H2Cost-2

Cost reduction of alkaline electrolysers
and hydrogen refueling stations

PROJECT END REPORT
MAY 2019

Project No.: 64016-0016

Figure 1: GreenHydrogen A-series electrolyzer

SUPPORTED BY:

1. Project details

Project title	H2Cost-2 – Cost reduction of alkaline electrolysers and hydrogen refueling stations
Project identification	64016-0016
Name of the programme which has funded the project	EUDP 2016
Project managing company/institution (name and address)	GreenHydrogen.dk ApS Platinvej 29B 6000 Kolding Denmark
Project partners	Nel Hydrogen A/S Gramstrup Køling A/S DTU Mechanical Engineering
CVR (central business register)	Greenhydrogen.dk ApS | 30548701 Nel Hydrogen A/S | 26933048 Gramstrup Køling A/S | 70112310 DTU Mechanical Engineering | 30060946
Date for submission (of report)	May 2019

2. Short description of project objective and results

English version (600-800 characters)

The goal of the HyCost-2 project has been to continue cost reduction, and increase of technical performance of the GreenHydrogen.dk ApS MW Electrolyzer system and Precooling technology for Hydrogen Refuelling Stations (HRS) from Nel Hydrogen A/S. GreenHydrogen has developed a hydrogen quality system for the electrolyser and achieved a cost reduction of 33% achieved through increase of stack performance. Nel Hydrogen has achieved a three times capacity scaling of hydrogen pre-cooling technology which has helped to reduce pre-cooling equipment costs with 55%, and enabled a following effort on demonstration and commercialisation of the technology.

Dansk version (600-800 characters)

Målet med HyCost-2 projected har været at forsætte bestræbelserne på at reducere pris 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. Greenhydrogen har udviklet et nyt system til måling af brintkvalitet, og forbedret ydeevne af elektrolysecellen, hvilket har muliggjort en kostreduktion på 33%. Nel Hydrogen har tredoblet kapaciteten på ny brintkølingsteknologi og reduceret udstyrspris med 55%, hvilket har muliggjort fortsatte demonstrations og kommercialiseringsaktiviteter på teknologien.

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3. Executive summary

The H2Cost-2 project has continued efforts on reducing cost and increasing technical performance of MW alkaline electrolyser technology (AEC) from GreenHydrogen.dk ApS and pre-cooling technology for Hydrogen Refueling Stations from Nel Hydrogen A/S. H2Cost-2 is a continuation of the successful H2Cost-1 project supported by EUDP in 2013.

3.1 Cost reduction of MW Alkaline Electrolyser

With the H2Cost-2 project GreenHydrogen and DTU have conducted the necessary developments in order to make possible a seamless integration of the company's hydrogen producing electrolysis technology with hydrogen refuelling stations servicing commercial proton exchange membrane (PEM) fuel cell vehicles. Particularly two areas of development have been addressed: (i) evaluation and monitoring of the quality of the hydrogen produced by the electrolyser, and (ii) further cost reductions, which are necessary in order to meet the targets for the early markets HRS. The main achievements of the project with respect to the electrolysis technology are:

- Development of a monitoring system that verifies that the quality of the hydrogen produced by the electrolyser complies with the SAE J 2719 standard[1], which provides background information and a hydrogen fuel quality standard for commercial PEM fuel cell vehicles.
- A reduction of the acquisition cost of the electrolyser unit (cost per production capacity, EUR/Nm3/h) by 33%, achieved by an increase of the stack nominal operating current density from 400mA/cm2 to 600mA/cm2.

The developed H2Cost-2 technology has been tested and validated in the laboratory with GreenHydrogen's A-series alkaline electrolyser, which is a high-efficiency, low-cost and modular electrolyser unit (shown in Figure1). Before the H2Cost-2 project the system had a hydrogen production capacity of 60 Nm3/h. With the technology developed in the H2Cost-2 project the electrolyser now has a production capacity of 90 Nm3/h. Originally, the electrolyser was developed during the project "HyProvide Large-Scale Alkaline Electrolyser (MW)" (EUDP 11-II, 64011-0105) during the years 2011 to 2015.

[1] http://standards.sae.org/j2719_201511

Figure 1. Prototype of a 60 Nm3/h alkaline electrolyser unit developed within the project "HyPro-vide Large-Scale Alkaline Electrolyser (MW)" during the years 2011 to 2015.

3.2 Capacity scaling of novel HRS pre-cooling

As part of the H2Cost-2 project Nel Hydrogen has successfully managed to develop and achieve a scaling of hydrogen pre-cooling system with substantial advances compared to the previous state-of-the-art, prior to the project:

- +200% increase of hourly fueling capacity – from 33,6 kg to 100kg
- +200% increase of daily fueling capacity – from 200 to 600kg
- -71% reduction of physical system volume
- -20 reduction in energy consumption
- Enabling fueling of two LDVs at the same time, or one HDV
- -55% cost reduction of pre-cooling system cost

Nel Hydrogen has conducted product maturing activities of the hydrogen pre-cooling technology, which has enabled integration into a new H2Station® hydrogen fueling station product designed for HDV fueling.

Nel Hydrogen has already secured sales and installation of the multiple new H2Station® for HDV fueling, e.g. NEL has received multiple orders from Shell on more than 85 million DKK for HDV stations to be installed in California, which will utilize the cooling system from H2Cost-2.

To further utilize the cooling system from H2Cost-2 for LDVs, EUDP funding has been secured for a new demonstration project, HyScale, which is to design a HRS for fueling of two LDVs at the same time. The project was commenced in 2018 and will elapse until 2020.

Since commencing of the H2Cost-2 project in 2016 the number of average employed persons (as stated in annual final report) at NEL in Denmark has grown from 50 to 85 (2018). At the time of this report issue, NEL employees 105 persons, with an expected conservative outlook of a 10% increase per year going forward, thanks to among others the results of H2Cost-2. With regards to annual revenue of NEL in Denmark this has grown from 44 million DKK in 2016 to 177 million DKK in 2018 with an expected conservative outlook of a 30% increase per year going forward, thanks to among others the results of H2Cost-2. Almost 100% of the revenue generated by NEL in Denmark is export to Europe, USA and Korea.

4. Project objectives

The objective of the H2Cost-2 project has been to continue cost reduction and increase in 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). H2Cost-2 is a continuation of the successful H2Cost-1 project supported by EUDP in 2013.

4.1 Electrolyser project objectives

The overall objective is to make possible a seamless integration of the electrolyser unit with HRS servicing commercial PEM fuel cell vehicles. More specifically:

Monitoring of gas quality

With the H2Cost-2 project GH wishes to conduct the necessary developments to make possible evaluation and monitoring of the gas quality of the hydrogen produced by GH's 60 Nm^3/h electrolyser unit. With such monitoring system it can be verified that the quality of the hydrogen meets the specifications that are necessary for proper and safe operation of the fuel cell in commercial vehicles. In particular it must be ensured that the gas complies with the SAE J 2719 standard, which provides background information and a hydrogen fuel quality standard for commercial PEM fuel cell vehicles.

