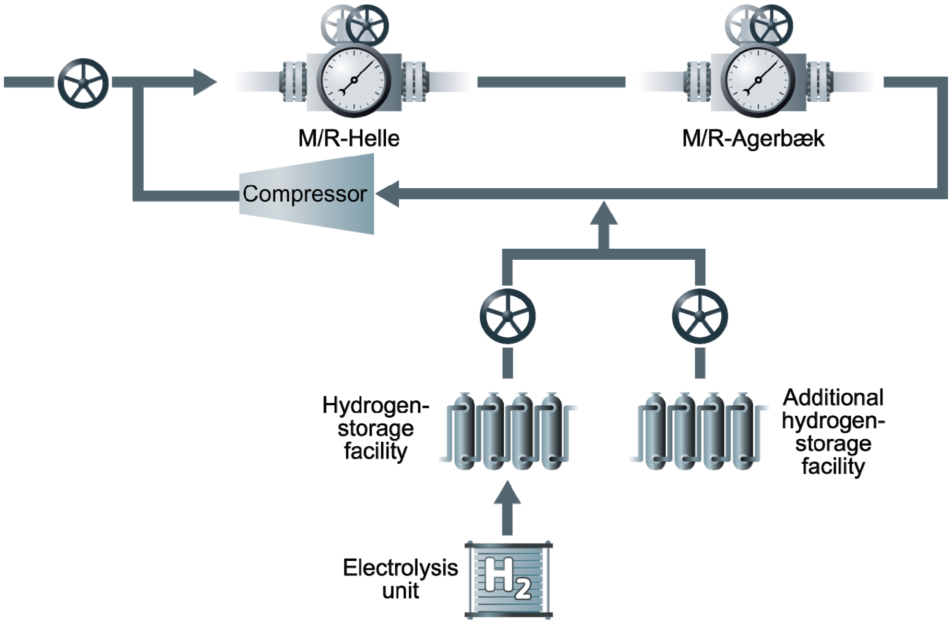
Energy Storage – Hydrogen injected into the Gas Grid via electrolysis field test

EUDP 13 – Special Pool Hydrogen



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1. Summary

1.1 Project details

Project title	Energy Storage – Hydrogen injected into the Gas Grid via electrolysis field test
Project identification (program abbrev. and file)	Hydrogen and Fuel Cells, J.no. 1936-0004
Name of the programme which has funded the project	EUDP
Project managing company/institution (name and address)	Energinet Gas TSO A/S Tonne Kjærsvej 65 Erritsø 7000 Fredericia
CVR (central business register)	39315084
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Project partners	Energinet, Danish Gas Technology Centre, Evida, IRD Fuel Cells
Date for submission	04-05-2020

1.2 Short description of project objective and results

1.2.1 English version

The gas system can potentially absorb, store and distribute large volumes of fluctuating energy production from renewable sources such as wind and solar PV, when the power production from these are converted to hydrogen through electrolysis. The project has demonstrated transportation of up to 15% hydrogen in natural gas in a closed-loop high-pressure system, consisting of components and infrastructure from both the transmission and distribution grids. The test has shown that there is no increased leakage of hydrogen from the system compared to natural gas and that the tested components from the gas system are capable of handling hydrogen in the tested concentrations without major modifications. The project has also produced detailed knowledge on the effects on electrolysis systems from long-term standby periods.

1.2.2 Danish version

Gassystemet har potentiale til at aftage, lagre og distribuere store mængder fluktuerende energiproduktion fra vedvarende energikilder som vind og sol, når elproduktionen herfra omdannes til brint gennem elektrolyse. Projektet har demonstreret transport af op til 15 % brint i naturgas i et lukket højtrykstestsystem, som består af komponenter og infrastruktur fra såvel transmissions- som distributionsnettet. Testen har vist, at der ikke er en forhøjet lækage af brint fra systemet i forhold til naturgas, samt at de testede komponenter fra gassystemet uden større justeringer er i stand til at håndtere brint i de testede niveauer. Der er i projektet opnået detaljeret viden om effekterne på et elektrolysesystem, som er udsat for lange standbyperioder.

1.3 Executive summary

Transportation of hydrogen in the existing gas infrastructure is an example of sector integration with a significant potential for stabilisation of the power grid in a future with increasing volumes of fluctuating production from wind and PV. The gas system offers practically unlimited storage capacity and can distribute renewable gases from production to consumers or sites with conversion technologies, in which the gases are used as feedstock for production of energy products of high value, e.g. liquid fuels for sea transportation and aviation.
The project successfully demonstrated transportation of mixtures of natural gas and hydrogen in a test facility, which includes infrastructure and systems that have been taken out of operation from the Danish natural gas transmission and distribution systems. The test facility is comprised of Measuring and Regulation (M/R) stations for both the transmission and distribution grid with flow meters, regulators etc., which have been supplemented with a compressor and a hydrogen analyser.

The project tested the system , which includes a low-pressure section (40 bar g design pressure) and a high-pressure section (80 bar g design pressure), with hydrogen concentrations up to 15%. The hydrogen concentration was analysed in test periods between 1-3 months after injection of natural gas and/or hydrogen to adjust pressure and concentrations. These long-term measurements of hydrogen concentration were performed with concentrations up to 12% hydrogen. The hydrogen concentration did not decline in the test periods, indicating that hydrogen is not leaking from the test facility in a higher rate than natural gas.
A mass balance analysis indicates a total gas leakage of natural gas and hydrogen corresponding to only 0.0005% of the transported gas volume, assuming an average volume of 1000 Nm^3/h in real operation for the system.

The feasibility of the test facility to handle natural gas/hydrogen mixtures was analysed carefully before initiation of the tests, and relevant authorities provided instructions for the test.
The project has shown, that the test system is capable of handling hydrogen concentrations up to 12% without modifications to the infrastructure. The existing routines and procedures for the operational staff at the M/R stations proved to a large extent to be sufficient for the operation and maintenance of the test facility with hydrogen injection. The process equipment of the M/R stations (regulator, flowmeter, safety systems, valves etc.) functioned well during the test phase.

If hydrogen concentrations are increased to approximately 30% or more, the consequences for explosion groups and ATEX classification of equipment in the gas infrastructure must be considered. Operation of gas infrastructure with 100% hydrogen would require new competences and personal protective equipment.

The project partners gained valuable practical experiences with hydrogen injection into natural gas infrastructure, which will be utilised in future activities, and the dialogue with authorities also provided a useful background for new projects.

The partners have decided to continue the operation of the test facility after the project and to increase the hydrogen concentration to 25% in the new test programme.

It was originally planned that the hydrogen used in the tests should be produced on-site with an electrolyser. As a result of changes in project partner consortium and scope the hydrogen was, however, purchased and delivered from a supplier. The change in scope implied that the effect on electrolysers from long-term standby periods should be analysed. The results are as follows:
As per the latest agreed project change, hydrogen was delivered by a supplier and not by the on-site electrolyser. The electrolyser system was in idle condition for more than 3 years, and due to that the performance of the system was assumed to be poor compared to a new system.
Consequently, the electrolyser system was analyzed for performance, and key components were analyzed for their conditions after the long idle time.
The analysis included the following testing after more than 3 years of idle condition:

- The leak rate was very low, about 2 ml/min, and was fine
- The performance was poor, about 50% of an equivalent new system
- The most critical component in the electrolyser is the MEA (Membrane assembly in the PEM stack). An MEA from a very poorly performing cell was tested in a single cell test set-up. It showed just a limited reduction in performance compared to an equivalent new MEA.
- The poor electrolyser performance cannot be explained by the function of the MEA. The explanation seems to be the contact resistances between the titanium fiber felt and the MEA where different oxides might have increased the resistance on the contact surfaces.

1.4 Acknowledgement

This report was prepared by Jesper Bruun Munkegaard Hvid, Energinet, Asger Myken, DGC, Bjarne Koch, EVIDA, and Thomas Graf, IRD Fuel Cells.

Other significant contributors to the project were the Energinet technicians Kent Jensen and Bent Johansen, Henrik Iskov, formerly employed at DGC, now retired, Alexander Nielsen, SDU Intern at Energinet, and Laila Grahl Madsen, IRD Fuel Cells.

The project would like to thank EUDP for the funding that rendered this project possible.

2. Project objectives

The following objectives were defined for the project:

- Surplus of power from renewable sources can be converted through electrolysis into hydrogen which can be stored in the gas infrastructure
- M/R[1] stations will be tested via on-site generated hydrogen for suitability for transport of hydrogen/natural gas mixtures
- Implications for operations, maintenance and cost of M/R stations and electrolyser will be analysed.

To fulfil these objectives, the following activities were planned:

1. Establishment of a closed loop between two M/R stations
2. Installation of an electrolysis plant for on-site production of hydrogen adjacent to the M/R stations, and hydrogen is injected directly into the closed loop
3. Examination of the M/R stations' ability to handle large amounts of hydrogen and conduction of the necessary modifications
4. The electrolysis system will be developed as a stand-alone production unit with associated user interface, monitoring and smart-grid-ready control systems
5. A lengthy test period of 24 months allows for a comprehensive test program, in which the interaction between electrolysis plant and M/R stations is investigated
    a. The test phase also includes lifetime testing of critical components in both electrolyser and M/R stations.
6. The project results in a practical, public guideline that describes how the M/R stations and gas grid must be adapted to handle the injection of hydrogen in the natural gas grid, including consequences for regulatory approvals and operation & maintenance.

The company Green Hydrogen was initially a part of the project but left the project shortly after the start-up due to an internal strategy change. Energinet became the new project manager of the project, and IRD Fuel Cells took over the tasks of Green Hydrogen. There was no change in the scope of the project.

IRD Fuel Cells has, together with DGC, worked with the CE certification process for the complete hydrogen production plant, but has concluded that the required certification task is a significantly more comprehensive activity than the budget allows for, even though some individual plant components are CE certified. The plant has not been in operation since late 2015, and IRD Fuel Cells has no experience in re-

[1] Measuring and regulation

activating plants after stand-by periods of this length but expects that it will be difficult.
EUDP has consequently approved an application for change of scope for IRD Fuel Cells' activities in the project from CE certification and plant operation to analysis of critical components with focus on damages and degradation after more than 3 years' stand-still period.

Instead of hydrogen produced on-site from IRD Fuel Cells' plant, the tests have been conducted with purchased standard hydrogen delivered to the plant. This has allowed the major part of the objectives to be fulfilled, even though the activities 2, 4 and the electrolysis part of activity 5 described above have not been completed.

3. Project results and dissemination of results

3.1 Design of test system and test programme

3.1.1 Test site and test system

The test facility is geographically located in the western part of Denmark, Bolhedevej 4A, 6753 Agerbæk in the Municipality of Varde.

The M/R stations at Helle were built in 1986. The facility was modified to a closed-loop system in 2016.

The test facility's M/R stations are designed for natural gas after the same specification as the rest of the Danish gas system.

Figure 1 depicts the system as it was constructed in 2016.

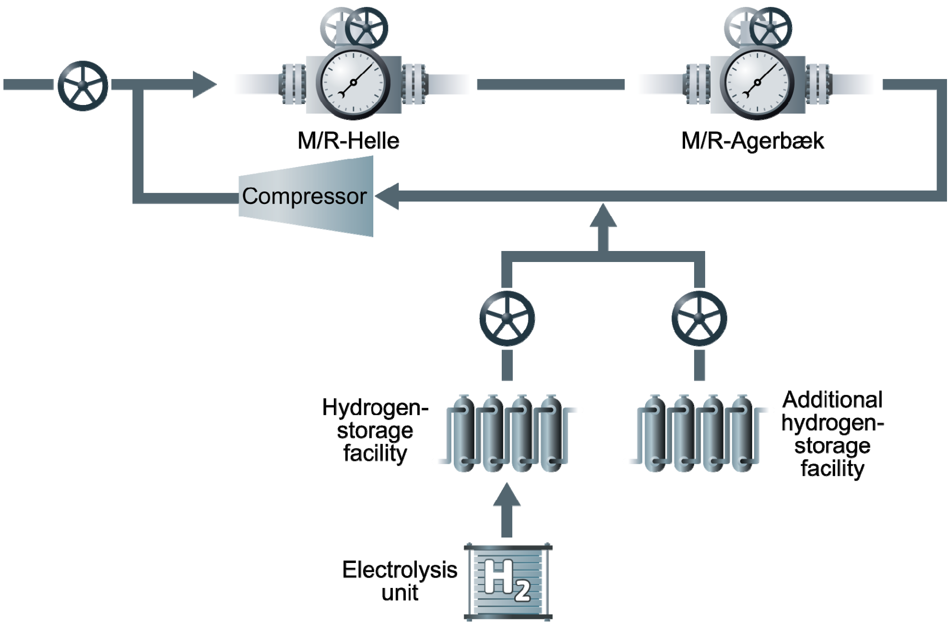


Figure 1. Test facility 2017 - 2019.

The test facility is divided into a high- and a low-pressure side.

The high-pressure side is 40-80 bar g, which includes outlet of the compressor, M/R Helle and inlet of M/R Agerbæk.

The low-pressure side is 4 bar g, which is the zone from M/R Agerbæk to inlet of the compressor.

The facility includes Energinet's meter and regulation station (M/R Helle), which regulates the pressurized gas from 80 bar g to 40 bar g.

The gas is then received by Evida's meter and regulation station (M/R Agerbæk), which is conveniently located at the adjacent parcel. The pressure of 40 bar g is then regulated to 4 bar g. The hydrogen is injected in low-pressure state between M/R Agerbæk and the compressor.

The hydrogen production system was developed and made by IRD Fuel Cells. This system was directly connected to the test facility in parallel to standard hydrogen cylinders. The fuel cells were dismounted at the end of august 2019.
The compressor at site ensures that the pressure is increased from 4 bar g to 80 bar g again with a flow rate of about 80 Nm^3/h, this ends the cycle.
The compressor is a membrane compressor that is especially suited for hydrogen containing gasses.
The facility is kept under surveillance by Energinet's control room and weekly checks by technicians where all relevant measurements and alarms are monitored and collected.

3.1.2 Electrolyser system – Hydrogen production unit at M/R Helle/Agerbæk in Varde

The hydrogen added to the natural gas in the test loop can be provided by either bottled hydrogen or by on-site production of hydrogen. Both hydrogen sources have been planned and installed in parallel at the test set-up at M/R Helle/Agerbæk. The following chapter focuses on the hydrogen production system.

The goal was to have an independent and stand-alone hydrogen system on-site.

