HighPEM

PROJECT END REPORT
MARCH 2016

Project No.: 64013-0515

SUPPORTED BY:

Project details

Project title	HighPEM
Project identification	64013-0515
Name of the programme which has funded the project	EUDP-2013-II
Project managing company/institution (name and address)	H2 Logic A/S Industriparken 34B 7400 Herning Denmark
Project partners	IRD A/S Dansk Gasteknik Center A/S (DGC)
CVR (central business register)	H2 Logic: 26933048 IRD: 14689605 DGC: 12105045
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Short description of project objective and results

English version

The HighPEM project has developed and tested a high pressurized PEM electrolyser and defined the connection interface with hydrogen refuelling stations. Based on the results a R&D & commercialization Roadmap has been formulated for PEM electrolysis to the HRS market and analysis of the potential for PEM electrolysis to infuse renewable hydrogen in the Danish natural gas grid.

Dansk version

HighPEM projektet har udviklet og testet en højtryks PEM eletrolysator og defineret forbindelsesinterface for brug ved brint tankstationer. Baseret på projektet er et F&U ’Road-map’ for PEM elektrolyse til HRS udviklet og de analyser foretaget af potentialet for brug af PEM elektrolyse til indfødning af brint i det danske naturgas net.

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1. Executive summary

The HighPEM project has developed and tested a high pressurized PEM electrolyser and defined the connection interface with hydrogen refuelling stations (HRS). Based on the results a R&D & commercialization Roadmap has been formulated for PEM electrolysis to the HRS market and analysis of the potential for PEM electrolysis to infuse renewable hydrogen in the Danish natural gas grid.

A technical interface definition between PEM electrolysers and HRSs has been developed. This enables use of PEM electrolysers for onsite production at HRSs and in particular enabling connection of equipment from different manufacturers as the interface is standardised. A detailed electrolyser standard specification has also been formulated, ensuring fit for use at HRSs and also act as basis for CE marking.

IRD Fuel Cells has designed and constructed a compact electrolyser system to be used together with HRS's. The complete system is built into a little isolated 8 ft. container. The system includes IRDs PEM electrolyser E1050 (1 Nm^3/h), a water purification system, a hydrogen purification and dryer system.

The container is equipped with a ventilation system proportioned for maintaining a safe and non-explosive atmosphere at any time within the container, a gas storage cylinder, a cooling system for the electrolyser stack, a safety control system and gas purge for both hydrogen and oxygen.

The PEM electrolyser is able to directly produce 50 bars of pressurised hydrogen. The developed gas dying equipment has proven to be able to dry the produced wet hydrogen (dew point $\geq$65ºC) in the pressurised state to a dew point of less than minus 70ºC (-70ºC).

DGC has inspected the available documentation for the electrolyser, and found minor inconsistencies. The overall conclusion is that the electrolyser complies with the Machinery Directive (2006/42/EC), the Low Voltage Directive (2006/95/EC) – based upon EN 60204-1 and ISO 227341-1 – and the Electromagnetic Compatibility Directive EMC-D (2004/108/EC) – based upon EN 61000-6-1, EN 61000-6-3, EN 61000-3-2(2006) and EN 61000-3-3(1995).

An analysis has been conducted on the potential use of PEM electrolysers for injection of hydrogen in the Danish natural gas grid. Injection of 2vol% hydrogen at every M/R station in the natural gas grid in Denmark would require installation of 20MWe electrolyser and 10%vol would require 100MWe.

A PEM electrolysis HRS Roadmap has been formulated with the aim to define targets that enable a commercial use of the PEM electrolysis technology in future HRS networks.

2. Project objectives

The objective of the HighPEM project has been to develop and test a high pressurized PEM electrolyser for use at Hydrogen Refuelling Stations (HRS) and formulate a R&D & commercialization Roadmap for PEM electrolysis including infusion of renewable hydrogen into the Danish natural gas grid.

PEM electrolysis can enable a very high outlet pressure (up to 100+ bar) which can help reduce cost for compression technology at HRS, reduce footprint and increase energy efficiency.

The HighPEM project has been one among few projects in the world with actual tests of a complete and operable PEM electrolyser on 50 bar. Present available PEM electrolysers typically only offers up to 30 bar pressure whilst higher pressure mainly only have been tested at small scale in laboratories.

HighPEM has helped to further develop IRD A/S PEM electrolyser technology previously only used for the µCHP market. Via the project high pressure has been tested and technical interfaces with the HRS has been defined. This enables a future potential use of the PEM electorlyser for the growing international HRS market.

Dansk Gasteknisk Center A/S (DGC) has assisted IRD on technical topics with the objective of achieving CE documentation of the PEM electrolyser and conducting hydrogen purity tests and analyses.

3. Project results and dissemination of results

The HighPEM project has involved five key tasks listed below.

- Specification of connection interfaces between PEM eletrolyser and HRS
- Development and design of PEM Eletrolyser
- Test of PEM Electrolyser
- Formulation of PEM R&D Roadmap
- Analysis on use of PEM electrolysers for natural gas injection

Results from each task is further elaborated in the sections below.

3.1 Connection interface for PEM Electrolyser and Hydrogen Refuelling Station

The motivation of the HighPEM project is to enable use of PEM Electrolysers at Hydrogen Refuelling Stations (HRS) and gain advantage of the potentially higher hydrogen supply pressure, compared to conventional state-of-the-art electrolysis.

A dedicated task of the project has therefore involved specification of the connection interfaces between the PEM Electrolyser and HRS, with the aim to ensure technical fit when installed at sites. In that regard both capacity sizing and technical interfaces are of relevance.

3.1.1 Electrolyser capacity modularity

During the HighPEM project the expected capacity modularity of future HRSs has been further analysed and clarified, mainly with basis in the capacities seen on conventional fuelling stations.

In past Danish and European demonstration projects the HRS daily fuelling capacity has ranged between 50-100 kg per day, dispensed with one fuelling hose/nozzle.

Electrolysers have typically been dimensioned with significantly less capacity, as the utilization of the HRS at present is very low, given the low number of Fuel Cell Electric Vehicles (FCEV) on the market.

Going forward in new European project, as well as the demand from major markets such as Germany and California the minimum requirements are expected to 200 kg/day per fuelling hose. This corresponds to the typical fuelling load per hose at conventional fuelling stations for gasoline today.

The capacity upgrade step is 200 kg as each upgrade involves adding an additional hose to the station and the required supporting equipment.

For electrolysers the relevant capacity modularity should be similar as for the HRS, however off-set with around 25% of the HRS capacity, as it will take time before the HRS is fully utilized.

For a 200 kg/day HRS, the relevant electrolyser base capacity would be less than 50 kg/day (25 Nm^3/hour). Depending on the market region the increase in utilization of the HRS to full level (~75-80%) may take five years or more. Having a smaller base capacity size of the electrolyser on 50 kg/day can reduce the investments during the early years where market risk is highest.

As the HRS utilization grows additional electrolyser capacity can be added in bundles of around 50 kg/day. The expected average utilization level to be reached for HRSs operated in a network will be around 75-80% of the 200 kg/day (150-160 kg), in order to have capacity for periods with peak demand.

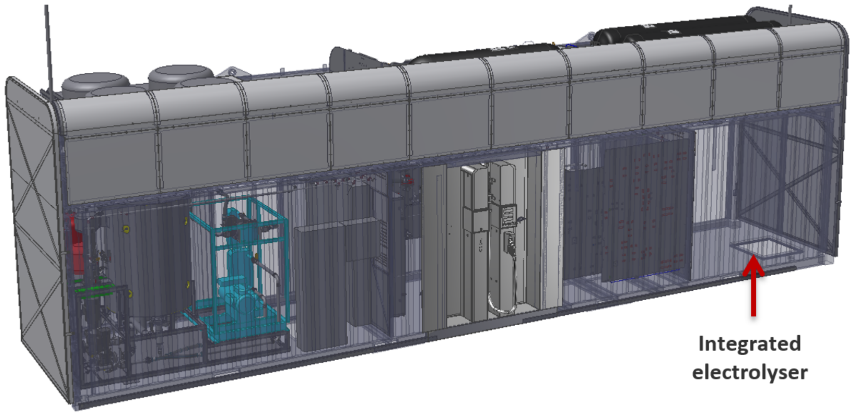
The most cost effective operation pattern for the electrolyser is likely to be continuous 24 hour operation where the required HRS demand is provided. This will provide the most operation hours where the investment can be recovered. Regional conditions in the power market, may make it relevant to over dimension the electrolyser capacity to enable optimizing the operation hours after the power price.

An electrolyser capacity modularity of 50 kg/day will be able to gradually scale up to meet the HRS full demand, as well as covering potential extra capacity needed to regulate the production rate of the electricity price.

3.1.2 Level of PEM Electrolyser integration in the HRS

At the time when the HighPEM project was prepared, H2 Logic was engaged in preparing tests of fully HRS integrated electrolysers, as outlined in figure below.

H2Station® CAR-100 electrolyser integration



In the case of H2 Logic the HRS product design included an extra room for full integration of the electrolyser. During the course of the HighPEM project H2 Logic has tested several fully integrated electrolysers at HRS sites.

The benefit of the full electrolyser integration was a reduced footprint and installation time as the entire HRS and electrolyser could be kept in one transportable module.

However several issues have also been identified with the full integration approach. Given the present state-of-the-art electrolyser footprint, only between 30-60 kg/day electrolyser capacity could be fitted into the space available in the HRS. Thus the electrolyser capacity cannot be upgraded in future and cover the full HRS demand.

Also the technical integration of the electrolyser required extensive efforts. When placed physically inside the HRS, the electrolyser becomes a component in the HRS, thus it has to be a fully integrated part of the HRS control and safety systems. Also the connections to utilities need to be shared and coordinated.

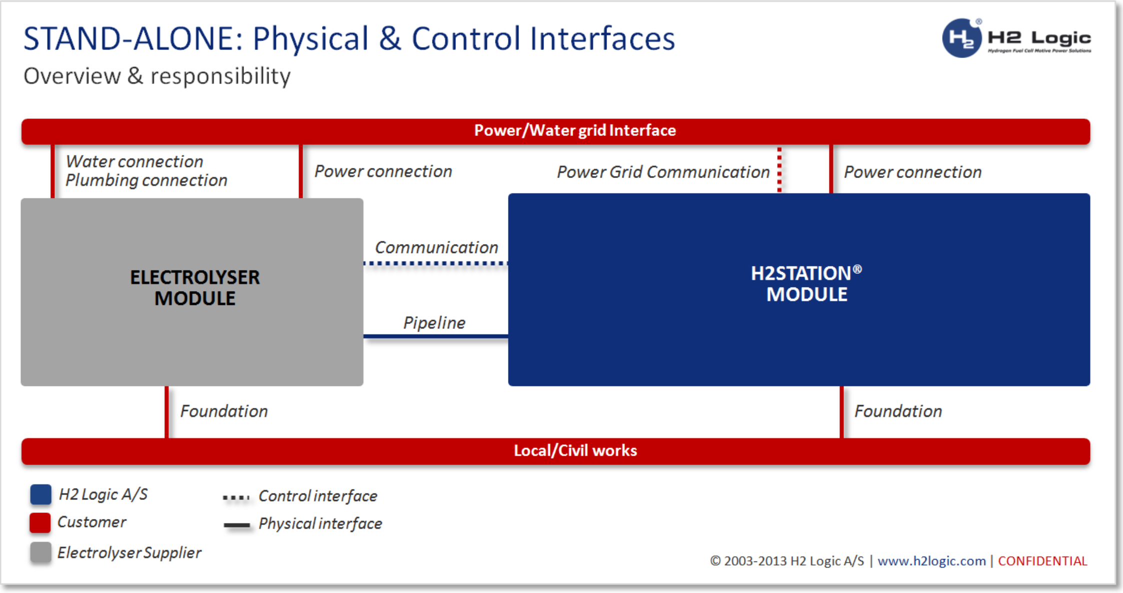
Whereas the technical integration is possible, the challenge arise when the HRS is to be capable of using electrolyser from different manufacturers. This means that an extensive integration exercise is to be conducted for each electrolyser manufacturer. The present market volume cannot justify such exercise yet.

For the electrolyser design, a full integration into the HRS, may also require customizations, compared to a use as a stand-alone unit for other markets, e.g. industrial gases and power-to-gas.

Going forward the recommendation therefore is to keep the Electrolyser as separate stand-alone modules at the HRS site, and where only the technical interfaces on hydrogen supply and control is coordinated and specified.

3.1.3 Connection interfaces between PEM Electrolyser and HRS

The figure below shows the physical and Control interfaces and the responsibility for handling:



The Electrolyser and H2Station® are two physically separated modules. The Electrolyser can either operate independently of the H2Station® or it can be operated by/via operation signals from the H2Station®.

Customer is to handle all the interfaces to the “surroundings” for both the Electrolyser and H2Station® modules. This includes the physical connections to the power and water grids and the foundations. Local works required for the physical and control interface between the Electrolyser and H2Station® modules are also to be handled by Customer.