Cost reduction

Further cost reductions on the electrolyser technology are necessary in order to meet the target for the early markets HRS with on-site production of green hydrogen. With the H2Cost-2 project, in collaboration with the Department of Mechanical Engineering at the Technical University of Denmark, GH wishes to conduct developments in order to further reduce the cost of the large-scale alkaline electrolysis technology. Based on the experience gained in the H2Cost-1 (EUDP 64013-0585) and HyProvide (EUDP 11-II, 64011-0105) projects, there is one route to cost reduction that is particularly viable and attractive. Significant cost reductions can be obtained if the hydrogen production capacity (Nm3/h) of the electrolyser unit is further increased without increasing the acquisition cost of the unit correspondingly. Such an increase of the production capacity requires modifications and optimisations of the electrolyser unit, however doing this in a well thought way any changes in cost will be negligible.

An objective is to test and validate the developed H2Cost-2 technology (gas monitoring system and increased current density) in the laboratory with GreenHydrogen's A-series alkaline electrolyser.

4.2 Hydrogen pre-cooling project objectives

For NEL in collaboration with Gramstrup Køling A/S (GK) the aim of H2Cost-2 has been to achieve a significant increase in capacity and reduction in cost of hydrogen pre-cooling technology for Hydrogen Refueling Stations (HRS). The increased capacity is to enable fast fueling of both multiple Light Duty Vehicles (LDV) at the same time, and also fueling of Heavy Duty Vehicles (HDV)

The H2Cost-2 objectives and targets for the hydrogen pre-cooling activities were:

- 100% increase of capacity from 200kg/day to 400kg/day and 33,6kg/1 hour to 67,2kg/1 hour and enable simultaneously fueling from two hoses – same capacity modularity as gasoline
- 50% reduction of cooling system volume – from 10 liter to 5 liter / kg H2 daily capacity
- 44% reduction of cooling system cost – from €900/kg daily H2 to >€500/kg H2
- 20% reduction in energy consumption – from 1,25kWh/kg to <1kWh/kg dispensed
- 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.

5.1 Cost reduction of MW Alkaline Electrolyser

Development efforts on the alkaline electrolyzer have included the following tasks:

- Development of a hydrogen quality monitoring system
- Acquisition cost reduction by 33% by increased current density

5.1.1 Development of a hydrogen quality monitoring system

Impurity Limits
ISO 14687-2 table 1 and SAE J2719 table 1 both contains a list of impurity concentration limits that hydrogen fuel must fulfill in order for the hydrogen to be used as fuel in mobile PEM fuel cells. The tables are nearly identical and the specific values are probably developed in collaboration.
The only minor difference is that ISO 14687-2 do not specify a maximum size for particulate impurities, but will later in the document under clause B.11 mention that it is important that you consider particle size requirements from other components in other parts of the overall gas system.

Impurities present in hydrogen produced in an alkaline electrolyzer
Impurities that will be present in conjunction with production of hydrogen by means of an alkaline electrolyzer will be significantly different (and overall less problematic), than the impurities that will occur in hydrogen produces by means of methane-reformation.

During hydrogen production from alkaline water electrolysis, there are a number of substances present, other than Hydrogen, which if the product stream is not processed correctly, risk being present in the final product Gas. To get a quick overview, we will go through the main process of hydrogen production, to identify any potential sources of impurities.

In alkaline electrolysis, the electrolyte used is a 30%weight Potassium Hydroxide (KOH). This gives rise to the impurities of Water and Aerosol/Particulate KOH.

In every cell of the electrolyzer, there is a diaphragm separating the Hydrogen and Oxygen half cells. This membrane is selected for its properties for high ionic conductivity, and a low degree of gas permeation. However, nothing in this world is perfect, and for any Alkaline electrolyzer system, there will always be a minor crossover by hydrogen moving to the oxygen side, and oxygen moving to the hydrogen side. This crossover is roughly around 1%, and will be lower or higher depending on operating conditions. This crossover gives rise to Oxygen impurities in the Product stream.

During maintenance where the system is opened, there will be a nitrogen purge of the system to prevent any explosive atmospheres from occurring in the machine after it has been exposed to atmospheric oxygen. Once hydrogen production is started again, there will be nitrogen present in the system that will need to be flushed from the system. If the nitrogen is not flushed sufficiently with hydrogen this can give rise to nitrogen impurities.

Because of the deoxo catalysts present in the system, there is a theoretical possibility for formation of Ammonia (NH3), it should be noted that though the equilibrium is in favor of NH3 formation at low pressure and temperature, the reaction rate practically non-existing.

The hydrogen gas processing system in an alkaline electrolyzer, contains a reactor containing palladium coated alumina (0.3%Pd, on Al2O3 pellets), for the purpose of recombining the crossover O2 with H2, removing O2 impurities down to <1ppm O2, creating water (H2O) in the process. Because the catalyst pellets in practice is made from porous ceramics, there is a risk that over time the catalyst support will decrepitate, and particles of Pd and Al2O3 will become impurities in the gas stream.

The last process of the hydrogen system is a temperature and pressure swing adsorption system, using Zeolite 13X. The synthetic zeolite molecular sieve have the chemical composition of roughly 1xNa2O 1xAl2O3 2.8xSiO2 X*H2O.
This process removes water from the stream down to <1 ppm. However, for the same reasons as the deoxo catalyst, the molecular sieve is also vulnerable to decrepitation in its lifetime, risking particulate impurities in the form of Na2O, Al2O3 and SiO2.

In the entire process of the alkaline electrolyzer, there are no direct sources of carbons/hydrocarbons. If one is to speculate of a potential source of such, it would be the presence of decrepitating gasket materials. This problem is simply solved by using appropriate gasket materials in the system. Generally Speaking PTFE and its relatives are outstanding for use in an alkaline electrolyzer system. And where the mechanical properties of PTFE are not desired, EPDM for the electrolyte and EPM for increased temperature resistance are materials that have proven to be very stable in the alkaline electrolyzer system.

Compiled list of potential impurities
Gasses:

- Water
- Oxygen
- Nitrogen

Particles:

- KOH
- Al_2O_3
- Pd
- Na_2O
- SiO_2

Figure 3:This cylinder was filled to 30 bars with hydrogen coming directly from the electrolyzer. Hereafter the cylinder was shipped to third party professional laboratory for detailed quality analysis

An exhaustive gas analysis should not be relevant to perform continuously, it is recommended that the complete analysis is only performed prior to commissioning and at service intervals (A suggestion will be in connection with yearly or bi-yearly maintenance.)

Water

The water content can be determined using one of the following instruments and procedures.

a) A dew point analyzer in which the temperature of a viewed surface is measured at the time moisture first begins to form.

b) An electrostatic capacity type moisture meter.

c) An FTIR with suitable cell path length, scan wavelength and detector.

d) A GC/MS and jet pulse injection

e) A vibrating quartz analyzer

Oxygen

The oxygen content can be determined using one of the following instruments.

a) A Galvanic cell type oxygen analyzer

b) A GC/MS and jet pulse injection

c) A Gas Chromatograph (GC) with Thermal Conductivity Detector (TCD)

Nitrogen

The (argon) and nitrogen contents can be determined using the following instruments.

a) A Gas Chromatograph with a Thermal Conductivity Detector (TCD), or a pulsed discharge helium ionization detector.

b) GC/MS and jet pulse injection

Particulates

The concentration of particulates can be determined using the following procedure. The particles are sampled with a filter as described in ISO 14687-2 Clause 6.3 and are weighed. The concentration of particulates is calculated from the weight and the total volume of sample hydrogen flowed through the filter.