Figure 2. Hydrogen system at M/R Helle/Agerbæk.

The needed amount of hydrogen is low and just needed sporadically when the test loop either ran low on hydrogen (due to leakage) or the pressure had to be increased according to the test program. The volume in the test loop at M/R Hel-

le/Agerbæk is about 100 Nm^3 and in average the hydrogen part will be about 7%, which is just 7 Nm^3.
For that reason, IRD's PEM[2] electrolyser with the hydrogen capacity of 1 Nm^3 per hour was more than enough to supply the needed volume for running the planned tests, and it was used as the key component in the hydrogen production system. The system, built into a container, was placed at M/R Helle in January 2016. A few challenges were met for establishing the system for M/R Helle/Agerbæk, e.g.:

- The electrolyser needs pure water, and there is no water supply at the M/R station, nor in the vicinity
- No water drain option is available on the M/R Helle/Agerbæk
- The temperature needs to be maintained above 3 °C to secure operation of the electrolyser
- The electrolyser would just run a few hours over the test period for supplying the needed amount of hydrogen for all the tests. IRD Fuel Cells wished to increase the operation time drastically to achieve more experience on this long-time test

Roughly, the issues were solved by building the whole system into a heated container including a 1 m^3 water tank to secure the water supply for a longer time period. A 1 kW Fuel Cell system, IRD's μCHP[3] was installed as well to utilise excess hydrogen and in this way increase the operation time of the electrolyser. Drain water from the μCHP and water from the H_2-drying system were recycled back to the PEM electrolyser together with condensed water from the ventilation system within the container.

Figure 3. Insulated 20-ft container at M/R Helle in Varde.

The hydrogen production system delivers hydrogen at 4 barg to the test loop, and several functions are needed to run this hydrogen production system. The most important functions are described in the following.

a) The container:
   An insulated 20-ft container (Figure 3) was used as the physical surrounding for all hydrogen related components. The inside environ-

Figure 4. Ventilation system with heat exchanger installed in the 20-ft container.

[2] PEM: Proton Exchangeable Membrane
[3] μCHP: Micro combined heat and power

ment was kept above 3°C by a radiator reusing the produced excess heat from the electrolyser and the µCHP. An additional electrical heat panel was added as well ensuring reliable operation of the system.

b) Ventilation system:
The ventilation system (Figure 4) ensures first of all the inside safety of the container. The ventilation ensures that the hydrogen amount in the container cannot exceed 25% LEL[4] which corresponds to 1% hydrogen in the air. At the same time, the ventilation system must keep down the temperature inside the container on hot summer days or reuse the heat from the air on cold winter days, by a heat exchanger.

Figure 5. PEM electrolyser with drying system on top.

c) The IRD electrolyser and H_2-drying system:
The electrolyser and dryer (Figure 5) have been developed and produced by IRD Fuel Cells, and it is a PEM electrolyser (Proton Exchange Membrane). The system produces 1 Nm³/h hydrogen and 0.5 Nm³/h oxygen from pure water and electrical power. The hydrogen is pure, >99.95%, and it is produced directly at 50 barg by the PEM electrolyser. The pressure is kept at the same level through the drying process and is then led further to the storage cylinder. The oxygen, produced at 2 barg, is not used and is led to the outlet of the ventilation path, where it is diluted before exhausting to the atmosphere.
The power consumption of the PEM electrolyser is 5.5 kWh and of this hydrogen is produced (75%) and heat (25%). The water consumption is about 5 litres per 1 Nm³ H_2 although the theoretical water consumption is only 1 litre. The electrolyser is fed with >100 times the theoretical water amount. The produced hydrogen of the PEM electrolyser is very wet and cannot be stored in this condition. For that reason, the hydrogen passes a drying sys-

[4] LEL: Lower Explosion Limit (4% H_2 in air)

tem with several different drying steps before it is led to the storage tank. To avoid formation of ice in safety valves and other installations, the dew-point of the stored hydrogen is lower than -45 °C at atmospheric pressure. The electrolyser unit is CE and EMC certified.

d) The hydrogen cylinder:
IRD has chosen a hydrogen cylinder made by Experion, a TC_500_1, made of a 350-litre plastic liner reinforced by carbon fibres wrapped in several layers around the liner. The cylinder is allowed to store hydrogen at a max. pressure of 250 barg, but in the system, the max. pressure reached is 55 bar. At this pressure the hydrogen volume is 19.25 m³.

e) The µCHP system:
The µCHP shown in **Fejl! Henvisningskilde ikke fundet.** has also been developed and produced by IRD Fuel Cells. The system is not directly necessary for the hydrogen production system, but it makes use of the excess hydrogen production capacity of the electrolyser and helps to achieve a longer operation time of the system and consequently more operation experience. The hydrogen consumption is 0.7 Nm³/h at 0.4 barg for the µCHP, and it produces 1.5 kW pr. hour electrical power and 1.5 kW heat pr. hour. The µCHP is CE and EMC certified.

Figure 6. µCHP as wall installation.

Figure 7. Hydrogen storage cylinder with protective cover.

f) Water supply and water preparation:

An electrolyser need electrical power and pure water. The conductivity of the water has to be equal to or better than2 µS/cm. For that reason, water from the common grid has to be cleaned quite carefully. A complete water preparation system has been installed including pumps, collecting buffers, reverse osmosis system for pre-cleaning, a demineralizing cartouche for final cleaning and for safety reasons a hydrogen removing system in the water collection tank. As no water supply is established at M/R Helle/Agerbæk, a big water tank of 1000 litres have been connected prior to the water preparation system. The volume keeps the system running for about one month. The produced water from the µCHP and the excess water from the drying system are collected, cleaned and reused. This extends the operation time drastically between the refilling time of the main water tank.

g) Cooling system and reuse of excess heat:

Both electrolyser and µCHP produce heat, which has to be removed from the systems. The heat is collected by a cooling system and in wintertime reused in the container heating installation and in the summertime transported to the outside environment.

h) HMI user interface:

As the hydrogen system is placed on the M/R Helle area and is quite far away from the operators, an HMI user interface is an important part of the system. There are different interfaces, one for the electrolyser, one for the H_2-dryer and one for the µCHP.

The HMI interfaces for the 3 systems are made in very similar ways. Here some information on the interface for the electrolyser is shown. The application is web-based, and important system information for the electrolyser stack and for the internal water system is listed. The CVMS table even shows the potential of all cells in the electrolyser stack (Figure 8).

Settings can be made for system on/off, for the stack current (min/max), and an operation time pattern can be defined for the electrolyser in the green timetable.

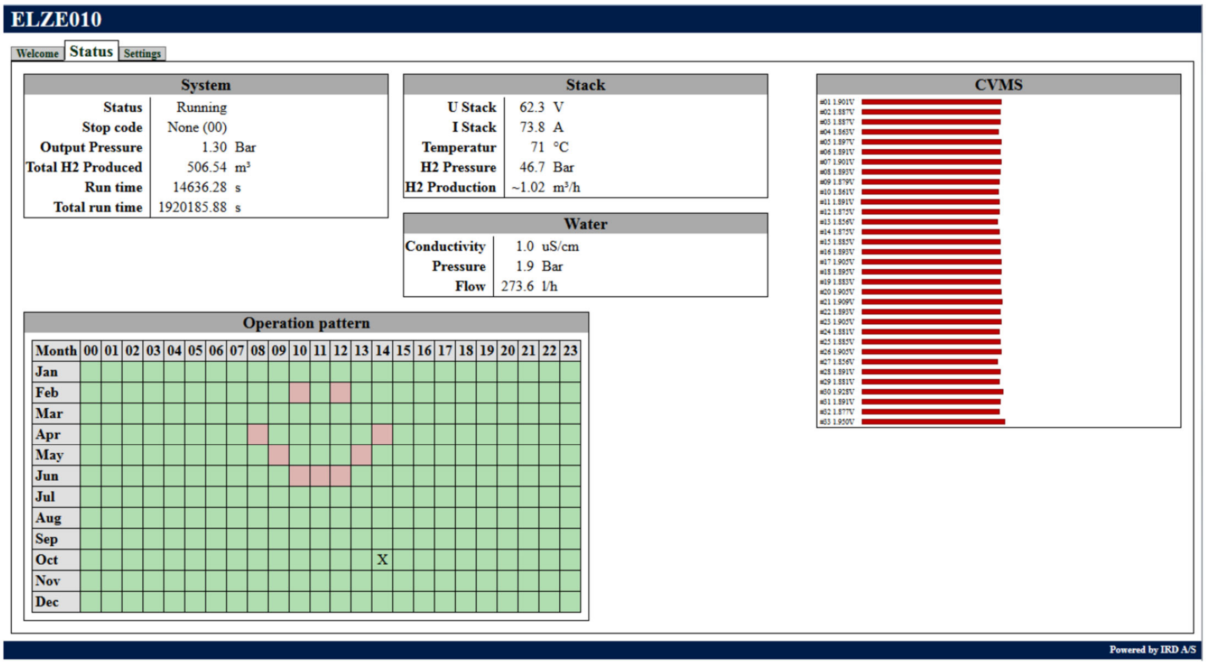


Figure 8. HMI interface for the PEM electrolyser - a web-based solution.

The entire system has no direct interface, but a GSM-unit has been installed sending an alert in case of low water level in the main tank. The alert goes to the operator of the water system.

3.1.3 PID diagram and main characteristics

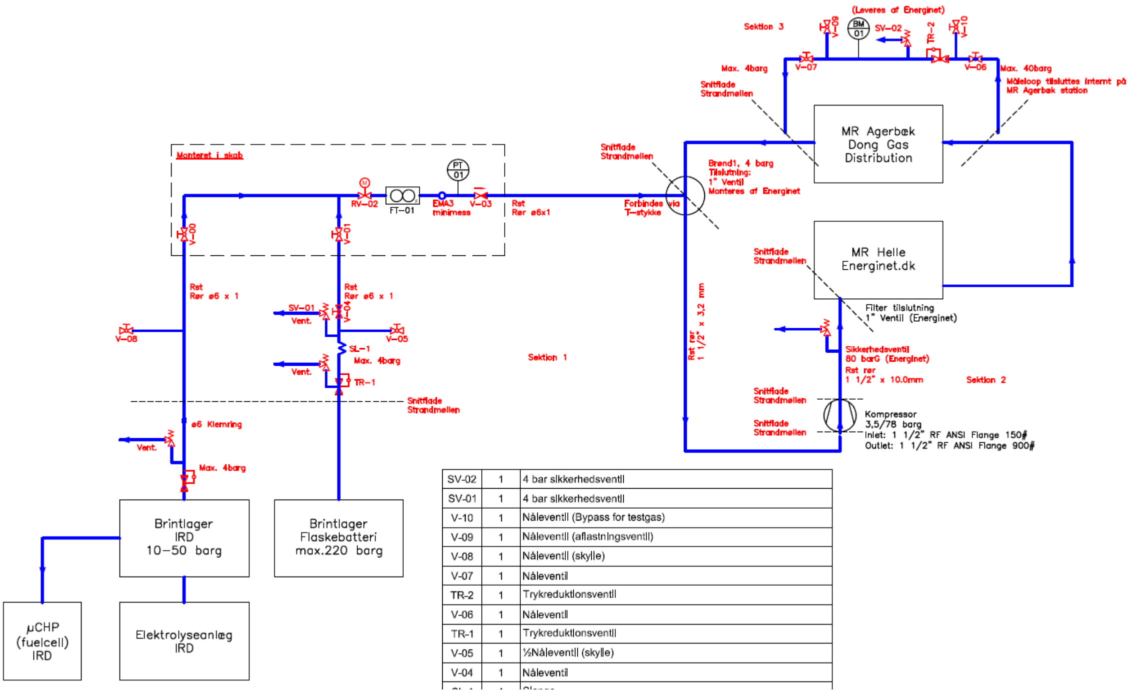


Figure 9. Piping and instrumentation diagram (PID) for the test facility. See appendix 1 for details.

Gasses: Natural gas from Danish gas system with hydrogen

Hydrogen content: 0 to 15 %-mole

Flow rate: Appr. 80 Nm^3 /h

Gas volume: Appr. 100 Nm^3

Compressor type: Membrane compressor

Short description	**Section elements**	**Design pressure (bar g)**	**Typical operational pressure during the test phase (bar g)**
High pressure part	Compressor, new high-pressure pipeline, filter, heat exchanger, regulator	80	65
Medium pressure part	Regulator, flow meter, filter, heat exchanger, DSO regulator	40	35
Low pressure part	Flow meter, new low-pressure pipeline, hydrogen supply point	4	3.4

3.1.3.1 Pipe specifications

The facility's M/R stations and pipe section from M/R station Helle to distribution M/R station Agerbæk are built as regular M/R stations from the 1980s. The facility was later modified to a closed-loop system, which enables injection of natural gas and hydrogen without distribution of the gas mixture to consumers.

Pipe & material specifications for the M/R stations, and the pipe sections between them, will be presented below.

Pipes in M/R Helle

The specifications can be read in Table 1

Pipe section	**Pipe length**	**Pipe diameter, mm**	**Pipe thickness, mm**	**Pipe material**	**Pipe pressure**
Section upstream the regulator		114.3	8.6	API-STD-5L, Grade B	
Section downstream the regulator		114.3	8.6	API-STD-5L, Grade B	

Table 1. Pipe specification for M/R Helle.

New pipes

The new pipe section is from the outlet of M/R Agerbæk to the inlet of M/R Helle. These pipes were installed by Strandmøllen.

The specifications of the pipe section from outlet of M/R Agerbæk and inlet M/R Helle can be seen in Table 2

Pipe section	Pipe length	Pipe diameter	Pipe thickness	Pipe material	Pipe pressure
Agerbæk to compressor	19.4 m	1.5 inch (48.00 mm)	3.2 mm	Stainless steel (EN1.4404/Aisi316)	4 barg
Compressor to the filter at M/R Helle	20.6 m	1.5 inch (48.00 mm)	10.0 mm	Stainless steel (EN1.4404/Aisi316)	80 barg

Table 2. Pipe specification for installed pipes by Strandmøllen.

Appendix 1 shows a PID of the pipes installed by Strandmøllen.

3.1.3.2 Volume capacity

The gas volume capacity of the facility was calculated in perspective of geometrically volume and normal volume.

The volume was calculated for different pipe sections. Each of these calculations are based on the gas's respective pressure and temperature in the specific pipe segment.

The total calculations and data foundation can be seen in appendix 2.

