WHEC 2014
20th World Hydrogen Energy Conference 2014
June 15[Sun] – 20[Fri], 2014 KDJ Convention Center, Gwangju Metropolitan City, Korea

Hynor Lillestrøm – A Renewable Hydrogen Station & Technology Test Center

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ABSTRACT

A small-scale renewable energy hydrogen refueling station (HRS) and hydrogen technology test center has been designed, built, and set in operation by Hynor Lillestrøm and partners. The HRS includes an alkaline water electrolyzer with a production capacity of 1 kg H_2 per hour (10 bar), a two-stage hydrogen compressor (10/1000 bar), a 45 kg H_2 storage (500 and 950 bar), and a 700 bar dispenser (with -40°C pre-cooling) that supplies hydrogen to fuel cell electric vehicles (PEM-based FCEVs). Inside the R&D building there is a process room for testing and development of new hydrogen and fuel cell technology. The following installations are currently being validated: (1) a thermally driven metal hydride (MH) hydrogen compressor (10 Nm^3/h at 10/200 bar); (2) a biogas (>90% CH_4) based sorption enhanced steam methane reforming (SESMR) system with a production capacity of 10 Nm^3/h (0.5 bar); (3) and a biogas fuelled solid oxide fuel cell (SOFC) with a rated power of 20 kW_{el}. The main system innovations currently being demonstrated at the Hynor Lillestrøm Test Center: (1) High pressure (200 bar) hydrogen gas system integration between the HRS and MH-compressor and (2) High temperature heat (1000°C) system integration between the SESMR and a SOFC. The design and first operational experiences of the hydrogen systems installed at Hynor Lillestrøm are presented.

Keywords: Renewable energy, hydrogen production, technology testing and development, water electrolysis, reforming, metal hydrides, solid oxide fuel cells

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1. Introduction

1.1 Overall goals and objectives

The main goal of the Hynor Lillestrøm demonstration project (2009-2013) has been to design, build, and operate a hydrogen station based on local renewable energy sources, and to demonstrate new and innovative hydrogen technology.

1.2 Scope of Work

The Hynor Lillestrøm concept focuses on two basic hydrogen production methods: water electrolysis based on renewable power and reforming of biogas (Figure 1). In practice, the project has been divided in two parts (1) a hydrogen refueling station (HRS) for hydrogen fuel cell vehicles and (2) a R&D building for testing and validation of new hydrogen technology.

1.3 Project Development

In the original Hynor Lillestrøm concept from 2007, the hydrogen station was designed to deliver hydrogen to five small battery electric vehicles, each rebuilt for range extension using PEM fuel cells (10 kW_{el}) and hydrogen storage (1.4 kg H_2, 700 bar) [1]. In 2010 it was decided to make the hydrogen station available for the *H2 Moves* project, which also included FCEVs from Hyundai and Mercedes-Benz [2]. In June 2012 the Hynor Lillestrøm was officially approved and opened for use by all types of fuel cell electric vehicles (Figure 2).