Methods for purification

Gasses:

- Water – TSA/PSA Dryer
- Oxygen – Deox Reactor
- Nitrogen – Sufficient Flushing on startup

Particles:

- Crystalline KOH
- Al_2O_3
- Pd
- Na_2O
- SiO_2

Common for all particles is they should be caught in a filter. Determining what filter size should be used is ambiguous in ISO 14687-2, while the J2719 sets a particulate size limit of 10µm.

The method for detection of particulates is to use a filter and weigh the particulate mass accumulated over time. Swagelok produces T-type filter with a pore size of 7µm, which seems a reasonable solution for avoiding particulates, by placing the filter right before the distribution nozzle. Swagelok nr.: SS-12TF-MM-7.
The filter can easily be exchanges for another pore size if it is necessary.

Laboratory Gas Analysis
We can roughly separate gas analysis into two categories. The first category is analysis methods that are suitable for a laboratory, where a sample is taken from a site, transported to a laboratory, and analyzed in detail.
The methods that are suited for laboratory analysis are primarily Gas Chromatography with Mass Spectrometer and Gas Chromatography with Thermal conductivity detector. Common for these methods is that they break down the gas, and analyze each constituent. These methods are very suitable if you have a gas sample with many species.

On site detection
The second category of gas analysis is gas analysis that can be performed on site. These methods of analysis are more suited for determining the gas concentration of a certain gas species within a narrow scope. Different technologies will be better suited than others, depending on the measurement windows and precision required. As noted in ISO 14687-2 Clause 7.1, Alternative analytic methods are acceptable, if their performances, including safety of use, are equivalent to those of the (in the standard) listed methods.

Conclusion
Recommended measurement setup for gas quality control in hydrogen production units supplying gas for the mobile PEM fuel cells (ISO 14687-2):

Water
Electrostatic capacity type moisture meter.
Green Hydrogen have had previous success with moisture meters from Vaisala (CS Instruments) and and Shaw Meters.
The market has a good availability of products that can measure very fine dew points, as it is used in many applications in the general gas industry. A number of dew point meters were tested and evaluated in the H2Cost-2 project. The most suitable one was identified. Measurements show that the water content of the hydrogen from GH's electrolyser complies with the relevant standards (ISO 14687-2 and SAE J2719).

Oxygen
Galvanic cell type: Servomex DF-310e. Green Hydrogen have bad experience with this component, as the galvanic cell seems to be poisoned very quickly from an undetermined source. KOH contamination should be ruled out, partly because of the sensor is placed far downstream, but most importantly is that the electrolyte in the

galvanic cell is a strong KOH solution, where trace amounts of KOH would not change this concentration to any significant degree. And any KOH, be it carried by aerosol or particulate, would diluted electrolyte very rapidly.

To prevent particulates in the gas, it is recommended to use a water lock for scrubbing the gas and/or a particulate filter. The electrode in a galvanic measurement cell is very vulnerable to poisoning from particulates (particles from catalyst and catalyst support in the Dryer/Deox reactors).

Oxygen Luminescence quenching: Visipro DO. An alternative method for detecting oxygen in water and gaseous medium is to use an oxygen luminescence quenching sensor. This type of sensor uses an optical principle to determine the fraction of oxygen present. This sensor type is based on exiting a luminophore, which in a vacuum or any background gas would consequently emit photons. However, due properties of oxygen, any oxygen molecules present will absorb the excitation energy, and will thereby prevent the fluorescent emission of photons. The reduction in luminescence detected can thereby be correlated to the concentration of oxygen

The method can be employed in 100% oxygen down to 4ppb, but sensors vary depending on the desired range of measurement. It should be noted that there is a wear on the luminophore material, as well as higher oxygen levels increase the rate of wear. (It is still left to be proven if this will have a noticeable effect service intervals)

The great advantages of this method, is that the measurement is independent of flow rate and tolerate particulate and gas impurities much better. And while the calibration depends on humidity, since the sensor was developed for oxygen measurement in water, the sensor works across all ranges of humidity. It should be noted that the sensor will most likely be vulnerable to any corrosive substances, as this will break down the luminophore.

A variety of oxygen luminescence quenching sensors were tested and evaluated in the H2Cost-2 project. The most suitable one was identified. Measurements show that the oxygen content of the hydrogen from GH's electrolyser complies with the relevant standards (ISO 14687-2 and SAE J2719).

Figure 4: Gas quality sensor being tested and evaluated with the electrolyser in GreenHydropgen's laboratory.

Nitrogen

No continuous measurement. Guidelines for purge times should be established for the series of units before the series is commissioned. The testing methods used for Nitrogen and other inert gasses require equipment only suitable for gas analysis lab. The electrolyzer is purged with Nitrogen after long term shutdowns or when maintenance requires it.

Particulates

No continuous measurement. A filter of sufficiently small pore size should be installed at the very end of the production line before the output nozzle. The recommended filter pore size is 10µm or less. (7µm is a common Swagelok filter size)

On a number of occasions during the H2Cost-2 project hydrogen samples was taken from GH's alkaline electrolyzer system. These samples were sent to a state-of-the-art professional laboratory for analysis. The samples were analyzed for:

- Water
- Total hydrocarbons
- Oxygen
- Carbon dioxide
- Carbon monoxide

The test results showed that the hydrogen from GH's electrolyser complies with the relevant standards (ISO 14687-2 and SAE J2719).

5.1.2 Development of a hydrogen quality monitoring system

With the H2Cost-2 project GreenHydrogen has developed a new product with at reduced acquisition cost. A comparison between the old product and the new "H2Cost-2" product is summarized in the following table:

	Start	Goal
Hydrogen production (Nm3/h)	60	90
Current density (mA/cm2)	400	600
Stack efficiency (% HHV)	85.0%	82.0%
System efficiency (% HHV)	76.5%	73.5%
System cost (DKK/Nm3/h)	31,000	20,000
Foot print (m)	1.8×1.1×2.3	Unchanged
Pressure (barg)	35	Unchanged
Response time (s)	<1	Unchanged
Dynamic range (%)	25 - 100	16 - 100

As can be seen from the table the system cost (DKK/Nm3/h) is reduced by 33% from 31,000 DKK/Nm3/h to 20,000 DKK/Nm3/h. This cost reduction is achieved by increasing the current density from 400 mA/cm2 to 600 mA/cm2. The reduced acquisition cost (capex) comes at the expense of a reduced system efficiency. New product: 73.5%. Old product: 76.5%. An increased current density will always give rise to a reduced efficiency, due to increased losses in the electrochemical cells.

