H2Cost

Cost reduction of alkaline electrolysers and hydrogen refueling stations

PROJECT END REPORT
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SUPPORTED BY:

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1. Project details

Project title	H2Cost – Cost reduction of alkaline electrolysers and hydrogen refueling stations
Project identification	64013-0585
Name of the programme which has funded the project	EUDP 2013 SÆRPULJE Brint
Project managing company/institution (name and address)	Nel Hydrogen A/S (former H2 Logic A/S Industriparken 34B 7400 Herning
Project partners	Greenhydrogen.dk ApS Gramstrup Køling A/S DTU Mechanical Engineering
CVR (central business register)	Nel Hydrogen A/S | 26933048 Greenhydrogen.dk ApS | 30548701 Gramstrup Køling A/S | 70112310 DTU Mechanical Engineering | 30060946
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2. Short description of project objective and results

English version (600-800 characters)

The goal of the HyCost project has been to reduce cost, and increase technical performance of the GreenHydrogen.dk APS MW Electrolyzer system and Precooling technology for Hydrogen Refuelling Stations (HRS) from Nel Hydrogen A/S. In a collaboration between GH and DTU-MEK, several areas of the alkaline electrolyser system have been improved, both in regard to cost and practical functionality, to bring the machine further towards commercialisation. Nel Hydrogen has developed a new hydrogen pre-cooling technology with substantial advances on capacity and cost reductions, and is now being used in station products offered to the market.

Dansk version (600-800 characters)

Målet med HyCost projected har været at reducere prisen, og øge den tekniske ydeevne af Green-Hydrogen.dk (GH) Aps MW Electrolyse system, samt brint kølings teknologi til Brinttankstationer fra Nel Hydrogen A/S. I et samarbejde mellem GH og Danmarks Tekniske Universitet – Mekanik (DTU-MEK), er adskillelige områder af det alkaliske elektrolyse system blevet forbedret, både med hensyn til pris og praktisk funktionalitet, for at modne maskinen frem mod kommercialisering. Nel Hydrogen har udviklet ny brintkølingsteknologi med betydelige fremskridt på kapacitet og reduktion af omkostninger – hvilket nu anvendes i stationsprodukter til markedet.

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3. Executive summary

The H2Cost project has developed a new MW alkaline electrolyser technology from GreenHydrogen.dk ApS (GH) and pre-cooling technology for Hydrogen Refueling Stations (HRS) from Nel Hydrogen A/S (NEL).

3.1 Development of cost reduced MW Alkaline Electrolyser

A fully scaled Pressurized alkaline electrolyzer with a capacity of 60Nm^3/h has been developed, testing out and refining technologies critical to the function of pressurized alkaline electrolysis. The goals of the project was to develop new pressure control concepts, test different membrane technologies, improve corrosion protection, and optimize the footprint of the electrolyzer system, and in all areas focusing on solutions that will bring the GH Alkaline Electrolyzers closer to commercialization at competitive price levels.

A pressure control system for controlling differential pressures to within a few mbar was made possible by a utilizing a series of proportional valves and motorized back pressure regulators. Rigorous corrosion protection was achieved by implementing high Ni-alloyed components and Ni-coating of all parts of the machine exposed to hot electrolyte. The ma-chine was carefully dimensioned to ensure a high degree of utilization of standard components, also taking accessibility during installation and maintenance into account, making it possible to do installations with a standard forklift.

By implementing the above mentioned measures it was possible for GH to reduce the overall cost per Hydrogen production capacity from ~9.300€ per Nm^3/h, to ~4.000€ per Nm^3/h.

3.2 Development of novel HRS pre-cooling

As part of the H2Cost project Nel Hydrogen has successfully managed to develop and test a new hydrogen pre-cooling system with substantial advances compared to the previous state-of-the-art, prior to the project:

- 140% increase of instant fueling capacity – from 14 kg to 33,6 kg
- 100% increase of daily fueling capacity – from 100 to 200kg
- 90% reduction of physical system volume
- 16% reduction in energy consumption
- Enabling placement of dispenser at long distance from cooling system
- 50% cost reduction of pre-cooling system cost

1 patent application has been submitted on the cooling technology and following the project, Nel Hydrogen has conducted product maturing activities of the hydro-

gen pre-cooling technology, which has enabled integration into the latest hydrogen fueling station product (H2Station®) currently being marketed for Europe and USA.

Nel Hydrogen has already secured sales and installation of the new H2Station® in Europe, and was recently awarded an order of 120 million DKK from Shell for stations to be installed in California.

To continue the efforts on the cooling system, the new H2Cost-2 project was initiated in late 2016, supported by EUDP. The aim is to achieve yet a doubling of fuelling capacity and a 44% cost reduction for the cooling system.

Since commencing of the H2Cost 10 more employees have joined Nel Hydrogen, and with an outlook of a 10% increase per year going forward, thanks to the results of H2Cost. Also Nel Hydrogen targets to grow annual sales with 30% on the new H2Station®, made possible by the hydrogen cooling technology developed in H2Cost. The majority of the annual sales are expected to be export outside of Denmark.

4. Project objectives

The objective of the H2Cost project has been reduce cost and increase technical performance of MW alkaline electrolyser technology from GreenHydrogen.dk ApS (GH) and pre-cooling technology for Hydrogen Refueling Stations (HRS) from Nel Hydrogen A/S (NEL).

4.1 Electrolyser project objectives

Earlier on this application covered the reduction of cost of GH's so-called 2nd generation AEC. However, GH has decided to change strategy from focusing on two different sizes of electrolyzers:

- 2nd generation AEC (1-8 Nm3/h)
- MW AEC (12 Nm3/h to 60 Nm3/h)

To only focusing on one – the MW AEC. The reason for this change in strategy is that GH believes that the demand for bigger machines will dominant in the future. Furthermore, the production cost per Nm3/h is significantly reduced by going to larger machines. Other than the focus on the different size of electrolyzer, the overall goals for the project have been more or less the same.

- **Balance of Plant - Concept for regulating pressure & liquid levels**
  Implementation and optimization of newly developed regulating concept enabling fluctuating loads.
- **Balance of Plant - Tests of new prototype membrane**
  Test conducted on a GH developed prototype membrane, enabling an increase in operation temperature.
- **Critical corrosion improvement**
  DTU-MEK is to analyze and develop methods for corrosion protection of critical parts of the electrolyzer system, e.g. pipe lines and BOP components. One of the methods that will be investigated is different nickel plating technologies.
- **Stack power density & rack capacity increased**
  Increase of stack current density from 300 mA/cm^2 to 400 mA/cm^2, increasing the over-all capacity of each electrolyzer module.
- **Cost Reduction of MW AEC technology**
  Enabling a production price of down to €4000 (DKK 30K) per Nm^3/h capacity, compared to GHs 2nd generation AEC presently at €9.300 (DKK 70K) per Nm^3/h capacity – a reduction of 57%.
- **Prototype build and laboratory testing**
  For verification of corrosion resistance, cost reduction and performance an existing GH proto-type will be updated with new components developed in this project. The prototype will be tested at GH's test facilities and critical components will be analyzed for degradation at DTU.
  The prototype unit will have the following specifications:

  - Modular design
  - Process rack 1100 x 1600 x 2300 mm
  - Hydrogen production 60 Nm3
  - Current density 400 mA/cm2
  - Total power consumption 4,5 kW/Nm3
  - Hydrogen outlet pressure 35 bar

4.2 Hydrogen pre-cooling project objectives

For NEL in collaboration with Gramstrup Køling A/S (GK) the aim of H2Cost has been to increase capacity and reduce cost of hydrogen pre-cooling technology for HRSs. This is to enable a continued roll-out HRS networks in global markets.

The H2Cost objectives and targets for the hydrogen pre-cooling activities were:

- 140% increase of instant fuelling capacity – from 14 kg to 33,6 kg
- 100% increase of daily fuelling capacity – from 100 to 200kg
- 50% reduction of physical system volume
- Enabling placement of dispenser at long distance from cooling system
- 44% cost reduction of pre-cooling system cost
- Construction and test of a laboratory prototype
- Planning and securing continued R&D and commercialisation efforts

5. Project results and dissemination of results

The H2Cost project has involved two key tasks listed below.

- Development of cost reduced MW Alkaline Electrolyser
- Development of novel HRS pre-cooling

Results from each task is further elaborated in the sections below as well as general dissemination activities.

3.1 Development of cost reduced MW Alkaline Electrolyser

3.1.1 Balance of Plant - Concept for regulating pressure & liquid levels

One of the great challenges with alkaline electrolysis, is to manage the electrolyte liquid levels in the many different vessels of the machine. In an alkaline electrolyzer, the process components connected to the electrolyzer stack are all hydraulically connected, which means that a differential in pressure between the vessels will result in a displacement of liquid. A quick rule of thumb, is that one mbar of pressure differential, will result in 1cm of electrolyte displacement. Through practical experience during prototype development, the pressure differential needs to be controlled within 0-5mbar for the system liquid levels to remain stable. So for a system that runs on 30-40 bar absolute pressure, the pressure will need to be controlled with a precision of at least 0.1% for the system to be stable. So developing a system that could accommodate this level control was a challenge.