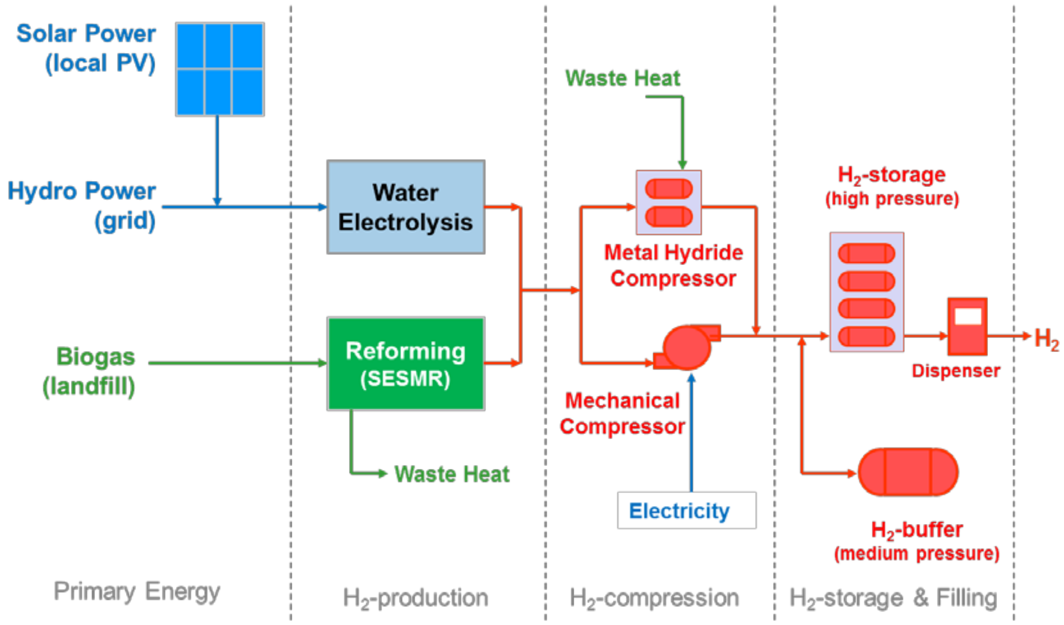

Figure 1 – Hynor Lillestrøm system concept

Figure 2 – Hynor Lillestrøm hydrogen station for refueling of FCEVs (left) and Test Center for RD&D (right)

The idea to build a renewable hydrogen energy demonstration project locally in the region was first established in 2006 by Institute for Energy Technology (IFE), Kunnskapsbyen Lillestrøm (Lillestrøm Centre of Expertise), and Kjeller Innovation AS. The development and establishment of Hynor Lillestrøm has taken several years, and has required a goal-oriented approach, with close collaboration between IFE, Akershus Energi AS (local utility), and several other partners.

A feasibility study was performed by IFE in 2007, with the aim to scope a holistic system concept. In 2008 this concept was further developed in a pre-project funded by The Research Council of Norway (NFR), Akershus County Municipality (Afk), Innovation Norway, and the Municipality of Skedsmo (which includes the city of Lillestrøm).

The main *Hynor Lillestrøm* project (2009-2013) was formally completed in December 2013. The project received funding from NFR, Afk, Akershus Energi, and Transnova (national organization for state funding of sustainable mobility projects). Two new projects have been added to Hynor Lillestrøm, both with activities that continue into 2014.

A R&D project (*BioSER*) with aim to further develop and optimize the sorption enhanced reforming process was started up in 2012. The *BioSER*-project (2012-2015) is run by IFE in collaboration with the Norwegian University of Science and Technology (NTNU) and ZEG Power AS (Norway), and is funded by Research Council of Norway and ZEG Power.

An innovation project (*BioZEG*) with the aim to demonstrate close thermal integration between a solid oxide fuel cell (SOFC) system and the SESMR pilot plant installed at Hynor Lillestrøm was started up in 2011. The *BioZEG*-project (2011-2013) was run by ZEG Power in collaboration with CMR Prototech AS (Norway) and IFE, and was funded by Innovation Norway and Statoil ASA.

1.4 Development of Hynor Lillestrøm

Hynor Lillestrøm AS is an independent company, established by Akershus Energi AS, IFE Venture, Kunnskapsbyen Lillestrøm, Kjeller Innovation and the Municipality of Skedsmo in December 2009. The main goal of the company has to date been to: (1) Design, build and operate a demonstration HRS, (2) Establish infrastructure for testing of new hydrogen technology, and (3) Educate and transfer knowledge on hydrogen, including the facilitation of seminars, meetings, and visits.

The formal approval of the R&D building (Figure 2) located in Akershus Energy Park was received from the Municipality of Skedsmo in 2013. The process room inside the R&D building operates as an industrial laboratory and a place for researchers and engineers to build and test out new technical concepts and ideas. The R&D building has therefore also been referred to as the Hynor Lillestrøm *"Innovation Zone"* [3].

In January 2014 new shares in Hynor Lillestrøm were offered to three of the most active users of the technical facilities, namely IFE, ZEG Power AS, and HYSTORSYS AS. The goal is to continue to develop the test center through more hydrogen and fuel cell R&D, demonstration, and innovation projects. The Hynor Lillestrøm Test Center is now opening for more international collaboration.

2. System Descriptions

2.1 R&D building

The R&D building and its technical infrastructure was completed in April 2013. The building includes gas infrastructure (biogas, hydrogen, nitrogen, instrument air), electricity (400 VAC and 350 VDC), ventilation (12 air changes per hour), process cooling (80 kW_{th}), and other technical services (gas detectors, alarms, control systems, etc.).