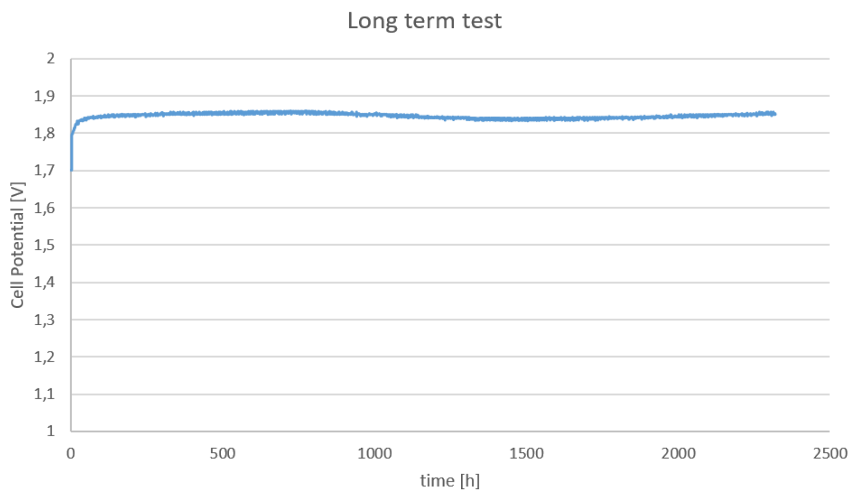


Figure 5: Longtermtest of NiCoS electrod at 600 mA/cm2

The stability of the hydrogen and oxygen evolving electrodes under increased current density has been evaluated during the H2Cost-2 project. No change in degradation rate was observed compared to operation at 400 mA/cm2.

Furthermore, the electrolyser cell stack has been thoroughly tested in order to investigate the effects of the increased amount of gas that is produced due to the increased current density. Test results have shown that the electrolyser stack is capable of operation at 600 mA/cm2.

Finally, with in the H2-Cost2 project the electrolyser balance-of-plant (BOP) has been tested for its ability to handle the increased amount of gas. In particular, the system for regulating pressures and liquid levels was tested and optimized for the higher production. Based on these test it was evident that some components in the BOP needed to be changed to other models. With these changes it was demonstrated that the system can operate with a gas production of 90 Nm3/h.

Figure 6:Each of these three ac/dc converters is able to deliver up to 600A DC for the electrolysis stack. The H2Cost-2 project required addition of the third converter in order to operate the stack at 600 mA/cm2.

5.2 Capacity scaling of novel HRS pre-cooling

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

- Specification for global usability
- Development of Cooling Compressor module
- Development of Heat Exchanger Module
- Development of dispenser pipeline
- Cooling system prototype design and construction

5.2.1 Specification for global usability

The HRS pre-cooling system developed in the former H2Cost project was only designed for use in Europe. Since then the markets outside Europe, in particular in USA and Korea have undergone substantial growth, in terms of deployment of both HRSs and supporting Fuel Cell Electric Vehicles (FCEV). Also NEL have expanded sales to these markets, thus requiring that HRS products and technology in general are developed for global use.

A detailed specification for the HRS pre-cooling was therefore developed at the beginning of the project – see example in figure 3.2.1.1.

Initially the intent was only to focus on Europe and USA – but as the Korean market have evolved rapidly, requirements for this market has also been taken into consideration.

Besides detailed specification on legal and standard requirements across the markets, a detailed analysis of the actual market need in terms of hydrogen capacity was also conducted.

Dual-Hose Pre-cooling System - Specification for Global Usability - (D3.1 H2Cost-2)

A. Cooling Capacity

A.1	Cooling capacity	Specification	Type	Requirement level
A1.1	Cooling capacity allocation	12 hours: 2x200kg (allocated on two indpendent fueli Hour 1: 2 x20kg (rush-hour) Hour 2: 2x16kg Hour 3: 2x16kg Hour 4: 2x16kg Hour 5: 2x16kg Hour 6: 2x16kg Hour 7: 2x16kg Hour 8: 2x16kg Hour 9: 2x16kg Hour 10: 2x20 (rush-hour) Hour 11: 2x16kg Hour 12: 2x16kg	Performance	MUST

B. Operational Environment

B.1	EUROPE	Specification	Type	Requirement level
B.1.1	Maximum *"Operation temperature"* (where 8 kg/hour is possible)	35°C	Performance	MUST
		40°C	Feature	NICE-TO
B.1.3	Maximum *"Safe temperature"* (that equipment can cope with)	45°C or possibly higher (depending on risk assesment)	Performance	MUST
B.1.4	*"Performance ambient temperature"* (2x200kg in 12 hours)	20°C	Performance	MUST

B.1	USA (California)	Specification	Type	Requirement level
B.1.1	Maximum *"Operation temperature"* (where 8 kg/hour is possible)	45°C	Performance	MUST
		50°C	Feature	NICE-TO
B.1.3	Maximum *"Safe temperature"* (that equipment can cope with)	50°C or possibly higher (depending on risk assesment)	Performance	MUST
B.1.4	*"Performance ambient temperature"* (2x200kg in 12 hours)	30°C	Performance	MUST

C. Dispenser pipeline

C.1	Dispenser pipeline	Specification	Type	Requirement level
C.1.1	Minimum to Maximum distance between cooling system and dispens	1-50m	Performance	MUST

D. Cooling module footprint

F.1	Cooling module footprint	Specification	Type	Requirement level
F.1.1	Cooling module footprint	Same as today - must stay inside existing Station Module	Performance	MUST

E. Approvals

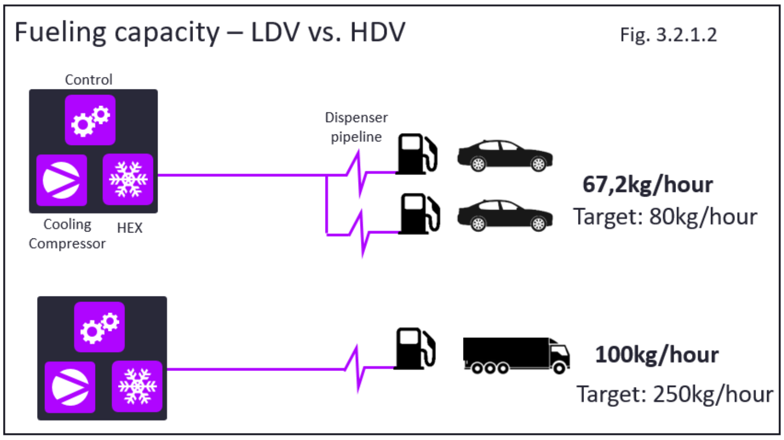
E.1	Approvals	Specification	Type	Requirement level
E.1.1	USA	UL listed as part of Station Module	Performance	MUST
E.1.2	Europe	CE marked as part of Station Module	Performance	MUST

F. Target cost price

F.1		Specification	Type	Requirement level
F.1.1	Cooling module cost	Max. cost increase is 1,5 x present cooling system (single hose)	Performance	MUST

Fig 3.2.1.1 – Specification for global usability

Initially the target for H2Cost-2 was to achieve a pre-cooling capacity of up to 67,2kg/hour and 400kg per day. This would enable serving of two Light Duty Vehicle (LDV) dispensers at the same time. However feedback from in particular car manufacturers showed a need for even more fueling capacity, not only for LDVs but in particular also for Heavy Duty Vehicles (HDVs) such as trucks – see figure 3.2.1.2.



On LDVs the average tank size is continuously increasing in order gain longer driving range. This also increases the average fueling from approximately 4kg/fill to 5kg/fill. The maximum hourly capacity on one dispenser is approximately 8 fuelings – this is primarily constrained by the available time (8 fuelings of 5 minutes + handling time). With an average fueling of 5 kg this results in an hourly load on 80kg allocated on two dispensers.