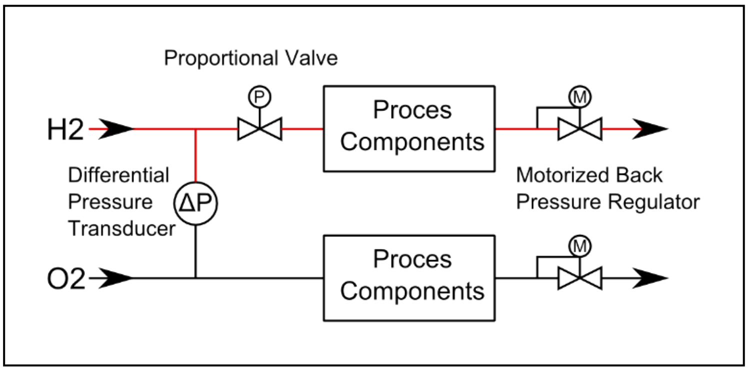
Among the earliest ideas, was a custom developed “equalization valve”, the concept here was to mechanically open and close a valve by the help of a diaphragm, which is communicating between the hydrogen and oxygen side of the electrolyzer. However, after a relatively short period of experimentation, this method control was rejected. The main problem was a safety precaution, as it was hard to construct the valve in such a way that diaphragm break would not cause gas mixture. And if a more sturdy construction method was used, there would be problems with increased hysteresis. Where the extend of the hysteresis would be more pronounced at higher absolute pressure.
There were spent a relatively large amount on energy on finding a solution using only mechanical components, but in the end a software controlled solution was deemed to be the best.

A high number of valve solutions were tested, including various massflow controllers as well as solenoid and proportional valves, where none had a satisfactory outcome.

Looking at the different valves in isolation:
The problem with a back pressure regulator is that it is very poor for controlling small changes in pressure, as there is

some amount of hysteresis because of the piston/diaphragm system.
And on the same note, a fast reacting control valve similar to those used in flow controllers, have the disadvantage that they either regulate small flow at high pressure differential, or high flow at a small pressure differential, because of natural limitation in coil force.
There are a number of suppliers that offer solutions for pressure regulation, often using pressurized air or exotic piloted configurations. However, there is to our knowledge no supplier that offers a solution which solves the problem elegantly and without a large price tag.

In the end, the developed solution was a hybrid between some of the tested components, where a motor controlled back pressure regulators was used together with a fast reacting proportional valve connected in series.
For the electrolyzer to operate optimally and autonomous, there are two primary requirements that the control system should be able to accommodate flawlessly.
The first is to have a high dynamic range, so the system can change electric load very fast without becoming unstable.



The second is the ability for the system to perform startup, shutdown, standby and maintenance sequences with minimal intervention. And here it is especially important, that the system can pressurize and depressurize in a stable manner.

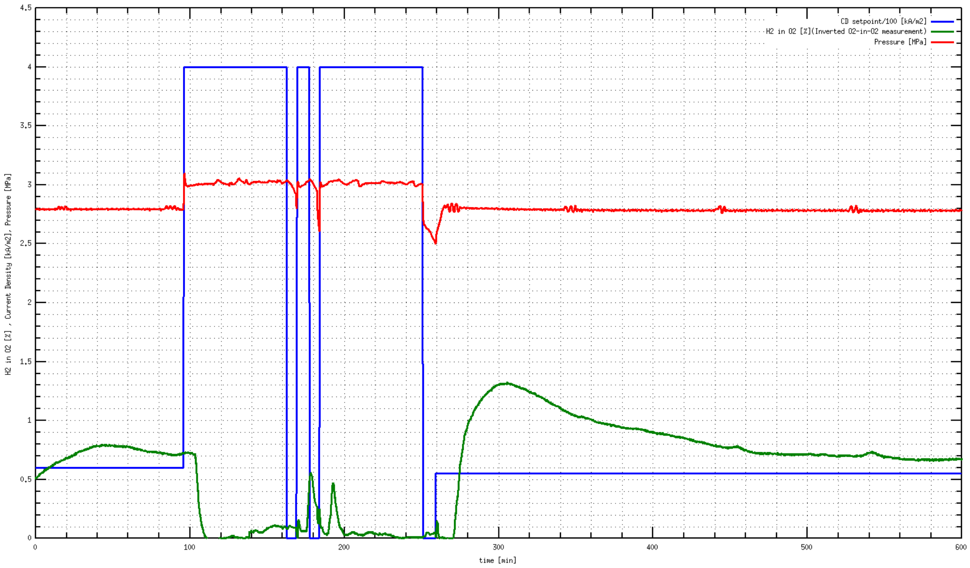


Figure 1 – Oxygen to Hydrogen Crossover in the MW prototype at nominal load with disruptions. Blue: Current density kA/m^2. Green: H2 in O2 %Crossover. Red: Absolute pressure in MPa.

3.1.2 Balance of Plant - Tests of new prototype membrane

A series of membranes have been on trial for the duration of the project with varying degree of success.

- Zirfon (Original membrane)
- Nonwoven PPS fibres
- Woven PPS fibres
- Inhouse developed composite membrane

The original membrane is a Zirconium based composite membrane sold under the name Zirfon. While Zirfon is a great membrane when it comes to gas seperations, pressure resistance, ionic conductivity and chemical stability, it also had its shortcomings when it comes to operating temperature, and price.
With regards to operating temperature however, newer Zirfon grades with higher temperature resistance became available during the project period, making up for this weakness. (Originally Zirfon was only stable up to 70C, while it is now stable up to 110C), which makes Zirfon a very good product at the present time.

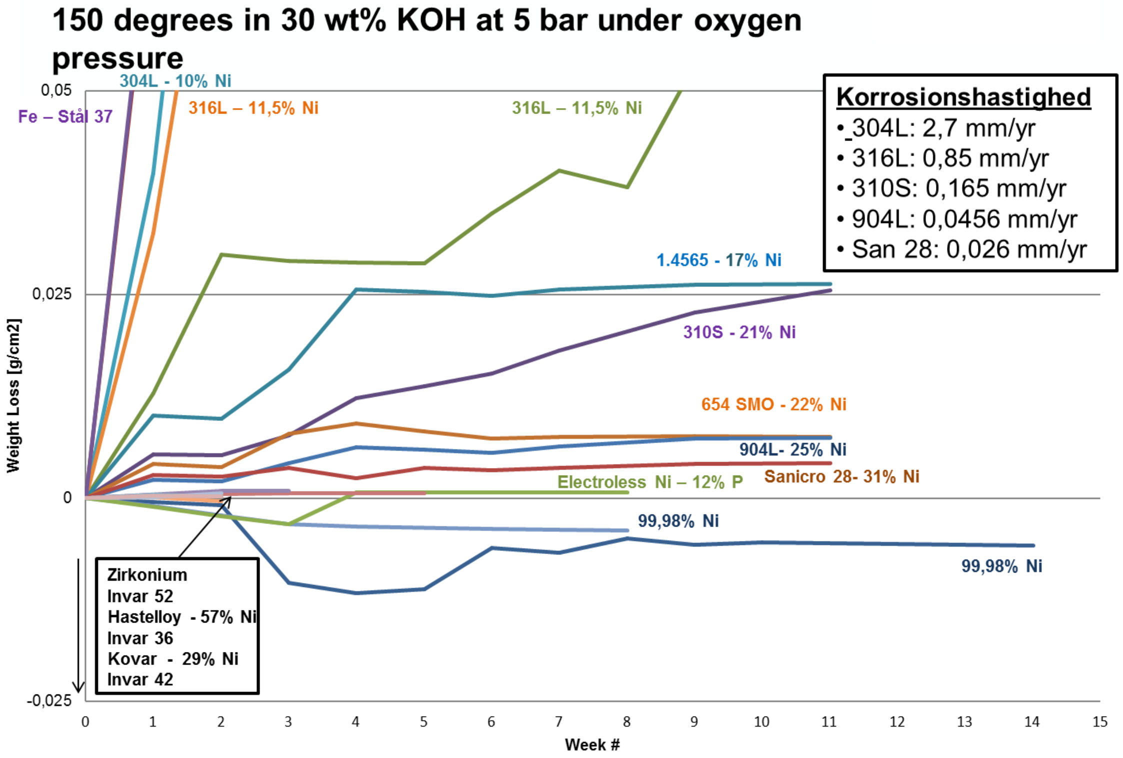
While the In-house developed composite membrane was indeed promising on many parameters, it was not possible to manufacture these membranes in a size that was necessary for the MW electrolyzer. And therefore these membranes were never put to use in the MW electrolyzer. Experiments from laboratory cells showed temperature resistance at 120C, with an ionic conductivity equal to Zirfon.

Traditionally, the method of choice for separating gas in an alkaline electrolyzer, have been to utilize a membrane made of asbestos cloth. However, asbestos have besides posing a significant health risk, also the problem that it is not stable in an alkaline environment above 70C-80C. Modern technology however makes it possible to make similar fabrics out of polymer, and specifically the engineering polymer Polyphenylene Sulfide (PPS). This polymer in itself shows chemical resistance in Potassium Hydroxide at 150C, where the conductivity, pressure resistance and gas separation is dependent on how the fabric is woven.
During the project, several experiments were performed with these fabrics.
Several grades of the nonvowen PPS fabric has during the project been procured and examined, and the most suitable of the grades was tested in the second generation electrolyzer system. The conclusion was however that for this system, the pores of the membrane was too open, as it allowed too high transport of the hydrogen and oxygen compartments. The result of this was that the control system had problems keeping equal the levels of electrolyte, and the balance of plant therefore became unstable.