The volumes can be seen in Table 3

System	**Section**	**Geometric volume (l)**	**Normal volume[5] (Nm³)**
M/R Helle	Inclusive of filter to regulator	392.9	35.8
M/R Helle	Regulator to isolate coupling	409.7	17.4
M/R Agerbæk	Isolate coupling to regulator	996	42.4
M/R Agerbæk	Regulator to flange in new well	1207	5.8
New piping	Flange in new well to compressor inlet	26.4	0.127
New piping	Low-pressure side of compressor	4	0.019
New piping	High-pressure side of compressor to outlet	4	0.365
New piping	Outlet from compressor to filter at M/R Helle	28.0	2.6
Total		**3068.0**	**104.5**

Table 3. Estimated volume capacity for the test facility.

As can be read from the table, the total geometrically volume is 3068 litres and normal volume is 104.5 Nm^3.

Some of the data was provided externally. The sources for the data foundation can be found in appendix 2 as well.

[5] At 10°C, 10% hydrogen and nominal pressures in individual sections of system

3.1.3.3 Hydrogen measurements

The hydrogen concentration is measured at M/R Agerbæk with a gas analyser (thermal conductivity analyser model XTC601) produced by Michell instruments. The gas analyser is based on thermal conductivity of the gas. Hydrogen has a higher conductivity than the other components in natural gas. This gap is utilised to measure the hydrogen concentration of the gas.

Figure 10 depicts the thermal conductivity for hydrogen in different gases and pure gas components which can be found in natural gas.

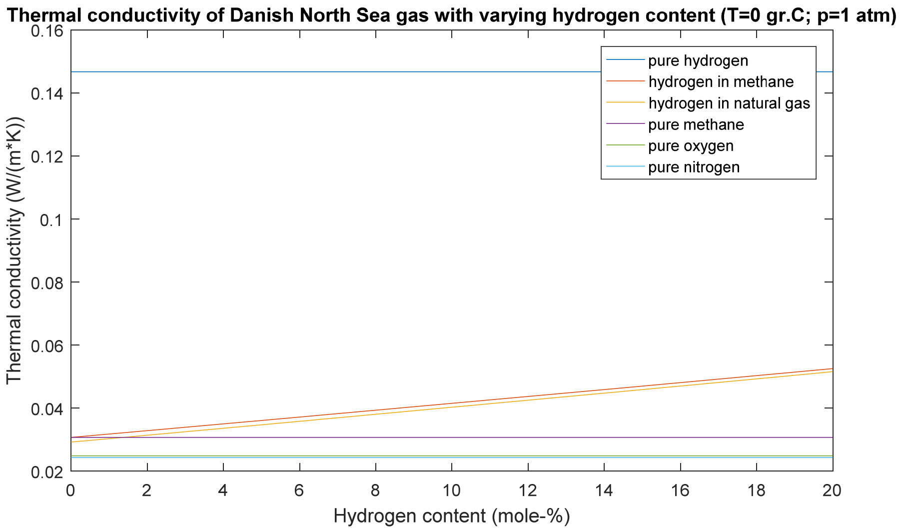


Figure 10. Thermal conductivity for hydrogen content in different gasses.

The gas analyser is customized, which means that the general manual for gas analyser cannot be used. The customisation was done together with Michell, and is certified.

The gas analyser is customised to measure the gas at M/R Agerbæk with a pressure of 3.7 bar g.

The original specifications of the gas analyser will not support meassurements of gas with pressure above 3 bar g.

For further information about installation, fault detection and field calibration, please see appendix 3

3.1.3.4 Hydrogen injection

The hydrogen is injected in low-pressure state, 4 bar g, after M/R Agerbæk, and before the compressor.

The hydrogen concentration can be increased by injection of more hydrogen, which is stored in pressurized bottles on site. The injection flow rate of hydrogen is typically 4.0 Nm^3 /h.

The injection of hydrogen is controlled by the control box, which regulates the pressure of the hydrogen to about 3.4 bar g. The pressure of the environment where the hydrogen is injected is around 3.4 bar g.

The hydrogen is delivered pressurized by Strandmøllen A/S. The hydrogen is stored at 200 bar g. The storage consists of 12 bottles with a capacity of 600 litres in total, see Figure 11.

Figure 11. Picture of the hydrogen storage.

3.1.3.4.1 Safety procedures for hydrogen injection

The hydrogen is manually injected into the test loop. Procedures and guidelines were compiled. The procedures and guidelines are especially suited for this test facility. For more general safety purposes, the procedures should be evaluated further.

An overview of the safety procedure can be seen in Table 4.

Overview of steps in procedure
1. Verification of the hydrogen analyser function
2. Control of hydrogen content in test loop
3. Injection of hydrogen in test system
4. Control of amount of injected hydrogen
5. Reporting

Table 4. Overview of the steps in the safety procedure "Procedure for tilførelse af brint".

3.1.4 Safety considerations

Safety has been a key topic for the project both in the preparatory phase and during the test phase of the project. Both a HAZID (appendix 4) and a HAZOP workshop (appendix 5) for the test setup were performed in order to ensure that a safe and robust test setup was established.

As an outcome of the HAZID and HAZOP, a new gas detector system, which is a catalytic type sensitive to natural gas and hydrogen, was installed in both M/R stations. This was evaluated as necessary to mitigate any risk of a heterogeneous leakage from the system where mainly hydrogen would leak.

3.1.4.1 Authorities

The authorities were involved in order to obtain permissions for the construction of the test facility.

Authorities were involved in the approval of the test facility at M/R Helle & Agerbæk. The implicated authorities are Arbejdstilsynet, *The Danish Working Environment Authority,* Sikkerhedsstyrelsen, *the Danish Safety Technology Authority* and the local fire department, "*Sydvestjysk Brandvæsen".*

The project applied for an approval from the Danish Working Environment Authority who is the competent authority for high-pressure gas systems in Denmark. The Danish Working Environment Authority responded that an approval was not necessary as the modifications must meet the requirements in the Danish Working Environment Authority's executive order 743 and directive 97/23/EF (PED). See appendix 6 for details.

The Danish Safety Technology Authority approved the hydrogen production facility in compliance with Gasreglementet[6], section C8. For a possible later further test period of the facility, in preparation for a permanent application of hydrogen injection in natural gas grid, the Danish Safety Technology Authority will demand specific gas qualities for hydrogen and natural gas.

- Requirements for the quality of hydrogen.
    - Section 8.1 and 10.8 of Gasreglementets C-12
- Requirements for the quality of natural gas.
    - Section 2.1, 3, 5 and 10.2 of Gasreglementets C-12.

Since gas was not distributed to consumers during the test phase, the Danish Safety Technology Authority did not decide the maximum volume percentage of added hydrogen cf. C-12, section 8.1.
The Danish Safety Technology Authority further required continuous monitoring of the hydrogen concentration of the facility.

In addition to Gasreglementets sections B-8 and B-12, The Danish Safety Technology Authority evaluated the project according to Gasreglementets section C-4, *Installation specifications for large gas fired units.* The approval from Sikkerhedsstyrelsen can be found in appendix 7.

[6] "Gasreglementet" was the rules in force at the time of the approval of the test system. It has been replaced with Gassikkerhedsloven ("Gas safety law") with effect from 21st April 2018.

The local fire department, Sydvestjysk Brandvæsen, approved the establishment of test facility with production of hydrogen at the M/R Helle and M/R Agerbæk.
The project application was further evaluated by the Danish Emergency Management Agency, *Beredsskabsstyrelsen*, since the facility is covered by Executive Order no. 1444 about technical rules and regulations of gasses.
The production facility is required to follow section 1.3.5 of *Technical rules and regulations of gasses*[7] and the Danish Preparedness Act paragraph 32, item 2.
Furthermore, *Sydvestjysk Brandvæsen* described conditions for establishment of the facility.
These conditions hold criteria of submitting safety procedures and classification plan (ATEX zones) to *Sydvestjysk Brandvæsen.* The complete approval from Sydvestjysk Brandvæsen for the project can be found in appendix 8.

3.1.4.2 Electrolyser system

As hydrogen together with oxygen or air is extremely explosive, safety is absolutely a key issue for such a hydrogen production system. The gas mixture from 4% (also defined as 100% LEL, Lower Explosion Limit) to 76 % hydrogen in air is explosive. The basic safety principle of the entire hydrogen production system is the exchange of air in the container. The air exchange ensures that the hydrogen concentration inside the container is lower than 10% LEL which corresponds to 0.4% hydrogen concentration in air (at full hydrogen production leaked to the container). A diagram of the safety installations is shown in Figure 12.

The ventilation has its own safety sensor for identifying proper operation. Additionally, a hydrogen detecting sensor is installed. The sensor generates signals at two hydrogen concentration levels, the first one at 10% LEL and the second one at 25% LEL.
In case of a ventilation stop or a 10% LEL alert, a valve in the outlet of the electrolyser will close and will force an ordinary and regular stop of the electrolyser, which will stop further production of hydrogen.
Should for any reason a 25% LEL alert occur, the entire system will be shut down immediately. Solely the ventilator placed outside the container will start up to run and will continue exchanging air in the container. It pumps air into the container, and the hydrogen enriched air will leave through an outlet tube placed in the top of the container. This ensures that the mixture does not pass an electrically powered component.

[7] Vejledning til tekniske forskrifter for gasser. Brandforebyggelse, vejledning nr. 15

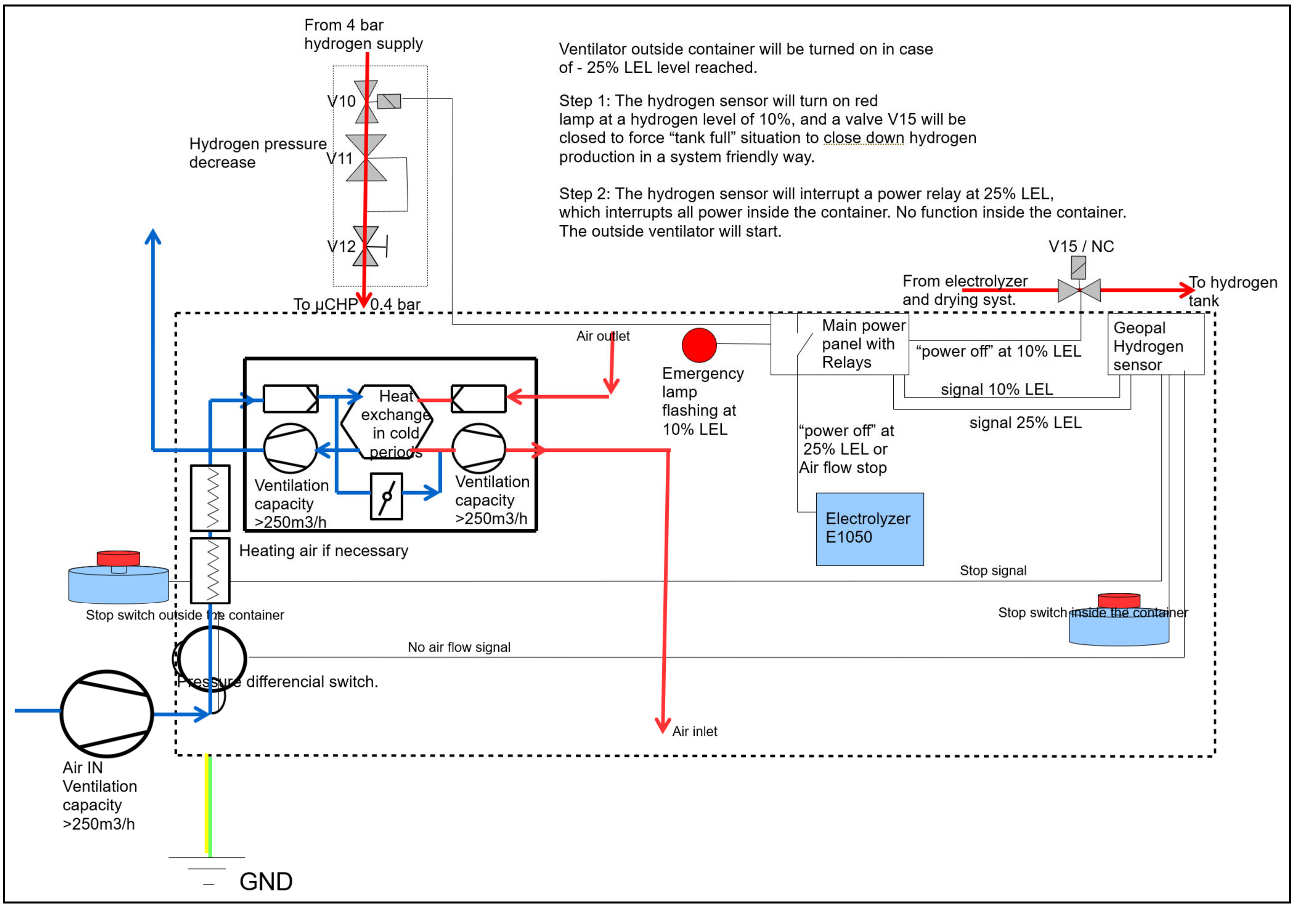


Figure 12. Safety scheme for the hydrogen production system at M/R Helle in Varde.

The electrolyser, the dryer system and the µCHP have their individual CE safety certification.

The ventilation is a standard system, and it has its own CE certification as well. Even though during the installation process at M/R Helle, we found out that the entire system should be CE certified as well. Together with our project partner DGC, we evaluated the needed effort for this certification. Together we concluded that the work to be done for the certification by far would exceed the budget frame for the project.

For that reason, we asked EUDP to introduce a change of part of the project scope in May 2019. The request was accepted, and according to the changed application, the container was moved to IRD Fuel Cells where the electrolyser was analysed for its quality and condition due to the long-time of no operation at M/R Helle according to the changed application.

3.1.4.3 Changes of explosion groups

As hydrogen is injected, the ATEX zones[8] and explosion groups might change.

A study by the German company BAM [1] investigated the change of explosion groups in various concentrations of hydrogen in methane.

Figure 13 describes the relationship between hydrogen concentration [mol - %] and change of explosion groups.