H2 Logic will handles physical and control interfaces between the Electrolyser and H2Station®.
Two different control interface methodologies are considered:

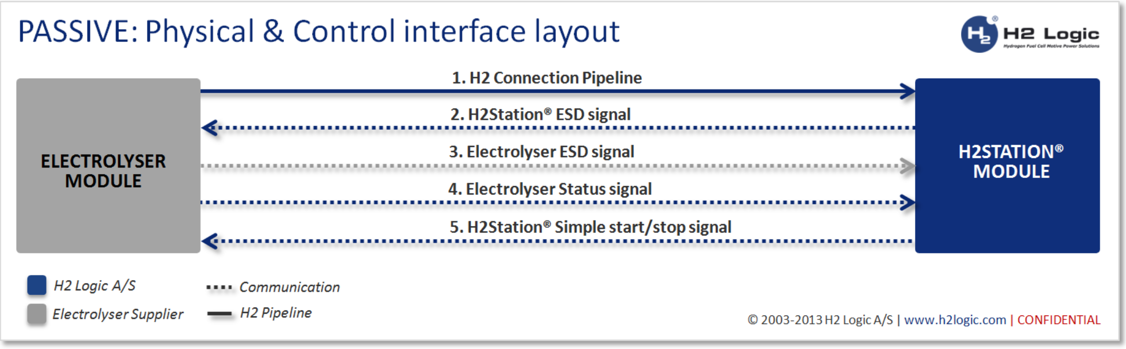
- Passive control interface: electrolyser operates independently of H2Station®
- Active control interface: electrolyser is operated by/via the H2Station®

The Passive control represents the simplest interface making it easier to apply across various eletrolyser brands and models. Active control requires more details control interfaces between the electrolyser and H2Station® but enables a more intelligent electrolyser operation.

The physical and control interface for each methodology is further elaborated below.

Passive control

The figure below shows the physical & control interface layout for the PASSIVE methodology:



The Electrolyser operates independently from the H2Station® based on the pressure in the pipe-line connection to the H2Station®. When pressure is sufficiently low the Electrolyser will start production and when pressure rises above the Electrolyser supply pressure production is stopped. An intermediate storage inside the H2Station® enables the Electrolyser to have a smooth operation.

Only three base hardwired signals between Electrolyser and H2Station® are required in terms of Emergency Shut Down (ESD both ways), status signal and simple start/stop signal.

With the Passive approach Customer are to monitor operation of the Electrolyser and H2Station® independently (two separate control systems).

The tables below outline the detailed specifications of each interface parameter.

1. H2 Connection Pipeline	
Pipeline type	Operation pressure to match outlet from electrolyser
Pipeline connection	To be defined after contract
Minimum pipeline length	Constrained by safety distances
Maximum pipeline length	To be defined in contract
Pressure level for start of operation	Minimum operation pressure level for electrolyser
Pressure level for stop of operation	Maximum outlet pressure of electrolyser

2. H2Station® ESD signal	
Communication protocol	Modbus TCP - PLC registers to be defined from H2Station® side
ESD signal	ESD signal for immediate shutdown of Electrolyser

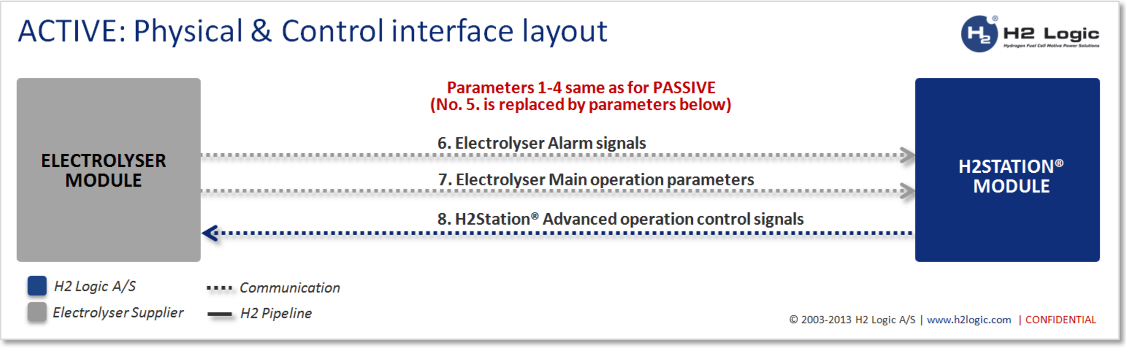
3. Electrolyser ESD signal	
Communication protocol	Modbus TCP - PLC registers to be defined from H2Station® side
ESD signal	ESD signal for immediate shutdown of H2Station®

4. Electrolyser Status signal	
Communication protocol	Modbus TCP - PLC registers to be defined from H2Station® side
Status level signal	E.g. “Ready”, “Operation”, “Alarm”, “Off” – to be defined after contract

5. H2Station® Simple start/stop signal	
Communication protocol	Modbus TCP - PLC registers to be defined from H2Station® side
Start signal	Signal to start production
Stop signal	Signal to stop production

Active control

The figure below shows the physical & control interface layout for the ACTIVE methodology:



ACTIVE: Physical & Control interface layout

Parameters 1-4 same as for PASSIVE
(No. 5. is replaced by parameters below)

ELECTROLYSER MODULE

6. Electrolyser Alarm signals

7. Electrolyser Main operation parameters

8. H2Station® Advanced operation control signals

H2STATION® MODULE

🟦 H2 Logic A/S
⬜ Electrolyser Supplier
···· Communication
— H2 Pipeline

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The Electrolyser is actively controlled by/via the H2Station® thus acting as a “slave” unit. This allows for a more intelligent Electrolyser operation e.g. depending on electricity price levels or offering of grid balancing.

The Active approach requires more detailed control signals and specifications of which operation parameters that are optimal for the electrolyser. This comes on top of the base hardwired signals as included in the Passive control interface.

With the Active approach Customer can monitor and operate the Electrolyser and H2Station® via the control system of the H2Station® Module. (One combined system).

The tables below outline the detailed specifications of each additional interface parameter.

6. Electrolyser Alarm signals	
Communication protocol	Modbus TCP - PLC registers to be defined from H2Station® side
Alarm 1	Controlled shutdown
Alarm 2	Total shutdown

7. Electrolyser Main operation parameters	
Communication protocol	Modbus TCP - PLC registers to be defined from H2Station® side

Operation parameters (examples)	Examples below only – to be defined in contract based on customer need: 7.1 Operation state (turned-off, standby, production) 7.2 Production rate (Nm3/h) 7.3 Production utilization (%) 7.4 Production pressure (MPa) 7.5 Energy consumption (kWh draw) 7.6 On hours over last 24h

8. H2Station® Advanced operation control signals	
Communication protocol	Modbus TCP - PLC registers to be defined from H2Station® side
Start signal	Signal to start production
Stop signal	Signal to stop production
Advance operation control signals	Examples below only – to be defined in contract based on customer need: 8.1 Load signal - Set operation/production load 8.2 Plan signal - Scheduled production cycle

3.1.4 Specification of CE requirements for PEM Electrolyser

A gross-list of technical performance parameters has been formulated, which act as the base document for specifying the electrolyser. Additional DGC will conduct thorough analysis of the CE requirements for the PEM electrolyser as part of the project activities. The analysis will be conducted on basis of a complete list of directives and standards the PEM electrolyser has to comply with completely or partly. Additional the requirements for the technical documentation and the installation, user and maintenance manual that must be a part of the technical dossier will be specified.

Below are provided the full list of parameters.

No.	Specification parameter
A.1	**General product information**
A.1.1	**Supplier specific product model/name**
A.1.1	**Year of product release**
A.1.3	**Electrolyser technology** *[Alkaline, PEM, or other]*
A.2	**Production Rates**
A.2.1	**Definition of Nm³ H_2** *[@ 15°C, 5°C or 0°C]*
A.2.2	**Maximum rated production capacity** *[Nm^3 H_2/hour]* @ 100% production rate

A.2.3	**Minimum rated production capacity** *[Nm^3 H_2/hour]* @ lowest possible production rate
A.2.4	**Peak / "over clocking" production capacity** *[Nm^3 H_2/hour]* *@ above 100% production rate - if possible*
A.2.5	**Continuous operation at max capacity possible?** [Yes/No]
A.2.6	**Production capacity @ optimal operation point** *[Nm^3 H_2/hour]* Ensuring optimal balance between efficiency & lifetime (suppliers recommendation)
A.3	**Start-up / Shut-down time**
A.3.1	**Ramp-up time to maximum capacity from cold start at 5°C** *[Sec. or Min.]*
A.3.2	**Ramp-up time to maximum capacity from standby 1** *[Sec. or Min.]*
A.3.3	**Ramp-up time to maximum capacity from standby 2** *[Sec. or Min.]*
A.3.4	**Ramp-up/down time between minimum to maximum capacity** *[Sec. or Min.]*
A.3.5	**Ramp-up/down time between maximum to peak capacity** *[Sec. or Min.]*
A.4	**Outlet pressures**
A.4.1	**Minimum nominal hydrogen outlet pressure** *[barg]***:**
A.4.2	**Maximum nominal hydrogen outlet pressure** *[barg]***:**
A.5	**Controlling & monitoring**
A.5.1	**Compatible with H2 Logic "Passive Control" definition?** *[Yes/no]*
A.5.2	**Compatible with H2 Logic "Active" Control definition?** *[Yes/no]*
A.5.3	**Possibility of remote control (not via HRS)** *[Yes/no]:*
A.6	**Electricity consumption & supply**
A.6.1	**Total system electricity consumption @ beginning of life** [kWh/Nm^3 H_2]: Including all peripheries (hydrogen purification/drying etc.) at 15°C
A.6.2	**Total system electricity consumption @ end of life - 20,000 hours** [kWh/Nm^3 H_2]: Including all peripheries (hydrogen purification/drying etc.) at 15°C
A.6.3	**Annual increase in electricity consumption due to cell degradation** *[% increase]***:** % increase of total system electricity consumption per 1 year 24 hours operation
A.6.4	**Standby 1 electricity consumption** *[kWh]***:**
A.6.5	**Standby 2 electricity consumption** *[kWh]***:**

A.6.6	**Shut down Power Consumption from 100% utilization to "ready for cold start"** [kW]**:**
A.6.7	**Maximum electrical supply requirement** *[amp & voltage]***:**
A.7	**Water consumption & supply**
A.7.1	**Water consumption** *[litre/Nm^3 H_2]***:**
A.7.2	**Water supply pressure required** *[barg]***:**
A.7.3	**Inlet water quality required** *[e.g. tap water or specify purity]***:**
A.7.4	**Maximum drain need at maximum production rate** *[litre/minute or hour]***:**
A.8	**Cooling requirements**
A.8.1	**Need for external cooling=** *[yes/no]:*
A.8.2	**Minimum & maximum flow of cooling water** *[m^3/h]:*
A.8.3	**Minimum & maximum cooling water temperature at outlet** *[°C]:*
A.8.4	**Minimum & maximum Temperature of cooling water at inlet** *[°C]:*
A.9	**Ventilation requirements**
A.9.1	**Need for external ventilation?** *[yes/no & m3/h]:*
A.9.2	**ATEX-requirement for ventilation** *[EX-zone ?]:*
A.9.3	**External ventilation part of electrolyser safety chain** [yes/no]:
A.10	**Other supply requirements**
A.10.1	**Nitrogen** *[barg, l/h]:*
A.10.2	**Pneumatic** *[barg, l/h]:*
A.10.3	**Others** *[state]:*
A.11	**Standard compliance / Approvals**
A.11.1	**Hydrogen outlet quality in compliance with SAE J2719** *[yes/no]***:**
A.11.2	**Product CE marking & directives/standard compliance** *[yes/no]***:**
A.11.3	**Product documentation requirements** [to be provided at delivery]:
A.11.4	**ATEX zone requirement** *[yes/no]:*
A.12	**Dimensions / Foot print / Enclosure**

A.12.1	**Total system footprint** *[width x height x length in mm]***:**
A.12.2	**Required outside area around system** *[width x height x length in mm]:* *E.g. for safety distances or access for service/maintenance*
A.12.3	**Total system weight** *[kg]***:**
A.12.4	**System packaging** *[e.g. rack/box for indoor or separate module for outdoor]***:**
A12.5	**Operation environment** *[min. – max. temperature degrees Celsius]***:**

3.2 Development & design of PEM Electrolyser

The objective has been to conduct development efforts designs for scale-up production capacity of existing IRD µPEM electrolyser technology, enabling use for HRS. CE marking effort to be conducted on complete electrolyser system.

3.2.1 Modular system design BoP

IRD Fuel Cells has designed and built a compact electrolyser system to be used together with an HRS. The complete system is built into a little isolated 8'-container. The system includes the electrolyser E1050 (1 Nm^3/h), a water purification system, a hydrogen purification and dryer system developed at IRD, a ventilation system for maintaining a safe and non-explosive environment, a gas storage cylinder, a cooling system for the electrolyser stack, a safety control system and gas purge for both hydrogen and oxygen. The system is built into an isolated 8-ft container.