Commercialization efforts on HDVs has picked up speed during the project execution and here the initial need is 100kg/hour on one dispenser, with a target of 250kg/hour. HDVs have tank sizes ranging from 30kg and up to currently 85kg and fueling time of 10-20 minutes. The 250kg per hour will allow for full time utilization of the dispenser with 10 minutes fueling. However fueling components that allows the flow required for 10 minutes (e.g. nozzle and vehicle receptacle) does not yet exist. Instead fueling is typically slower and less vehicles served every hour – reducing the initial market need to 100kg/hour.

Given these changes in market need towards greater capacity, it was decided to adjust the H2Cost-2 capacity target from 67,2kg/hour to 100kg/hour. This would allow for serving LDVs with a higher average kg/fill whilst also addressing the initial HDV market. Future R&D activities would then have to address the ultimate target of 250kg/hour.

5.2.2 Development of Cooling Compressor module

A new Cooling Compressor module (CC) has been developed as part of the project. Aim has been to substantially increase capacity without having a substantial increase in compressor size – and also to optimize energy consumption.

The previous CC developed in H2Cost-1 did had a simple on/off control system, thus whenever there was a cooling need, the compressor would ramp up to full capacity – regardless of the actual cooling need. Also the compressor could only go to the rated capacity and e.g. over-clocking for shorter periods to gain higher peak capacity was not possible

A new control system has been developed that features a frequency controlled motor for the cooling compressor. This enables variable speed operation depending on the required cooling capacity. Also it allows for over-clocking of the compressor to achieve high peak capacities for a shorter period.

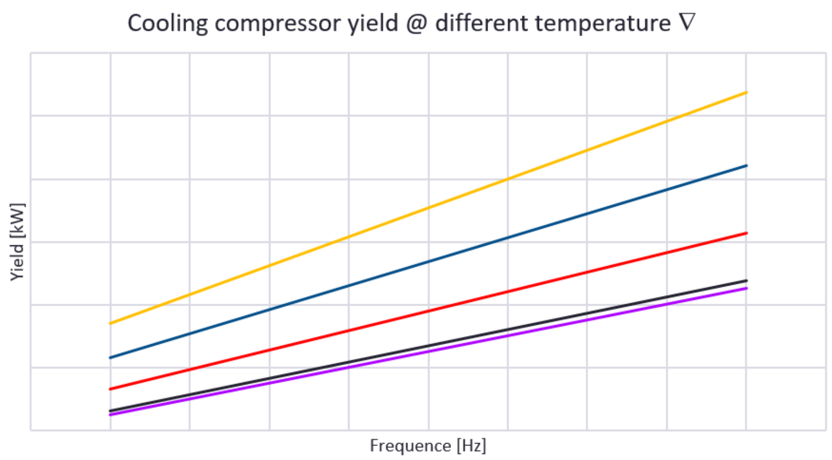


Figure 3.2.2.1

As can be seen in figure 3.2.2.1 varying the frequency provides a wide range in capacity (yield kW). The capacity can approximately be doubled compared to the lowest operation point by varying the frequency. The figure shows the yield gain depending on the temperature difference (delta between ambient temperature and targeted cooling temperature).

Typical operation of an HRS are similar to gasoline, with different loads during the day as illustrated in figure 3.2.2.2. During late evening and night the hourly load is limited to 1 or few fuelings, whereas during late afternoon it will peak with 80kg per hour on two dispensers.

With the frequency control, the cooling compressor can adjust the capacity to fit the exact hourly need. Generally the lower cooling capacity, the higher Coefficient Of Performance (COP) can be achieved and thus lower energy consumption.

The optimization of capacity for each hour will overall reduce the total energy consumed during one day, and reduce the average kWh/kg dispensed.

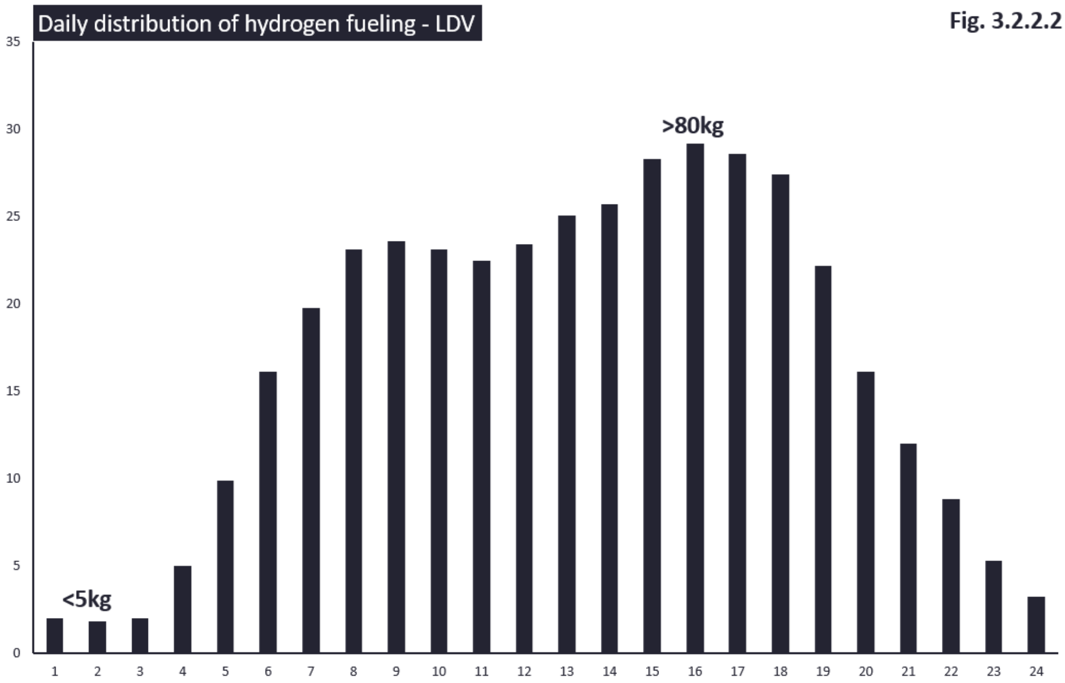


Fig. 3.2.2.2

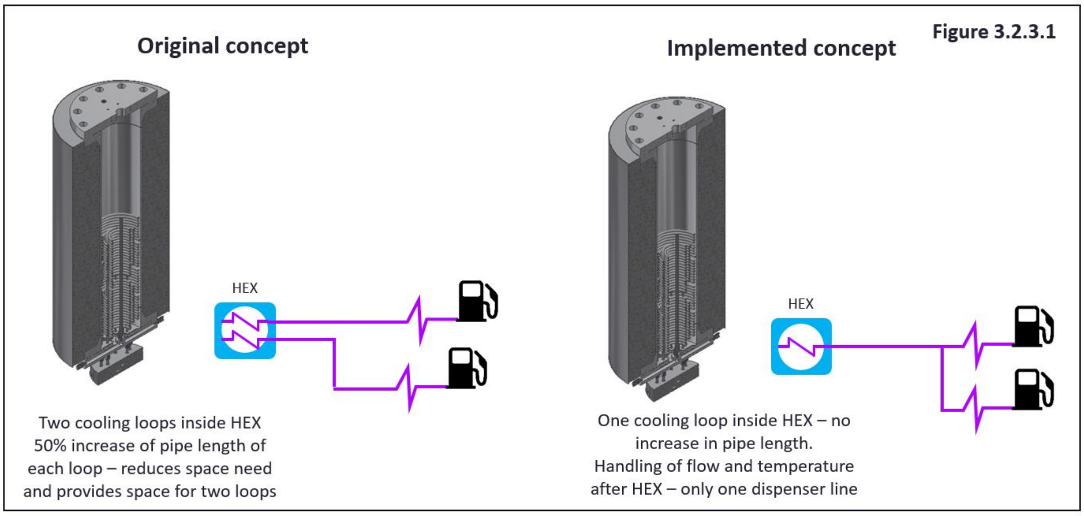
To accommodate the higher target capacity of 100kg/hour (compared to the original target of 67,2kg/hour) a new cooling compressor was also selected and designed into the system. The compressor has slightly more capacity, but still with the majority of the capacity increase is achieved via the frequency control. The new compressor has the same footprint as the older and smaller compressor.