3.1.3 Critical corrosion improvement

The purpose for improving corrosion resistance is twofold. The first and most intuitive is prevention of corrosion that damages the structural integrity of tubing and pressure vessels. However, besides this obvious issue, it was during laboratory testing determined that the presence of certain metallic ions in the electrolyte, resulted in these ions being deposited on the electrodes, with a following reduction in electrode efficiency. The primary culprits were Fe, in the case of carbon steel grades, and Cr for the corrosion resistant grades.

From laboratory experiments of a wide range of alloys, it showed that the content of Ni in the alloy was a good indicator of how well the alloy would resist the high temperature alkaline electrolyte.



The conclusion was that it took an alloy of at least 25% Ni, for corrosion resistance to become adequate for use in the electrolyzer, where higher Ni content would make the alloy increasingly more corrosion resistant.

However, one thing is to identify what alloys are suitable, and another thing is if it is feasible to manufacture the electrolyzer in exotic alloys. After a number of experiments and a good deal of research into what was technically available to an affordable price, the following design methodology where established.

- All fittings that are connected with threaded connection should be made from Monel alloy. Monel is a 70Ni/30Cu alloy, which is distinguished by being the only high Ni alloy, from what is commercially available that is easily machinable.
- Tubing should similarly be high Ni-alloys. Pure Ni tubing seems to be the cheapest option.

- The weight of pressure vessels makes them very costly to produce from Ni-alloys, so the method here was to coat the surface. For the coating process, the primary method is electroless nickel plating. The electroless method can be applied on almost all geometries, and are especially suited for concave geometries.

In the prototype machine, the machine was built with full corrosion protection on almost all parts that where in contact with electrolyte. The few exceptions were places which were not exposed directly to hot electrolyte.

During the time of testing the prototype, the machine have been regularly monitored to check if the corrosion protection have been holding up, following is a series of pictures taken to at a visual inspection after ~2 years of prototype operation. It should be noted that the prototype have in many regards been treated very rough, because of many assemblies/ disassembly of connections to facilitate the numerous tests. Some of the connection hold up to this better than others. A description of the individual images can be seen in the image captions.

Figure 2 – Lye inlet at the separator. The connection is a Teflon Face seal with a 1"BSPP swivel. The separator and its connections are Ni-coated carbon steel. On the outside the regular surface shows no sign of corrosion, while the on the threaded part some surface rust is present, as the coating on the thread is very vulnerable, especially when the swivel nut is tightened. On the inside however, there are significant differences. On the hydrogen side (bottom left), the face still retains its shine, indicating the Ni coating for the most part is intact. For the Oxygen side (Top and bottom right), the sealing face have been damages and delamination of the coating have occurred. The inside of the fitting have similarly lost its lustre, indicating possible damage to coating. Regardless of the damage to the sealing face, the connection is still leak free.

Figure 3 – Hydrogen outlet at the end flange. The white crystals in the picture are KOH crystals. Nearest the flange is seen an inserted Monel body. With the flange made from carbon steel. It is seen that some surface rust is present on the flange where the painting have been scraped off. The monel body is very resistant to corrosion, and still shine if wiped clean. One thing that should be noted is the slightly green color of the swivel and gland. These parts have been coated with electroless nickel where the slightly green color indicates some nickel is present in the KOH crystals. Meaning some nickel from the plating has been dissolved. There is however no indication that this corroded nickel is of a significant magnitude, as the electrolyte does not appear to become green in the same manner. (or take on any other strong color for that matter.) There is a slight blackening of the inside surface, and some sludge seen in the fitting. The subtle red tinge on the on the Picture on the Monel part is not rust from the Monel, as there is no Iron in the Monel alloy

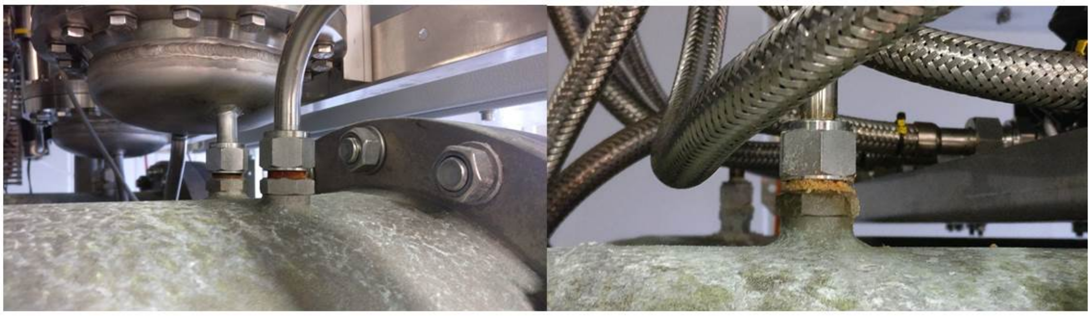


Figure 4 – In the picture is seen a compression fitting connection. Where the fitting has been coated with Ni. As seen the threaded part has surface rust. Meaning the tightening of the nut has most likely destroyed the Ni layered on the thread. The connection in the picture to the left is still leak tight, if not, there would be visible KOH crystals present. On the right is the same type fitting with a slight leakage.

Figure 5 – Connection between the level sensor and the level sensor tube. No outside visuals indicate any corrosion. However, this connection is the only one in the machine with a threaded seal connection, that is also coated with Ni, and further, it is also a 1” connection, making this seal one of the most problematic in the machine. Making the connection tight have proven to give some difficulty. However, the good news for this connection is that it is neither exposed directly to electrolyte or temperature. So corrosion in the thread is very slow.

Figure 6 A view of the springs on the stack. It should be noted that all parts seen are some grade of carbon steel, The black disc springs are phosphorized spring steel and the white disc springs are Zink galvanized with chromate treatment. As seen on the picture, a small amount of surface rust is present on some of the phosphated springs. For The chromated springs the electrolyte is very corrosive to the zinc, so for most springs discolored white areas can be seen, where the spring have been in contact with KOH. It should be noted though, that this discoloration is of very little significance to the integrity of the spring. As the spring will only begin to corrode once a significant portion of zinc has been completely corroded away. And even with the rugged treatment in the laboratory, none of the chromated disc springs show sign of corrosion in the steel beneath the plating.

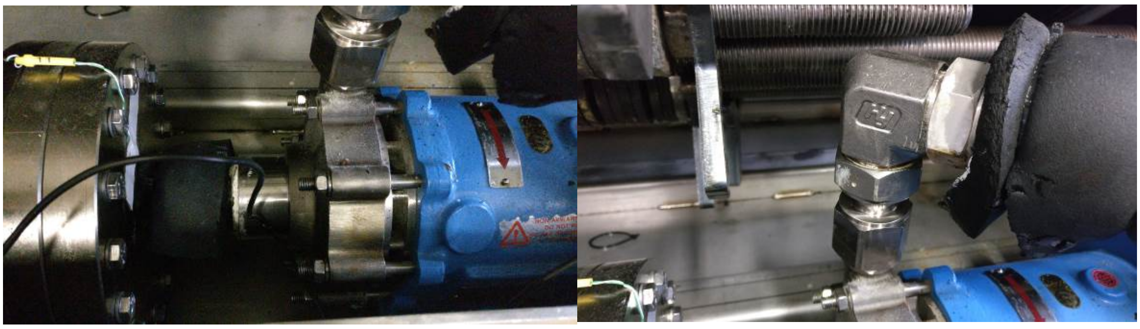


Figure 7 – On the left is the part of the heat exchanger. It should be observed that edges have been rounded to reduce impact damage to the Ni coating. On the right is the Hastelloy house and couple of the pump. While the motor is painted cast iron and shows minor corrosion in places where the painting has chipped, The Hastelloy have no visable corrosion. The fittings connected to the pump are Monel, and show no sign of corrosion either. The outgoing connection on the pump is a 1”MNPT in Hastelloy connected to a 1”FNPT Monel fitting. This fitting have proven to be quite problematic to get leak free, but is very tight once the seal is established.

Figure 8 – Inside of the separators is seen some sludge in the bottom while the bulk of the coating it is intact. Some slight attacks are seen near the welds of the ramp brackets. There are also a few points where slight damage has been done to the edges of the flange because of mechanical chipping of the Ni coating on the edges. To prevent this, there need to be a chamfer on all sharp edges. The separators where the first parts to be manufactured with the electroless Ni-coating, so the experiences here have helped us design the parts to be better suited for the coating process.

To conclude the section on corrosion protection, it can be said that not all measures was equally successful. The most successful solutions from a corrosion perspective are definitely the high alloy parts, As no signs of corrosion are seen on Monel, Hasteloy and Ni parts. However, these are as mentioned earlier, very expensive, they should only be used where absolutely necessary. Also important to note, is that even though the high alloy parts are protected chemically, these alloys are more vulnerable than ordinary steel when it comes to mechanical damage during assembly/disassembly.