Nilan ventilation system with heat recycling.

Hydrogen dryer system developed and manufactured at IRD.

Electrolyser E1050, capacity 1Nm3/h.

Figure 1: Container with electrolyser system

Hydrogen storage cylinder, covered

Hydrogen purge for electrolyser and dryer

Pre-ventilator for initial safe environment in container

Part of cooling system, heat exchanger with ventilator

3.1.2 Design of modular PEM electrolyser for HRS

IRD has developed and designed a 1 Nm^3 H_2/h PEM electrolyser[1]. The electrolyser is built into a cabinet. The electrolyser in the cabinet includes the PEM cell stack with 33 cells, the BoP – balance of plant, the power supply for the PEM-stack and the control unit. The system is self-controlled.

Not included in the cabinet are the water purification system and the gas purification and drying system.

Figure 2 shows the electrolyser with the dryer system on top of it. Figure 3 shows the water purification system. The entire system is built into an 8-ft container with ventilation and safety system integrated and a hydrogen storage cylinder on top of the container. The container can be transported and connected easily to any HRS. The pictures in Figure 2 and Figure 3 are taken in this container.

Figure 2: Electrolyser with dryer

IRD has developed and manufactured a hydrogen purification system which can work at high pressure, see also Figure 7. This system removes water and oxygen from the hydrogen.

Water purification: A little standard water purification matching to the water consumption of the electrolyser has been chosen. It consists of an RO – Reversed osmosis filter system and an ion exchange filter.

Figure 3: RO and ion exchange of water

Figure 4 shows the entire flow path for the hydrogen and oxygen including purge of both gasses installed in the container system for the HRS. All related components are inserted in the diagram to show the connections.

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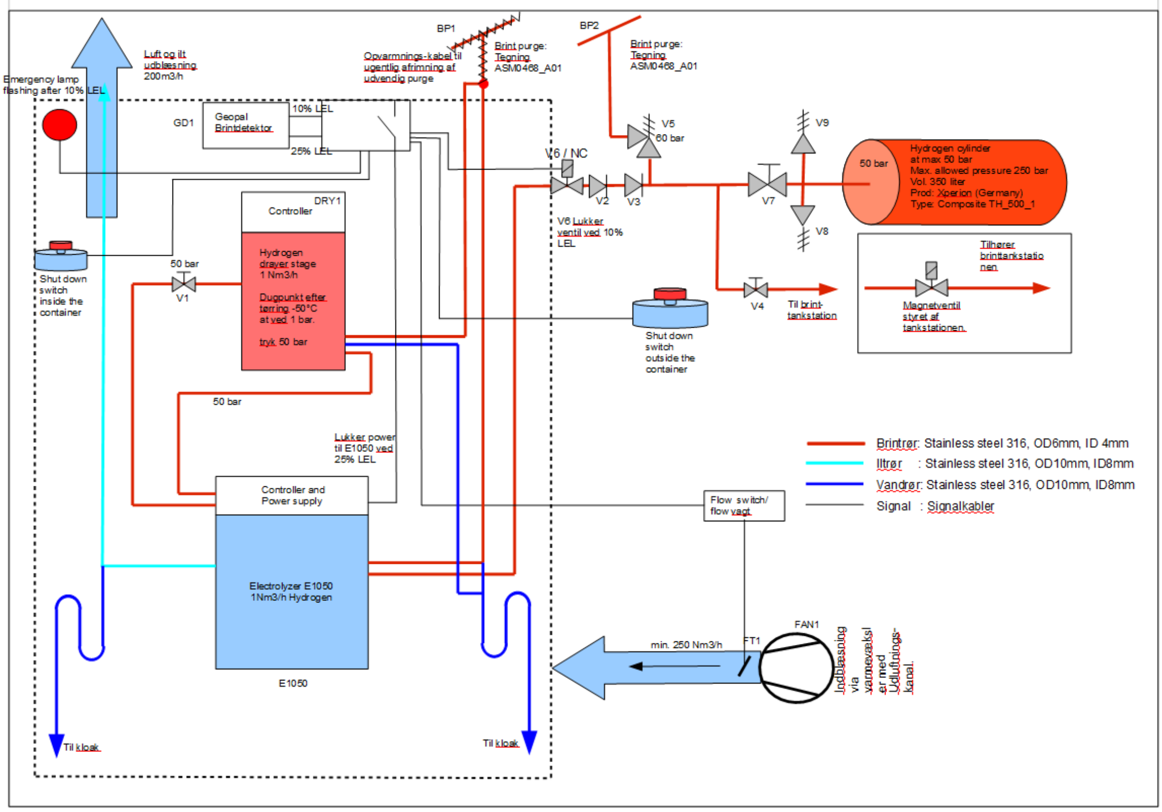
[1] The electrolyser was developed within the parallel running EUDP-project: HyProvide – the LT PEM track (EUDP-2011 64011-0107)

Figure 4: Hydrogen and oxygen path and related components



Electrolyser ventilation system:

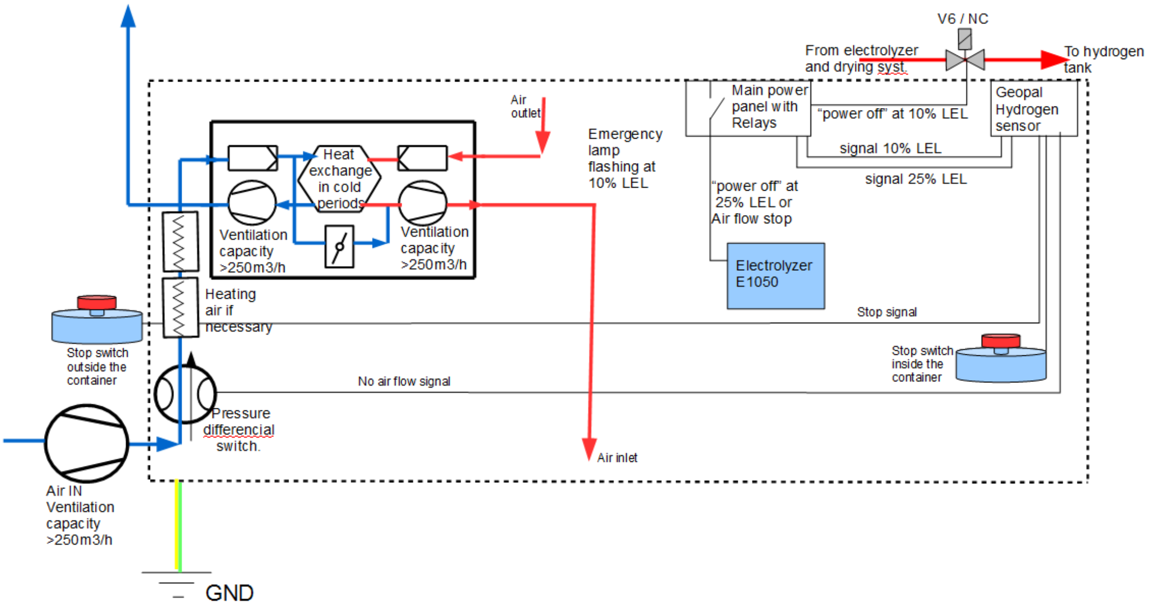


Figure 5: Ventilation system for the electrolyser system

A ventilation system in the container installation ensures a safe environment inside the container. A pre-ventilator outside the container will initially start and will exchange the air in the container through the entire ventilation system. This will prevent any hydrogen to be in the container before start-up of the inside installations. The main ventilation will after 4 minutes take over. This system is located inside the container and will reuse the heat in the container with a heat exchanger. The system is shown in Figure 5.

Electrolyser E1050:

Technical specifications for the electrolyser:

Table 1: Specification for electrolyser E1050

Technical data characteristics	**Value**	**Units**
Electrical power input: 400 V, 3 phases + N + E	400 50 16 Max. 5.5	V (AC) Hz A kW
Water input: De-mineralized water Water quality Water inlet pressure	5 <2 1.5 to 5	l/h µS/cm ASTM type II barg
Hydrogen production capacity Hydrogen purity Max. Hydrogen pressure	1 High purity (saturated with water) 5 (50)	Nm^3/h MPa (bar)
Heat power Water temp. to heat circulation	1.3 max. 70	kW °C
Oxygen out: Waste – not used, purged to environment	0.5	Nm^3/h
Durability, life time	> 2,500	h
Dimension: - Height - Width - Depth	 101 60 60	 cm cm cm
Weight system only Weight system and packing mat.	130 150	kg kg

Function and layout of electrolyser for HRS:

The electrolyser consist of the following sub-system:

- The PEM stack (PEMEC stack) – part of E1050
- The Power supply and the control unit (PCB) – part of E1050
- The BoP with a hydrogen and oxygen path and purge, see Figure 4
- Cooling water path and water supply for stack – part of E1050
- Cooling – external subsystem
- The water supply & purification and drain - external subsystem
- The hydrogen purification & drying – external subsystem

The Figure 6 below shows the flow design of the electrolyser. The water purification and the hydrogen purification/drying are external components, not built into the electrolyser cabinet.

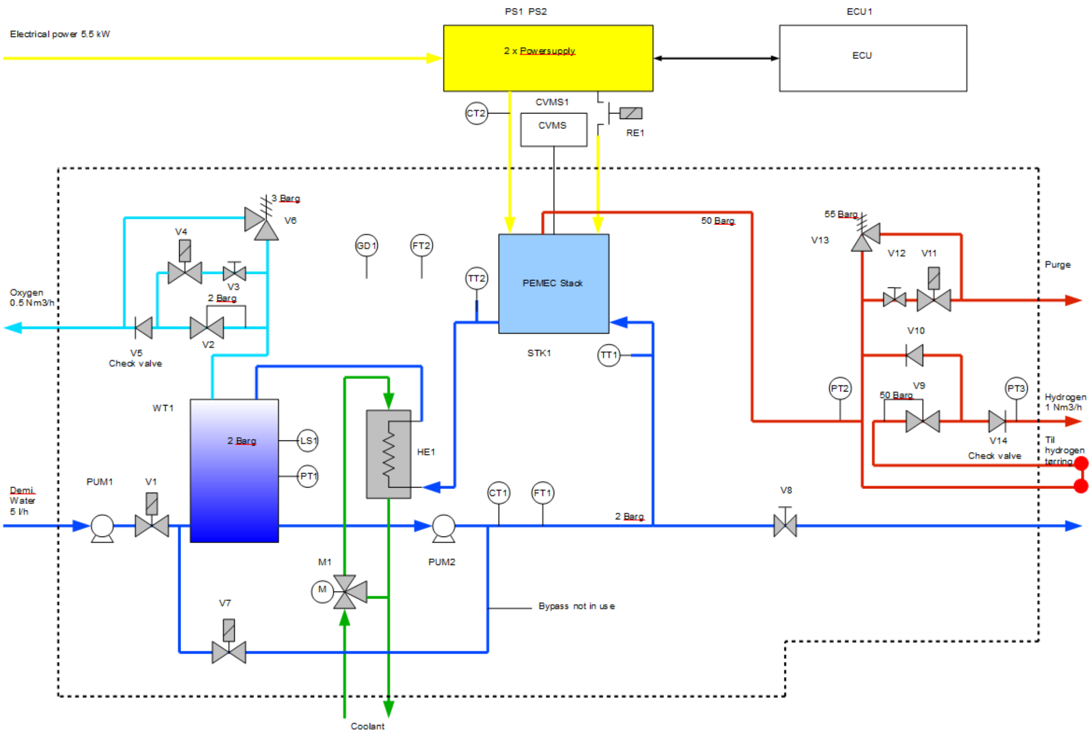


Figure 6: PI scheme for electrolyser E1050

The PEM stack: The IRD PEM stack has been designed for high pressure. The stack and in general the whole system has originally been designed for production of hydrogen at 100 bar. The system has thou been tested with 50 bar. To run the stack with 100 bar it needs a few further design optimisations. For using the electrolyser

in a HRS it is preferable to produce hydrogen at high pressure due to cost reductions at the compression process of hydrogen.
Most commercial available electrolyser systems achieve a max. Pressure of 30 bar.
The PEM stack is made of 33 cells, which together produce 1 Nm^3/h hydrogen. To supply water, maintain the correct stack temperature of about 69 to 72°C, supply power and keep a constant high pressure, the following modules are used to run and control an effective hydrogen production process.

The pressure has to be set manually in the electrolyser cabinet with a back pressure valve, in the Figure 6 shown as V9. The electrolyser will initially be pressurized internally up to 50 bar, and no hydrogen will leave the system before the system pressure of 50 bar has reached.
The electrolyser produces 0.5 Nm^3/h oxygen. As there is no need for oxygen, it is ventilated to the outside environment in an appropriate and safe way.

The hydrogen produced in the electrolyser is very clean, but wet. Even water in liquid phase will leave the electrolyser. Hydrogen delivered to the HRS has to be both clean and very dry. The dew point has to be as low as -75°C.