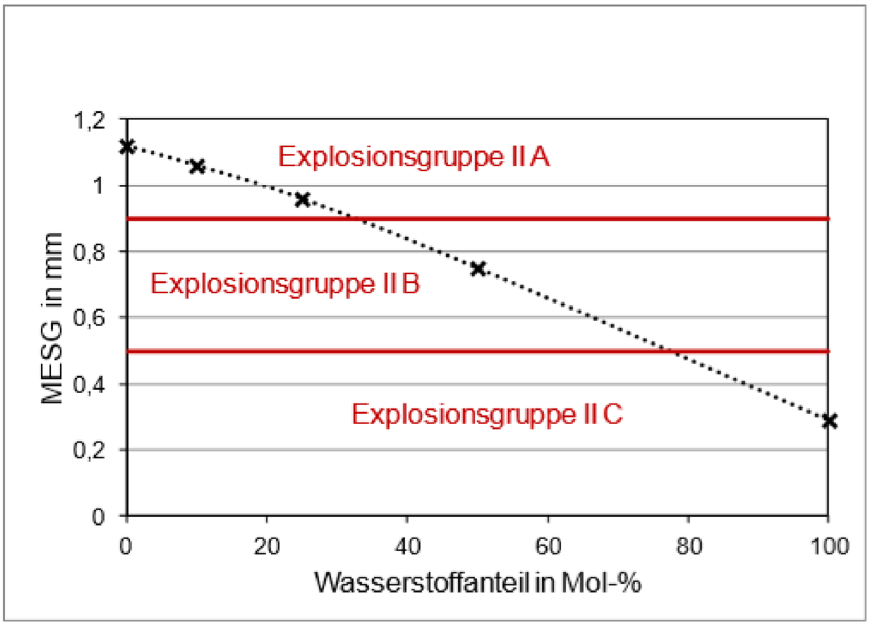


Figure 13. Explosion groups for various hydrogen concentrations. [1]

As the study from BAM indicates, the explosion groups change from explosion group II A to explosion group II B at a hydrogen concentration of 30 mole-%, and a change from explosion group II B to explosion group II C at a hydrogen concentration of about 80 mol-%.

Based on this study, the explosion groups for the facility were determined.

Since the authorities approved a maximum hydrogen content of 15 % mole-%, it was not necessary to replace existing electrical equipment.

The electrical equipment complies with standards for equipment within explosion group II A.

This implies that existing M/R stations do not need replacement of existing electrical equipment for a hydrogen concentration below 30 mole-%.

[8] According to IEC 60079-10

3.1.5 Test programme

Leakage tests

During the test phase, investigation of leakages was given special focus, and the integrity of materials, seals, wear and tear of parts were also areas of interest for the project.

During the test phase, periodical leakage testing was performed after normal procedures.

It is known that the closed loop will leak in periods without flow.

Before the test phase was initiated, a static leakage test was performed, to investigate if any leakages were found at the two M/R stations. Where leakages were identified, repair would be done.

The static test was performed by Strandmøllen, the same company that later installed external pipes from the outlet of M/R Agerbæk to the inlet of M/R Helle.

For the static leakage test formier gas was used (90% nitrogen and 10% hydrogen). Both M/R stations were pressurized with formier gas based on the design pressure of the M/R stations.

The stations were tested on the high-pressure side first, so that the gas could be reused in several tests. The pressure was increased by steps of 10 bar.

All potential components which could leak, was sprayed with soap water. If bubbles from the soap water was appearing, this could imply a leakage from the component.

The leakage test was done on the filter, preheater, regulator string and measure string at M/R Helle, the pipeline between the two M/R stations, and also the regulator string, measure string and plastic grid to the new valve at outlet of M/R Agerbæk were tested.

Main strings, instruments and facilities for blow-offs of gas was tested as well. Underground valves were tested using a balloon on the lubricate pipe. The report about the static leakage test can be found in appendix 9.

3.1.6 Hydrogen related material integrity effects

As hydrogen can cause destructive effects on materials such as steel, the project arranged a discussion with experts among the project partners. The slides from the meeting can be found in appendix 10 The conclusion from the meeting was that the risk of hydrogen induced cracking in the facilities for the tested hydrogen content was evaluated as negligible as the materials used in the system were evaluated as robust for hydrogen up to 30 %-mole. However, the weakest point of the facilities was considered to be welds in the system, as the material of the weld could have a higher hardness that the joint pipe spools making them more vulnerable to hydrogen induced cracking. It was therefore decided to make inspections of a number of welds in the test facility. These inspections will be repeated at the end of the following phase 2 of the project where the hydrogen content is planned to be higher, up to 25 %-mole.

3.2 Test results

3.2.1 Concentration measurements

7 test-periods were successfully completed, without hydrogen related faults of the operation.
Throughout the test phase, the hydrogen content has been increased from 0% to 14%, with periodic increases in concentration of hydrogen in each test-period.

A test period is defined as a period starting with an injection of hydrogen and ending when either a fault occurs, or additional natural gas or hydrogen is injected. Any injection of hydrogen or natural gas will introduce a new test period.

The amount of injected hydrogen in the test period can be seen in the below *Table 5*.

Date	Flow [Nm^3/h]	Total time of injection [min.]	Amount injected [Nm^3]
06-06-2017	2.5	30	1.25
27-09-2017			2.33
10-01-2018	3.75	65	4.0
21-11-2018	4	90	6.0
15-01-2019	3.6	100.0	6.0
20-02-2019	4.0	30.0	2.0
17-05-2019	3.7	25.0	1.5
18-07-2019	3.7	90.0	5.6
26-09-2019	3.6	100.0	6.0

Table 5. Date and specification for injection of hydrogen in the test facility.

The progress of hydrogen concentration in the test phase can be seen in Figure 14.

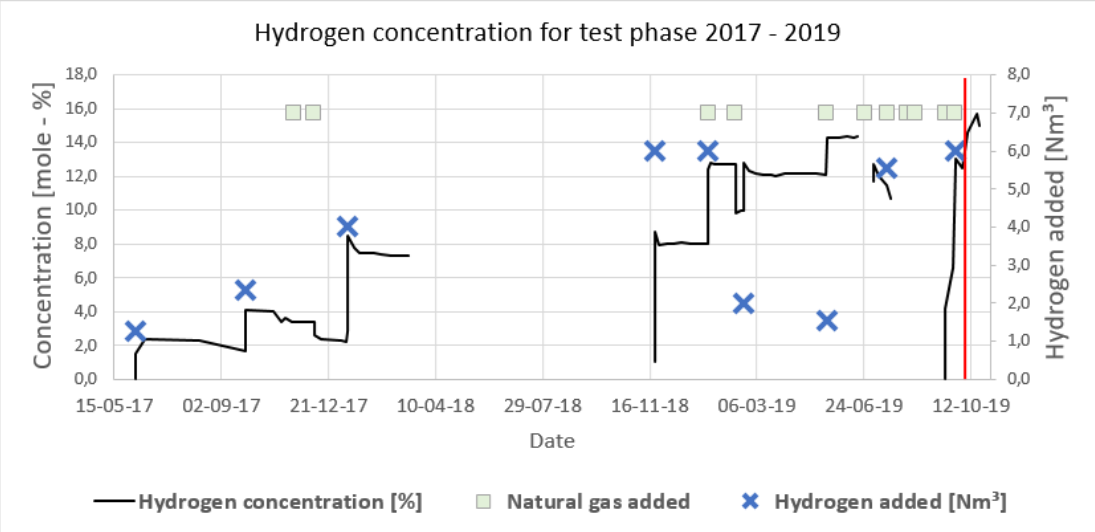


Figure 14. Overview of the test phase for the test facility.

Figure 14 depicts the concentration for the whole test phase. Each test period will be described further.

The drop in the beginning of a test period is most likely caused by the time to achieve a homogeneous mixture of hydrogen and natural gas.

The data for hydrogen concentration can be validated until 3/10/2019, which is marked with a red line in Figure 14

The gas analyser was dismounted 25/10/2019, due to instability measurements and calibration. As it can be seen, the gas analyser measured the concentration to be 15.6%

The last validated hydrogen concentration was 13%.

The period from 13/03/2018 – 21/11/2018 without measurements of the hydrogen concentration is due to technical issues with M/R Agerbæk.

Test results for 2017

To start the test period, hydrogen and natural gas were injected to the system. The first test period began 14th of June 2017. Two test periods were successfully conducted in 2017.

Test period 1. 14/06/17 – 27/9/17

The first test of the facility was over 3 months and started in the middle of June. The specifics for the test period can be seen in Table 6.

Test no.	Goal for hydrogen content [%]	Content before feeding hydrogen [%]	Hydrogen flow [Nm³/h]	Time for feeding [Min]	Total hydrogen injected [Nm³]
1	1	0	2.5	30	1.25

Table 6. Specifications of hydrogen injection for test period 1.

The goal for first test period was to achieve a stable hydrogen concentration of 1%.

The results of the concentration for test period 1, is depicted in Figure 15.

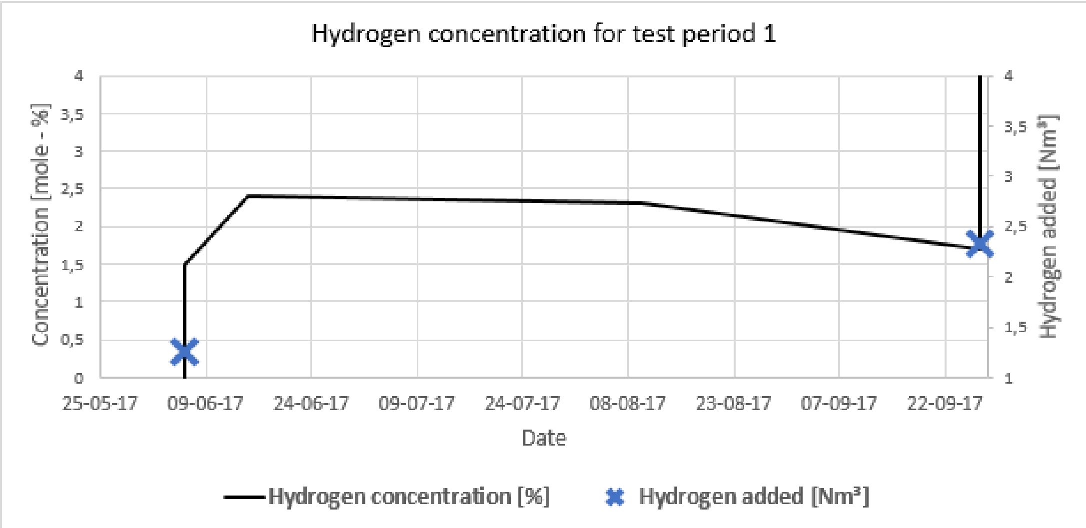


Figure 15. Result for hydrogen concentration in test period 1.

The concentration for hydrogen was kept stable for 2 months and began to decrease until the next injection of hydrogen, and a new test period.
The total decrease from the highest hydrogen concentration to the lowest was 0.7% point.
The end concentration for test period 1 was 1.7%. As the goal was 1%, test period 1 was seen as completed compared to the goal for it.

Test period 2. 27/9/17 – 15/11/17

The second test of the facility was over 2 months and started at the end of September.

The test period ended due to injection of natural gas the 15/11/2017.

The specifics for the test period can be seen in Table 7.

Test no.	Goal for hydrogen content [%]	Content before feeding hydrogen [%]	Hydrogen flow [Nm³/h]	Time for feeding [Min]	Total hydrogen injected [Nm³]
2	-	1.7	-	-	2.33

Table 7. Specifications of hydrogen injection for test period 2.

Information regarding goal for concentration, hydrogen flow and time for feeding the hydrogen for test period 2 is not available.

The result for test period 2 is depicted in Figure 16.

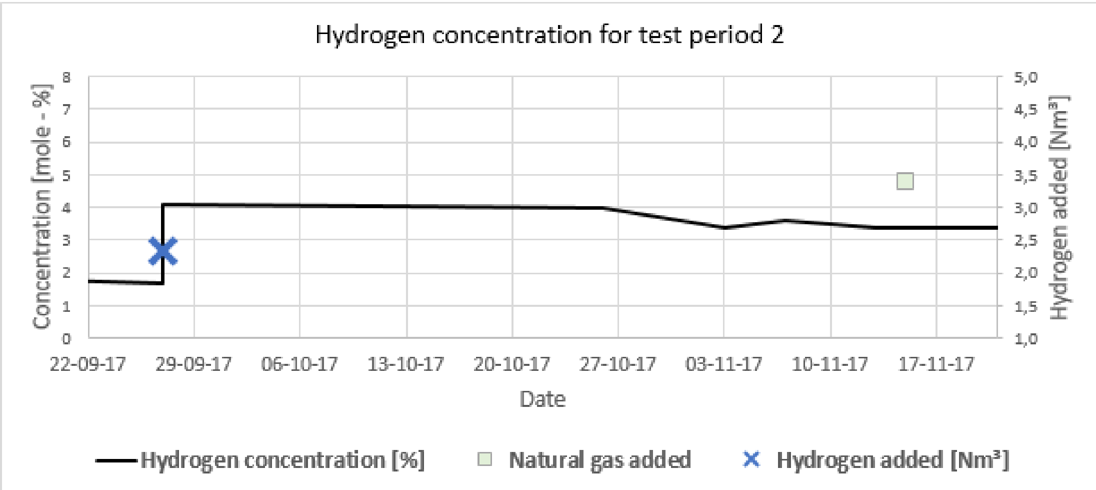


Figure 16. Specifications of hydrogen injection for test period 2.

The concentration of 4% for hydrogen was kept stable for one month and decreased to 3.4% due to blowing-off of gas in relation to a weekly check.

The total decrease from the highest hydrogen concentration to the lowest was 0.6 percentage point.

For another 2 weeks, was the concentration kept stable of 3.4% until the injection of natural gas ended the test period.

3.2.1.1 Test results for 2018

The facility was out of order for nearly 9 months in 2018, due to technically issues.

Therefore, only two test periods were introduced and conducted.

The two test periods and their results are described further.

Test period 3. 10/1/18 – 13/3/18

The third test of the facility was over 2 months and started at the beginning of January.

The test period ended due to the technically issues on site.

The specifications for the test period can be seen in Table 8.

Test no.	Goal for hydrogen content [%]	Content before feeding hydrogen [%]	Hydrogen flow [Nm³/h]	Time for feeding [Min]	Total hydrogen injected [Nm³]
3	7	2.8	3.75	65	4

Table 8. Specifications of hydrogen injection for test period 3.

The goal for first test period was to achieve a stable hydrogen concentration of 7%. The total hydrogen injected was nearly twice the amount of the previous injection of hydrogen.

The results of the concentration for test period 3, is depicted in Figure 17.