2.2 Hydrogen station

The hydrogen station, provided by H2 Logic A/S (Denmark), consists of a hydrogen production module (15' container), a hydrogen station module (20' container), and a hydrogen dispenser, all located adjacent to the R&D building in Akershus Energy Park. Inside the hydrogen production module there is an alkaline water electrolyzer (NaOH electrolytic solution) from Erredue s.r.l (Italy), with a rated hydrogen production capacity of 10.66 Nm3/h (ca. 21 kg H_2 per day) and a maximum outlet pressure of 13 bar. The hydrogen from the water electrolyzer (10 bar design pressure) is passed to the hydrogen station module for compression and storage (950 bar) and pre-cooling (-40°C), before it is sent to the hydrogen dispenser (700 bar) (Figure 4). The hydrogen dispenser is designed and built in compliance with the SAE J2601 and SAE J2719 standards, which allows for 3-minute refueling of FCEVs equipped with 700 bar hydrogen storage systems with a capacity of 1-7 kg.

The hydrogen station module includes a two-stage diaphragm hydrogen compressor from PDC Machines Inc. (Connecticut, USA), with a rated capacity of 15 Nm^3/h at 10 bar and 35 Nm^3/h at 150 bar, a minimum inlet pressure of 5-500 bar, and a maximum outlet pressure of 1000 bar. A hydrogen buffer storage is installed on the roof of the hydrogen station module. The main high-pressure hydrogen buffer consists of three composite pressure vessels (Type 4) from Hexagon Composites ASA (Raufoss, Norway): two 255 liter vessels (water volume) with a rated maximum pressure of 1050 bar and one 531 liter vessel rated at 500 bar. The total hydrogen storage capacity here is ca. 45 kg. There are also three 50 liter pressure storage vessels rated at 450 bar (Type 2) for intermediate storage of hydrogen between the first and second stage compression.

2.3 Metal hydride hydrogen compressor

One of the key technologies demonstrated in Hynor Lillestrøm is a thermally driven metal hydride (MH) based hydrogen compressor system, which has been designed, built, installed, and commissioned by HYSTORSYS AS (Norway). This installation (Figure 3) is a thermally driven two-stage MH-system designed to compress hydrogen from 10 to 200 bar at a steady hydrogen flow rate of 10 Nm^3/h.

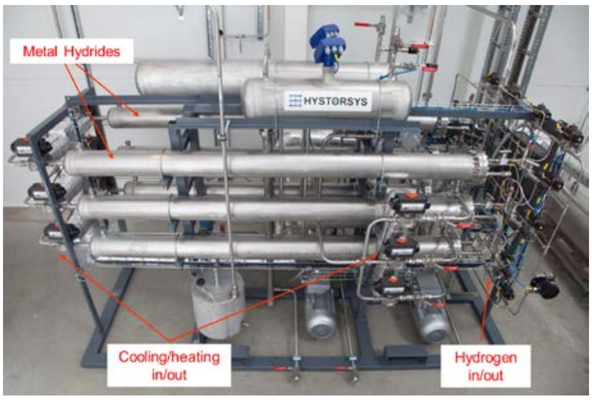

Figure 3 – Metal hydride hydrogen compressor

The MH-system consists of three high-pressure (270 bar) steel vessels for each of the two stages. Each of the six vessels contains about 34 kg of metal hydride material. An AB_5-alloy ($La_{1-x}Ce_xNi_5$) is used for the first compression stage from 10 to 70 bar, while an AB_2-alloy (Ti-based) is used for the second stage from 70 to 200 bar. The MH-system operates in thermal cycles between 20-150°C, and has been designed to compress hydrogen by only using low-temperature heat at ca. 160°C, cooling water at 16°C, and small amounts of electricity to power control valves, and other small pieces of auxiliary equipment. An electrical external oil heater with a maximum capacity of 27 kW (and 175°C) is installed to emulate the *"industrial process heat"*, and the heat transfer to the MH-compressor is facilitated by a heating oil loop using a commercially available heating oil (THERMINOL®LT). The system integration between the hydrogen station module (H2 Logic) and the metal hydride compressor (HYSTORSYS) is illustrated by the process flow diagram in Figure 4. The system is designed so that the first stage in the mechanical diaphragm hydrogen compressor is bypassed when the metal hydride compressor is in operation.