Hydrogen purification and dryer system:

For that reason IRD has developed a dryer system, which can ensure the production of hydrogen at the very low dew point, and at the same time the system removes oxygen to a very low level.
Initially the marked has been investigated for existing drying systems. The systems on the marked have usually a higher capacity than needed for our situation and at the same time the prices were fairly high. A major point for our decision to develop a dryer system was that the pressure of commercial available dryer systems wasn't high enough for our case.

The IRD dryer removes water and water vapour in three steps. In Figure 7 the dryer steps are illustrated.

1. A water trap removes liquid water (about 3 litre/h) – in figure see WD1.
2. Two coolers (Cool1 and Cool2) condensates water vapour and a following second water trap (WD2) removes the liquid water. After this step the dew point is about -35°C at 50 bar.
3. A continuously regenerating absorber column system (CEO1 and CEO2) will remove water vapour and dry hydrogen down to a dew point <-75°C.

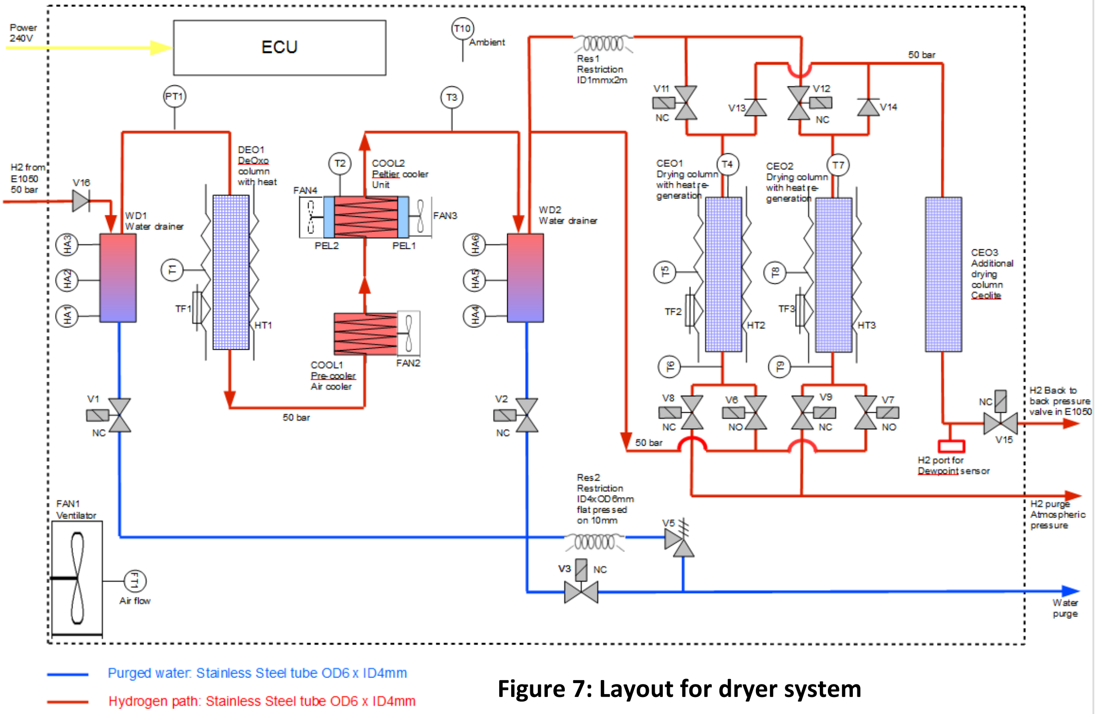


Figure 7: Layout for dryer system

Two further steps are included in the dryer flow path. A catalytic column (DEO1) removes oxygen from hydrogen. Due to a very low cross over effect in the electrolyser stack a very low amount of oxygen will be transported through the membrane from the low pressure side to the high pressure side with hydrogen.
A final absorber column ensures a stable and equal low dew point. The column will have an effect in case of a "nearby" saturated column (CEO1 and CEO2) right before a regeneration cycle.

Water purification system:

The electrolyser splits water into hydrogen and oxygen. For that reason clean water has to be supplied to the electrolyser stack. The water quality - conductivity, has to be better than 2 µS/cm. IRD has tested a little system containing a reversed osmoses filter system, BWT WFA Unit, including an ion exchange filter. The ion exchange filter is a cartridge, BTW bestdemin XL, which very easily can be exchanged.

The main specifications for this system:

- Conductivity of 0.5 µS/cm for 2,000 liter
- Filter lifetime RO about one year, Ion exchange 2,000 liter
- Min. input water quality 35 dH°
- Pressure range between 2.5 and 6 bar
- Production capacity max. 5 L/h in average and short term 5L/min

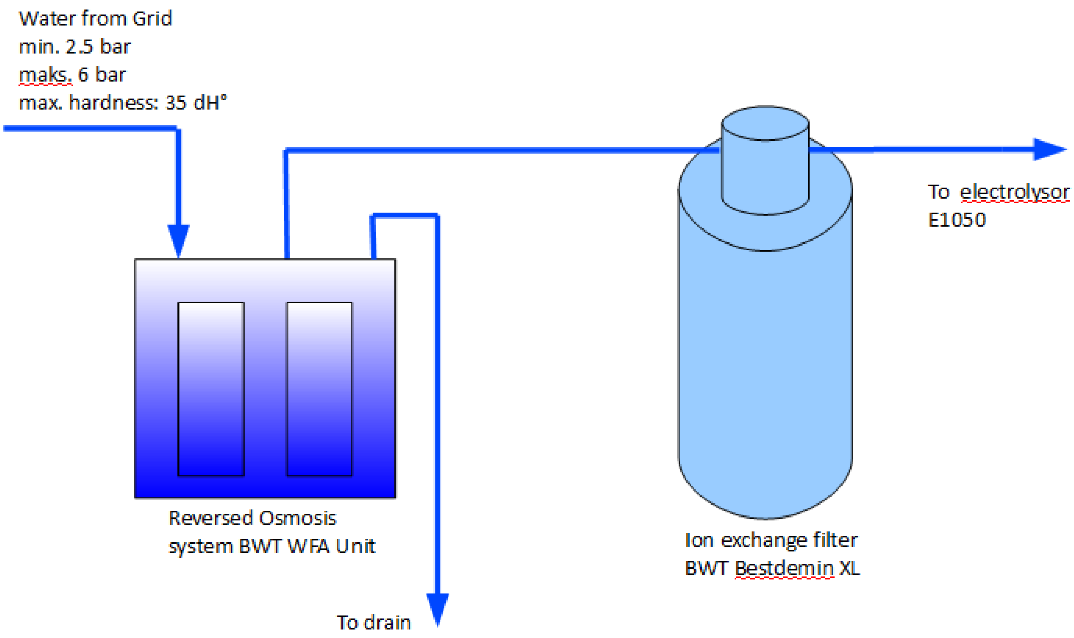


Figure 8: Water purification system HighPEM

The reversed Osmosis, RO, system see Figure 8 pre-cleans the water using a multi-step filter system. The main step is thou the RO filter. The RO filter will always produce an amount of about 40% clean water, and the bigger part of about 60% will include the minerals of the 40% cleaned water. The 60% will go to waste.

Modular electrolyser system:

Hydrogen Refuelling Stations, HRS will, depending on geographically location and how many hydrogen driven cars in the region, need different capacities for hydrogen production. The electrolyser supporting the HRS should for that reason be built modular to address the different needs for capacity.

There are mainly to obvious ways of creating modular electrolyser systems:

- Simply stacking the whole electrolyser system, including cabinet side by side. This scale up method is very easy but will need place and will be expensive as the whole system will be multiplied. For HRS the hydrogen has to be cleaned and dried and for that reason the dryer will also be part of a modular system. As the IRD dryer system is designed as a standalone system and the dryer capacity is larger than the production capacity of the electrolyser, it has not to be added for each electrolyser. The dryer system will be able to maintain the needed gas

Figure 9: 4 stacked electrolysers.

quality for up to 4 electrolyser units – this means up to 4 Nm^3/h of hydrogen. This has thou to be prooven by a system test with 4 Nm^3/h hydrogen flow – read also about this issue in the following chapter.

- The water treatment system has also to be scaled up depending on the needed hydrogen production. This issue will also be analysed more in the following chapter.

- Stacking PEM cell stacks in the cabinet system. This scale up method needs less place, and it is more cost efficient as parts of the BoP can be reused for different hydrogen production capacities. The exact number of stacks per unchanged BoP is not known exactly, but it will be analysed in the following chapter. Subsystems like water path, hydrogen path, oxygen path, cooling system, water treatment and hydrogen dryer/cleaner can be reused also for larger hydrogen volumes than 1 Nm^3/h.

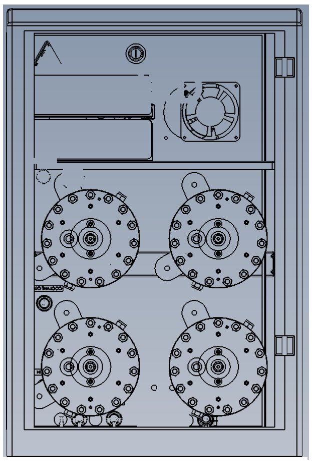


Figure 10: 4 stacks in one cabinet.

3.1.3 Analysis of electrolyser system

Firstly a deep analysis of the present system will be conducted with the aim of identifying which BoP components that are required for the PEM electrolyser stack in order to function in a multi module system.
The BoP components will be analysed separately as the capacities for the different components/subsystems will be different. Both the integrated components in the electrolyser cabinet and the external subsystems like water treatment and hydrogen drying will be analysed.

The following components/subsystems can be defined and analysed:

- **The stack**, which might be called the core part, as it is the hydrogen producing unit. It also defines the capacity of the electrolyser. The capacity of the stack is mainly depending on the active membrane areal in the electrolyser. The areal can be varied by sizing the single active cell areal and it can be sized by stacking cell units. IRD has designed a 1 Nm^3/h stack with circular cells with an active areal of 69 cm^2 and with 33 cells. This combination results in the 1 Nm^3/h capacity. Other parameters will influence the capacity as well but it is not subject of this project.

- **The power supply**, which transforms the AC power from the grid to an appropriate DC power for the stack. IRD has decided to run the electrolyser with to Powerfinn PAP3200/48. The max. power of this model is 3,200 W. The stack runs ideally with 5,000 W, and for that reason each stack needs 2 power supplies. By scaling up hydrogen capacity the power supply will have to be scaled up one by one.

- **The control and I/O board**, which controls the whole electrolyser system. IRD has reused a PCB, which was developed earlier for Fuel Cell applications. The board includes both the controller and the I/O ports connecting sensors valves, power supplies and internet. By scaling up the electrolyser system the IRD board has to be scaled up as well – one board per stack. The PCB can easily manage multiple stacks in principal, but as the board also includes the I/O connections, the amount of ports pr. board is too low for 2 or more stacks pr. system. To solve this issue it would be preferable to have a PCB board and an I/O board. The I/O board only would have to be scaled up for each additional stack.

- **The hydrogen path**, is shown in Figure 6, which includes the pressure sensors (PT2, PT3), back pressure valve (V9), safety valve (V13) and purge valves (V11, V12) and a few other components. The path is made of stainless steel 316L tubes of ID 4mm, and the process pressure is max. 50 bar. The path connects the stack outlet, the dryer system and an external hydrogen cylinder. The system can be used with an extended capacity, or with several stacks. To estimate how big the max capacity for the hydrogen path is, the component with the lowest flow value Cv has to be found. The Cv value is depending on the pressure range the component is used with, and this value is defined in our case to be 50 bar. The flow coefficient Cv is the volume of a gas that will flow per minute through a valve with a pressure drop of 1 psi across the valve. (All Cv coefficient for air):

  a) Backpressure valve V9: Cv=0.1
  b) Safety valve V13: Cv=0.38
  c) Backpressure valve: Cv=0.47
  d) Tubing: Not known for the system, but > 0.1

  The other valves in the hydrogen path will not influence the process flow.
  The most flow limiting item in the path is the backpressure valve V9. The pressure drop over the valve V9 must not increase 1 bar to avoid gas relieve through the safety valve. The pressure drop pr. Cv of 0.1 is 1 psi or 0.069bar.

  The capacity max. capacity for a valve with Cv=1, a pressure input of 50bar and a max allowable pressure drop over the valve of 1 bar can be red out from a table (Swagelok[2], values for air). The read out flow value for Cv=1 is 2,800 L/min. This value has to be multiplied with the actual Cv value:

Max. flow over valve V9 is 2800 L/min. x 0.1 = 280 L/min.

Even the V9 is the component with the lowest Cv coefficient the the whole system will have a lower Cv value and for that reason the flow of 280 L/min. will be reduced to the half to be on the safe side for an estimation. The total flow over the whole hydrogen path is for that reason estimated to be max. 140 L/min.
The system flow with one stack (IRD Fuel Cells, E1050) produces a hydrogen flow of 16.6 L/min. The estimation based on the above calculation and conditions results in a number of stack per unchanged hydrogen path of 8. The capacity can be scaled up to 8 stacks without scaling up the hydrogen path.

