertheless, informative and illustrative of the challenges to be faced. All the market testing activities were impacted by various limitations in the current policy regulations in the EU.

4
THE HAMBURG-REITBROOK PROJECT

4.1 Objectives for the Hamburg-Reitbrook Project

The primary technical objective of the Hamburg-Reitbrook project was to demonstrate the deployment of PEMEC technology as a more efficient and compact hydrogen production system in comparison to conventional AEC technology, at a scale appropriate to P2G facilities. The project would use a 1 MW scale PEMEC system for a 12-month field trial period, at a time when such units were only commercially available up to 100 kW. The project also sought to demonstrate that PEMEC systems would have faster load dynamics and a greater capacity for temporary overload operation than AEC systems, together with acceptable cold-start performance. Figure 4-1, below shows the Hamburg-Reitbrook facility.

Figure 4-1
The Hamburg-Reitbrook P2G facility

Commercially, the project aimed to show that utility-scale PEMEC systems could be more cost-effective in P2G applications than conventional AEC systems. The implication would be that the introduction of utility-scale PEMEC technology could support the expansion of P2G as an effective method to store surplus energy from renewables.

Uniper Energy Storage GmbH is the site owner and was the project leader for the Hamburg-Reitbrook P2G demonstration project. Hansewerk AG[13] is the operator of the local gas grid. Hydrogenics GmbH supplied the PEMEC system as a complete package. Solvicore GmbH & Co

[13] Hansewerk AG is a subsidiary of Uniper SE.

KG (now owned by Toray Group and called Greenerity[14]) developed the membrane electrode assembly for the PEMEC system. The Fraunhofer Institute for Solar Energy Systems[15] (ISE) and the German Aerospace Centre[16] (DLR), both undertook scientific monitoring during the 12-month trial period. Public sponsorship, covering 48% of project costs, was received from the German National Hydrogen and Fuel Cell Technology Innovation Program and Digital Infrastructure. This is a program of the Federal Ministry of Transport and Digital Infrastructure (BMVI) acting to support approaches to decarbonizing transportation. The project was also supported by Project Management Jülich[17] and the National Organization for Hydrogen and Fuel Cell Technology[18].

4.2 Design of the Hamburg-Reitbrook Facility

The original project specification was for a 1 MW PEMEC system capable of being run at 50% overload for a period of eight hours. The facility was designed around the prototype 1500[E] PEMEC platform supplied by Hydrogenics (as this was a prototype there is no published information on this product). The unit was packaged in a single 40-foot ISO container, suitable for outdoor installation in Northern Europe and meeting applicable ATEX requirements. Design parameters for the proton exchange membrane (PEM) stack were a maximum hydrogen production rate of up to 300 Nm^3/h, an operating life of greater than 50,000 hours, an operating pressure of 30 bar(g), and operating temperature of 65 °C.

The design purity of the hydrogen was 99.9% with oxygen less than 800 ppm. Delivery pressure for this application was 25 bar(g) but the system had a normal operating pressure of 30 bar(g) and a maximum operating pressure of 40 bar(g), so no hydrogen product compression was required.

The design of the balance-of-plant at Hamburg-Reitbrook reflected Uniper's experience at Falkenhagen, so that the innovation at Hamburg-Reitbrook was all about the core electrolysis technology. Power was supplied to the facility via a 10 kV, 50 Hz grid connection. It was transformed down to 400 V and rectified to DC for supply to the PEMEC system. Process water, from the normal potable water mains supply, was filtered and deionized using reverse osmosis to a conductivity level of below 2.6 μS/cm.

The process water conditioning plant (shown in Figure 4-2 below), the gas treatment and monitoring equipment, and the specification of the hydrogen produced were almost identical to the Falkenhagen demonstration, but re-iterated here for completeness. On the outlet side of the PEMEC system, oxygen came out in the process water stream. The oxygen was separated and vented to atmosphere. The process water was re-circulated. The wet hydrogen went through a twin-bed silica drying unit. The system included a catalytic combustion unit to control oxygen levels in the product hydrogen but in practise oxygen levels were already sufficiently low. Finally, the hydrogen went through a chiller unit.

