HyScale

Scaling hydrogen fueling to match gasoline

PROJECT END REPORT
APRIL 2021

Project No.: 64017-0576

SUPPORTED BY:

EUDP

1. Project details

Project title	HyScale – Scaling hydrogen fueling to match gaso-line
File no.	64017-0576
Name of the funding scheme	EUDP17-II
Project managing compa-ny/institution	Nel Hydrogen A/S Vejlevej 5 7400 Herning Denmark
Project partners	Force Technology QA-Tech ApS ABB A/S DTU Mechanical Engineering
CVR (central business register)	Nel Hydrogen A/S | 26933048 Force Technology | 55117314 QA-Tech ApS | 34231079 ABB A/S | 31371716 DTU Mechanical Engineering | 30060946
Date for submission (of report)	April 2021

2. Summary

2.1 English version

HyScale has successfully managed to develop various subsystems and components for a new third generation (3. Gen) Hydrogen Refueling Station (HRS) that can fuel both Light Duty Vehicles (LDVs) and Heavy Duty Vehicles (HDVs) vehicles.

Various fueling control optimization efforts have been conducted, covering among others, development of a new innovative hydrogen regulation valve and fueling control strategies. The technical results have been published in four scientific articles, as well as one master thesis conducted.

HyScale has also made the pioneering groundwork for achieving type approval of a hydrogen dispenser metering accuracy. A new comprehensive guideline document on test and metrological approval of hydrogen dispensers have been developed, as well as supporting mass flow test device equipment. This was applied to the hydrogen dispenser developed in HyScale, and enabled achieving of the first third-party verified hydrogen dispenser certification in Europe according to OIML R139.

A prototype of the 3rd gen. HRS has been designed constructed at the NEL facilities in Herning as part of the project. This involved various efforts on both scaling components and sub-systems to enable connecting of two dispensers as well as integrating the various development results from HyScale. Also new compressor and cooling technologies from previous EUDP funded projects was integrated into the 3rd gen.

NEL has conducted product maturing activities of the 3rd gen. technologies, which has enabled integration into the H2Station® hydrogen fueling station product portfolio. Offerings for the market and sales efforts are underway in Europe, US and Korea.

Since commencing of the HyScale project in early 2017 the number of average employed persons at NEL in Denmark has grown from 95 to 150 and annual revenue increased from 72 million DKK to 200 million DKK. Annual revenue is expected to grow 20-30% per year going forward, thanks to among others the results of HyScale.

2.2 Dansk version

HyScale har succesfuldt udviklet forskellige systemer og komponenter til en ny 3. generation (3. gen) brint tankstation som kan tanke biler og køretøjer indenfor tung transport.

Projektet har inkluderet en udviklingsindsat indenfor optimering af påfyldningsprocessen, dækkende blandet andet over udvikling af en ny innovativ brint reguleringsventil, og nye kontrol strategier for selve påfyldningen. De tekniske resultater er blevet publiceret i fire videnskabelige artikler og i en kandidat afhandling.

HyScale har også udført pionerende arbejde for at opnå en typegodkendelse af målingsnøjagtigheden for brint tankstandere. En ny guide for metrologisk godkendelse af brint tankstandere er blevet udarbejdet samt understøttende testudstyr. Dette er også blevet anvendt på brint tankstanderen udviklet i HyScale, hvilket har ført til opnåelsen af den første tredjeparts certificering af en brint tankstander i Europe, i henhold til OIML R139.

En prototype af den nye 3. gen. brint tankstationer er blevet konstrueret ved NEL i Herning, som en del af projektet. Dette har involveret forskellige aktiviteter på skallering af komponenter og systemer med henblik på at kunne tilslutte to brint tankstationer samt integration de forskellige udviklingsresultater fra HyScale. Ligeledes er nye kompressions og kølingsteknologier fra tidligere EUDP støttede projekter blevet integreret i 3. gen.

NEL har også gennemført yderligere produktmodningsaktiviteter af 3 gen. teknologierne, hvilket har muliggjort en integration heraf i den eksisterende H2Station® produktportefølje for brint tankstationer. Salgsaktiviteter er ligeledes blevet iværksat i Europe, USA og Korea.