- **The Oxygen path** is also shown in Figure 6 and coloured light blue. The oxygen flow rate is 0.5 Nm^3/h or 8.3 NL/min. The components with its Cv values are:
  a) Back pressure valve V2: Cv=0.1 ved 1-10 bar
  b) Check valve V5: Cv=1.48 ved 3 bar
  c) Safety valve V6: Cv=0.64 ved 3 bar

  The pressure range for the oxygen path is 2 bar.
  Using the same table as above from Swagelok for estimating the max. flow capacity in the oxygen path and by choosing the Back pressure valve, V2 with the lowest Cv coefficient of 0.1, the max. flow is 65 L/min. Again the coefficient for the whole oxygen system must be lower, but the tubings are wide (ID 8mm) and the other valves have a high Cv coefficient. Taking the pressure drop for the whole system into account the max. flow will be reduced to 52 L/min (reducing factor 0.8).
  The stack produces a flow rate of 8.3 L/min and therefor the capacity can be scaled up with a factor 52 L/min divided by 8.3 L/min → Factor 6 without scaling up the oxygen path.

- **The water path** in the electrolyser consists of a number of components, and the path has two functions. The first is to supply water to the stack for the electrolysis process and second to remove heat from the stack and exchange the heat to an external cooling system for utilization of the heat. In the following a few components will be evaluated with regard to limitation of scaling up the Capacity of hydrogen production without changing the water system.

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[2] http://www.swagelok.com/downloads/webcatalogs/EN/MS-06-84.PDF and table on page 9 “Low Pressure Drop Air Flow – Metric Units”.

a) The booster pump, which supplies the system with water. It has no cooling related function. The needed water consumption for one stack is 5 L/h. The capacity of the pump is much higher and is 1.500 L/h. The device is not limiting the capacity.
b) A filter in the water loop, type S82 from 3B Filters Inc. The filter insert is wide meshed with 200 µm mesh size. The pressure drop over the filter is very low and will not limit the capacity.
c) The circulation pump (Pum2) in the water loop (dark blue in Figure 6) with a flow capacity of up to 2.4 m^3/h (depending on flow resistance) doesn't limit the water supply for several stacks but the heat transport has to be calculated for an up-scaled version with more than one stack. Each stack contributes with about 1.3 kW heat which has to be removed. The water system in the electrolyser itself is a kind of "radiator", and this system should be isolated to transport all of the heat energy through the heat exchanger to the external cooling system.
d) The heat exchanger AlfaNova 14, HE1 in Figure 6, between external and internal cooling system has 10 exchanger plates and a max. capacity of 22 kW. For that reason the exchanger capacity, seen isolated from the whole system, is enough for scaling up the hydrogen production by a factor 16.

The subsystems above are integrated parts of the electrolyser, and at least to more subsystems are needed to deliver hydrogen to the HRS. A water system and a hydrogen dryer/cleaner system. Both systems are external systems and will be placed side by side with the electrolyser. The systems are described in the following chapter 3.2.2 and for that reason focus here is on a short analysis of the system's capacity only.

- **Water treatment**: The limiting part for production capacity is the RO, reversed osmosis filter unit with 5 L/H in average. The IRD electrolyser needs 5 L/h – the full capacity. The RO unit can supply up to 3 electrolysers as the real use of water for the hydrogen and oxygen production is 1 Liter and the other 4 liters will be lost to the hydrogen side (a minor transport of water through the membrane) and to the oxygen path (water vapor in oxygen). The water can be collected easily in the water traps (WD1 and WD2) in the dryer system, see Figure 7, about 3 liters, and it can be led back to a water collecting tank.
- **Hydrogen dryer**: The dryer system, developed by IRD, has a capacity of more than 1 Nm3/h. The max. capacity for drying hydrogen has not been calculated or tested, as we solely have tested with one electrolyser – 1 Nm^3/h. Two parameters can influence the capacity. The flow speed and the life time capacity of the absorber columns.
-

Conclusion of the analysis of the BoP for running multi module systems:

- 2 power supplies are needed for each m^3 of H_2 ($1m^3 = 1$ stack)
- 1 PCB/IO board is needed for each m^3 of H_2
- For each H_2 path, 8 m^3 of H_2 and 8 stacks can be driven
- For each O_2 path, 6 m^3 of H_2 and 6 stacks can be driven
- For each water path, a final conclusion can't be made without test-runs with a multi module set-up. Scaling up will be possible, but a specific factor for scaling up can't be made without test runs of the specific configuration.
- Water treatment system can supply max. 3 Nm^3/h IRD stacks, if the lost water from the electrolyser is reused.
- The IRD hydrogen drying system support more than 2 Nm^3/h wet hydrogen. Testing though is needed for higher capacities.

Scaling up by running multi module systems is possible for some parts of the BoP. This will have an important positive impact of the price per m^3 of produced hydrogen or more precisely the system price will be lower for the multi module system in our IRD case for a system with up to 8 stacks or production capacity of up to 8 Nm^3/h.

3.2.4 CE marking of PEM Electrolyser

DGC has conducted all the necessary tests and third party review of the electrolyser documentation, among other:
- Risk analysis of design
- Risk analysis of design scale up
- Risk analysis of Electrolyser before field-test
- Determination of relevant standards and directives
- CE marking counseling
- Technical dossier
- Risk analysis of interface between the electrolyser and HRS
- Determination of safety level for the interface between electrolyser and HRS
- CE-marking

The Electrolyser has to fulfil the requirements in the relevant Directives and the technical documentation has to be according to the requirements before it can be put on the market in the European Union. The term market is defined as making it available for the first time with a view to distribute or use whether for reward or free of change.
- The Directives considered according to the electrolyser:
- Machinery Directive (2006/42/EC)
- Low voltage Directive (2006/95/EC)
- Electromagnetic Compatibility (2004/108/EC)
- Simple pressure vessels (2009/105/EC)

In connection to the above mentioned Directive the Pressure Equipment Directive (97/23/EC) has to be taken into account when building the Electrolyser into a process.

The overall CE-marking of the Electrolyser has to be according to the Machinery Directive. It is the manufactures responsibility to ensure that the essential requirements for health and safety given in Annex I is fulfilled. In addition to the Machinery Directive the other relevant Directive has to be fulfilled too.

Process in CE marking according to the relevant Directive:
- Evaluation of the product to determinate the relevant Directive
- Risk evaluation
- Risk elimination
- Validation to the essential health and safety requirements
- Verification of compliance to essential health and safety requirements
- Compile the technical documentation
- Draw up the EC declaration of conformity
- Place CE marking on the machine

IRD must be able to compile the complete technical documentation in a reasonable time (normally 2 weeks), and disclose it to the relevant national authority. The technical documentation shall include all necessary information to demonstrate that the appropriate actions taken to handle the risks associated with the Electrolyser.
The overall conclusion of the reviewed documents is that they are “a” part of the documentation process and only valid as so. Therefore these documents are not to be considered as final documents which would possibly require several revisions to e.g. every design change and so on, which require a more rigorous workflow. Furthermore some documentation is missing to fulfil the requirements of the Directive. It is recommended that the technical documentation is reviewed and necessary documentation is added.
The Machinery directive annex VII specifies demands for technical documentation for the Electrolyser. The list below specifies the Machinery Directive minimum requirement for technical documentation and comments.

MD: Requirement Machinery Directive Annex VII

DGC: DGC comments

IRD: DGC comments to IRD documentation

MD	General description of the machinery
DGC	A description of the machinery function that makes it possible to understand the function of the machinery in a way that makes it possible to understand the principles of the design and operation.
IRD	The description in the manual point 3.1 fulfil this requirement

MD	The overall drawing of the machinery and drawings of the control circuits as well as the pertinent description and explanations necessary for understanding the operation of the machinery
DGC	IRD shall be able to collect machinery and electrical drawings. Where it is needed explanations for understanding the documentation shall be a part of the documentation. The documentation shall be available for 10 years after manufacturing of the last Electrolyser. Updates to the Electrolyser shall be included in this documentation.
IRD	The Documentation DGC had available were not complete and some inconsistence between the documentation were noted. All drawings and explanations to the drawings shall be available. With the product name, where some documents refers to E1050 and others MOE0001. With water quality (ASTM type II), where CR specifies 1 µS/cm and Ma < 2 µS/cm Hydrogen output temperature range required from ISO, where CR specifies the range to be 20-70 ºC, Ma does not supply such information and Mae only specifies an upper limit < 70 ºC Hydrogen quality required from ISO, where CR specifies 99.95 % quality and Ma only specify *high purity*

MD	Full detailed drawings accompanied by any calculation notes test results certificates etc. required to check the conformity of the machinery with health and safety requirements
DGC	All relevant test notes etc. for the machinery that supports the conformity to the essential health and safety requirements stated in annex I and demonstrates the operation conditions for the machinery
IRD	DGC expect that all drawings are detailed and a part of the technical documentation.

MD	The documentation on risk assessment demonstrating the procedure followed including a list of the essential safety requirements which apply to the Machinery directive and the description of the protec-

	tive measures implemented to eliminate identified hazards or to reduce risk and where appropriate the indication of the residual risks associated with the machinery
DGC	A risk assessment carried out for the final version of the machinery including an explanation for the chosen risk assessment tool used. This also including identified hazards and the solution to eliminate or reduce the risk (passive or active risk elimination/reduce)
IRD	The method used shall be a part of the documentation, the risk assessment shall be for the final machinery. If there are made changes to the machinery later on, the risk assessment shall be updated and it shall be possible to track the different versions of the machinery.

MD	The standards and other technical specifications used indicating the essential health and safety requirements covered by these standards
DGC	Including listing the essential health and safety requirements form Annex I, describe standard used to eliminate, reduce or if the risk is not applicable. This is one of the documents that demonstrate conformity to the directive.
IRD	The essential requirements annex I in Machinery Directive can be listed. The relevant standards and parts from the standards noted for each requirements. Not relevant for the requirements marked as not relevant. This shows that the Machinery Directive is followed and integrated in the project.

MD	Any technical report giving the result of the test carried out either by the manufacturer or by a body chosen by the manufacturer or his authorised representative.
DGC	The tests carried out e.g. oxygen/hydrogen cross over I the stack, energy consumption, produced hydrogen, temperature demonstrates and prove the operation conditions to use when its proven that the solution chosen by the manufacturer demonstrates conformity to directive and relevant technical data for marking of the machinery
IRD	Relevant test results for the final machinery. This includes the test results that state the energy consumption ant the hydrogen produced. At the same time the test results that state the machinery full fil the requirements in Annex I should be included in the technical documents.

MD	A copy of the instructions for the machinery
DGC	The instruction manual shall include the instructions assembly operation and maintenance. Where it is appropriate components that have to be replaced during the expected live cycle shall be specified.
IRD	The manual ought to be revised to ensure conformity to the machinery.

MD	Where appropriate copies of the declaration of incorporation for included partly completed machinery and the relevant assembly instructions for such machinery
DGC	If the subassemblies are delivered together with declaration to machinery directive, then it is not required to include detail drawing in the documentation.
IRD	With no access to the complete technical documentation it is not possible to state the conformity.

DGC has conducted a third party survey of the necessary product documentation in the commercialization attempt of the developed electrolyser E1050 by IRD. The reviewed documents with related abbreviations are seen in the table below, where information such as the document holder and release dates are included.

Reviewed documents with included reference for use

Abb.	Document
Ma	E1050 – User Guide and installation manual, IRD, June 2014
Ha	HAZOP Elze E1050 (MOE0001) vers. 1, IRD, June 2014
Mae	MOE0001 – Mærkeplade E1050, IRD
PI	MOE0002, Electrolyser PI Diagram, IRD, July 2014
De	CE declaration 140301522, KIWA, November 2014
CR	Constructional review, KIWA, April 2013
TR	Test Report, KIWA, November 2014
TF	Test forms, KIWA, May 2014

It is DGCs understanding that KIWA with the declaration (De) among their other documents has ensured that the electrolyser complies with the Machinery Directive (2006/42/EC), the Low Voltage Directive (2006/95/EC) – based upon EN 60204-1 and ISO 227341-1 – and the Electromagnetic Compatibility Directive EMC-D (2004/108/EC) – based upon EN 61000-6-1, EN 61000-6-3, EN 61000-3-2(2006) and EN 61000-3-3(1995).
Note in De KIWA does not supply an approval but merely insure that the electrolyser complies with the mentioned directives. Among other documents can the constructional review (CR) be mentioned which notoriously follows ISO 227341-1

As previously mentioned the electrolyser is still in the commercialization phase and therefore it is reasonable to expect inconsistence between the newest documents. A quick examination of table 1 show such the inconsistency, seen in the different and opposed release dates between the documents. E.g. the latest User and installation manual (Ma) from IRD is newer than the CR from KIWA, where the opposite would be expected in the final product. Also the P&ID (PI) is newer compared to the older HAZOP analysis (Ha) which is based upon a previously P&ID.