On the other side is the corrosion protection through coating. It seems from the investigation, that the coating seems to hold up reasonably well, as long as it is regular surfaces. From a design perspective, small adjustments will be attempted on future iterations of the different components, to avoid sharp edges and other vulnerable geometry.

The most critical point however, is the Oxygen side inlet tube to the scrubber. This connection is distinguished by having also damage to a surface, which is not normally vulnerable to corrosion. The question remains therefore, if the problem can be solved by a more careful coating process or thicker layers. Or the Chemically deposited nickel has an inherent vulnerability to the chemical environment exacerbated by the mechanical stress on the component. For the immediate future, we will use thicker layers at vulnerable points.

3.1.4 Stack power density & rack capacity increased

An electrolyzer is a costly piece of equipment, and to reduce the relative acquisition costs, some thoughts have been put into developing the concept, with as high capacity as possible. Here there are 2 main axis of development.

The first one is to increase the overall capacity as much as possible. The balance of plant for an alkaline electrolyzer system, is more or less identical regardless of the size of the machine. So the obvious development line is to scale the system as large as possible, so that the relative cost of the balance of plant components become as small as possible. There are of cause limits to this exercise, because availability of standard process components in the correct sizing becomes a limiting factor. And if the system requires too many custom designed components, we will have a cost increase, and not a cost reduction.

The second axis of cost reduction is to increase the current density in the electrolyzer cell. Higher current density is what every electrolyzer system chases, regardless of technology. And for all cases, the increase in current density is enabled by having efficient electrodes, and sufficient internal flow homogeneity and flow rate, to avoid the occurrence of internal hot spots in the stack.

For the MW system it was decided to use zero-gap electrodes, with an activated surface to further increase the efficiency. It is worthy to note that one of the most costly parts of the machine is the stack, and one of the most costly parts of the stack is the electrodes. So it is not without consideration it was decided to go for a more efficient electrode design with a more costly and complicated geometry.

However, when we are interested in higher current density, the only feasible method, is to reduce the over potential of the cell at all levels of design. With the current technology we have been able to increase the current density of the stack to 400mA/cm^2, Where we believe the overall architecture of the machine should be able to accommodate up to 600mA/cm^2 with some modification, if satisfying electrode efficiencies can be achieved.

3.1.5 Cost Reduction of MW AEC technology

As it has been mentioned in other section of this report, reduction of the overall system price has been a goal of this project through the whole development process, where the aim is to achieve as low a price/capacity ratio as possible within the MW concept.

Breaking down the costs of the machine, we see that the stack cost is 35% of the overall price of the machine. The cost distribution of the stack can be seen In the diagram below.

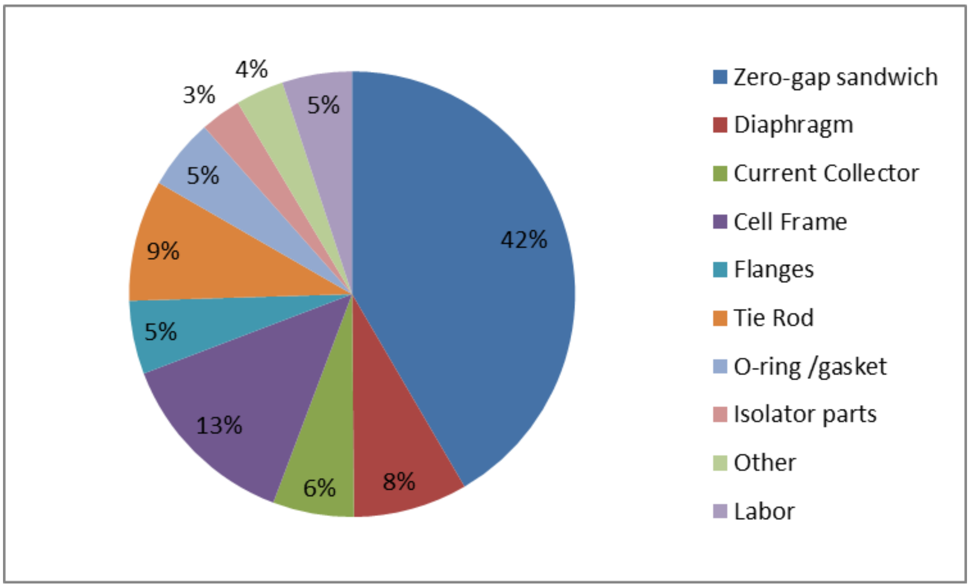


Figure 9 – Cost distribution in the Cell Stack.

As seen in the diagram, the greatest component cost in the stack is the price of Zero-gap electrode sandwich. And while this component is obviously the most expensive components, it should also be understood that the cost is acceptable because it is enabling the stack to operate at significantly higher current densities compared to electrodes without the Zero-gap geometry. And is actually expected that following the current line of development, the electrodes will be able to operate at current densities at up to 600mA/cm^2, and while it will require some changes to the design of the system, it will increasing the output of the stack do a great degree, without increasing the costs significantly.
It should be noted that the costs displayed are the actual costs for the stack prototype, and we therefore also expect some cost reduction on the electrodes as the manufacturing processes are optimized.
For the other components of the stack, we have during the development phase attempted to bring in small innovations to the design of the cell frame that reduce the cost wherever possible while still maintaining the desired functionality. And while we believe it will be possible to have cost reductions on future iterations of the stack, these reductions are expected to come from increased production volumes.

Calculating the full cost of the prototype machine and representing it as manufacturing cost per capacity, the overall cost is determined to be 3976€ per N/m^3 Hydrogen.
Taking the cost reductions that we believe are possible, when manufacturing a smaller series of ~10 units, we estimate a manufacturing cost per capacity of 3382€ per N/m^3 Hydrogen.

3.1.6 Prototype build and laboratory testing

The main result of the project has been the build of the prototype MW machine and the development of the laboratory as well as the testing. In other section it has been discussed in more detail about some of the specific challenges regarding alkaline electrolysis, but it this section we will look a bit more of the process of building the prototype machine itself.

The prototype build was started with the prior knowledge attained through building the previous generation of 2nd Generation Alkaline Electrolyzers.

The electrolyzer control system and auxiliary systems was developed in tandem with the development of the stack. To give an overview of the system, we can start with presenting the primary components an alkaline electrolyzer system.

- Separator - Separates electrolyte from gas.
- Scrubber – Prevents aerosolized electrolyte from escaping the system
- Differential Pressure Control – An elaborate system to ensure equal pressure on H2 and O2 side.
- Process Cooling – Cooling of electrolyte and Gas
- Deox – Purification of H2 by catalytically burning away residual O2
- Dryer – Water removal by Pressure and Temperature Swing Adsorption (PTSA)

Describing the development in broad terms, the first challenge was to make a bare minimum electrolyzer system that could operate under pressure.
For this very first iteration of the system a temporary separator and scrubber was designed and manufactured. The cooling problem was initially solved by integrating a cooling jacket on the separator. Level sensors, flow sensors and pumps were procured, mounted and connected with compression fittings. The control system was mocked up using solenoids valves, back pressure regulators mass flow controllers, temperature, pressure and gas sensors. A PLC system was used for controlling and data logging. And during this development, the construction of a more elaborate data logging infrastructure was begun.

All the procured components were mounted in a test rack assembled from square steel profiles, mounted on a sturdy drip pan. The advantage of this approach was that we could with relative ease modify the frame, to test different positions for the components.

Aside from the big main components mentioned, all valves, regulator and sensors where placed on the horizontal panels, in order to reduce footprint, but still be able to remove the panel in case of major maintenance.

After the intermediate electrolyzer stack was completed, the currently seen Electrolyzer module, as well as all its contents was developed. A great deal of the sensors, pumps, valves and the control system was moved from the first prototype into a freshly manufactured rack, which in time would become the fully scaled prototype. At this time, all the pressure vessels for a fully scaled system was designed manufactured, complete with corrosion protection for components with direct contact to electrolyte. From this point on, the system was in many ways complete. Our experience has been that the system from a balance of plant perspective became much more stable with the increased volumes of fluid. When the capacity of the electrolyzer stack was increased (from 12 - 60 Nm^3/h), we had some concerns that the system would become unstable. However, this turned out to be much lesser of an issue than expected.