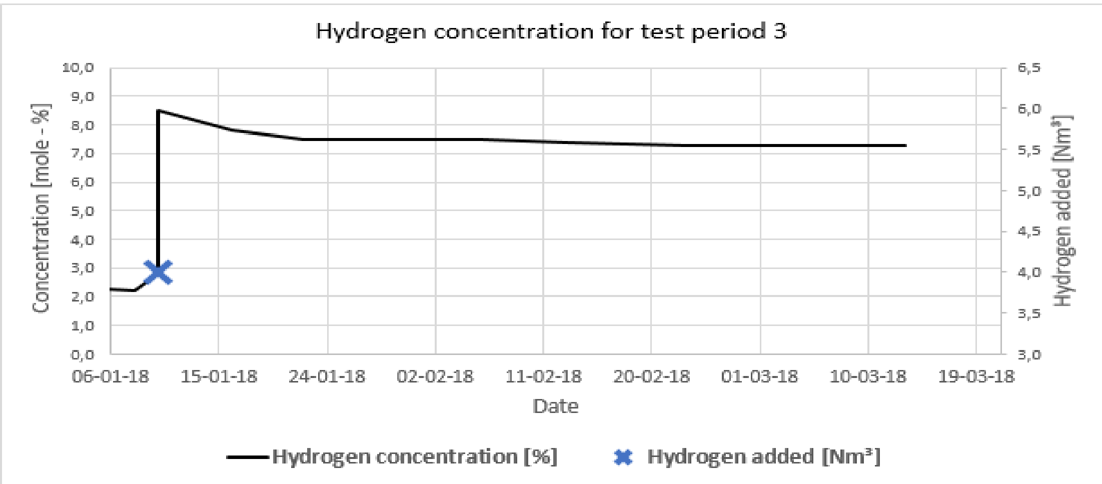


Figure 17. Specifications of hydrogen injection for test period 3.

The concentration of hydrogen was kept stable at 7.3% for two months.

The goal for test period 3 was to keep a stable hydrogen concetration of 7%.

As the result showed a stable concentration of 7.3%, the goal for test period 3 was met.

Test period 4. 21/11/18 – 15/1/19

The fourth test of the facility was conducted over 2 months and started mid-November.

The test period ended at the beginning of January 2019, where hydrogen was further injected, and a new test period was introduced.

The specifications for the test period can be seen in Table 9.

Test no.	Goal for hydrogen content [%]	Content before feeding hydrogen [%]	Hydrogen flow [Nm³/h]	Time for feeding [Min]	Total hydrogen injected [Nm³]
4	8	1	4	90	8.7

Table 9. Specifications of hydrogen injection for test period 4.

The goal for fourth test period was to achieve a stable hydrogen concentration 1% point above the previous test period: 8%.

The fourth test period was started from 1% of hydrogen, due to technical issues.

The hydrogen concentration was raised from 1% to 8% in the first injection of hydrogen, which required a huge amount of hydrogen. This has been the highest amount of injected hydrogen in a test period.

The results of the concentration for test period 1 is depicted in Figure 18.

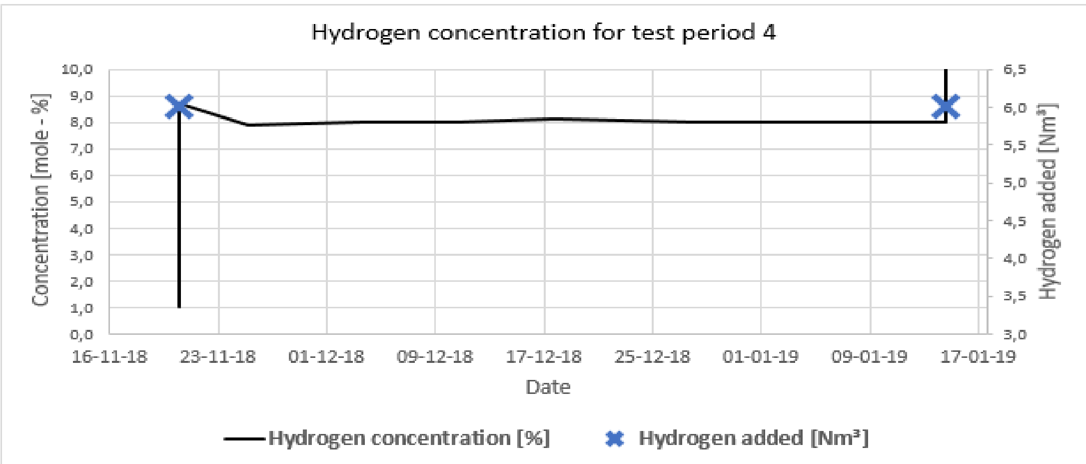


Figure 18. Specifications of hydrogen injection for test period 4.

The concentration of hydrogen was kept stable at 8% for two months.

The goal for test period 4 was to keep a stable hydrogen concetration of 8%.

As the result showed a stable concentration of 8%, the goal for test period 4 was met.

The test period ended due to additional injection of hydrogen, to introduce a new test period, with a higher concentration of hydrogen.

3.2.1.2 Test results for 2019

3 successful test-periods were completed in 2019, where hydrogen was injected 5 times and natural gas 6 times.

The goal related to hydrogen concentration for 2019 has been achieved: to increase the hydrogen concentration from 8% at the end of 2018, to 14% in 2019.

The last validated hydrogen concentration was 13%

Test period 5. 15/1/19 – 20/02/19

In January 2019, the concentration of hydrogen was successfully increased from 8% to 12%. The test period was conducted over 1 month.

Both hydrogen and natural gas were injected in the beginning of test period 5.

The specifics for the test period can be seen in Table 10.

Test no.	Goal for hydrogen content [%]	Content before feeding hydrogen [%]	Hydrogen flow [Nm³/h]	Time for feeding [Min]	Total hydrogen injected [Nm³]
5	12	8	3.6	100	6

Table 10. Specifications of hydrogen injection for test period 5.

The goal for the fifth test period, was to achieve a stable hydrogen concentration of 12%

The results of the concentration for test period 5, is depicted in Figure 19.

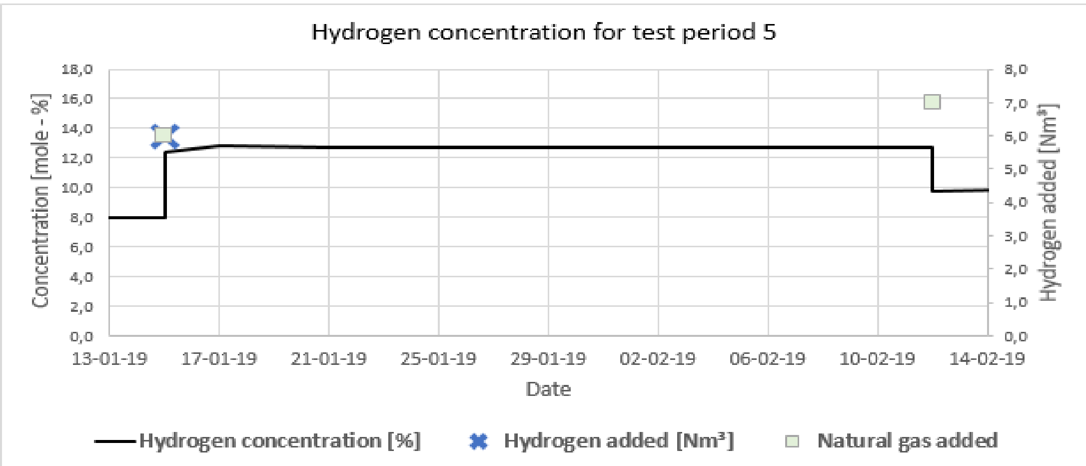


Figure 19. Specifications of hydrogen injection for test period 5.

The concentration of hydrogen was stable at 12% for about one month.

The hydrogen concentration decreased to 10%, where a new test period was introduced. The decreasing was due to a restart of the compressor and injection of natural gas on 12/2-2019.

Test period 6. 20/2/19 – 16/5/19

In February 2019, the concentration of hydrogen was increased from 10% to 12%.

The test period was conducted over almost 3 months.

An injection of hydrogen 20th February introduced the sixth test period.

The specifications for test period 6 can be seen in Table 11.

Test no.	Goal for hydrogen content [%]	Content before feeding hydrogen [%]	Hydrogen flow [Nm³/h]	Time for feeding [Min]	Total hydrogen injected [Nm³]
6	12	10	4	30	2

Table 11. Specifications of hydrogen injection for test period 6.

The goal for the sixth test period was to achieve a longer stable hydrogen concentration of 12% than in the previous test period.

The results of the concentration for test period 6, is depicted in Figure 20.

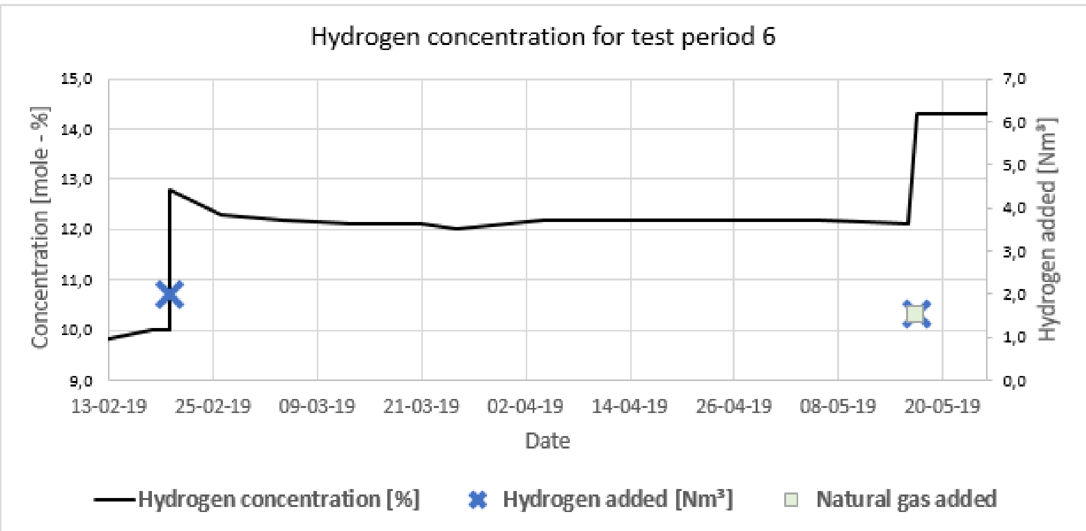


Figure 20. Specifications of hydrogen injection for test period 6.

The concentration of 12-12.1% for hydrogen was kept stable for one month.

As the result showed a stable concentration of 12%, the goal for test period 6 was met.

The test period ended due to additional injection of hydrogen, to introduce a new test period, with higher concentration of hydrogen.

Test period 7. 16/5/19 – 17/6/19

Test period 7 was introduced in continuation of test period 6, where additional hydrogen was injected to achieve a higher concentration of hydrogen.

The seventh test period was conducted over 1 month.

The overall goal for 2019 was to increase the hydrogen concentration from 8% to 14%.

Table 12 shows the specifacations for the 7th test period.

Test no.	Goal for hydrogen content [%]	Content before feeding hydrogen [%]	Hydrogen flow [Nm^3/h]	Time for feeding [Min]	Total hydrogen injected [Nm^3]
7	14	12	3.7	25	1.5

Table 12. Specifications of hydrogen injection for test period 7.

The goal for first test period was to achieve a stable hydrogen concentration of 14%.

Natural gas was injected, and an additional small amount of hydrogen was injected, to increase the concentration from 12% to 14%.

The results of the concentration for test period 7, is depicted in Figure 21.

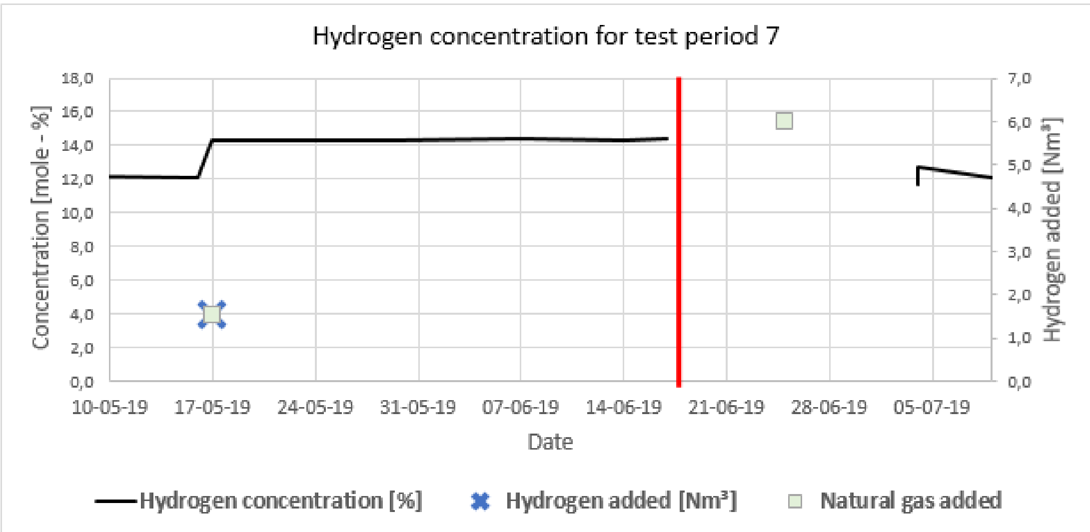


Figure 21. Specifications of hydrogen injection for test period 7.

The concentration of 14% for hydrogen was kept stable for one month.

As the result showed a stable concentration of 14%, the goal for test period 7 was met. Additional test should be conducted to evaluate the result of a hydrogen concentraion of 14% over a longer period of time.

The test period ended 18/6 - 19 due to shut-down reset of the compressor. This is marked with a red line.

3.2.2 *Mass balance analysis*

Mass balance analysis was performed to investigate potentially leaks, which could not be determined from analysing the hydrogen concentration.

Whether a leak can be determined by decrease in hydrogen concentration is related to whether the leak is homogenous or heterogenic.
If a leak is assumed a heterogenic leak, a hydrogen concentration analysis could detect whether or not a leak has occurred.

If the leak is homogenous, the method of analysing the hydrogen concentration cannot be used as a detector.

The mass balance analysis was performed on data from the test period from 20/2/19 to 17/5/19.
This test phase was chosen due to its nearly 3 months of steady and constant value of hydrogen concentration.

The volume balance for the chosen period is depicted in Figure 22.