Based on the experience from H2Cost-1, a new oil management system was also designed to improve reliability of the cooling system.

5.2.3 Development of Heat Exchanger Module

A new Heat Exchanger module (HEX) has been developed in the project. Aim has been to enable serving of two dispensers at the same time.

The original concept envisaged before project start was to increase the pipe length of the cooling loop with 50%, which would halve the number of pipes needed. Overall this would create more room inside the HEX for a second cooling loop for the second dispenser – see figure 3.2.3.1.



Besides having two cooling loops the concept also required two dispenser pipelines.

During the project a new concept was however developed, with only one cooling loop. The pipeline length have been maintained and the extra cooling capacity is instead provided by the compressor (see previous section). A cost-benefit analysis was made on either making the cooling loop longer vs. more compressor capacity. And it showed that compressor capacity was generally more cost effective, in particular when taking into consideration HDV fueling.

Previously when fueling only one LDV the average cooling need was low and the HEX provided the peak cooling capacity needed during fueling. But when moving to two LDV fuelings at the same time, or one large HDV fueling – the average cooling capacity increases and gets closer to the peak. This means that the HEX capacity are to be increased substantially - and here it was found more cost effective to increase the compressor capacity instead.

The new concept was also made possible because of a new sub-component that handles temperature and flow after the HEX. This way only one cooling loop is needed, and this one support both dispensers. Hydrogen is then transferred to the dispenser island in one pipe, and then the hydrogen flow is split to each dispenser at the island.

Overall the developed concept provides a cheaper HEX as only one cooling loop is needed. Also it has enabled a 20% reduction in the physical volume of the HEX it-self. Also extra costs for an additional dispenser pipe is avoided.

5.2.4 Development of dispenser pipeline

A new dispenser pipeline has been developed in the project, with the aim to opti-mize in particular the insulation and heat transfer, compared to the dispenser pipe-line developed in H2Cost-1 – see figure 3.2.4.1.

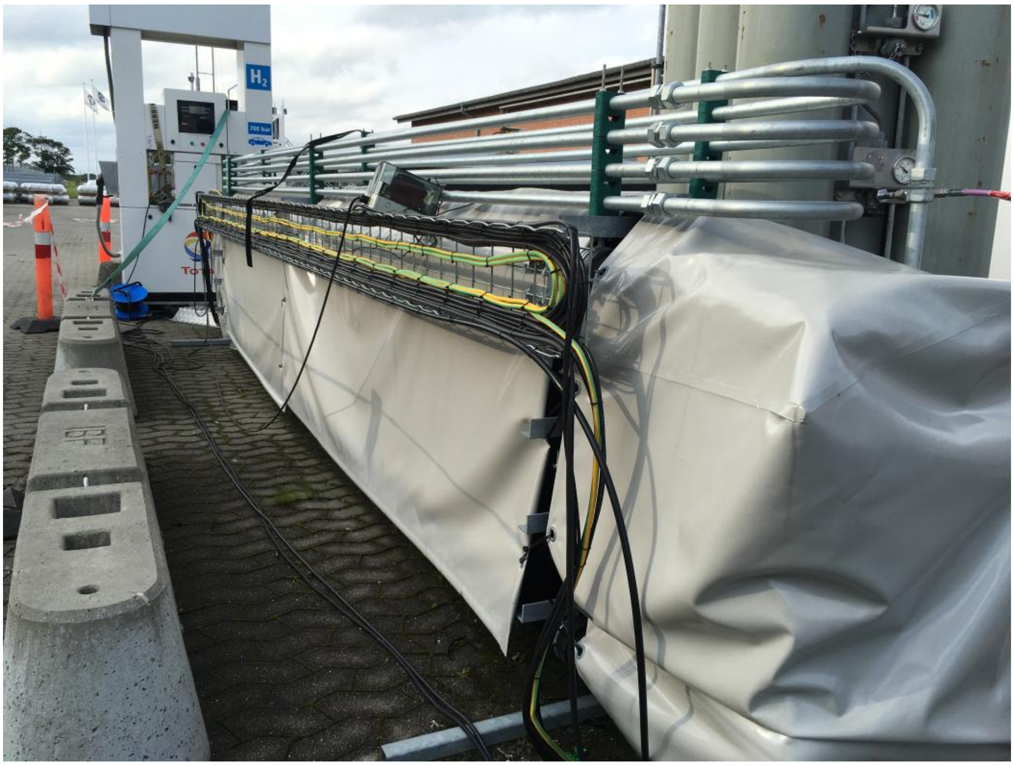


Figure 3.2.4.1 – Old dispenser pipeline design from H2Cost-1

The old dispenser pipeline consisted of a hydrogen line and two cooling lines, but with manual bundling of the pipes and wrapping of insulation. Besides more labor required during manufacturing, both the heat transfer between the cooling and hydrogen lines as well as the insulation was not optimal.

A new pipeline design has therefore been developed in the project as outlined in figure 3.2.4.2.

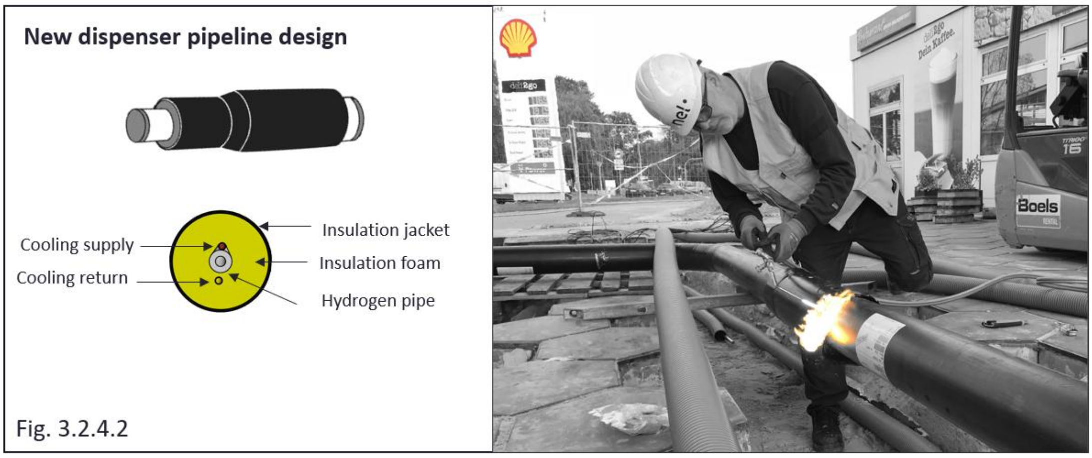


Fig. 3.2.4.2

The design utilizes existing pipe insulation technology used in district heating pipes, consisting of an insulation foam with a solid plastic wrapping.