Figure 10 - Cell frame sizes of the different stack generations, 2, 12 and 60 Nm^3/h

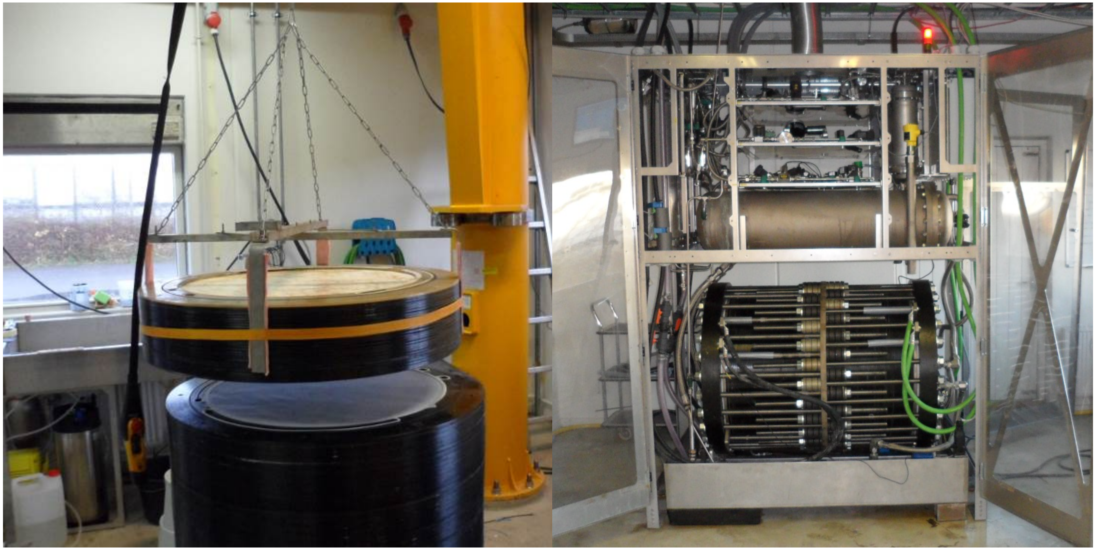


Figure 11 – Construction of the Cell Stack. And the full prototype in operation (The red light on the top of the machine indicates the system is powered and pressurized)

The fully scaled prototype has the overall system specifications

- Outside dimensions 1100 x 1800 x 2440 mm
- Rack and Stack can be moved by a standard forklift.
- Operational pressure: 35 bar
- Current Density: 400mA/cm^2
- Hydrogen Production: 60 Nm^3/h
- Power consumption ~4.5kWh/Nm^3

3.2 Development of novel HRS pre-cooling

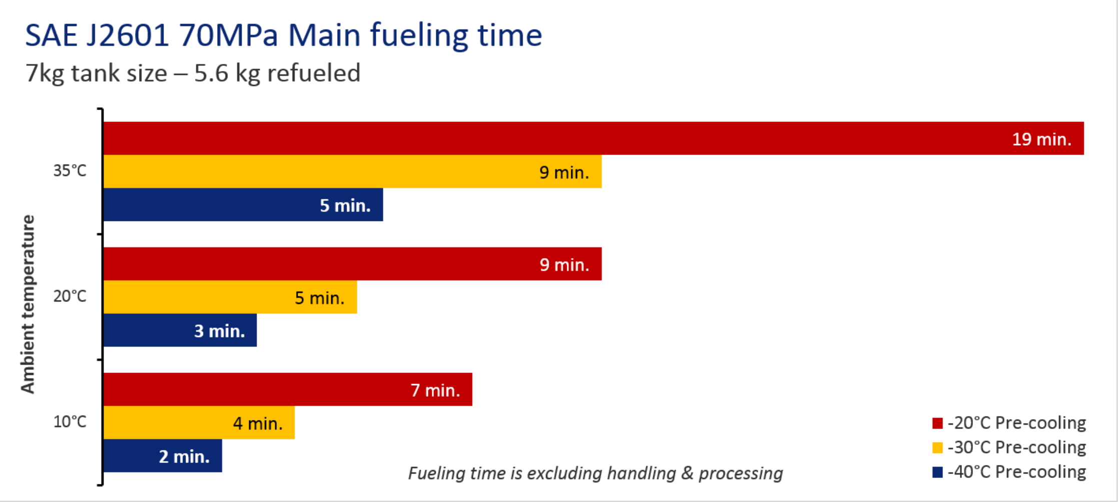
Development efforts on the HRS pre-cooling has included the following tasks:

- Assessment of hydrogen cooling energy need
- Hydrogen heat exchanger & buffer
- Dispenser cooling line set-up
- Cooling and heat exchanger skid
- Cooling system prototype constructions and test

3.2.1 Assessment of hydrogen cooling energy need

The purpose of the pre-cooling system is to enable a fast and safe refueling according to the SAE J2601. The 2014 revised standard allows for use of either -20°C, -30°C or -40°C (T20, T30, 40) pre-cooling of hydrogen at the nozzle during refueling – where the refueling time varies.

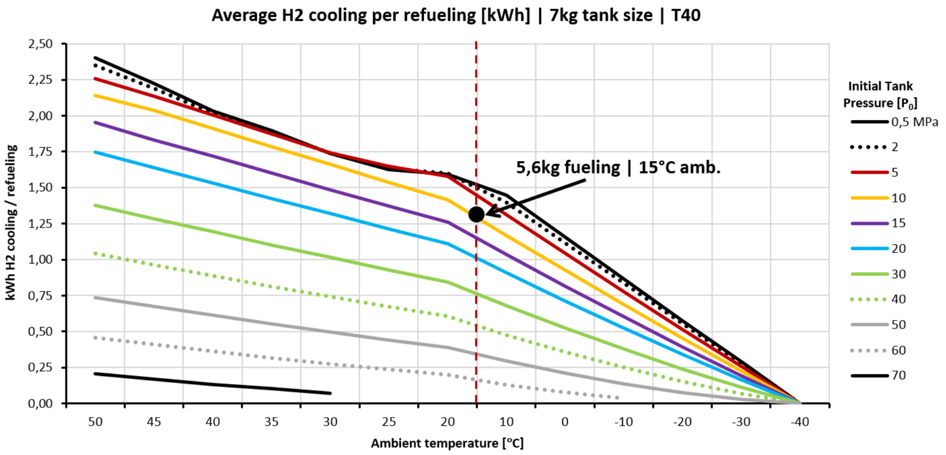
The motivation for a lower pre-cooling level is a faster fueling time, as illustrated below.



As can be seen from the figure only T40 pre-cooling ensures a 2-5 minutes fueling time in ambient conditions ranging from 10°C to 35°C. Pre-cooling at T30 enables between 4-9 minutes and T20 between 7-19 minutes fueling time.

The ambient temperature range (10°C to 35°C) reflects the most extreme refueling times. Below 10°C the refueling time is almost the same, whereas above 35°C it increases significantly, how-ever 35°C is extreme situations or geographically limited to few regions or periods of day.

The average cooling energy required to achieve 40°C during a fueling is linked to both the ambient temperature and the empty level (start pressure) of the vehicle tank when commencing fueling. A calculation of the theoretical average required fueling energy for a range of ambient and start pressures has been conducted – with results shown in graph below.



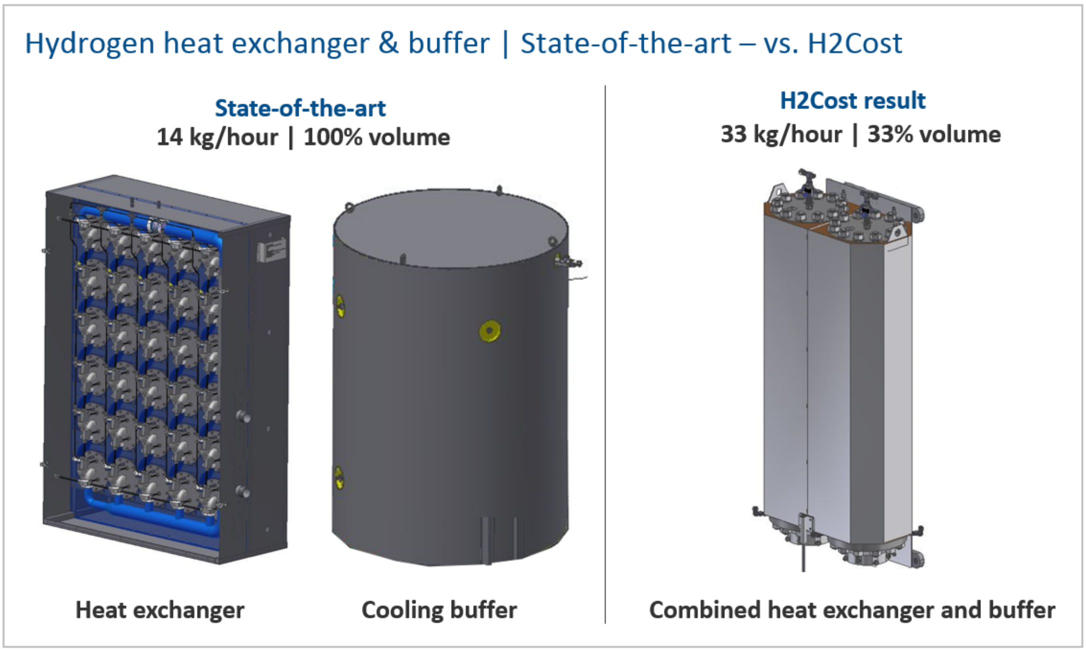
The figure shows the theoretical cooling need per fueling, meaning the “heat” that needs to be removed from the hydrogen in order to achieve T40 at the nozzle. At the standard fueling of 5,6kg at 15°C ambient this corresponds to ~1,3kWh.

In order to remove the “heat” from the hydrogen the cooling system will operate with a certain efficiency, meaning that the actual total energy consumption will be higher.

Simulations of the new cooling system with expected efficiencies showed that around 41kWh would be required to conduct a 1 hour fueling profile of 33kg (1,25kWh/kg). This was used as basis for the dimensioning of the cooling system and buffer.

3.2.2 Hydrogen heat exchanger & buffer

A new combined hydrogen heat exchanger and cooling buffer has been developed that reduces footprint volume to 1/3 and more than doubling the cooling capacity compared to state-of-the-art, as outlined in the figure below.