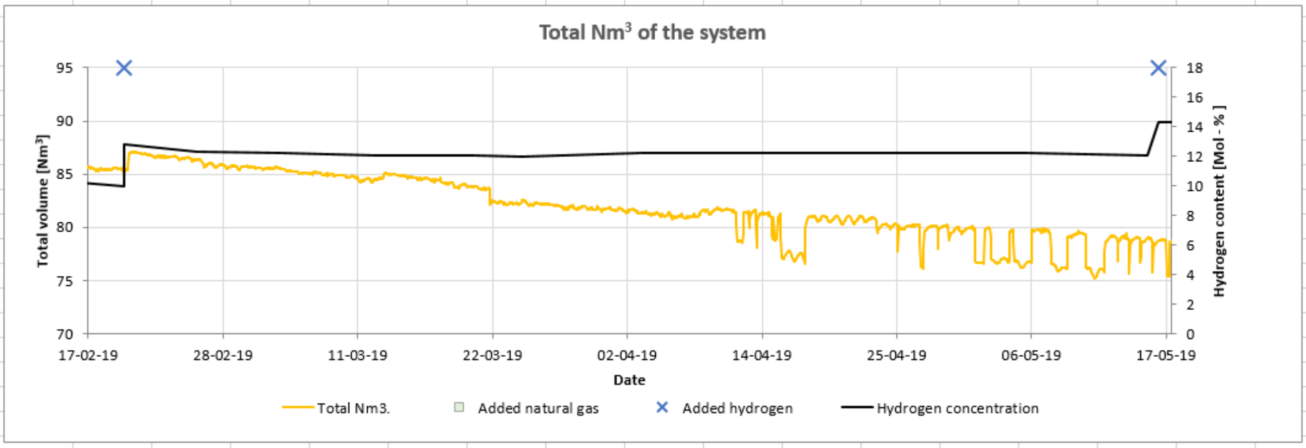


Figure 22. Total Nm^3 of test facility over time for the period 20/2/19 - 17/5/19.

As can be seen from the graph, the gas volume is decreasing over the 3 months. 20th February the total normal volume is 86.02 Nm^3, while at the end of the test period, 17th May, the total normal volume for the test facility is 75.36 Nm^3. This resulted in a decrease of 10.66 Nm^3 corresponding to 0.124 Nm^3 per day. If an average flow of 1000 Nm^3/h during normal operation is assumed for a plant of this size, the leakage rate corresponds to approximately 0.0005% of the transported gas.

As this could be a single case of a potential leak, the whole testing phase was analysed further regarding volume balance.
The result of volume balance for the whole test phase period is depicted in Figure 23.

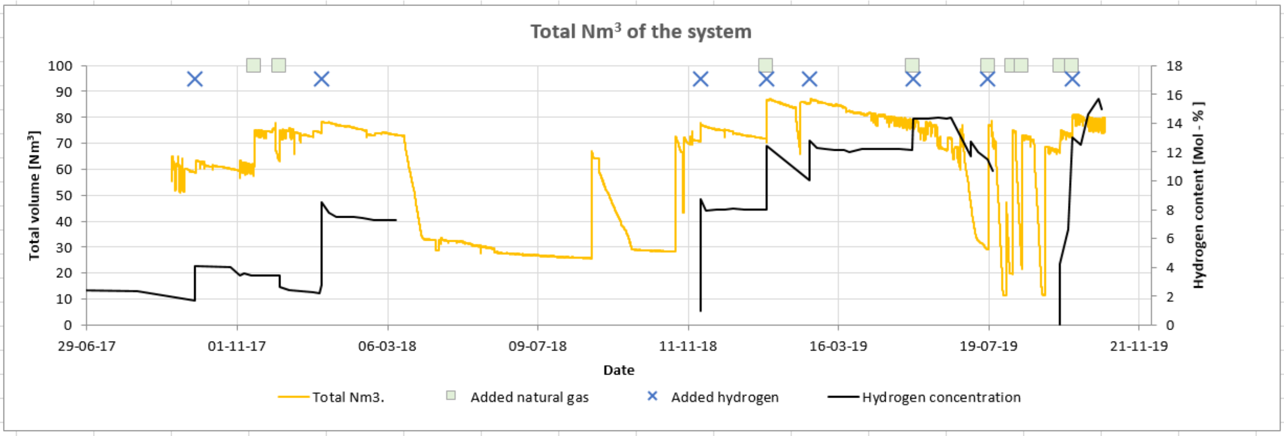


Figure 23. Total Nm³ over time for the test phase.

The analysis shows a tendency of decrease of the total normal volume [Nm^3] after injection of natural gas or hydrogen in the system.

The specific numbers and data foundation can be seen in appendix 11 (spreadsheet, not included in report).

3.2.3 Leakage tests

The static test resulted in 11 identified leakages on components. The main leakages were related to the original hydro-balls valve at the M/R stations. These are not of stainless steel. The leakages were repaired by replacing the original hydro-balls to new hydro-balls of stainless steel.
The report about the specific leakages can be found in appendix 9.

One fault related to leakage was observed during the test phase. The leakage occurred at M/R station Helle.
The leakage was related to a Trunnion ball valve on flow string one, see Figure 24, and was found manually during a weekly check the 6/8/19. The valve was replaced at site shortly after the fault detection.

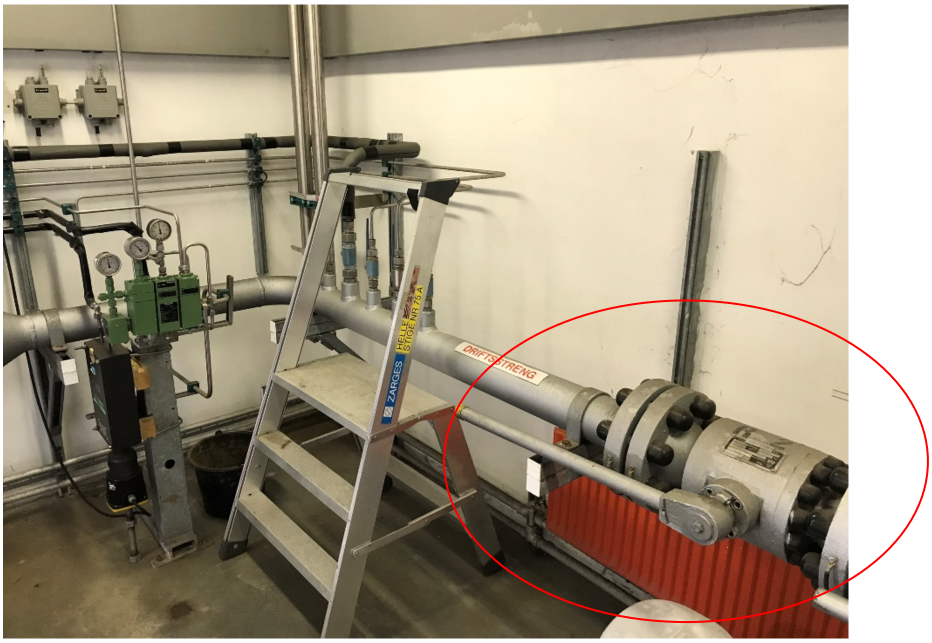


Figure 24. Picture of the leaking valve in M/R Helle.

The hydrogen concentration was decreasing, which indicated a heterogenous leak of the mixture. The valve was diagnosed further, to determine if the leakages were related to hydrogen or not. The result of the inspection indicated that the reason for the leakage was a teared O-ring at the grip of the valve.
The conclusion of the inspection was that the fault was not related to hydrogen. Furthermore, was it concluded that the condition of the valve was fine, and a replacement of the O-ring would prevent homogenous and heterogenous leaks.
Further information and visualization about inspection of the valve can be seen in appendix 12.

3.2.4 Analysis of critical components in the electrolyser

As of the accepted change of the application in May 2019, the electrolyser stack and its main components were analysed for degenerative effects or damages due to the long idle time of more than 3 years while standing at M/R Helle. Idle in this context is used as time where the system was completely shut off.

IRD Fuel Cells has many years of experience with operation of fuel cell systems in real life environment. It is known that the main components such as membranes in the stacked cells will be worn or degenerate faster in non-operating systems than the same in operation. So far, IRD has very limited knowledge about the same issue with the PEM electrolyser stack and its components.

For that reason, the results of the analysis of both stack and the main components are important and are explained with the following test program:

- Evaluation of tightness of the stack – leakage rate.
- Analysis of performance of the whole stack.
- Analysis of MEAs from selected cells of the stack.

We considered whether or not to discuss visual inspection of the cell components like flow plates, Ti-felt and Ti-plates as well as sealings as well. When disassembling the PEM stack, we found out that the visual impression of the components was fine compared to new components. For that reason, the visual inspection was not further discussed.

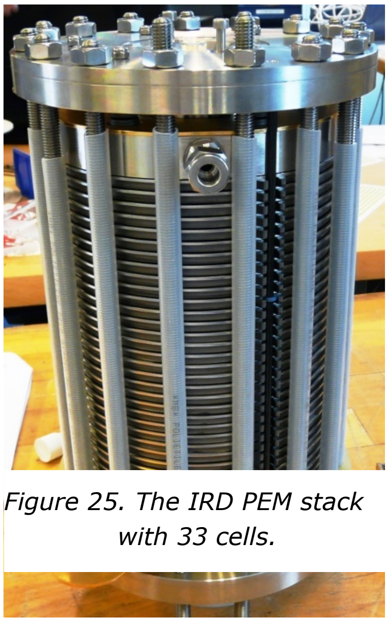


Figure 25. The IRD PEM stack with 33 cells.

<u>Evaluation of tightness of the stack – and leakage measurement:</u> An important stack test is the measurement of crossover leakage through the membranes in the cells of the stack from the hydrogen side to the oxygen side. As the hydrogen pressure is high (50 barg) and the pressure on the opposite side of the membrane is low, there will always be a limited transport of hydrogen through the membrane, which is called crossover. The crossover leakage must be as low as possible for safety reasons, and it must be lower than 75 ml/min for a full PEM stack to be accepted. For the leakage test, nitrogen was used instead of hydrogen. The test pressure of the nitrogen was 50 barg and it was applied to the hydrogen inlet of the PEM stack for a time period of 2 min. The leaked nitrogen was collected at the oxygen outlet and the leak rate of the PEM stack from M/R Helle was 2 ml/min, which is very acceptable. With regard to leakage, we cannot see any deterioration of the stack during the long time of more than 3 years in idle condition.

<u>Analysis of performance of the whole stack:</u> Performance is of main interest in the evaluation process of the IRD PEM electrolysis stack at M/R Helle. The performance

of the complete stack is very much dependent on the performance of the single cells in the stack. The stack consists of 33 cells. We assume that the membranes in the cells are the weakest component with regard to degeneration over time.
After moving the hydrogen system from M/R Helle in Varde to IRD Fuel Cells, the water quality inside the stack was checked for its conductivity. It must be very low in order to safeguard the cells and especially the membranes in operation. The conductivity was >19 μS/cm, which in fact is much higher than acceptable, and it would lead to poor and harmful operation of the stack. The conductivity should be below 2 μS/cm. The high conductivity indicates that the membranes may have had bad conditions in the stack for a long time.

A preliminary operation test of the stack showed poor performance. At normal condition, e.g. a new approved stack, the individual cells would operate at an average voltage of the cells of about 1.9 V and at a nominal current of about 70 A. The temperature would in normal condition increase to about 71 °C and would be kept at this temperature for continuous operation.

A test series at three different temperatures was performed. It was not possible to run the stack at 70 A nominal. The stack current could not exceed 40 A in the first test, and in the second and third tests the performance went even worse. Figure 26 shows the cell voltages in dependency on current and temperature. As the cell voltage must not exceed 2 V, a few poor performing cells denominate the current. Examples of poor performing cells are cell 7 and 8, the ones showing the highest voltage.

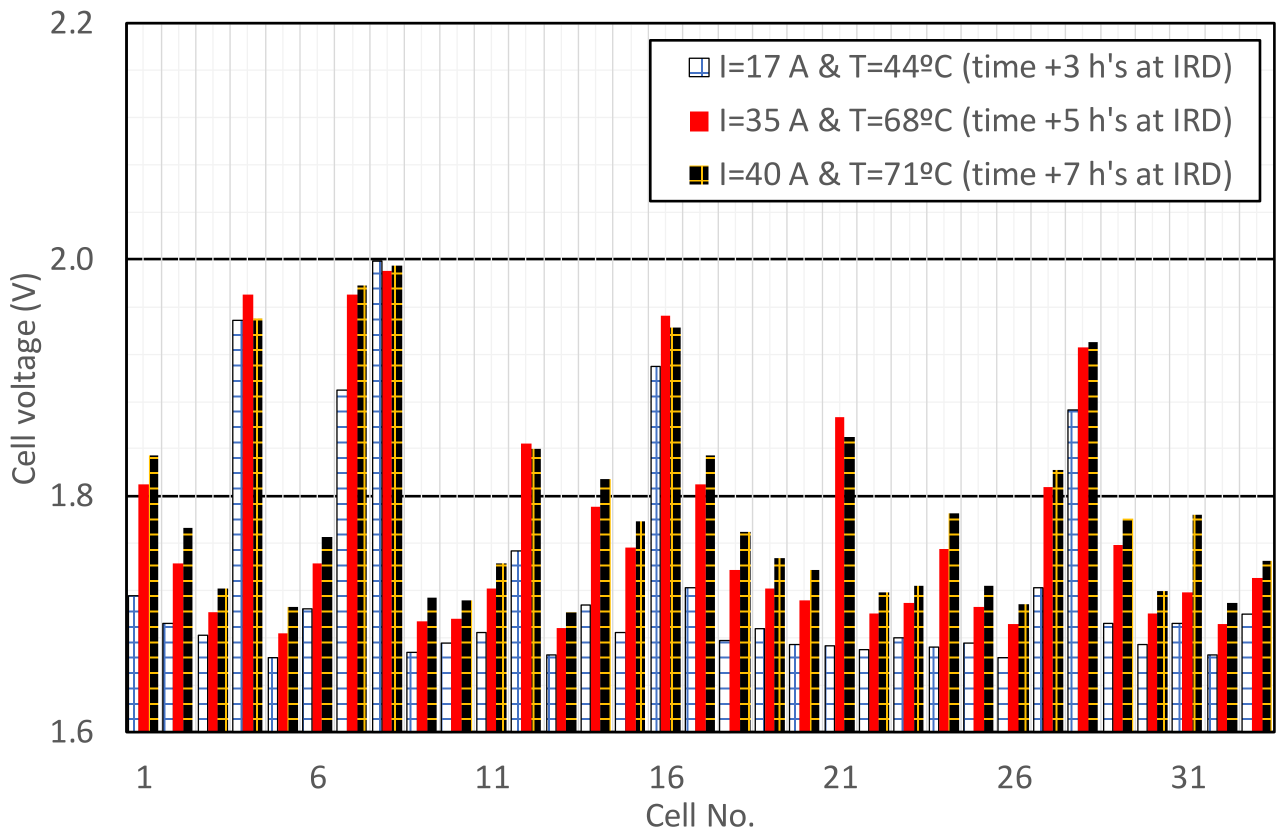


Figure 26. Test of the PEM electrolysis stack that was located at the M/R station Helle for more than 3 years. Individual cells are not allowed to exceed a voltage above 2 V, which means that the lowest common cell performances denominate the stack current. As examples, cell 7 and 8 are performing poorly, and cell 9 and 10 are performing well.