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[14] http://www.greenerity.com/

[15] https://www.ise.fraunhofer.de/en.html

[16] http://www.dlr.de/dlr/en/desktopdefault.aspx/tabid-10002/

[17] https://www.ptj.de/

[18] http://www.now-gmbh.de/en

Figure 4-2
Process water conditioning

The grid-injection module monitored water content, oxygen, and nitrogen – using gas chromatography. For injection into the grid the hydrogen must have a water content below 50mg/m^3 and a temperature between 5 ºC and 40 ºC. Off-specification hydrogen was vented to atmosphere. The hydrogen content limit for the grid was 2%. Uniper's central dispatch system controlled the PEMEC system – turning down or switching off the plant if the local grid was unable to accept hydrogen because of low flow. The local grid operator could only stop injection if the hydrogen was off-specification. A simple process diagram for the Hamburg-Reitbrook facility is shown in Figure 4-3.

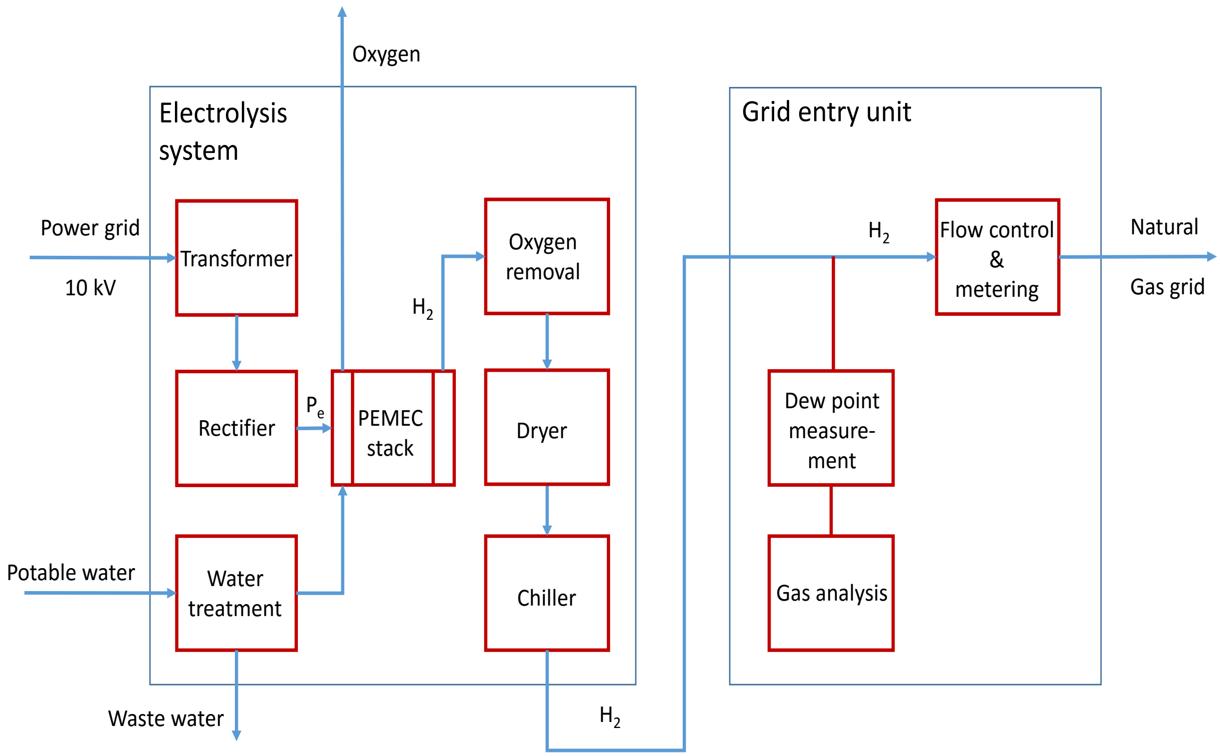

Figure 4-3
Hamburg-Reitbrook process diagram

4.3 Operator Experience at Hamburg-Reitbrook

Total costs for the whole project, including the full PEMEC system and all development engineering and scientific programs, were €13.6M. Commissioning was completed in October 2015.