The former state-of-the-art cooling technology featured a heat exchanger (HEX) connected to a large cooling buffer (cooling media storage). This enabled cooling of 14kg of hydrogen per hour (peak). The system uses a liquid-to-gas cooling principle, where cooling media from the buffer is circulated through the HEX where it cools hydrogen pipe coils.

The aim within the project was to double the cooling capacity to 33kg/hour corresponding to the peak 1 hour fueling capacity. At the same time the footprint volume were to be reduced with at least 50% in order to allow for integration into the station module.

This required the development of a completely new heat exchanger with integrated cooling buffer. This involved the development of a new and patented gas-to-gas cooling principle. Instead the cooling gas is stored in the same compartment where the hydrogen pipe coils are placed, thus a combined HEX and cooling buffer.

The new cooling system consist of two compartments, each with a hydrogen coil and cooling gas but at different temperature levels. The first compartment reduces the hydrogen temperature from ambient, and the remainder compartment further down to below -40°C. This is a significant reduction compared to state-of-the-art, that had 30 separate hydrogen pipe coils and compartments for the cooling media.

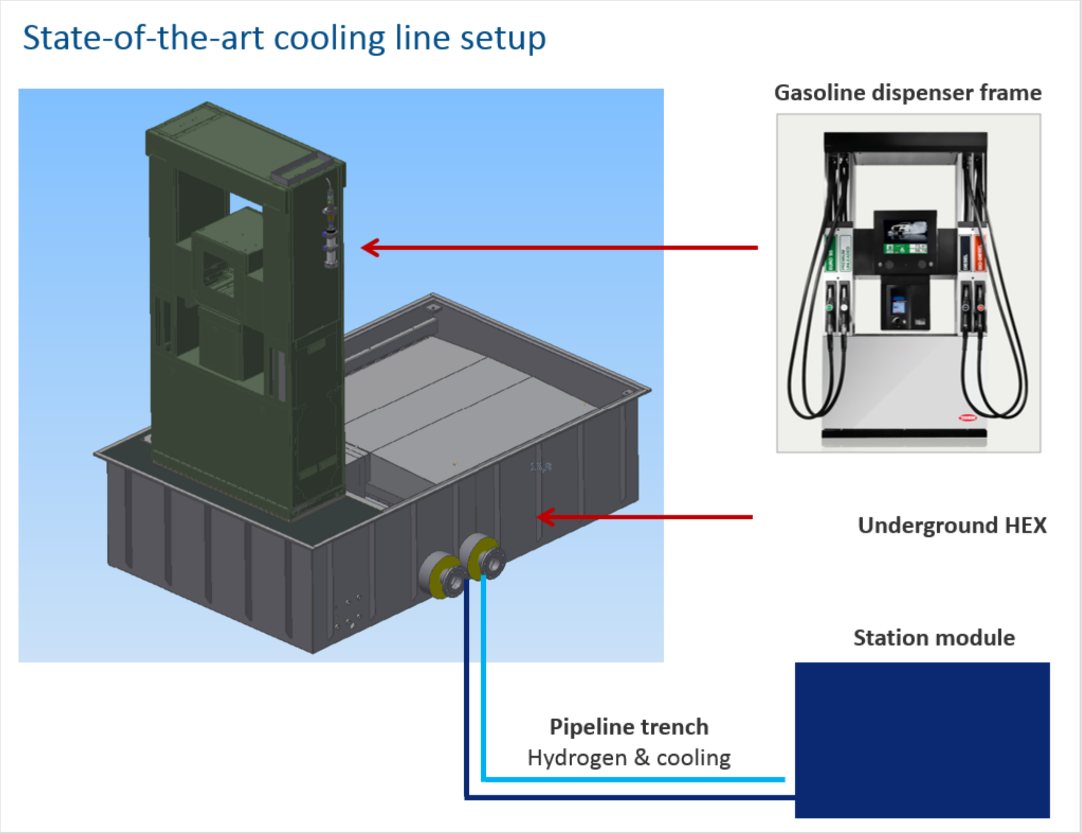
Besides reducing footprint it also contributes greatly to cost reduction through use of less materials and more simple assembly.

The combination of the HEX and cooling buffer has reduced the total volume footprint to 1/3, compared to state-of-the-art, whilst at the same time doubling the hourly cooling capacity to 33kg.

The developed HEX and cooling buffer is unique in the sense that the approach has never been applied to hydrogen cooling. A patent application has therefore been submitted on the technology.

3.2.3 Dispenser cooling line set-up

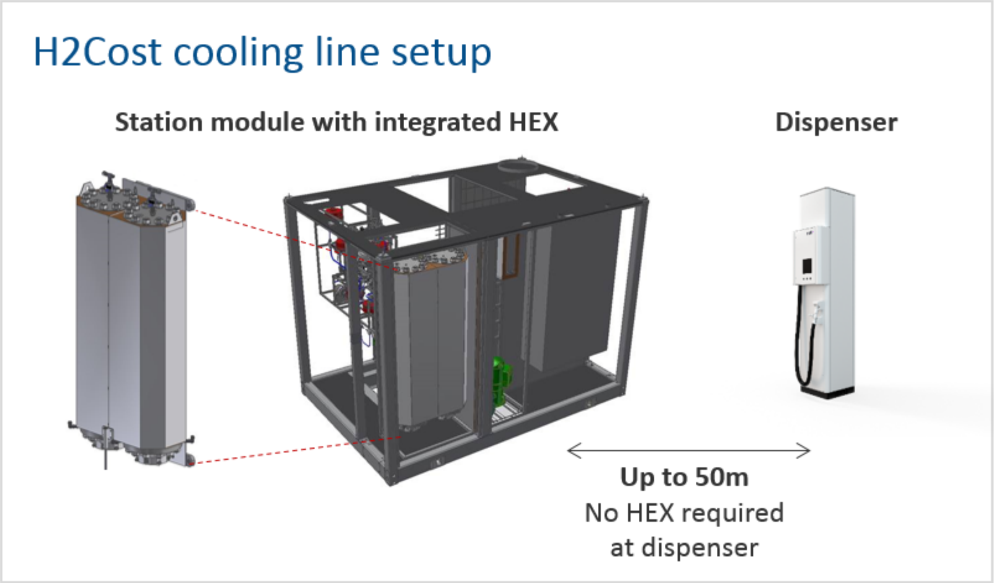
The scope within the project were to address several issues experienced with the existing state-of-the-art cooling line setup, which is shown in the figure below.



The limited cooling capacity of the state-of-the-art system, required the Heat Exchanger (HEX) to be located as close as possible to the dispenser (point of cooling). Given the large size of the HEX, this needs to be located beneath the dispenser in a pit box. This complicates and increases cost of civil works significantly. Also service access to the HEX in the pit box is not optimal.

The liquid-to-gas cooling principle used previously also required the liquid cooling media to be pumped all the way to from the station module to the HEX at the dispenser. Due to the viscosity of the cooling liquid this required large pumps to be placed in the station module and thus also caused significant energy consumption for the circulation of the cooling liquid. This complex setup was required when distances between the dispenser and station module exceed 5 meters, which in many cases are required when integrating hydrogen at conventional forecourt gasoline stations.

The new developed gas-to-gas cooling principle in H2Cost has a significantly higher peak cooling capacity, which has enabled a great simplification of the cooling line setup as outlined in the figure below.



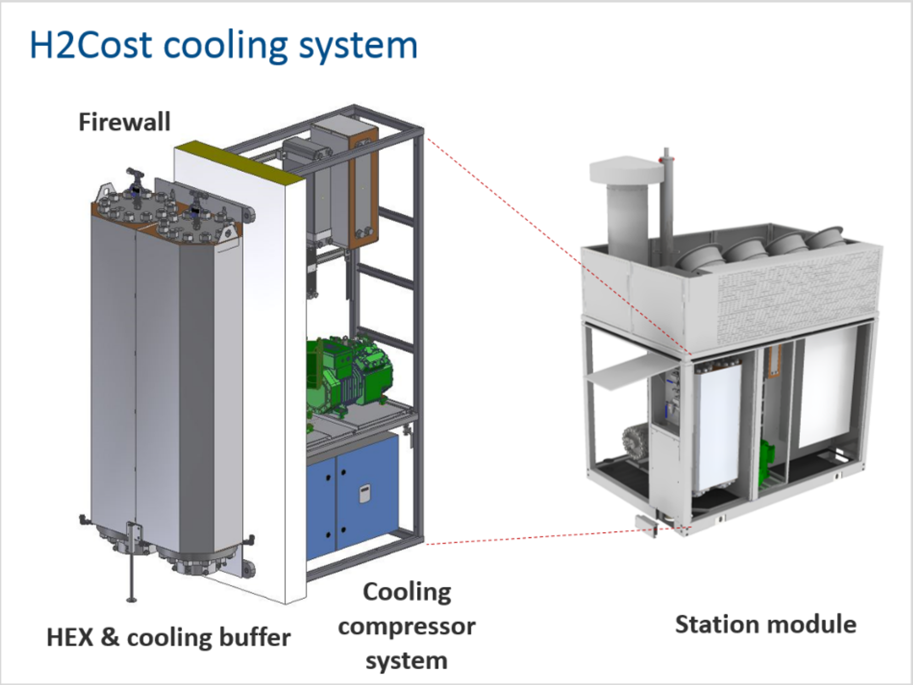
For H2Cost, the combined HEX and cooling buffer is placed inside the station module, and not beneath the dispenser as with previous state-of-the-art. As the HEX and cooling buffer in combination provides a very high peak cooling capacity, cooling at the dispenser is not required. Instead the gas cooling media is only circulated out to the dispenser in order to keep the pipeline and dispenser components cold.