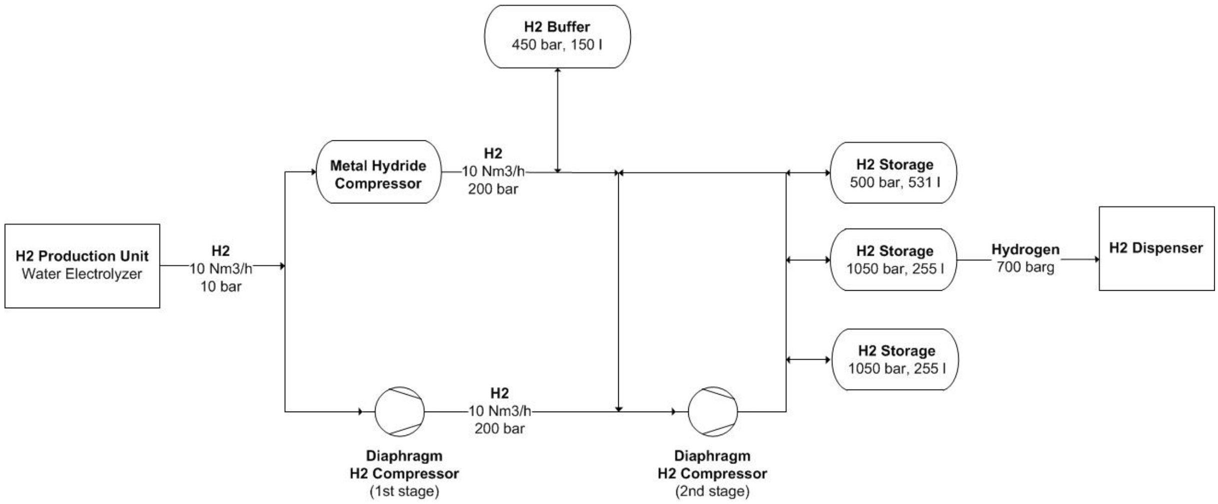

Figure 4 – Process flow diagram of hydrogen compression system with metal hydrides

2.4 Gas upgrading system

The biogas source to Hynor Lillestrøm comes in a pipeline from a municipal waste landfill site located 5 km north of Akershus Energy Park. This gas contains about 41% CH_4, 30% CO_2, 27% N_2, and 2% other gases, including H_2S (up to 1600 mol ppm) and siloxanes. Hence, a small-scale gas upgrading system, designed and built by HyGear B.V. (The Netherlands), was installed to purify and upgrade the landfill gas. This gas upgrading system includes systems for desulphurization and pressure swing adsorption (4 × 550 liter PSA vessels), and has a nominal methane production capacity of 8-10 Nm3/h at 5-6 bar_g, depending on the required yield and methane output purity (85-90% CH_4).

2.5 Sorption enhanced reforming with CO_2-capture

Another key technology demonstrated in the Hynor Lillestrøm Test Center is a sorption enhanced steam methane reforming (SESMR) dual bubbling fluidized bed (DBFB) reactor system, which has been designed, built, and installed by IFE (Norway). This unique SESMR pilot plant consists of two different reactors and a piping loop that carries the CO_2-sorbent and reforming catalyst material between the two reactors (Figure 5). The sorbent used is a natural CaO-based material (Arctic Dolomite) from Franzefoss AS (Norway), while the catalyst material is a conventional reforming catalyst used in larger industrial plants.

The first reactor in the SESMR pilot plant is the reformer, where the reforming, water gas shift and carbonation reactions all take place in one single step at temperatures around 600°C. The second reactor, namely the regenerator, releases CO_2 from the carbonated sorbent ($CaCO_3$), in a process that requires the addition of high temperature heat at 950-1000°C. The product gases from the reformer and the regenerator contains respectively > 95% H_2 and >96% CO_2 (after condensation). The dry gas purity of H_2 and CO_2 will be slightly higher (> 96-97%) after drying of the product gases.