Whilst the original project specification was for a 1 MW system capable of being run at 50% overload for a period of eight hours, it was found that the PEMEC system was able to be run in continuous operation at 1.5 MW without efficiency levels falling significantly below those expected and without accelerated degradation of the stack. It was not possible to test further levels of overload because the system was limited by the capacities of various balance-of-plant items such as the rectifier.

The most striking feature of the Hamburg-Reitbrook PEMEC system, versus the Falkenhagen AEC systems, was its high power density and consequent small footprint. At Falkenhagen, the system was installed in six 20-foot ISO containers and one 40-foot ISO container and had a nominal capacity of 360 Nm^3/h. At Hamburg-Reitbrook, a single 40-foot ISO container contains the same scope for a system with a nominal capacity of 290 Nm^3/h. At the heart of this compact system, the PEMEC stack module measures only 700 mm x 900 mm x 500 mm and has a power density of greater than 4 kW/liter. The stack module is shown in Figure 4-4.

Figure 4-4
PEMEC system's compact stack

The trial period results showed system efficiencies of between 75% and 90% through ramping and stop-start loading cycles, as illustrated in Figure 4-5 below. The left-hand side of the graph shows how stack efficiency varied during a gradual increase in load. As is characteristic of electrolysis systems efficiency declined at higher loads. The right-hand side of the graph shows how stack efficiency responded to sudden changes in load. Other results showed that the PEMEC system efficiency was still in the range 70-75%, based on the higher heating value of hydrogen, when operated at high loads, up to 1.5 MW. Uniper reported that the dynamic load-following performance of the PEMEC system was very good and fully met the requirements of the German secondary negative balancing power market. The responsiveness of the PEMEC system could be measured in milliseconds, not dissimilar to batteries, but P2G is not regarded by Uniper as direct competition to batteries, batteries being for grid stabilization and P2G being for large-scale, long-term energy storage. As with the AEC systems at Falkenhagen, it was found that the PEMEC system should be left in standby, rather than operated from a cold-start, and that this could be achieved with a very low power consumption to maintain system pressure, water purity and other operating conditions.