The change from a liquid cooling media to a gas cooling media, greatly reduces the efforts required for the circulation out to the dispenser. Also the cooling gas media as is noncorrosive which enables a very simple pipeline construction, compared to the liquid media used previously, which required extensive corrosion protection efforts.

At the dispenser no pit box is required, instead the dispenser is placed on top of the pipeline trench and connected directly to the pipeline. In addition the dispenser can be placed up to 50 meters fromt the station module, compared to only 5m today.

3.2.4 Cooling & heat exchanger skid

Based on the cooling system dimensioning and Heat Exchanger design (HEX) a complete cooling system skid has been developed, intended for integration into the a new hydrogen fueling station module as outlined in the figure below.



The cooling system is separated into two submodules, which are separated by a firewall.

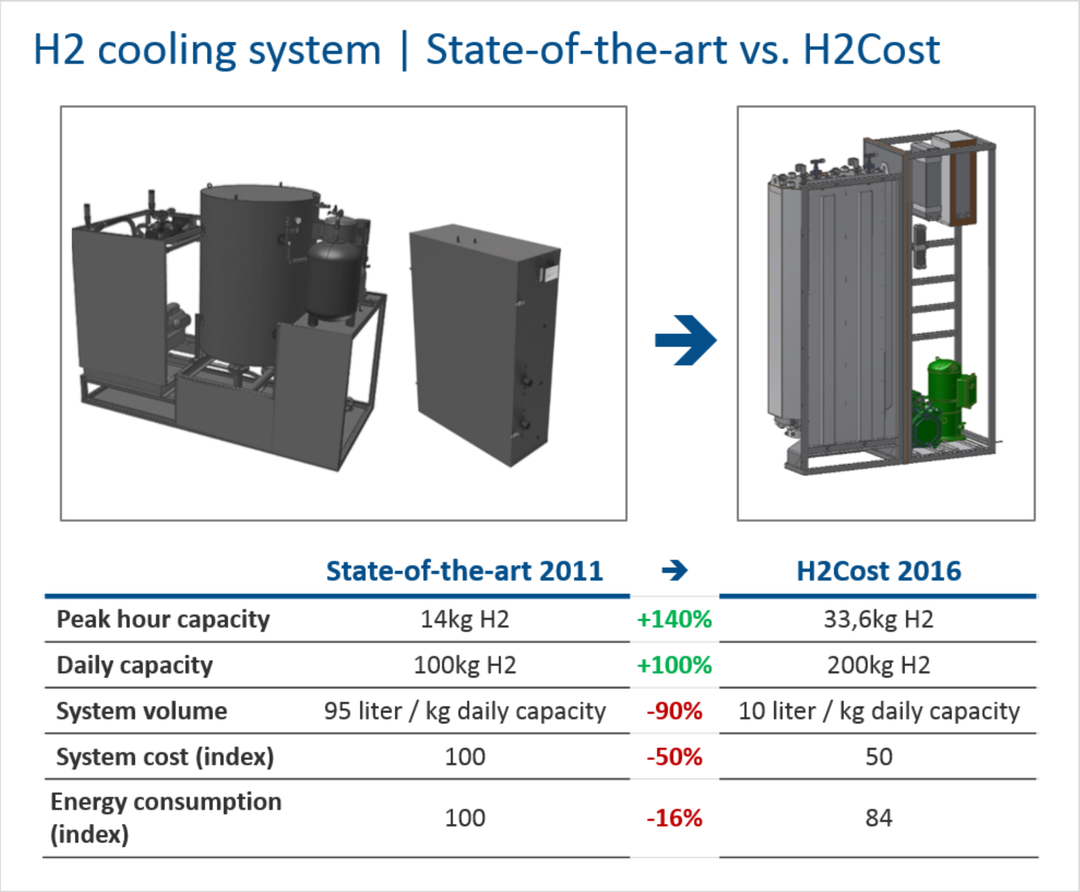
The combined HEX and cooling buffer is placed in hydrogen compartment of the station module, whereas the cooling compressor system is placed in the electronics compartment. Each submodule is designed with specified interfaces so that assembly of both submodules into the station module is fully defined and documented with drawings of pipeline interfaces.

The separation of the HEX from the cooling compressor with a firewall, ensures a safe separation of hydrogen and electronic components. The station module consists of two compartments, where the hydrogen compartment has the required ventilation and equipment to cope with potential hydrogen leakages, whereas the electronics compartment is fully sealed from the hydrogen.

The HEX is placed vertically with service access to both sections of the HEX. Pipeline connections are placed at the top and bottom of the HEX and designed so that servicing is possible from “outside-in” of the station module.

The cooling system is also accessible from the side, with all components placed horizontally (tower structure) to allow for outside-in service assess.

The new complete H2Cost cooling system has resulted in significant progress compared to the previous state-of-the-art cooling system as outlined in the figure below. The achievement has been validated by prototype tests, see later section.



H2 cooling system | State-of-the-art vs. H2Cost

	State-of-the-art 2011	**➔**	**H2Cost 2016**
Peak hour capacity	14kg H2	**+140%**	33,6kg H2
Daily capacity	100kg H2	**+100%**	200kg H2
System volume	95 liter / kg daily capacity	**-90%**	10 liter / kg daily capacity
System cost (index)	100	**-50%**	50
Energy consumption (index)	100	**-16%**	84

The peak hourly hydrogen cooling capacity has been increased with 140% from 14kg/hour to 33,6kg/hour, meeting the target. The daily cooling capacity is doubled from 100kg to 200kg, also meeting the target.

System volume of the entire system has been reduced with 90%, superseding the target of a 50% reduction. This is mainly enabled by the combining of the HEX and cooling buffer. Also the shift from liquid-to-gas and to gas-to-gas cooling principle has enables a simplification of the cooling compressor system, e.g. avoiding large pumps for the liquid cooling media.

The smaller and much simpler cooling system also enables a cost reduction of 50%.

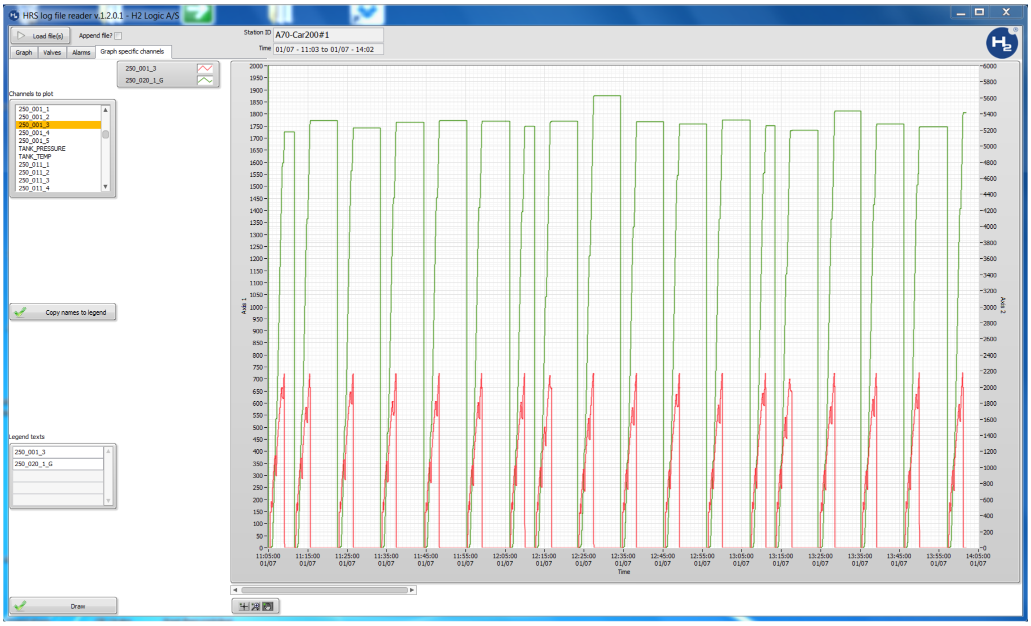
Energy consumption for the hydrogen cooling has been reduced with 16%,. This is mainly due to the shift from liquid-to-gas and to gas-to-gas cooling principle as well as the combining of the HEX and cooling buffer. Overall the new H2Cost cooling system has achieved all the initial development targets.

3.2.5 Cooling system prototype constructions and test

A complete cooling system prototype has been constructed and tested in a complete hydrogen fueling station, as shown in picture below.

Besides of the cooling system inside the station module, this also included a prototype pipeline of 50 meters connected to a dispenser. This enabled test of the ability to achieve -40°C at the nozzle despite of the long distance.

Besides of various single fueling tests to validate reaching of targets, the main test was a 3 hour consecutive rush-hour fueling test of total 100kg, which was successfully achieved (see test log below). This is the world’s first announced achieving of 100kg hydrogen fueling in 3 hours, and is the most extreme operation condition that the cooling system may experience in real operation.