According to the test results in Figure 26 we assume that the long idle time had a degenerative effect on the stack and its cells and assumable the membranes. In the following, a few standard tests of MEAs of the specific stack are described to evaluate the MEA condition.

Analysis of MEAs from selected cells of the stack: As shown in Figure 26, the cells in the PEM stack of the electrolyser at Varde, performed very differently. A standardized single cell test for MEAs was accomplished for a well performing membrane of cell 9 and a poor performing membrane of cell 7. The test cycle is shown in Figure 27 for cell 9 and in Figure 28 for cell 7. The MEAs were carefully removed from the electrolyser cells, and a standardized area was cut from each. Due to the long idle state at the M/R station the PFSA (Nafion) membrane was rather fragile. These two MEA samples were used in the shown standard test in Figure 27 and Figure 28. On top of the two MEAs from cell 7 and 9, a further three MEAs were single cell tested, but quickly developed crossover due to fragile membranes and the tests could not be continued. The test results for these three MEAs is not shown and not further discussed.

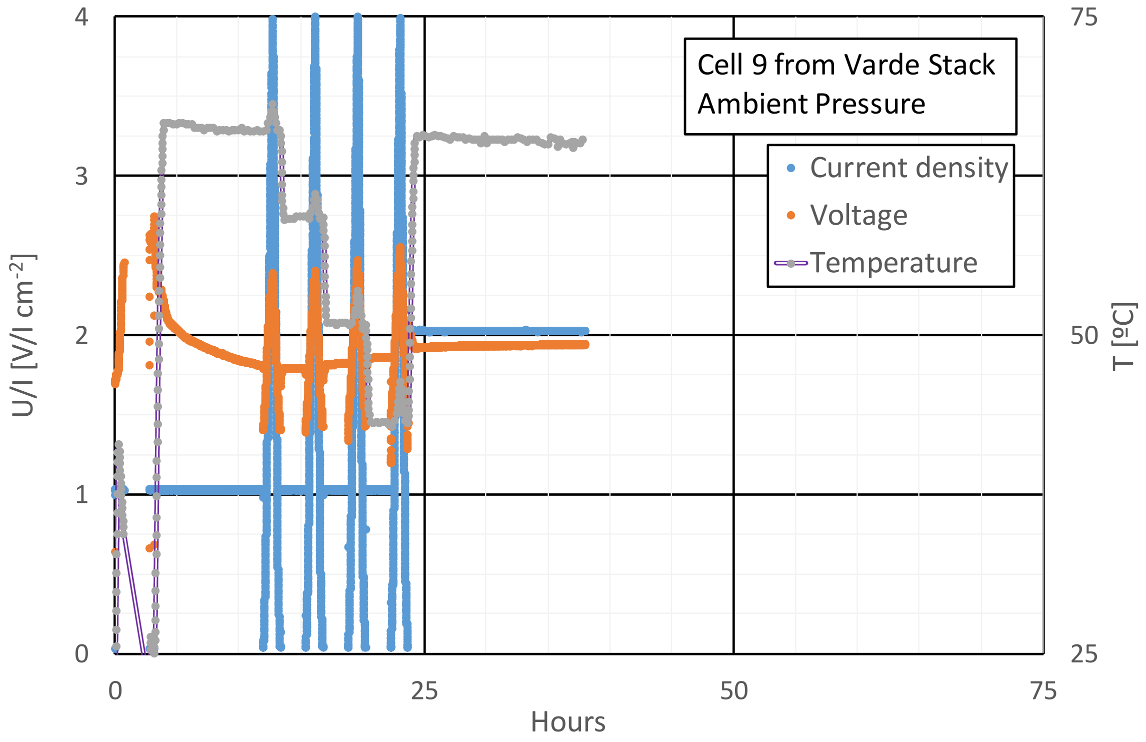


Figure 27. Overview of test of single cell from electrolyser stack - here the EoL test (End of Life) of the membrane of cell 9 (see Figure 26), a well performing membrane.

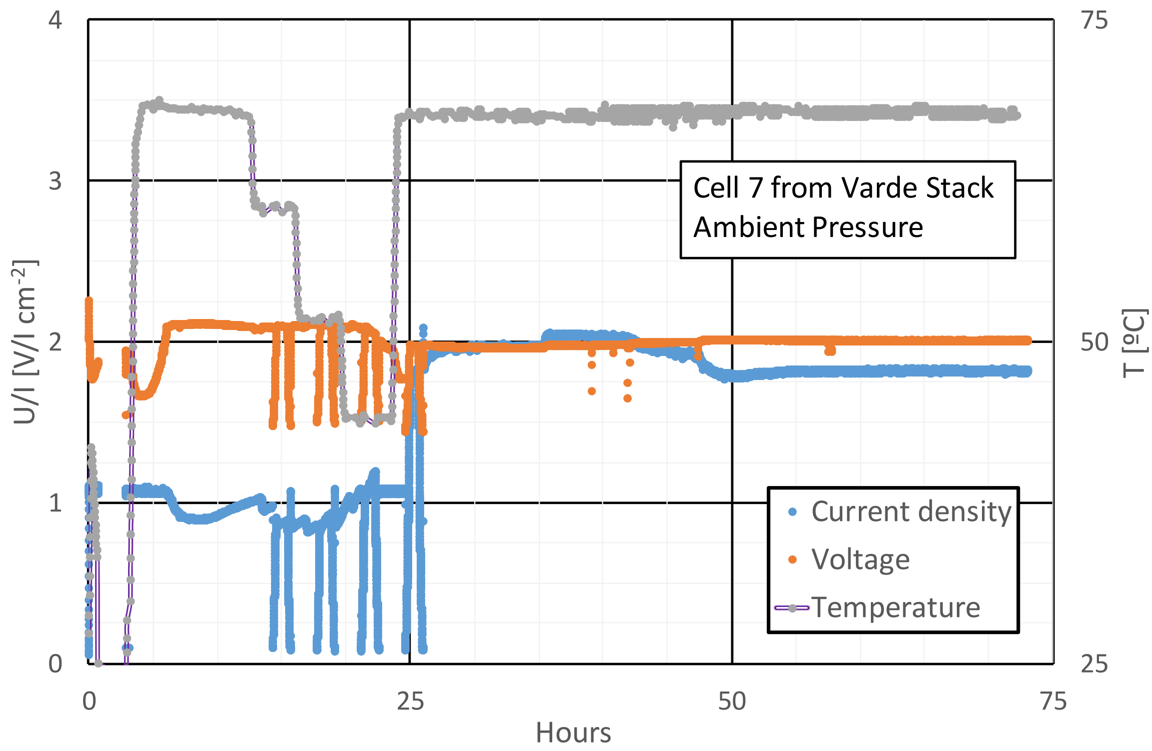
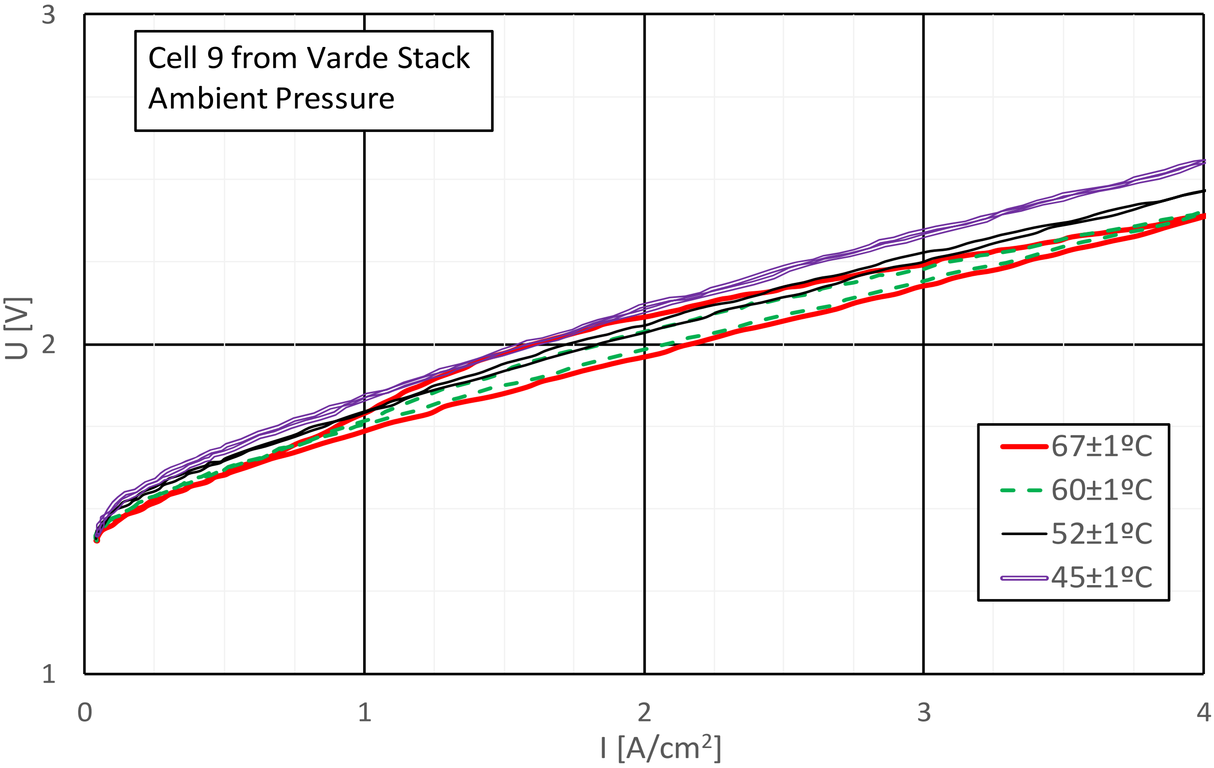


Figure 28. Overview of test of single cell from electrolyser stack - here the EoL (End of Life) test of the membrane of cell 7 (see Figure 26), a poor performing membrane.

Each test was performed at 4 different temperatures, and the voltage was limited to 2V for long term run. The test system tries to optimize the current shown in A/cm² (current density) at the defined temperature and at max. 2V. The best performance is expected at higher temperatures at around 70°C.

In Figure 29 the performance results are shown for cell 9 (good performance in preliminary test) and cell 7 (poor performance in preliminary test). The higher the current density per voltage is, the better the cell performs. The test set-up for cell 9 is a newer version than the set-up for cell 7, and the newer version can run sample tests over a wider U/I range (see Figure 29 for cell 9).



A.

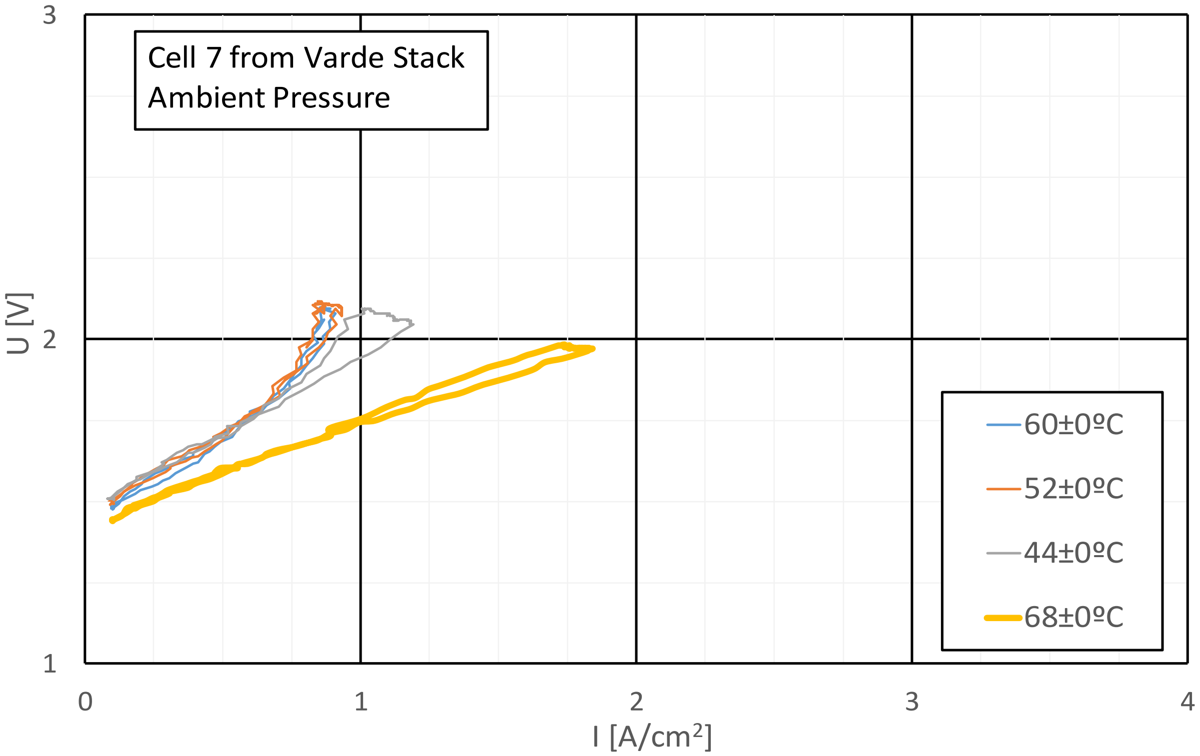


Figure 29. Single cell performance test of two selected cells from the electrolyser stack. A) Cell 9, which performed well in the preliminary EoL test at IRD cf. Figure 26. B) Cell 7, which performed poorly in the preliminary EoL test at IRD cf. Figure 26.