The cooling supply line is wrapped onto the hydrogen line with an metallic tape to allow for optimal heat transfer. The cooling return line is placed with a distance to both the cooling supply line and hydrogen pipe, to avoid heat transfer.

Then afterwards the insulation foam is applied to the three pipes ending with the plastic wrapping. The manufacturing process is the same as for district heating pipe, with the only different that the heating pipe is replaced by the three pipes (2 x cooling and 1 x hydrogen).

The district heating pipe design is a well-proven technology from decades of use, thus achieving a long lifetime of the insulation. Due to the low temperatures of the hydrogen pipeline, ice-build-up is a general challenges, which happens if there are cracks in the insulation allowing for hot air to enter the cold surfaces. With the solid plastic wrapping, this is avoided.

Also the pipe design allows for flexible design of pipes specifically for each site, where pieces of pipes are welded together at the site, ending with a foam/plast wrapping kit.

The dispenser pipe was developed early in the project is already today in use at HRSs delivered by Nel Hydrogen in multiple countries. The reason for advancing the development efforts, was an urgent need for improvement of the pipeline design.

5.2.5 Cooling system prototype design and construction

A prototype of the cooling system has been designed and constructed, as shown in figure 3.2.5.1.

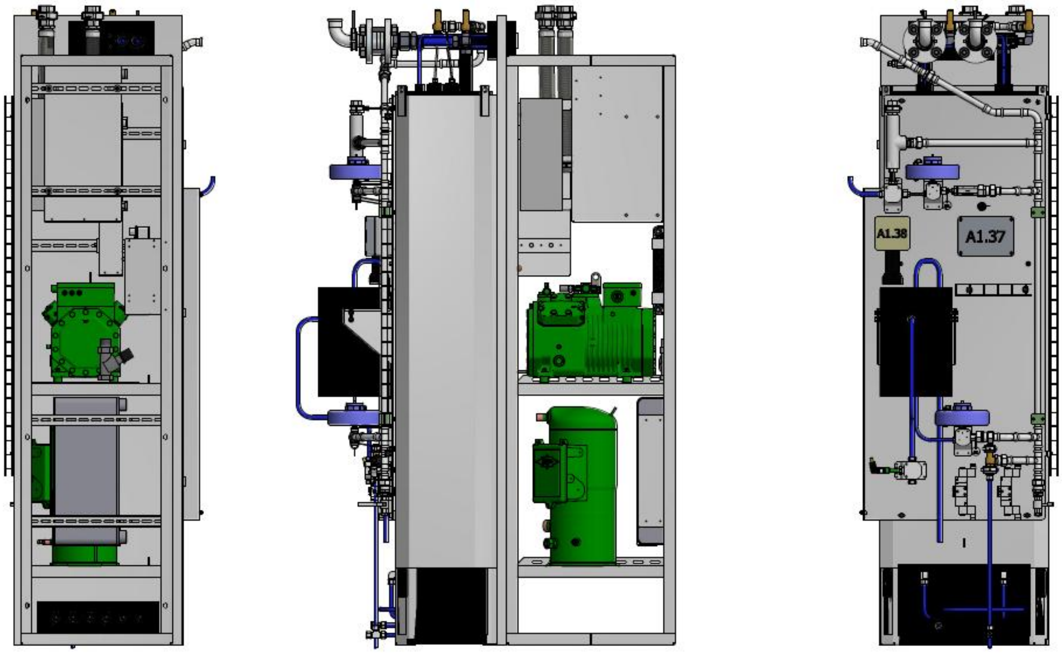


Figure 3.2.5.1 – Cooling System Prototype

The skid is dived in two sections, one containing all hydrogen related components and the HEX, and the other containing the cooling compressors including motor and frequency drive. The sections are separated by a gas tight wall, which enables the cooling compressor and motors to be in an environment classified as non-explosive – this greatly reduces costs of components.

The cooling system design has superseded several of the targets formulated for the H2Cost-2 project back in 2016 as outlined in figure 3.2.5.2.

The peak hour capacity has increased three times (+200%) compared to the cooling system from the H2Cost-1 project. This is primarily due to the frequency control added to the cooling compressor, allowing for overclocking, and a slightly larger compressor engine. This also enables a similar increase in the daily capacity. The original targets of H2Cost-2 was only a twofold increase of capacity.

The cooling system enables fueling of two LDVs at the same time, as targeted, however in addition it can also support fueling of HDVs (due to the 100kg/hour capacity), which was not originally targeted for the project.

The increased capacity has not impacted the system volume – on the contrary the HEX itself has been reduced with 20% in size, primarily due to avoiding having two cooling loops as originally envisaged. This results in a reduction of 71% of system volume relative to daily capacity, compared to H2Cost-1 – the target was 50%.

The increase in capacity, has increased the actual cost of the system with 20%, compared to H2Cost-1, but yielded a +200% increase in capacity. On a cost per kg daily capacity this results in a cost reduction of 55%, where the target for H2Cost-2 was 44%.

The energy consumption is within the target for H2Cost-2 with a 20% reduction, primarily due to introduction of the frequency control and improved dispenser pipeline.

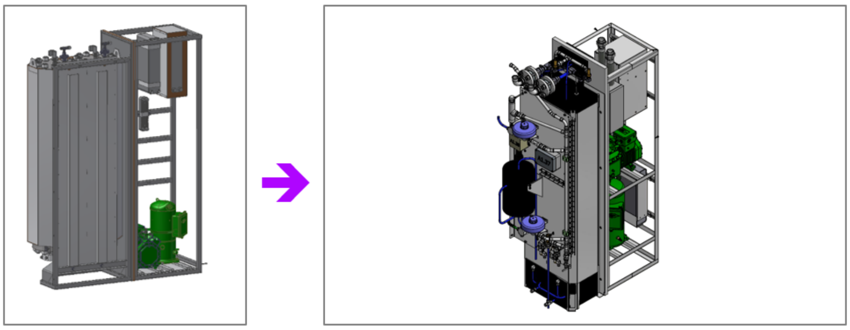


Fig. 3.2.5.2

	H2Cost-1 State-of-the-art 2016	➔	H2Cost-2 Target 2016		H2Cost-2 Achieved 2019
Peak hour capacity	33,6kg H2	**+100%**	67,2kg H2	**+200%**	100kg H2
Daily capacity	200kg H2	**+100%**	400kg H2	**+200%**	600kg H2
Fueling hoses served	1 hose LDV	**+100%**	2 hoses LDV	**+100%**	2 hoses LDV 1 hose HDV
System volume	10 liter / kg daily capacity	**-50%**	<5 liter / kg daily capacity	**-71%**	2,9 liter / kg daily capacity
System cost	€900 / kg daily capacity	**-44%**	<€500 / kg daily capacity	**-55%**	€400 / kg daily capacity
Energy consumption	<1,25kWh/kg	**-20%**	<1kWh/kg	**-20%**	0,98kWh/kg

Originally it was planned to construct a laboratory prototype of the cooling system. However increasing market demand within the HDV market, justified an acceleration of scope and initiation of commercialisation activities in parallel.