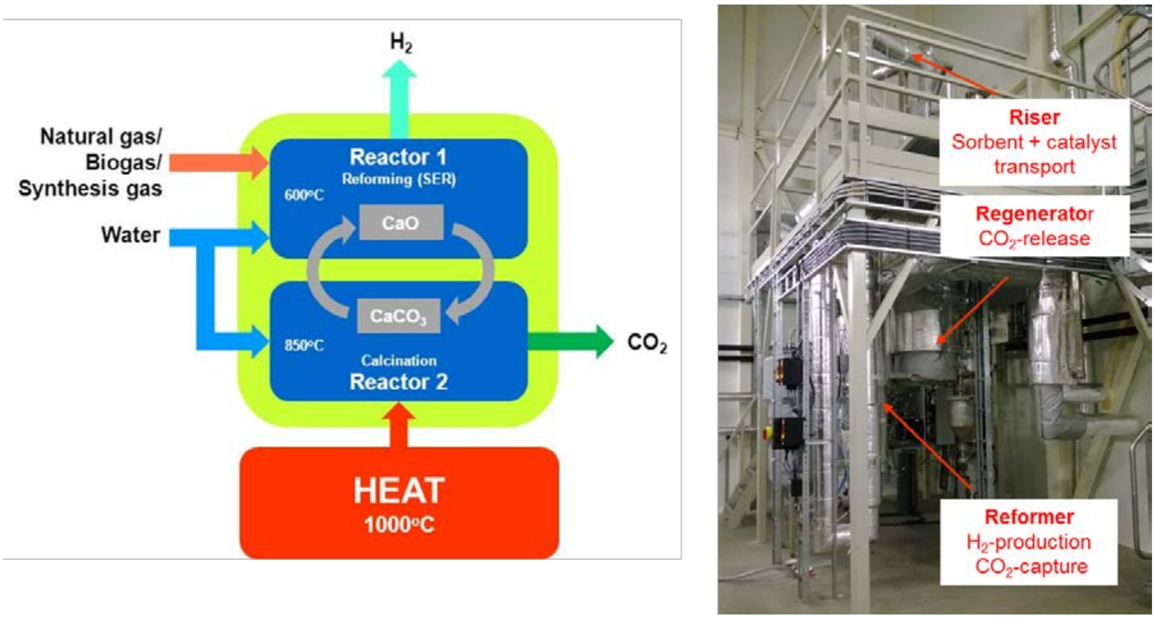

Figure 5 – Sorption enhanced steam methane reforming (SESMR) process principle (left) and bubbling fluidized bed (DBFB) pilot plant (right)

2.6 Hydrogen purification system

A containerized hydrogen purification system that can take reformed hydrogen from the SESMR and purify it to PEM fuel cell vehicle quality hydrogen has been designed, but not constructed yet. A palladium micro-channel hydrogen purifier with a capacity of producing 10 Nm^3/h with ultrapure hydrogen (9.0 N) at 10 bar has been acquired from Power+*Energy* Inc. (Pennsylvania, USA). A hydrogen compressor from PDC Machines Inc. with a capacity of 10 Nm^3/h (at inlet/outlet pressure of 0.5/20 bar_g) has also been acquired. The final system will also include an adsorption dryer, which will be placed between the reformer and the hydrogen compressor. The pressure across the Pd membrane hydrogen purifier has been estimated to drop from 20 to 10 bar_g at hydrogen flow rates of 10 Nm^3/h. Hynor Lillestrøm is seeking extra funding and partners to complete this project.

2.7 Solid oxide fuel cell system (*BioZEG-project*)

A 20 kW_{el} solid oxide fuel cell (SOFC) system has been designed, installed, and commissioned by ZEG Power AS (Norway), as part of the abovementioned *BioZEG-project.* The system integration between the SOFC and SESMR system is illustrated in Figure 6. The SOFC module developed and installed has a nominal operating temperature of 830°C. The SOFC system is therefore equipped with an afterburner, in order to boost the anode gas temperature to 1000°C before it can be used to heat the regenerator (reactor 2) of the SESMR system.

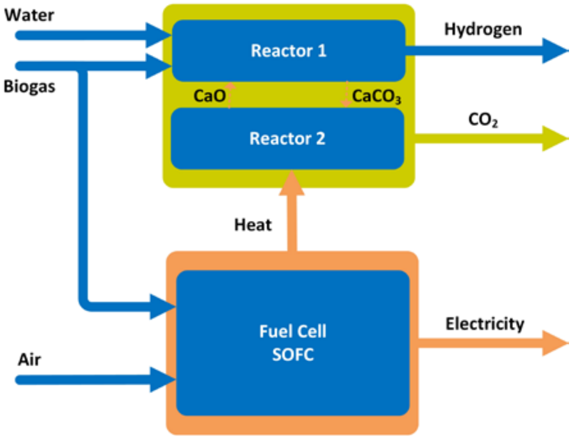

Figure 6 – The BioZEG-concept: SESMR and SOFC system integration

The SOFC module installed and commissioned by ZEG Power in 2013, was designed and built by CMR Prototech (Norway). The SOFC module consists of 24 CFY-based stacks delivered by Plansee SE (Austria) and Fraunhofer IKTS (Germany). The SOFC-stacks consists of Chromium based interconnects and electrolyte supported cells based on Scandia doped Zirconia. The SOFC module consists of 12 hot boxes with 2 stacks in each box, where the fuel and air are fed via manifolds connected to each hot box. All of the stacks are electrically connected in series, which gives a typical SOFC module operating voltage around 575 V (0.8 V/cell) and a full voltage range of ca. 470 – 900 V (max. load – zero load).