B.

The performance differences between the EoL test of cell 9 and 7 are actually limited and it is more clearly illustrated in Figure 30, where a standard test of a new membrane of the same Nafion material has been added to the Fig.s of cell 9 and 7 for comparison reasons.

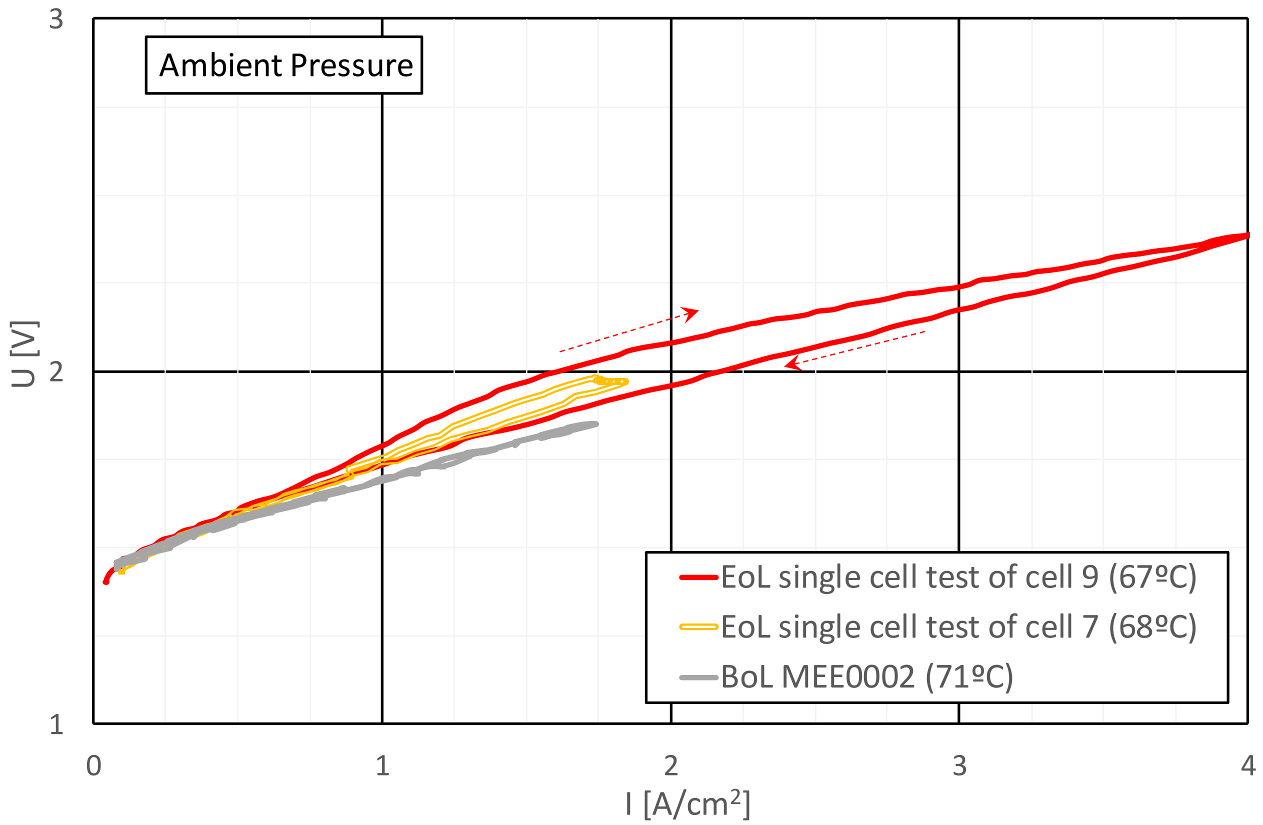


Figure 30. Comparison between BoL[9] performance in the IRD single cell test stand, the EoL cell 9 performance and the EoL cell 7 performance.

Figure 30 shows the performance of the three membranes in the single cell test, EoL of cell membrane 9, EoL of cell membrane 7 and BoL of the new membrane. The comparison shows the following:

a) There is no significant difference between the poor and well performing MEAs when tested in a single cell setup. This indicates that the cell performance difference in the full stack EoL test might be caused by differently developed contact resistances between the anode Titanium-felt (differently developed oxides over time) and the MEA (the Membrane Assembly with its anode coating). Please note that coated Titanium-felt is utilised in the single cell test setup.

b) A minimal degradation is observed due to the >3-year idle condition at M/R station Helle. As expected, the BoL test shows the highest performance (the highest current density per voltage), but it is not significantly better than the ones of the idle stack from M/R Helle.

[9] BoL: Beginning-of-Life

Conclusion of the analysis

The conclusions of this analysis work cannot be generalized due to the limited sample amount, but it gives a good assumption on what happens for IRD's PEM electrolyser stacks over time of idle condition. In our case, the idle condition was more than 3 years.

The leak rate of the PEM stack was measured, and it was very low, ≈2 ml/min (it must be <75 ml/min). The tightness seems not influenced by the idle condition of the stack.

The performance of the full PEM stack developed adversely in idle condition, and it ended at less than half of the performance of a new equivalent stack. The poorest cell limits the performance of the entire stack as the voltage of a single cell must not exceed 2 V and the cell performances were very diverse.

The most exposed component in the cells is the MEA (membrane assembly). For that reason, standard tests in single cells were performed for a few MEA samples of the PEM electrolyser stack of interest. The tests showed despite of the different cell performance in the entire stack a very limited performance difference between the MEA of a well- and a poor-performing cell of the PEM stack. Compared to a standard test of a new MEA (BoL test) the EoL, End of Life test, of the two ">3-year MEA" showed just a limited reduction in performance.

The poor performance of the full stack seems to be caused by differently developed contact resistances between the Ti-felt and the MEA. Different oxides might have increased the resistance on the contact surfaces.

3.3 Operational experiences and recommendations

A key objective of the project is to strengthen competencies of operating the gas grid with higher concentrations of hydrogen. An integral part of the project has therefore been to educate all involved parties.

The qualitative method of interview with an on-site technician was done to determine challenges, which might occur in relation to the safety procedures.

The interview focussed on the individual person's experience and thoughts about safety, operational experiences and recommendations.

The goal of the interview was to evaluate the existing safety procedures and to determine safety procedures, which are strong and useful, which are further needed and which should be changed.

The interview should be interpreted as a possible way of adjusting the existing safety procedures.

The interview with specific questions regarding safety procedures was done with technician Kent Michael Jensen. Experiences were evaluated through the interview and general conversation with the technicians.

The safety procedures such as HAZID and HAZOP were well known, and the descriptions in these were followed without deviations.
Furthermore, the safety procedure for injection of hydrogen, "*Procedure for tilførelse af brint"*, was used as foundation for the interview.
The technician read every step and commented on the steps afterwards.
The safety procedure "*Procedure for tilførelse af brint"* can be found in appendix 13.

Under step two: "*Kontrol af brintindhold i testloop"*, where the procedure for injection of hydrogen in the test-loop is specified, a deviation between procedure and practice was identified.
The section is translated into English for better understanding:

"It's controlled that the hydrogen content in the test-loop doesn't exceed target value, which can be found in the latest operating instructions. The hydrogen content in the test-loop need to be minimum 1 percentage point lower than the measured value in the operating instructions, before injection of hydrogen.

Example 1: Target value is 5 %. Measurement of the test loop results in 4.5%. Action: No additional hydrogen is injected in the test-loop."

Technician Kent Michael Jensen commented on this section and said that this step doesn't follow what is done in practice.
The reason for this is that the target value in the operating instructions is not mentioned or relevant for the people who read the operation instructions.
Only few technicians are certified to work at the test-site.
He further added that the target value and the operation instructions are discussed with the project manager.
This could imply adjusting this step to follow the technician's comments.

From general conversation it could be concluded that the closed-loop facility has challenges when doing maintenance, specifically when securing that there is no gas in the system, as these activities are influencing the ongoing test.
Since these challenges are specifically related to the fact that the test is performed in a closed-loop system, they are not relevant in relation to distribution of hydrogen in the gas grid.

3.4 Discussion

The Danish gas grid contains some components, which is not part of the test facility. It is recommended to initiate an evaluation of the components in order to obtain full knowledge of the entire Danish gas grid.

It is additionally recommended to initiate the following initiatives based on the results from the project:

- Phase 2: Test at increased hydrogen levels (up to 25%) in same test system
- Phase 3: Test and demonstration at increased hydrogen levels with supply to consumers

3.5 Dissemination of results

During the project the project partners have actively communicated about the project and shared results.

Selected conferences:

- International Gas Union Research Conference (IGRC) 2014 and 2017 (presentation and paper).
- World Gas Conference (WGC) 2015
- Gastekniske Dage 2015 and 2018.
- Poster presentation by Energinet at Den Danske Brint- & Brændselscelledag ("The Danish Hydrogen & Fuel Cell Day"), 2016, 2018 and 2019.

Selected Article:

- Prelimiary results from 2019 have been disseminated in an Energinet article, which has been quoted in several other technical media: https://energinet.dk/Om-nyheder/Nyheder/2019/05/21/Det-danske-gassystem-kan-lagre-vindenergi

The full list of communication about the project can be found in appendix 14. The project partners are considering additional dissemination activities and expects to publish the final project results in an international paper.

4. Utilization of project results

Energinet and Evida will initiate an expansion of the test period after the EUDP project. In addition to the prolonged period for the hydrogen/natural gas test, the hydrogen level will be increased to a level above 15%, expectedly 25%. DGC will participate in the project, which will produce further information on the potential of the gas system as a hydrogen carrier.

The project results will be used by the projects partners as input to international R&D projects and standardisation work aiming at elimination of barriers for injection of hydrogen into the natural gas system.

5. Project conclusion and perspective

The project successfully demonstrated the feasibility of a high-pressure test system, simulating a real natural gas transmission and distribution grid, to transport mixtures of natural gas and hydrogen with hydrogen concentrations up to 15%. The long-term test at the facility has been performed with hydrogen concentrations up to 12% hydrogen. The demonstration in a real natural gas system, which was taken out of operation, is unique, and the project results contribute to establish the required knowledge to allow introduction of hydrogen into the natural gas system.
Large-scale introduction of hydrogen to the gas system can potentially enable sector integration between the power and gas systems and unlock the potential of the gas system to balance and absorb fluctuation renewable energy production from wind and solar power.
Electrolysis is a key process for the above-mentioned sector integration, and the project has provided valuable experiences and learnings, which can be exploited for further maturation and commercialisation of electrolysis production.

The learnings and experience among the partners are considered as a key output from the project as they enable the parties to continue their work with hydrogen activities.

The conclusions from the project are as follows.

It was initially anticipated that gas detection systems in the gas infrastructure would have to be modified in order to be able to operate with hydrogen/natural gas mixtures. The observation in this project is, however, that this is not the case for hydrogen concentrations up to 12%, as tested in this project. The gas detection systems typically used in the M/R stations in the transmission grid would be fit for purpose if the transmission system was operated with a hydrogen/natural gas mixture with a hydrogen content similar to the levels tested in this project.

As hydrogen is introduced to natural gas in increasing concentrations, ATEX zones and explosion groups can change, which can potentially affect installed equipment in the natural gas infrastructure, if the explosion group of the gas mixture exceeds the applicable range of the equipment. It has been concluded that the conducted tests would not result in such critical changes of explosion groups, but if the hydrogen concentration exceeds 30% in future tests, this aspect needs to be reconsidered.

Operation of gas infrastructure with 100% hydrogen requires new competences and personal protective equipment (calibrated detectors).

The existing routines and procedures for the operational staff at the M/R stations has to a large extent proven to be sufficient for the operation and maintenance of the test facility with hydrogen injection.
The process equipment of the M/R stations (regulator, flowmeter, safety systems, valves etc.) have functioned well during the test phase.

We have not observed increased leakage of hydrogen compared to natural gas from the test facility, even though the equipment has not been modified since it was established for natural gas operation.

The hydrogen analysis was applicable for the project, but it is not an optimal solution for continuous analysis at an unmanned facility due to sensitivity for fluctuations in pressure and temperature.

The test consisted of several long-time test periods of up to 3 months.

While pressure and flow were rather stable during the test, the temperature of the system and the gas in the closed loop fluctuated due to variations of air temperature.

Any hydrogen related effects on the material integrity of the test facility is evaluated to be negligible for the hydrogen content used in the project. However, it was therefore decided to make inspections of a number of welds in the test facility as these are evaluated as the weakest point for hydrogen related material integrity effects. These inspections will be repeated at the end of the following phase 2 of the project where the hydrogen content is planned to be higher, up to 25 %-mole.

The Danish authorities were involved via relevant applications for the operation of the test facilities. The dialogue resulted in definition of conditions for the facility that was implemented before operation. The co-operation with the authorities has been good and the conclusion of this project will be useful as background for adaption of the legal framework for future hydrogen activities in Denmark.

<u>Analysis of effect of long-term idling on electrolyser systems</u>

The conclusions of this analysis cannot be generalized due to the limited sample amount, but it gives a good assumption on what happens for IRD Fuel Cells' PEM electrolyser stacks over time of idle condition. In our case, the idle condition was more than 3 years.
The leak rate of the PEM stack was measured, and it was very low, ≈2 ml/min (it must be <75 ml/min). The tightness does not seem to be influenced by the idle condition of the stack.
The performance of the full PEM stack developed adversely in idle condition, and it ended at less than half of the performance of a new equivalent stack. The poorest cell limits the performance of the entire stack as the voltage of a single cell must not exceed 2 V and the cell performances were very diverse.

The most exposed component in the cells is the MEA (membrane assembly). For that reason, standard tests in single cells were performed for a few MEA samples of the PEM electrolyser stack of interest. Despite of the different cell performances in the entire stack, the tests showed a very limited performance difference between the MEA of a well- and a poor-performing cell of the PEM stack. Compared to a standard test of a new MEA (BoL test) the EoL, End of Life test, of the two ">3-years MEA" showed just a limited reduction in performance.
The poor performance of the full stack seems to be caused by differently developed contact resistances between the titanium fiber felt and the MEA. Different oxides might have increased the resistance on the contact surfaces.

6. References

[1] Publica - Publikationsserver der Bundesanstalt für Materialforschung und -prüfung (BAM). *Ermittlung der Zündwahrscheinlichkeit mechanisch erzeugter Schlagfunken in explosionsfähigen Brenngas/Luft- Gemischen*.
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