Instead of a laboratory prototype, a complete cooling system has been constructed and integrated into an H2Station® HRS from NEL, intended for HDV fueling, see pictures in figure 3.5.2.3.

The HRS with the cooling system is installed at NEL in Herning and undergoes tests before shipment to the first HDV fueling customers in California, among others Shell and Toyota, see further on commercialisation in section 6.2.

Figure 3.5.2.3 – Pictures of constructed cooling system prototype, integrated into H2Station®

5.3 Dissemination of results

Dissemination efforts during the project period has focused on extensive dialogue with market stakeholders of the project partners, in particular customers such as energy companies and car manufacturers.

The aim has been to secure a detailed dialogue on specifications and market requirements during the project execution, and to foster potential sales channels for the following commercialisation of the developed technologies.

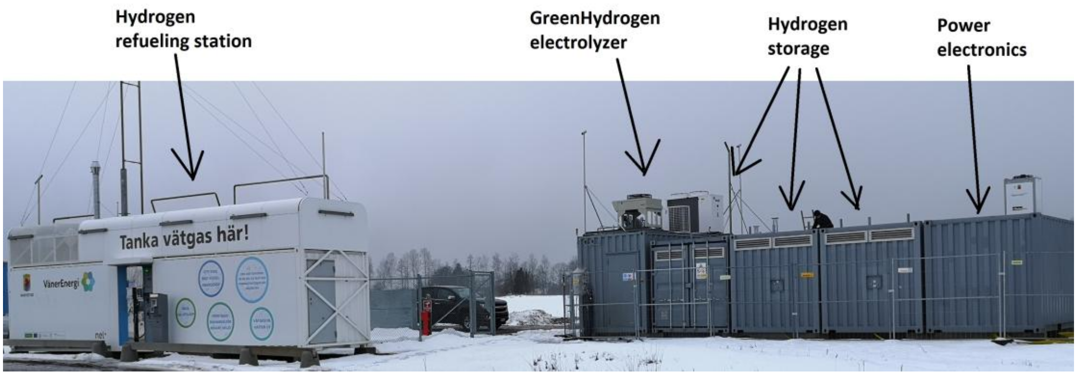
Project progress and results have been disseminated on a continuous basis through the Hydrogen Denmark (Brintbranchen) organisation e.g. in meetings and conferences. The partners have also ensured dissemination through international organisations such as the European Fuel Cells & Hydrogen Joint Undertaking, California Hydrogen Fuel Cell Partnership and the US Fuel Cell & Hydrogen Energy Association.

6. Utilization of project results

The participating companies have successfully ensured continued R&D and commercialisation activities of the technologies developed in the H2Cost-2 project.

6.1 Continued R&D and Commercialisation of MW electrolyser

In 2018 GreenHydrogen lauched its alkaline electrolyser (HyProvide A-series) as a commercial product. In 2018 a single electrolyser was sold to an operator of a hydrogen refueling station in Sweden, see Figure below. This system is a containerized 60 Nm3/h electrolyser. The electrolyzer system encompass all of the technology developed in the "H2Cost-2" project. Three similar systems are to be delivered to customers in 2019.



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

The H2Cost-2 results on the hydrogen pre-cooling system has successfully been commercialised for the HDV market by Nel Hydrogen (outside of the project) and with new R&D and demonstration efforts ongoing for the LDV market.

Nel Hydrogen has already secured sales and installation of the multiple new H2Station® for HDV fueling, e.g. NEL has received multiple orders from Shell on more than 85 million DKK for HDV stations to be installed in California[2] [3], which will utilize the cooling system from H2Cost-2 – as outlined in figure 6.2.1.

Figure 6.2.1 – HDV H2Station® orders for Shell in California

To further utilize the cooling system from H2Cost-2 for LDVs, EUDP funding has been secured for a new demonstration project, HyScale, which is to design a HRS for fueling of two LDVs at the same time. The project was commenced in 2018 and will elapse until 2020.

The ability to fuel HDVs steeming from the H2Cost-2 project, also has enabled NEL to enter into a strategic collaboration with Nikola Motors, acting as exclusive supplier of hydrogen infrastructure for the Nikola truck deployments. Nikola is the world leading pure-play developer of hydrogen powered trucks and is setting the standard for driving forward innovations and investments into advancing towards price and performance parity of hydrogen heavy duty trucks with diesel. Nikola Motors has more than 8.000 pre-orders of hydrogen trucks already placed. Earlier in 2018 year Nikola announced a $1 billion investment into a new manufacturing facility in Arizona onwards 2021[4] and the same year Nikola raised $100 million for the first investments[5]. Also Nikola and NEL entered into the strategic collaboration, with a potential of up to 1GW of electrolyser and fueling capacity across 28 sites in the USA[6].

[2] https://nelhydrogen.com/press-release/nel-asa-reference-is-made-to-stock-exchange-announcement-regarding-contract-for-heavy-duty-h2station-solution/
[3] https://nelhydrogen.com/press-release/nel-asa-receives-purchase-order-from-shell-for-two-additional-heavy-duty-fueling-stations/
[4] https://dxtn4vayafzin.cloudfront.net/nikolamotor/uploads/press_release/pdf/25/nikola_corp_013018.pdf
[5] https://nikolamotor.com/press_releases/nikola-raises-100-million-in-august-49
[6] https://nelhydrogen.com/press-release/awarded-multi-billion-nok-electrolyzer-and-fueling-station-contract-by-nikola/

Since commencing of the H2Cost-2 project in 2016 the number of average employed persons (as stated in annual final report) at NEL in Denmark has grown from 50 to 85 (2018). At the time of this report issue, NEL employees 105 persons, with an expected conservative outlook of a 10% increase per year going forward, thanks to among others the results of H2Cost-2. With regards to annual revenue of NEL in Denmark this has grown from 44 million DKK in 2016 to 177 million DKK in 2018 with an expected conservative outlook of a 30% increase per year going forward, thanks to among others the results of H2Cost-2. Almost 100% of the revenue generated by NEL in Denmark is export to Europe, USA and Korea.

7. Project conclusion and perspective

The H2Cost-2 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

As part of the H2Cost-2 project GreenHydrogen has successfully managed to achieve the objectives initially set up. I.e. reducing cost (capex) by 33% and developing a hydrogen quality monitoring system.

Next development steps are to further optimize cost and performance (capex and opex) in order to meet the long term market targets.

7.2 Hydrogen pre-cooling

As part of the H2Cost-2 project Nel Hydrogen has successfully managed to develop and achieve a scaling of hydrogen pre-cooling system with substantial advances compared to the previous state-of-the-art, prior to the project:

- +200% increase of hourly fueling capacity – from 33,6 kg to 100kg
- +200% increase of daily fueling capacity – from 200 to 600kg
- -71% reduction of physical system volume
- -20 reduction in energy consumption
- Enabling fueling of two LDVs at the same time, or one HDV
- -55% cost reduction of pre-cooling system cost

Nel Hydrogen has conducted product maturing activities of the hydrogen pre-cooling technology, which has enabled integration into a new H2Station® hydrogen fueling station product designed for HDV fueling.

Nel Hydrogen has already secured sales and installation of the multiple new H2Station® for HDV fueling, e.g. NEL has received multiple orders from Shell on more than 85 million DKK for HDV stations to be installed in California, which will utilize the cooling system from H2Cost-2.

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