A custom-made 2 × 20 kW DC/DC power conditioning system for the SOFC module was designed and built by Hot Platinum Ltd. (South Africa), and integrated by IFE and partners into a local PV-based 350 VDC mini-grid. This system is also configured for exporting surplus fuel cell power to the local 400 VAC grid via a 20 kW DC/AC inverter from KACO new energy GmbH (Germany).

2.8 Solar PV and fuel cell power system

A 17 kW_p PV-system (355 – 600 VDC) based on solar panels from SWEMODULE AB (Sweden) supplied by Nordic Power AB (Sweden) has been roof-mounted at Hynor Lillestrøm. This PV-system is connected directly to a DC-based uninterrupted power supply system (UPS) supplied by Netpower Labs AB (Sweden). There is also a 50 kVA (400 VAC 3 phase / 230 VAC 1 phase) transformer that supplies the user with power, when there is no power generation from the PV or fuel cell systems (Figure 7, left side).

The UPS-cabinet consists of 15 × 2.3 kW AC/DC rectifiers, 4 × 4 kW DC/DC solar regulators, 156 lead-acid battery cells (nominal voltage: 2.3 V/cell), and 6 outlets for DC-distribution circuits. This PV UPS system was originally configured to supply power from the PV-panels and/or the transformer, but has now been expanded to include power conditioning equipment for the SOFC; namely, a 20 DC/DC converter, a 20 kW grid-tied inverter, and a 20 kW dump load to prevent overvoltage on the DC-bus (Figure 7, right side).

The local mini-grid built up at Hynor Lillestrøm is electrically configured and custom-made for simple connection of other DC-based electrochemical sub-systems and components, such as batteries, fuel cells, and water electrolyzers. The voltage on the DC-bus typically varies from 351-354 VDC (only power from the transformer) to 360-368 VDC (only power from the solar cells and/or fuel cells). Hynor Lillestrøm is now looking for new partners that are interested in testing and validating new and more robust DC-based power conditioning systems for dynamic operation of fuel cells and water electrolyzers.