DGC has reviewed the technical documentation to find inconsistence and lack of documents.
The results of the review show that some documents are not up to date and therefore cannot be valid or classified as final documents. In order to establish and ensure valid coherence between the documents, depending documents must be revised likewise when their relying documents is changed. This can simply be solved with a more rigorous workflow pattern.

3.3 Test of PEM Electrolyser

Connection of PEM electrolyser to HRS

A complete electrolyser system for installation with an HRS has been designed and manufactured. The system is already described in chapter 3.2.1 above.
The intension in WP4 is to modify a HRS system to enable the installation of a PEM electrolyser. All interface connections and subsystems have been included in a separate PEM electrolyser system built into a compact 8' container. This complete system is described above in chapter 3.2.1. The idea was to place this container side by side with the HRS and to connect the 2 systems in passive mode as described in 3.1.3 above.
Unfortunately it was not possible to find a HRS where the electrolyser system could be tested with. So testing has been done at IRD Fuel Cells address.

Capacity of the electrolyser:

The IRD electrolyser E1050 has a capacity which is by far below the needed capacity a HRS should it operate in a well-established hydrogen society with many cars running with hydrogen fuel cells. In our current situation just a few hydrogen driven cars are on the marked and in this situation the electrolyser will be able to supply the HRS station in average.
The future fuel supply pattern for an HRS in Denmark is estimated for a 24 hours period and it is shown in the table below:

Table 1: HRS load per day distribution

Hour	Time	Load (kg)			Load (m3)
1	06:00	16	Morning rush hour	80% in 12 hours	178,08
2	07:00	24			267,12
3	08:00	16			178,08
4	09:00	8			89,04
5	10:00	8			89,04
6	11:00	8			89,04
7	12:00	8			89,04
8	13:00	8			89,04
9	14:00	8			89,04
10	15:00	16	Afternoon rush hour		178,08
11	16:00	24			267,12
12	17:00	16			178,08
13	18:00	8			89,04
14	19:00	8			89,04
15	20:00	4			44,52
16	21:00	4			44,52

17	22:00	4			44,52
18	23:00	4			44,52
19	00:00	0			0
20	01:00	0			0
21	02:00	0			0
22	03:00	0			0
23	04:00	4			44,52
24	05:00	4			44,52
	Total	**200**			**2226**

The average load per day will be 200 kg of hydrogen or 2,226 Nm^3 of hydrogen. The electrolyser E1050 has a max. capacity pr. Day of 24 Nm^3 of hydrogen. Here it is important to have an electrolyser design which can be manufactured modular and can be scaled up to the actual needs. To achieve such high hydrogen volumes per day a modular stack system is needed. On top of that it would also be necessary to design a stack module with a higher capacity than 1 Nm^3/h of hydrogen to achieve the volume of 2,226 Nm^3/day.
This distribution scheme would need 93 electrolysers of the type E1050. This would be too expensive and too space consuming. A larger module would be necessary.

The actual IRD electrolyser system will supply hydrogen to its own storage cylinder which can store up to 17.5 Nm^3 of hydrogen at 50 bar. The HRS will be supplied from this cylinder. In that way the electrolyser can be driven constantly, which is the most optimal operation pattern for it. With a larger electrolyser system, with larger capacity, the operation pattern could be depending on electricity prices on the grid.

Hydrogen purification and drying:

A major issue with production of hydrogen by PEM electrolysis is, that the gas will be wet and there will even be water in liquid phase in the hydrogen outlet of the electrolyser. Water in the gas is a major problem. The water liquid water and water vapour will stay and condensate in all valves and in the storage cylinders. For several reasons this must not happen. The gas has to be dried.
The demands for quality of hydrogen used to fuel cars are very high. The gas has to be extremely clean and dry – as low as described by the dew point of -75°C.
Hydrogen produced by an IRD PEM electrolyser E1050 is clean, but wet. IRD has focused on drying the gas and the purification/drying system has already been described above.

The IRD dryer achieves a dew point of less than -75°C which is acceptable for the HRS purpose. Figure 9 shows a drying cycle of the system. The drying process takes place at a pressure of 50 bar whereas the dew point sensor is placed in pressure less place (1 bar) at the end of the hydrogen path. This measuring set-up will have some delay influences at the place of the sensor as there can be water vapour or small droplets at some place in the hydrogen path, which can influence the signal of the dew point sensor.

In general, mainly two drying levels can be monitored and seen in Figure 9.

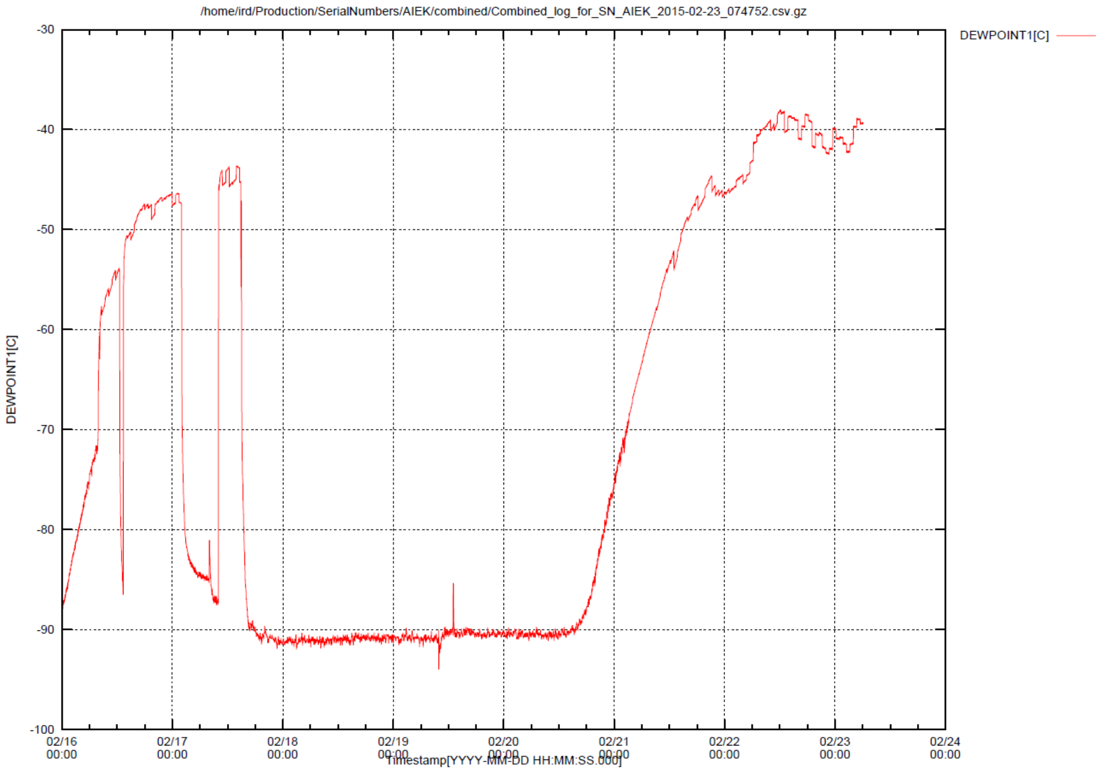


Figure 11: Dew point over time for the IRD hydrogen dryer.

- Level at about -35°C to -40°C:
  This drying level is performed by the hydrogen cooler – water trap component in the dryer system. These components can be seen in the Figure 7 (Components COOL1, COOL2 and WD2). The cooler/water trap installation will dry hydrogen at 50 bar to about -35°C. These components will work continuously and don't need any form for regeneration.

- Level at -75°C or lower:
  This drying level is performed by the absorber columns. The absorber material is zeolite. In Figure 9 the dew point is as low as -90°C over a time of more than 60 hours. After this time the column will start to be saturated, and it needs to be regenerated. A two column system is running continuously, and while one column is saturated and is regenerated the other will be ready to take over. The system controls the regeneration process.

In Figure 9 the column is saturated completely after a few days and the dew point will reach the level where the cooler and water trap only are performing.

The system contains a third zeolite column in the very end of the hydrogen path of the system, thou still at 50 bar. This columns function is solely to even the dew point in case of a starting saturation effect right before the start of regeneration of the dual column system. This third column (CEO3) is used in systems like for the automobile fuelling station HRS or cases with similar high demands for hydrogen quality.

Water purification:

The water purification system is described above in chapter 3.2.1 and with Figure 3. It is a commercial available little purification system.

The life time of the system is an important factor as it needs the exchange of filters, a service step, each time the water quality decreases.
The water quality is defines with the conductivity, and the purified water has to be better than 2 µS/cm.

IRD has measured the water quality over time after the Ion exchange filter of the BWT purifier unit. The water amount was measured in litre.

The BWT unit is, regarding BWT's product specification, 2,000 litre with one Ion exchange filter cartridge in connection with the RO filter unit. IRD's data support their specifications. The Ion exchange filter cartridge lasted for 2,500 litre before the conductivity passes 2 µS/cm. The filter cartridge has to be exchanged for every 2,000 litre water volume to keep the conductivity below 2 µS/cm.

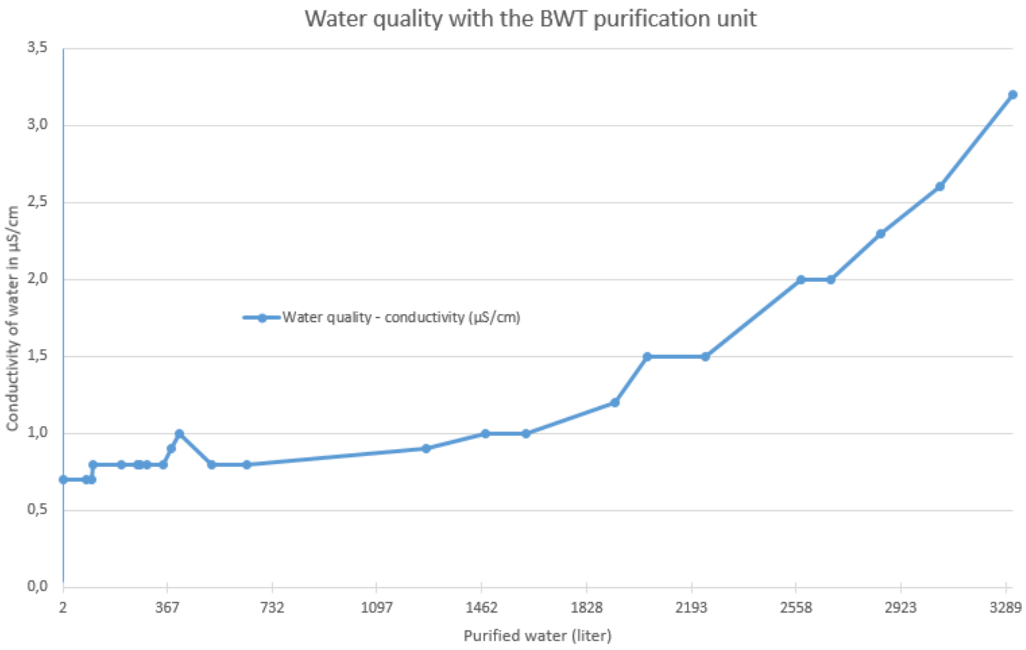


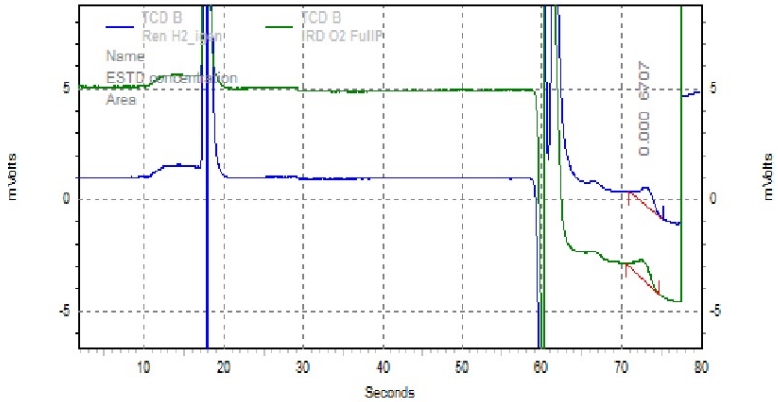
Figure 12: Water quality of purified water in µS/cm.

DGC has performed crossover measurement to the electrolyser.
The tests are performed by using Compact GC and performed the 29th and 30th April 2015.
Determination of hydrogen in the oxygen is determined from a standard curve containing 2, 4 and 6 percent hydrogen in nitrogen using three test gas bags with nitrogen and hydrogen.