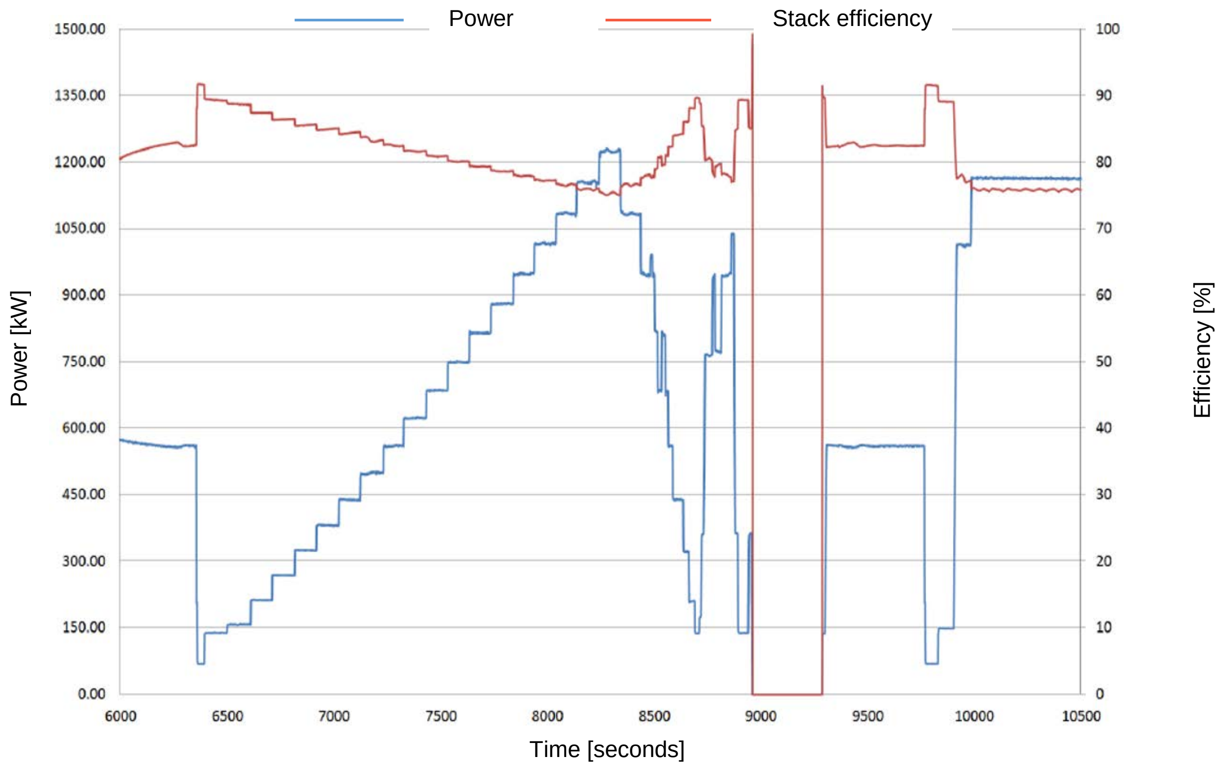

Figure 4-5
PEM stack efficiency results from the Hamburg-Reitbrook P2G facility

At a nominal capacity of over 1 MW, the Hamburg-Reitbrook PEMEC system was much larger than commercially available systems and therefore was expected to present some scale-up challenges. The first challenge was to produce reliable membranes of the size required for this application (with surface areas of 1,500 cm^2). The system also needed to have sufficiently rugged valves and other mechanical components for industrial use. However, despite being a prototype by the end of the trial the system was achieving satisfactory levels of reliability.

There were periods when the facility was not able to inject hydrogen into the grid without breaching the 2% concentration limit. These were periods of low demand on the grid. This can be seen as a significant limitation of injecting into a local grid, but these relatively rare periods must be considered in the light of the cost benefits of lower-pressure grid injection.

Now, one year after commissioning, the budgeted demonstration program at Hamburg-Reitbrook is complete. The technical capability has been proven but with no sustainable economic model for continued operation the plant has been ‘moth-balled’.

4.4 Key Lessons Learned at Hamburg-Reitbrook

Up-scaling the PEMEC technology for the Hamburg-Reitbrook P2G facility was successful and the new PEMEC equipment was very compact and efficient in this application. The system proved itself capable of continuous operation at 1.5 MW. Overall system efficiency of the PEMEC system at Hamburg-Reitbrook was in the region of 10 percentage points better than the AEC systems at Falkenhagen. Operating the PEMEC system at a pressure of 25 bar(g) made injection into the low-pressure grid possible without using a hydrogen product compressor – this contributes to the competitiveness of the PEMEC system. The PEMEC overall system efficiency was much better than anticipated in this application. The project showed that PEMEC systems can easily fulfill the technical requirements of the German secondary negative balancing power market.

The capital costs for PEMEC systems are already becoming comparable with AEC systems, even when setting aside the cost of the large plot required for AEC systems, but as a relatively immature technology at this scale the future opportunities for cost reduction are likely to be much greater. Economies of scale and cumulative production experience alone should lead to significant cost reductions. Reductions in platinum loading on the membranes is likely and ways should be found to reduce the costs of other expensive components.

5
IMPLICATIONS FROM FALKENHAGEN AND HAMBURG-REITBROOK FOR P2G IN EUROPE AND ELSEWHERE

The Falkenhagen P2G project has demonstrated that hydrogen production using conventional AEC technology leads to a robust and market-ready system for this application. It can respond effectively to a variable source of excess electricity, such as wind power, and fully meet the technical requirements of the German secondary negative balancing power market. The facility was also able to consistently meet all the gas grid entry control requirements. However, AEC technology has a low power density and therefore a large footprint, and as a mature technology relatively less opportunity for future cost reduction.