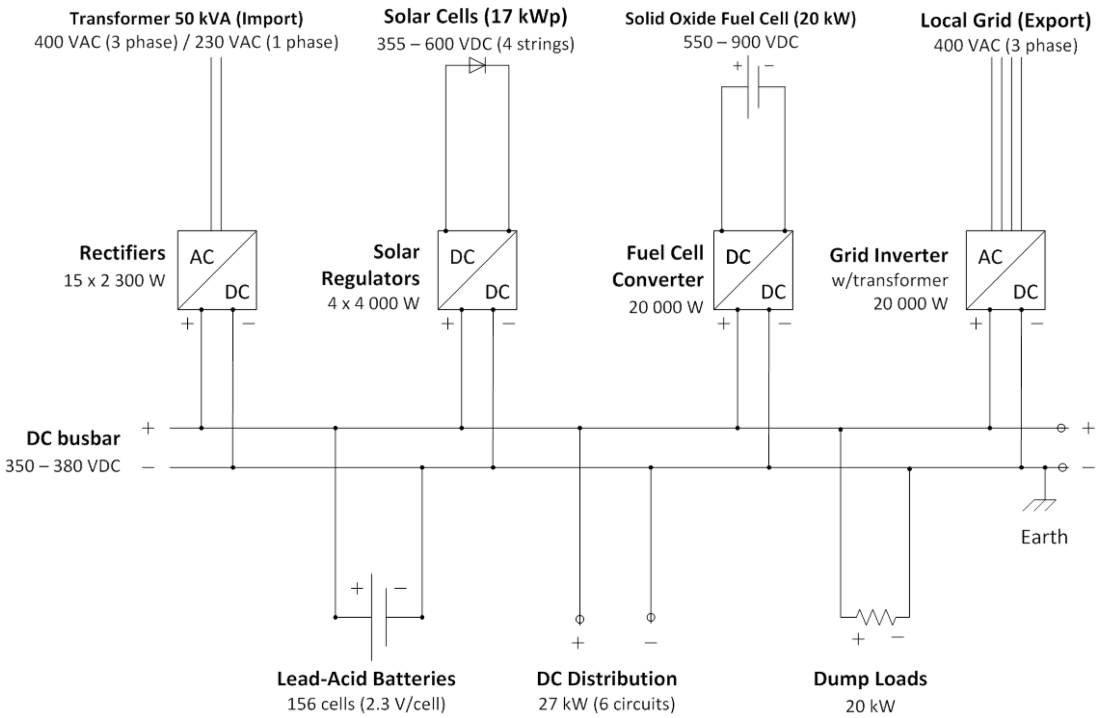

Figure 7 – PV and fuel cell power system

3 System testing and operation

3.1 Hydrogen station

The Hynor Lillestrøm hydrogen refueling station was commissioned in April 2012 and officially opened in June 2012. The hydrogen station was subject to thorough testing before it was approved and recommended by Daimler AG (Germany) for refueling of Mercedes-Benz B-class F-CELL vehicles [4]. Gas samples were taken after the electrolyzer and hydrogen dispenser, and analyses showed that the purity was as prescribed by the SAE J2719 standard

(>99.97 H_2, < 5 ppm H_2O, <5 ppm O_2, < 0.2 ppm CO, among others). New gas samples taken in 2013 gave similar results [5].

Other FCEVs, such as the THINK H2EV (Norway) and the Hyundai ix35 FCEV (Korea), have also been refueling regularly at the hydrogen station over the past two years, first as part of the *H2 Moves* project and later as part of a small network of HRS demonstration system in Oslo and Akershus. The local waste management company ROAF and the Municipality of Skedsmo have recently acquired Hyundai ix35 FCEVs, and are regular customers at the Hynor Lillestrøm station. The HRS at Hynor Lillestrøm was serviced by H2 Logic A/S from Denmark for the first 18 months of operation. In November 2013 the service contract was taken over by HYOP AS, a newly establish Norwegian company dedicated to operate hydrogen infrastructure for the transport sector.

3.2 Gas upgrading system

In the preliminary design and development of the gas upgrading system it became clear that it would be difficult to design and build a small-scale PSA system capable of upgrading the poor quality land fill gas (41% CH_4, 30% CO_2, 27% N_2, and 2% other gases) to standard quality biomethane (> 95% CH_4), as originally specified by IFE. Laboratory experiments on a small-scale PSA prototype system performed at HyGear in 2012 showed that CO_2 could be removed completely, but that it was difficult to separate all the N_2. It also proved difficult achieve a satisfactory high yield (Figure 7). The gas upgrading system was therefore redesigned, with a new specification on the yield (50%) and product output purity (90% CH_4).

A six week long and thorough factory acceptance test of the gas upgrading system was completed at HyGear's facilities in Arnhem in January 2013. The results showed that a purity of 85-87% CH_4 at a yield between 42-45% could be reached for product flows equivalent to 7-9.5 Nm^3 CH_4/h. The optimal performance of the PSA-system was found at an adsorption pressure of 6 bar_g and a cycle time (adsorption time) of 5 minutes [6]. At the on-site commissioning of the gas upgrading system in April 2013 the gas supply from landfill was unstable, and it was only possible to test and validate the desulphurization system. Gas samples taken for analysis at IFE showed no traces of H_2S.

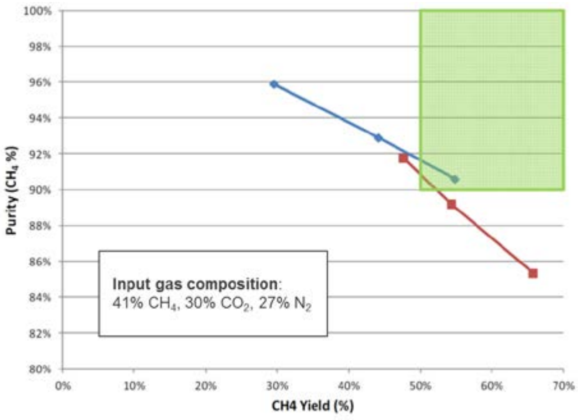

Figure 8 – Summary of small-scale PSA laboratory tests performed at HyGear [6]. Green area: Multiple tests performed at fixed operating conditions (adsorption pressure, cycle time, etc). Blue and red curves: Tests with different control settings.