HRS log file reader v.1.2.0.1 - H2 Logic A/S

Station ID A70-Car200#1

Time 01/07 - 11:03 to 01/07 - 14:02

3.3 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 a new electrolyser strategy in 2016.

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

6. Utilization of project results

The participating companies has successfully ensured continued R&D and commercialisation activities of the technologies developed in the H2Cost project.

6.1 Continued R&D and Commercialisation of MW electrolyser

The goal for GreenHydrogen.dk has always been to use the lessons learned from the projects to move one step closer to a fully commercial product. And with the production of the fully scaled prototype, we are close to the milestone of manufacturing early series machines that are able to be operated at external locations.

Over and above having met the project objectives for improved price/performance for the alkaline HyProvide MW scale electrolyser, we have compared the improved performance and specifications with official information from competitors on their electrolyser specifications for efficiency, price and performance. This shows us, that on efficiency and price/performance HyProvide is today the leading alkaline electrolyser available in the market. Combined with the limited footprint, output volume and dynamic production capability, HyProvide is ideally suited for on-site hydrogen production for hydrogen fuelling stations. It facilitates a considerable growth in fuelling requirements in the coming years, as the fleet of hydrogen powered cars is growing. The market "norm"/recommendation for on-site hydrogen generation for hydrogen fuelling stations is currently 100 kg $H_{2/}$day – the HyProvide product delivers 120 kg H_2/day.

One of the important objectives for the Hyprovide product is also to bring down costs for electrolysers by standardising and delivering a complete, pre-tested unit ready to be connected and powered up on the customers' site. This way cost of installation and commissioning – and the technical risks in any delivery - can be reduced dramatically. This makes HyProvide ideal for a partner strategy, and GreenHydrogen expects to expand our reach and build a strong market position by entering partnerships with Value Adding Resellers/system integrators and industry specialists.

In autumn 2016 we initiated the commercialisation of the MW scale HyProvide - primarily by addressing specific, potential partners in the automotive market/hydrogen fuelling station market as one of our high priority market segments. Our contacts with potential partners - including NEL Hydrogen - have confirmed that HyProvide is highly competitive and offers the expected advantages over competition on technology, price/performance. Dialogs are ongoing, and we have a number of fixed price proposals delivered for specific, joint projects with different partners. This market is fast growing and becoming a commercial market, driven primarily by strategic interests of key industry players in the automotive and hydrogen industry, though publicly funded projects still play a major role in some markets.

Another priority market is onsite hydrogen for industry purposes, and we have initiated dialog with partners in the industry and found, that hydrogen consuming industries – as well as their hydrogen suppliers - are very interested in the new type of high performing electrolysers that offer a much lover threshold for a positive business case/ROI in having onsite hydrogen generation replacing deliveries of hydrogen in cylinders. This opens a new market to our electrolysers – a market that is purely commercial and independent of public funding.

Whereas the automotive market provides opportunities for a number of single electrolyser unit installations, the on-site industry as well as the long term market for power–to-gas provides opportunities for multi-unit installations of HyProvide – realistically 1-2 MW short term and up to 5 MW or above longer term. We will deliver the first HyProvide unit for the first power-to-gas installation in NGF Nature Energy's biogas plant Heden in Q2/3 2017. This will be a major showcase for HyProvide in a daily, live operation and an important reference customer where we can bring our partners and customers.

We consider our market activities so far as "test marketing". We have acquired more insight, knowledge and understanding of the market opportunities for HyProvide and how to position HyProvide in the market - and furthermore we have established our first commercial partnerships. Based on this we see a big potential for HyProvide A60 in commercial as well as more strategic markets.

We will continue our focused commercial activities and once the CE approval for HyProvide is obtained we will increase our market efforts. HyProvide will be launched officially as a commercial product at the Hannover Industry Fair in April 2017. Based on the experience and input we have gathered in the last 8 months of commercial activities we are in the process of defining a new go-to-market strategy and business plan.

Based on partner input and specific project activities we expect that our sales target will be +10 HyProvide units sold in the next 24 months - mainly for automotive/hydrogen fuelling stations and onsite industry.

6.2 Continued R&D and Commercialisation of hydrogen pre-cooling

The H2Cost results on the hydrogen pre-cooling system has successfully been commercialised by Nel Hydrogen (outside of the project).

1 patent application has been submitted on the cooling technology, and following product maturation conducted. This has enabled launch of a new generation hydrogen fuelling station product (H2Station®) with improved capacity and reduced costs, which is currently being marketed in Europe and USA.

Nel Hydrogen has already secured sales and installation of the new H2Station® in Europe, and was recently awarded an order of 120 million DKK from Shell for stations to be installed in California[1]. Below is shown a picture of two new H2Station® undergoing final tests in Herning, Denmark before shipments to customers.

To continue the efforts on the cooling system, the new H2Cost-2 project was initiated in late 2016, supported by EUDP. The aim is to achieve yet a doubling of fuelling capacity and a 44% cost reduction for the cooling system.

Since commencing of the H2Cost 10 more employees have joined Nel Hydrogen, and with an outlook of a 10% increase per year going forward, thanks to the results of H2Cost. Also Nel Hydrogen targets to grow annual sales with 30% on the new H2Station®, made possible by the hydrogen cooling technology developed in H2Cost. The majority of the annual sales are expected to be export outside of Denmark.

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[1] https://fuelcellsworks.com/news/nel-hydrogen-solutions-awarded-frame-contract-for-multiple-hydrogen-fueling-stations-in-california-b/

7. Project conclusion and perspective

The H2Cost project has secured key results on two areas that enables a continued use by the partners and the Danish hydrogen sector.

7.1 MW electrolyser

Balance of Plant - Concept for regulating pressure & liquid levels

A new control system based on a combination of proportional regulator valves and motorized back pressure valves, have enabled the system to operate in a stable manner at a wide range of pressure and loads.

Balance of Plant - Tests of new prototype membrane

A series of different membranes have been tested during the development of the full scaled cell stack. It was not possible to test the in-house developed composite diaphragm in the full scaled system because of manufacturing difficulties. During the progression of the project, the existing Zirfon diaphragm has been improved with regards to operating temperature, making it currently the best diaphragm option for traditional alkaline cell stacks.

Critical corrosion improvement

The most successful solutions from a corrosion perspective are to use high Ni-alloy parts, as no signs of corrosion are seen on Monel, Hasteloy and Ni parts in the electrolyzer. However, these alloys are also very expensive, and should therefore only be used where absolutely necessary.
For components such as pressure vessels, These can be coated by Electroless Nickel, paying special attention to vulnerable geometries, where thicker layers of Ni should be applied.

Stack power density & rack capacity increased

The system was from its inception designed to optimize the rack footprint in such a way that the rack had a size that was manageable with a standard fork lift, but at the same time had the largest production capacity possible, also making the relative cost of balance of plant components as small as possible.
With the current technology we have been able to increase the current density of the stack to 400mA/cm^2, Where we believe the overall architecture of the machine should be able to accommodate up to 600mA/cm^2 with some modification.

Cost Reduction of MW AEC technology

The production costs in respects to capacity of the electrolyzer system has been reduced from 9300€ per Nm^3/h Hydrogen in the 2nd Generation AEC to a cost of 3976€ per N/m^3 Hydrogen for the MW AEC. These cost reductions has been possible by increasing the overall capacity, while still focusing on using standardized components in the system, as well as improvements on electrode design and catalytic surfaces. We believe further cost reductions are possible when manufacturing a smaller series of ~10 units. For this volume we estimate a manufacturing cost per capacity of 3382€ per N/m^3 Hydrogen.

Prototype build and laboratory testing

The main result of the project has been the build of the prototype MW machine and the development of the laboratory as well as the testing.

The fully scaled prototype has the overall system specifications

- Outside dimensions 1100 x 1800 x 2440 mm
- Rack and Stack can be moved by a standard forklift.
- Operational pressure: 35 bar
- Current Density: 400mA/cm^2
- Hydrogen Production: 60 Nm^3/h
- Power consumption ~4.5kWh/Nm^3

7.2 Hydrogen pre-cooling

As part of the H2Cost project Nel Hydrogen has successfully managed to develop and test a new hydrogen pre-cooling system with substantial advances compared to the previous state-of-the-art, prior to the project:

- 140% increase of instant fueling capacity – from 14 kg to 33,6 kg
- 100% increase of daily fueling capacity – from 100 to 200kg
- 90% reduction of physical system volume
- 16% reduction in energy consumption
- Enabling placement of dispenser at long distance from cooling system
- 50% cost reduction of pre-cooling system cost

1 patent application has been submitted on the cooling technology and following the project, Nel Hydrogen has conducted product maturing activities of the hydrogen pre-cooling technology, which has enabled integration into the latest hydrogen fueling station product (H2Station®) currently being marketed for Europe and USA.

Nel Hydrogen has already secured sales and installation of the new H2Station® in Europe, and was recently awarded an order of 120 million DKK from Shell for stations to be installed in California.

To continue the efforts on the cooling system, the new H2Cost-2 project was initiated in late 2016, supported by EUDP. The aim is to achieve yet a doubling of fuelling capacity and a 44% cost reduction for the cooling system.

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