Results:

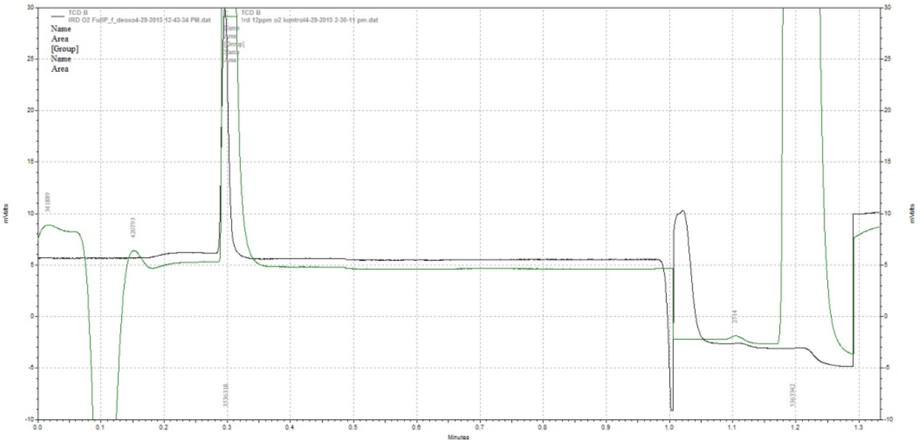
Load (%)	Pressure (bar)	Calculated H_2 %
120	44	3.5
100	44	3.5
90	44	3.9
80	44	4.2
100	27	2.7

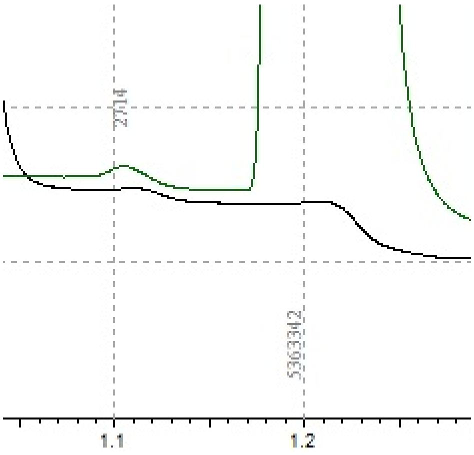
Determination of oxygen in hydrogen after the deoxfilter is determined from comparing the diagram from H_2 5.0 and O_2 at 100% load and 44 bar.



Result: oxygen level lower the GC detection limit

Determination of oxygen in hydrogen before the deoxfilter is determined by comparing the diagram.





Result: Oxygen level lower than 12 ppm.

3.4 Formulation of PEM-HRS Roadmap

The most efficient way to utilize wind power for transport, are through battery-electric vehicles – the second best way is in hydrogen-electric vehicles. Hydrogen fuelled cars has a longer reach and faster refuelling compared to battery-electric vehicles. The need for hydrogen to passenger transport is currently limited. Forecasts of the development in the rollout of hydrogen cars in Denmark predicts between 50,000 and 100,000 cars on the road by 2025. This will create a need for 100 to 200 RFS nationwide. Each station with an average daily production capacity of 200 kg of hydrogen eq. to an average H_2-production of 93 Nm^3/h. However, the size of the optimal electrolyser depends on the approach to cheap RES. The following PEM-HRS Roadmap formulate the long-term goals beyond 2020+ with the aim to reach targets that enable a commercial use in HRS networks. The road-map is based on the present project experience, the national Danish strategies for transport[3] & electrolysis[4] as formulated by the Partnership for hydrogen and fuel cells, and the data sheet for PEMEC developed by IRD for the Danish Energy Agency within an on-going EUDP-project[5].

	PEMEC				
	2015	**2020**	**2030**	**2050**	**Note**
Energy/technical data					
Efficiency, year one (kWh_e/Nm^3)[6-7]	4.7	4.3	4.2	4.0	A
Efficiency, end of stack life (kWh_e/Nm^3)	6.5	6.0	5.5	5.0	B
Efficiency, average lifetime (kWh_e/Nm^3)	5.6	5.2	4.9	4.5	B
Average lifetime efficiency, electricity to H_2 (%); LHV	54%	58%	62%	67%	C
Average lifetime efficiency, electricity to H_2 (%), HHV	63%	69%	73%	78%	C
Useful heat out (kWh_e/Nm^3), BoL[8]	NA	NA	12%	10%	D
Average lifetime efficiency, electricity to heat (%)	NA	NA	15%	13%	D
Operating temperature (ºC)	65-70	80	85	90	E
H_2-pressure, directly produced (Bar)	30	100	300	+300	
Technical lifetime (years)	15	15	>15	>15	B

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[3] http://www.hydrogennet.dk/fileadmin/user_upload/PDF-filer/Partnerskabet/Strategier/Transportstrategi_Final.pdf

[4] Will be available in 2016 on http://www.hydrogennet.dk/

[5] EUDP project: Analyser for kommercialisering af brintteknologier (J.no. 64013-0581)

[6] Bertuccioli, L; Chan, A; Hart, D; Lehner, F; Madden, B & Standen, E (2014): Development of Water Electrolysis in the European Union. Final report. Available on-line at http://www.fch-ju.eu/sites/default/files/study%20electrolyser_0-Logos_0.pdf

[7] Marcelo Carmo, David L. Fritz, Jürgen Mergel & Detlef Stolten (2013): A comprehensive review on PEM water electrolysis. International journal of Hydrogen Energy 38(12)4901-34

[8] BoL: Beginning of Life

Regulation ability					
Ramp up time, linear to full load (minutes)	NA	NA	NA	<1	
Ramp down time, linear to full load (minutes)	0	0	0	0	F
Start-up time (minutes)	NA	NA	NA	<1	G
Financial data					
Turnkey price (M€/MW)	1.9	1.3	1.1	0.8	H
-hereof equipment (M€/MW)[6]	1.6	1.0	0.8	0.6	I
-hereof installations (M€/MW)	0.3	0.3	0.3	0.2	B
O&M (€/MW_e per year)	24,000	20,000	18,000	15,000	B,I,J

Notes:

A. Central values[6] are listed (2050 is estimated); although the range is rather large as shown below:

	2015	2020	2025	2030	
Central	4.7	4.3	4.3	4.2	kWh_e/Nm^3
Range	4.2-6.6	4.0-5.5	4.0-5.1	4.0-4.8	kWh_e/Nm^3

The efficiencies in 2050 are all estimates

B. 2015 & 2020, based on an estimate made by DGC 2013

C. LHV (10,797.05 kJ/Nm^3)
HHV (12,715.54 kJ/Nm^3)

D. The waste heat is presently not utilised in large commercial systems, but IRD has proven that it is possible to utilise the waste heat in a simple design. The 2030 and 2050 numbers are estimates based on the average hydrogen production lifetime efficiencies. Improvements in efficiency will entail less waste heat to utilise.

E. Operational temperature and heat utilisation temperature
The 2015 operational temperature is informed by Proton-On-Site 2013

F. 2014: Proven by IRD for a μPEMEC system

G. Cold start-up target (2050)

H. The turnkey cost scales with the plant size, as exemplified by Proton-On-site in 2013 (Fig. 3.1)

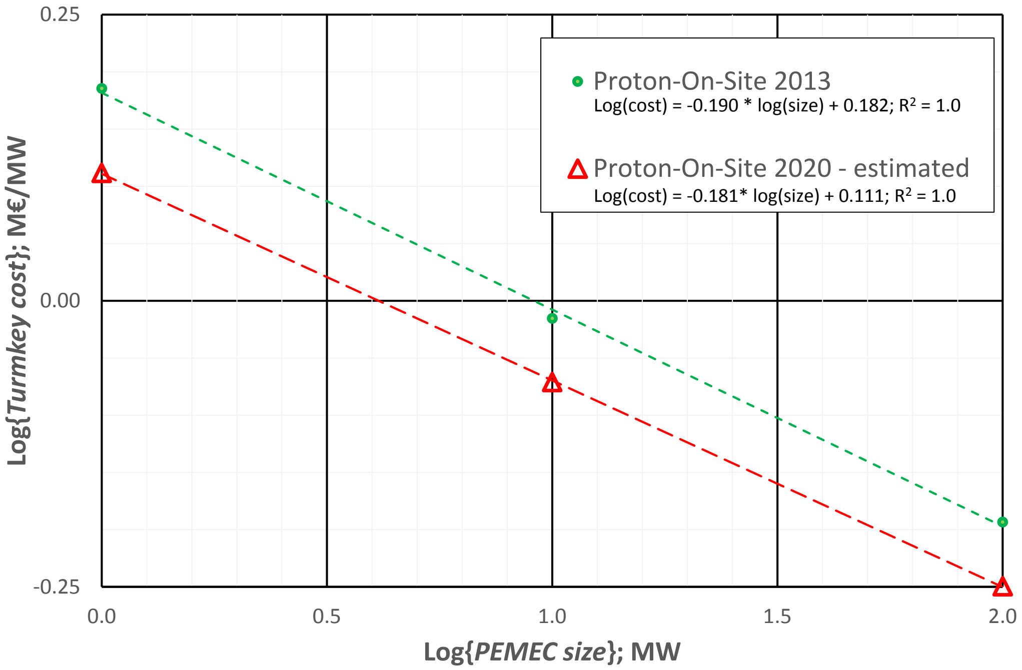


Fig. 3.1 Turnkey cost versus PEMEC plant cost, estimated by Proton-On-site 2013.

I. Incl. power supply, system control, gas drying (purity above 99.4%); excl. grid connection, external compression, external purification and hydrogen storage. Central values are listed (2050 is estimated); although the range is rather large as shown below:

	2015	2020	2025	2030	
Central	1.57	1.00	0.87	0.76	€/MW
Range	1.20-1.94	0.70-1.30	0.48-1.27	0.25-1.27	€/MW

J. 2015 Including stack exchange cost at modulating operation (4,000 full load hours per year)

3.5 Analysis on use of PEM Electrolysers for natural gas injection

DGC in collaboration with IRD will conduct an analysis on the potential use of PEM electrolysers for injection of hydrogen to the Danish natural gas grid at various grid MR stations. Specific analysis topics will be:

- Estimation of relevant PEM electrolyser sizes for natural gas injection - taking into consideration limitation in hydrogen content for various flow at the MR-station, and the range of appliance applications connected to the natural gas net.
- Calculation of economical feasibly of various plant sizes & defining of R&D and cost targets
- Projections for a potential use beyond 2020 and impact on balancing & storage of renewable electricity

3.5.1 Estimation of PEM electrolyser sizes for natural gas injection at M/R stations

Main sizing factors:

End user equipment such as CNG vehicles and gas turbines limit the maximum allowable hydrogen content to 2 vol% in the natural gas network. Considerable work is done in these years to find solutions to increase the allowable hydrogen content to 10 vol%.

The natural gas consumption in Denmark is expected to continue to decrease in the future.

A case study had been done based on the expectations for 2035 from the national TSO operator for gas and electricity in Denmark, energinet.dk.

The year 2035 has been chosen because scenario simulations of the Danish energy system indicate that electrolyser may have a role to play at that time.

Sizing is done based on the expected average gas hourly gas flow at every M/R station in Denmark for both 2 and 10 vol% hydrogen in the gas. The flow varies considerably during a year as a major part of the gas is used for room heating. Daily variations add further to this. Injection will be based on and limited by continuous measurements of upstream gas flow and hydrogen content.

To compensate for the flow variations and enable a the electrolyser plant to be part of electricity balancing system a hydrogen buffer storage with a capacity of 8 hour full load hydrogen production is part of the system. The optimal size will depend on the different energy prices in 2035 and the other balancing alternatives. Part of the hydrogen production may be used for fuelling fuel-cell vehicles as the automotive sector is expected to be able to pay the highest price for hydrogen.

Table one shows the result of this sizing for all the Energinet.dk M/R stations with 2 % hydrogen volume limit. The electrolyser lifetime average total plant efficiency is assumed to be 50%.

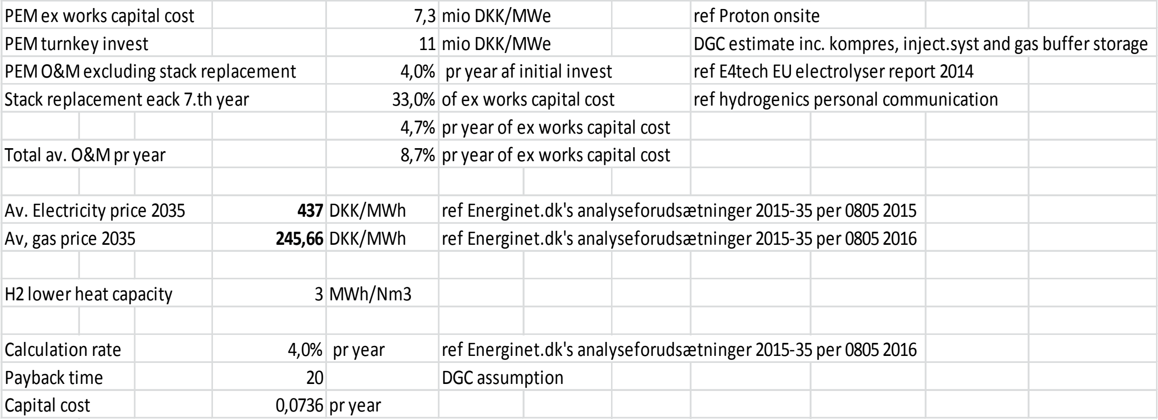
Total installed electrolyser power with 2 vol% max hydrogen volume hydrogen is around 20 MWe. With 10 vol% hydrogen the installed electrolyser power can reach 100 MWe.