The landfill gas site was in 2013 upgraded, and stable gas production is expected in the second half of 2014. The output from the gas upgrading system is expected to be 10 Nm^3 CH_4/h with a purity of 90% CH_4 under normal operating conditions.

3.3 Metal hydride compressor

The commissioning of the metal hydride hydrogen compressor started in May 2013. The first testing of this demonstration system (first of a kind *proof-of-concept*) has been challenging, as it was necessary to make some modification on the auxiliary systems (oil heater, hydrogen supply, and controls) before the overall system could operate properly.

The main control parameter for the metal hydride compressor is its operating temperature. In order to increase the hydrogen pressure gradually, the operating temperature needs to be stepped up from 50°C to 160°C in a highly controlled manner. Due to some constraints on the auxiliary systems (described above), it has so far only been possible to reach a maximum temperature of 105°C inside the metal hydride bed. At this temperature it has only been possible to reach a maximum output pressure of 150 bar and a hydrogen flow rate of 6-7 Nm^3/h. The auxiliary systems are now being re-commissioned, and an improved thermal management strategy will be implemented in the control system. Hence, it is expected that the MH compressor will reach the design output pressure (200 bar) and hydrogen flow rates (10 Nm^3/h). Results from the final test campaigns of the metal hydride compressor will be published at a later stage.

3.4 Sorption enhanced steam methane reformer

The commissioning and testing of the SESMR pilot plant started in October 2013, and the system has been tested carefully, one sub-system at the time.

The control system (PLC-based), including signal alarms and automatic shutdown procedures, has been commissioned and tested. The high-temperature heating and cooling cycles have also been successfully tested, and the mechanical design has been validated. The high temperature cycling shows that the system is gas tight. The 30 kW_{th} catalytic burner, which provides high temperature heat to the regenerator, has been tested up to 1025°C. The steam generation system has also been tested, but flow regulation to the reformer and regenerator (Figure 5) must be improved. (Improper control of steam can cause coking and damage of the catalyst in the reformer, and must therefore be avoided.) The solid materials that are to be used as CO_2-sorbent in the SESMR pilot plant have been produced and quality tested at IFE.

The next steps in the testing of the SESMR pilot plant is to resolve the last few technical issues with the steam flow regulation, fill up the DBFB reactors with sorbent and catalyst materials, and run another hot test with steam/nitrogen gas mixture to validate the process steam management. After this the SESMR pilot plant will be ready for testing with steam/biomethane mixtures. The goal is to reach about 500 cumulated hours of steady operation. Results will be reported after the system has been tested continuously over some time.

3.5 Solid oxide fuel cell system

The mechanical construction of the solid oxide fuel cell system was completed in Decemeber 2013, while the function testing of the control system (same PLC as used for the SESMR) was completed in March 2014 [7]. The SOFC-system will be started up and operated over the next 2-3 months, in parallel with the SESMR-system. After the first individual tests of SOFC and SESMR systems have been completed, the two systems will be thermally connected via a high-temperature heat transfer loop that has already been installed. The goal in the *BioZEG project* is to operate the combined SESMR/SOFC system for 500 hours and validate an overall system efficiency of 70% ($CH_4 \rightarrow H_2$ + electricity). The results from this activity will be reported at a later stage.

4 Conclusions

A small-scale renewable energy hydrogen refueling station and technology test center has been designed, built and set in operation by Hynor Lillestrøm and partners. A 10 Nm^3/h water electrolysis based hydrogen station with a 700 bar dispenser has refueled fuel cell vehicles regularly since June 2012, while the test center has been in operation since June 2013. A thermally driven metal hydride hydrogen compressor that receives hydrogen from the water electrolyzer was commissioned by HYSTORSYS in May 2013, and is currently being tested. A biogas upgrading system was commissioned in April 2013, and the testing of a sorption enhanced steam methane reformer system built by IFE began in October 2013. A 20 kW_{el} solid oxide fuel cell system is ready for testing by ZEG Power.

Acknowledgements

The authors would like to acknowledge the Research Council of Norway, Innovation Norway, Transnova, Akershus County, and Akershus Energi AS for providing financial support. A special thanks goes to Akershus Energi AS and the Municipality of Skedsmo for hosting Hynor Lillestrøm; Akershus Country for the strong political support; and the Board of Hynor Lillestrøm and our partners for their long-term commitment and support.

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