The Hamburg-Reitbrook P2G project demonstrated the ability to produce hydrogen using PEMEC technology at 1 MW scale. The overall efficiency of the PEMEC system (70-75%) was better than expected and better than the AEC system (60-65%). Avoiding the need for hydrogen product compressors significantly simplifies P2G facilities and reduces capital and operating costs. The PEMEC facility was also able to consistently meet all the gas grid entry control requirements. PEMEC technology with its smaller footprint, higher efficiency, superior dynamics, and more opportunity for future cost reduction appears to be the clear leader over AEC technology for future P2G facilities. Durability and the operating lifetime of the PEMEC system were not issues that could be explored within the scope and duration of the Hamburg-Reitbrook project, and these will likely remain areas of concern for operators.

During the period of the two projects, the costs of purchasing electricity were approximately €120/MWh of which only 32% were generation costs, the remainder being grid fees, EEG fee (renewable energy fee), taxes, and other charges. This equates to €240-250/MWh for hydrogen energy into the grid – over 10 times the cost of natural gas. The stored gas energy would only have this value for a few hours each year. This simple arbitrage is not a viable economic model for P2G today and other market mechanisms are required, and those mechanisms for P2G also need to address the opportunities and challenges of coupling different sectors; electricity, heat, transportation, and chemical feedstocks[19]. However, there seems to be no inherent reason why P2G cannot contribute to the further economic development of renewable energy sources, and existing market mechanisms for natural gas storage, where storage companies are paid for providing a storage service and do not own the energy, might show the way for energy storage more broadly.

[19] In October 2016 Uniper and BP announced a cooperation agreement to examine the technical and economic feasibility of using P2G technology to supply 'green' hydrogen to BP's Lingen refinery.

6
REFERENCES AND FURTHER READING

References

1. Hydrogen-Based Energy Conversion Fact Book, pages 102-113, published by the SBC Energy Institute, February 2014, at http://www.sbcenergyinstitute.com/_/media/Files/SBC%20Energy%20Institute/SBC%20Energy%20Institute_Hydrogen-based%20energy%20conversion_FactBook-vf.pdf
2. Hydrogen Data from HyWeb, prepared by Ludwig-Bölkow-Systemtechnik GmbH and published on the internet at www.h2data.de/

Further Reading

1. Renewable Power-to-Gas: A technological and economic review, by Manuel Götz, Jonathan Lefebvre, Friedemann Mörs, Amy McDaniel Koch, Frank Graf, Siegfried Bajohr, Rainer Reimert and Thomas Kolb, Renewable Energy 85 (2016) 1371-1390, published by Elsevier, 2015.
2. A perspective on the potential role of biogas in smart energy grids, prepared by Tobias Persson, Jerry Murphy, Anna-Karin Jannasch, Eoin Ahern, Jan Liebetrau, Marcus Trommler, and Jeferson Toyama, published by IEA Bioenergy, 2014, electronic book ISBN 978-1-910154-13-7.
3. Technological and economic aspects of power to gas and upgrading of biogas to natural gas quality, by Aksel Hauge Pedersen and Koen G. Wiersma, Gasunie, WOC 5.4/TT1 – a committee report, published by the International Gas Union, 2015, at http://members.igu.org/old/IGU%20Events/wgc/wgc-2015/committee-reports-with-tnematic-sessions/woc-5-4-paper.pdf
4. Water Electrolysis & Renewable Energy Systems, report published by Fuel Cells Today, 2013, at http://fuelcelltoday.com/analysis/surveys/2013/water-electrolysis-renewable-energy-systems
5. PEM Electrolysis for Hydrogen Production: Principles and Applications, edited by Dmitri Bessarabov, Haijiang Wang, Hui Li, and Nana Zhao, published by CRC Press, 2015, hardback book ISBN 978-1-4822-5229-3.

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Electric Power Research Institute
3420 Hillview Avenue, Palo Alto, California 94304-1338 • PO Box 10412, Palo Alto, California 94303-0813 • USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com