Curren	2015 DKK		**Expected flow**		**Dimensionering for max 2% vol H2**	
MR-nr	MR-name	capacitet	natural gas av. flow 2035	natural gas Min. load 2035	2%vol h2 of av. Load	Elektrolyse power **)
		[Nm^3/h]	[Nm^3/h]	[Nm^3/h]	Nm^3/h	[MWe]
451	Frøslev	39492	4077	1165	82	0,49
452	Nybro	4373	451	129	9	0,05
453	Terkelsbøl	33637	3472	992	69	0,42
457	Ll. Selskær	39460	4073	1164	81	0,49
458	Pottehuse	29407	3036	867	61	0,36
459	St. Andst	39457	4073	1164	81	0,49
460	Egtved	74812	7723	2206	154	0,93
462	Varde	32192	3323	949	66	0,40
464	Viborg	106753	11020	3149	220	1,32
468	Taulov	27101	2798	799	56	0,34
473	Haverslev	18973	1959	560	39	0,24
474	Ellidshøj	12754	1317	376	26	0,16
476	Ålborg	157645	16273	4650	325	1,95
481	Nørskov	24271	2505	716	50	0,30
482	Brande	13542	1398	399	28	0,17
483	Herning	151853	15676	4479	314	1,88
484	Karup	21373	2206	630	44	0,26
486	Ll. Torup MR	11414	1178	337	24	0,14
496	Lilballe	9011	930	266	19	0,11
551	Middelfart	11214	1158	331	23	0,14
553	Billesbølle	11069	1143	326	23	0,14
554	Koelbjerg	43830	4525	1293	90	0,54
557	Højby	99404	10261	2932	205	1,23
559	Ullerslev	7359	760	217	15	0,09
560	Nyborg	10697	1104	315	22	0,13
646	Amager Fælled	6316	652	186	13	0,08
653	Slagelse	24206	2499	714	50	0,30
658	Sorø	37621	3884	1110	78	0,47
661	Ringsted	29228	3017	862	60	0,36
663	Køge	34134	3524	1007	70	0,42
664	Karlslunde	81802	8444	2413	169	1,01
665	Torslunde	25347	2617	748	52	0,31
667	Vallensbæk	25700	2653	758	53	0,32
668	Brøndby	122562	12652	3615	253	1,52
672	Dragør	23336	2409	688	48	0,29
682	Lynge	129930	13412	3832	268	1,61
684	Måløv	72874	7523	2149	150	0,90
691	Stenlille MR	60913	6288	1797	126	0,75
	Total	1705063	176010	50289	3520,20	21,12

Table 1: Sizing of PEM electrolysers at Energinet.dk’s M/R stations

3.5.2 Calculation of the economic feasibility

A simplified calculation will be presented. Simplified assumptions will be made to find indications of the feasibility of hydrogen injection in the natural gas grid in 2035.
Average lifetime efficiency of total electrolyser plant including degrading and stand by etc: 0.5.
Equivalent full load operation time per year
6,000 hours
This equals base load as actual running time due to part load will approach 8,000 hours per year. The electricity price used in the calculations for the electrolyser is the average price expected by energinet.dk in 2035 shown below, 437 DKK/MWh. The electricity price is expected to vary mostly between 300 and 600 DKK/MWh.



PEM ex works capital cost	7,3	mio DKK/MWe	ref Proton onsite
PEM turnkey invest	11	mio DKK/MWe	DGC estimate inc. kompres, inject.syst and gas buffer storage
PEM O&M excluding stack replacement	4,0%	pr year af initial invest	ref E4tech EU electrolyser report 2014
Stack replacement eack 7.th year	33,0%	of ex works capital cost	ref hydrogenics personal communication
	4,7%	pr year of ex works capital cost	
Total av. O&M pr year	8,7%	pr year of ex works capital cost	
Av. Electricity price 2035	**437**	DKK/MWh	ref Energinet.dk's analyseforudsætninger 2015-35 per 0805 2015
Av, gas price 2035	**245,66**	DKK/MWh	ref Energinet.dk's analyseforudsætninger 2015-35 per 0805 2016
H2 lower heat capacity	3	MWh/Nm3	
Calculation rate	4,0%	pr year	ref Energinet.dk's analyseforudsætninger 2015-35 per 0805 2016
Payback time	20		DGC assumption
Capital cost	0,0736	pr year	

	Currency:	2015 DKK		**Expected flow**		**Dimensionering for max 2% vol H2**				**Economics for max 2% vol H2**			
MR-nr	MR-name		capacitet [Nm^3/h]	natural gas av. flow 2035 [Nm^3/h]	natural gas Min. load 2035 [Nm^3/h]	2%vol h2 of av. Load Nm^3/h	Elektrolyse power **) [MWe]	Elektroly- invest [mio DKK]	Capital cost [mio DKK/year]	O&M cost [mioDKK/year]	H2 prod at 6000 h/y [MWh/year]	Electricity cost [mioDKK/year]	**H2 prod cost at 6000 h/y** DKK/MWh
451	Frøslev		39492	4077	1165	82	0,49	5,38	0,40	0,47	1468	1,28	1463
452	Nybro		4373	451	129	9	0,05	0,60	0,04	0,05	162	0,14	1463
453	Terkelsbøl		33637	3472	992	69	0,42	4,58	0,34	0,40	1250	1,09	1463
457	Ll. Selskær		39460	4073	1164	81	0,49	5,38	0,40	0,47	1466	1,28	1463
458	Pottehuse		29407	3036	867	61	0,36	4,01	0,29	0,35	1093	0,96	1463
459	St. Andst		39457	4073	1164	81	0,49	5,38	0,40	0,47	1466	1,28	1463
460	Egtved		74812	7723	2206	154	0,93	10,19	0,75	0,89	2780	2,43	1463
462	Varde		32192	3323	949	66	0,40	4,39	0,32	0,38	1196	1,05	1463
464	Viborg		106753	11020	3149	220	1,32	14,55	1,07	1,27	3967	3,47	1463
468	Taulov		27101	2798	799	56	0,34	3,69	0,27	0,32	1007	0,88	1463
473	Haverslev		18973	1959	560	39	0,24	2,59	0,19	0,22	705	0,62	1463
474	Ellidshøj		12754	1317	376	26	0,16	1,74	0,13	0,15	474	0,41	1463
476	Ålborg		157645	16273	4650	325	1,95	21,48	1,58	1,87	5858	5,12	1463
481	Nørskov		24271	2505	716	50	0,30	3,31	0,24	0,29	902	0,79	1463
482	Brande		13542	1398	399	28	0,17	1,85	0,14	0,16	503	0,44	1463
483	Herning		151853	15676	4479	314	1,88	20,69	1,52	1,80	5643	4,93	1463
484	Karup		21373	2206	630	44	0,26	2,91	0,21	0,25	794	0,69	1463
486	Ll. Torup MR		11414	1178	337	24	0,14	1,56	0,11	0,14	424	0,37	1463
496	Lilballe		9011	930	266	19	0,11	1,23	0,09	0,11	335	0,29	1463
551	Middelfart		11214	1158	331	23	0,14	1,53	0,11	0,13	417	0,36	1463
553	Billesbølle		11069	1143	326	23	0,14	1,51	0,11	0,13	411	0,36	1463
554	Koelbjerg		43830	4525	1293	90	0,54	5,97	0,44	0,52	1629	1,42	1463
557	Højby		99404	10261	2932	205	1,23	13,54	1,00	1,18	3694	3,23	1463
559	Ullerslev		7359	760	217	15	0,09	1,00	0,07	0,09	273	0,24	1463
560	Nyborg		10697	1104	315	22	0,13	1,46	0,11	0,13	398	0,35	1463
646	Amager Fælled		6316	652	186	13	0,08	0,86	0,06	0,07	235	0,21	1463
653	Slagelse		24206	2499	714	50	0,30	3,30	0,24	0,29	900	0,79	1463
658	Sorø		37621	3884	1110	78	0,47	5,13	0,38	0,45	1398	1,22	1463
661	Ringsted		29228	3017	862	60	0,36	3,98	0,29	0,35	1086	0,95	1463
663	Køge		34134	3524	1007	70	0,42	4,65	0,34	0,40	1268	1,11	1463
664	Karlslunde		81802	8444	2413	169	1,01	11,15	0,82	0,97	3040	2,66	1463
665	Torslunde		25347	2617	748	52	0,31	3,45	0,25	0,30	942	0,82	1463
667	Vallensbæk		25700	2653	758	53	0,32	3,50	0,26	0,30	955	0,83	1463
668	Brøndby		122562	12652	3615	253	1,52	16,70	1,23	1,45	4555	3,98	1463
672	Dragør		23336	2409	688	48	0,29	3,18	0,23	0,28	867	0,76	1463
682	Lynge		129930	13412	3832	268	1,61	17,70	1,30	1,54	4828	4,22	1463
684	Måløv		72874	7523	2149	150	0,90	9,93	0,73	0,86	2708	2,37	1463
691	Stenlille MR		60913	6288	1797	126	0,75	8,30	0,61	0,72	2264	1,98	1463
	Total		1705063	176010	50289	3520,20	21,12	232,33	17,10	20,21	63364	55	

These rough calculations shows that the hydrogen production price is around 1500 DKK/MWh. The gas price in the gas network in 2035 is expected to be 250 DKK/MWh - 6 times lower than the hydrogen production price.

R&D targets: What can be done to improve electrolyser competitiveness?

Higher efficiency? The PEM technology is not expected to exceed 70% as a lifetime average value including total plant with cleaning stages, part load and stand by losses.

Lower capital cost? Yes, but the cost applied in the calculation are already based MW size extrapolations 5-10 years ahead and further price reductions is expected to be limited.

Other services? Grid Balancing? Yes, but it will need additional capacity reserved for this purpose and there will be competition from alternative balancing measures.

Other services? Fuelling fuel-cell vehicles: Yes, this is expected to be best paying customer group. But this service may also need additional electrolyser capacity and solving of the transport problem of moving hydrogen from production site (M/R station are often placed far from cities). A separate hydrogen network including own caverns would enable seasonal electricity grid balancing services. Moving hydrogen by truck would necessitate compressing to 1000 bar.

3.6 Dissemination of results

Dissemination efforts during the project period has focused on the Danish stakeholders within the Danish Hydrogen & Fuel Cell Partnership.

Project progress and results have been disseminated on a continuous basis during the projects in the meetings of the working groups “Electrolysis” and “Transport”.

The project results has been used to update the national R&D strategies within the two working groups, in 2014 the Transport strategy and with a new electrolyser strategy scheduled to be released during 2016.

IRD and H2 Logic has also ensured dissemination through the European Fuel Cells & Hydrogen Joint Undertaking, by participating and contribution to similar working groups on a European scale.

4. Utilization of project results

The Electrolyser is covered by the Machinery Directive and some other directives. DGC have got specialised insight in the requirements of the Directive and used standards. This makes it possible for DGC to provide consultancy in CE-marking according to the Machinery Directive.

The knowledge gained by IRD within the project comprises mainly valuable understanding on how to design and operate a safe modular system. DGC has in this respect been a key partner in the HAZOP and in the guide to fulfil the relevant directives. This part of the work has been done in the parallel and with great synergy with on-going project "Energy Storage – Hydrogen injected into the Gas Grid via electrolysis field test".[9] The integrated system has attracted international attention from several European universities e.g. IRD delivered in November 2015 a container with an integrated IRD electrolyser, a high pressure hydrogen dryer, a hydrogen storage tank and an IRD µCHP to a university in Finland.

A novel business strategy has been decided by the board for IRD. The new strategy implies that IRD will focus their commercial business solely on PEM fuel cell & PEM electrolysis components (MEAs [cells] & bipolar plates). However, the project has resulted in significant knowledge for IRD and has strongly contributed to support their component business.

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[9] EUDP J. No 1936-0004

5. Project conclusion and perspective

The HighPEM project has secured key results on four areas that enables a continued use by the partners and the Danish hydrogen sector.

The developed technical interface definition between PEM electrolysers and HRSs enables that electrolysers and HRSs from any manufacturer can be connected and operate together. In the past the technical interface were customized for each project, but with the interface definition new products can be developed to comply with this, and enable flexible connection and use.

IRD has developed and tested a fully working PEM electrolyser and validated the hydrogen purity and fit for use at HRSs and with 50bar outlet, one of the highest reported for a CE marked system.

The HighPEM project results has enabled IRD to commence the implementation of a new business strategy, where IRD will focus their commercial business solely on PEM fuel cell & PEM electrolysis components (MEAs [cells] & bipolar plates).

The analysis conducted on the potential use of PEM electrolysers for natural gas grid injections, can provide a basis for continued assessments on the topic. The application is a potential long term, thus more considerations are required.

The PEM electrolysis roadmap has provided input for the new Danish National Electrolyser R&D strategy that is expected to be released during 2016.