Siden starten af HyScale projektet tilbage i begyndelsen af 2017 er antallet af ansatte ved NEL i Danmark, øget fra 95 til 150, og den årlige omsætning steget fra 72 millioner DKK til 200 millioner. Fremadrettet forventes omsætningen at stige 20-30% årligt, bl.a. takket være resultaterne i HyScale projektet.

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3. Project objectives

The objective of HyScale has been to develop a new third generation (3. Gen) Hydrogen Refueling Station (HRS) for fast fueling of long range for Fuel Cell Electric Vehicles (FCEV).

The current 2. Gen HRS product was launched in 2016 and is currently successfully being marketed in Europe & US for fueling of Light Duty Vehicles (LDVs).

With HyScale the aim was to add capacity and a second dispenser to the 3rd gen. so that both LDVs and Heavy Duty Vehicles (HDVs) can be fuelled with the same equipment.

Fueling both LDVs and HDVs will increase the combined capacity of the 3rd gen. station and also support the changed market trend on expanding into HDVs. The indirect capacity increase from two dispensers will be similar to that of gasoline/diesel where multiple fuel products are offered from the same dispensing point.

The aim has also been to reduce cost in order to enable hydrogen to be competitive with gasoline at European average levelized cost of electricity for land wind (electrolysis hydrogen supply).

In addition it was a target to improve energy efficiency through an optimized fueling control to be developed in the project, as well as improvements on the cooling system. Also remaining obstacle on dispenser accuracy certification were to be addressed, as HyScale targeted to develop a methodology for achieving metering accuracy certification by national authorities in EU, which can enable a widespread roll-out of hydrogen fueling.

The substantial advances to be achieved in HyScale, is based on a proven track-record of advances on past product generations and comprehensive prior R&D efforts of €3 million on key components for the new 3. Gen. HRS in the HyBoost-2 project (EUDP 64016-0057) and H2Cost-2 project (EUDP 64016-0016).

The aim of HyScale has been to achieve a a HRS prototype at the NEL facilities in Herning. This is to enable a following product maturation and market launch of the 3. Gen. HRS in EU and USA beyond 2020.

The HyScale project has been led by Nel Hydrogen with participation of Force Technology, QA-Tech ApS, ABB A/S and DTU-MEK.

4. Project implementation

Overall the project outcome has been successful, however with some challenges, delays and changes during the period.

Originally project scope were to increase capacity of the 3rd gen. hydrogen fueling station by addition of a second dispenser for fueling of light duty vehicles (LDVs). However during the project market interest for fueling of Heavy Duty Vehicles (HDVs) grew substantially and made a change in project scope relevant. Project efforts were therefore focused on adding an HDV dispenser, so that these vehicles can be served from the same fueling station and LDVs.

Activities on achieving accuracy certification of the hydrogen dispenser had a slow and challenging start. Main reason was that hydrogen only recently were included in the OIML standard and only few countries had started the process on ratifying this. The project therefore had to act as a first-mover in Europe on achieving the first hydrogen dispenser accuracy certification.

The COVID-19 situation also impacted the project in early 2020, and contributed to delays. Overall the project end date was postponed with 7 months, from June 2020 to January 2021.

5. Project results

The HyScale project has involved the following key tasks listed below:

- Hydrogen fueling control optimization
- Dispenser accuracy optimization & test methodology
- Station Module capacity scaling
- Hydrogen Fueling Station prototype construction

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

5.1 Hydrogen fueling control optimization

HyScale included several activities on optimizing the hydrogen fueling process and control, among others the following tasks:

- Development of new innovative hydrogen regulation valve
- Implementation of innovative MC and direct fueling method

5.1.1 Development of new innovative hydrogen regulation valve

This section analyses the design, analysis and optimization of an ejector for high-pressure hydrogen. An ejector is a compression device utilizing pressure differences. In theory an ejector in an HRS will allow for a larger utilization of the low pressure tanks and a lower utilization of the high pressure storage and thereby both reduce energy consumption and increase fueling capacity of the HRS.
The analysis focus was on the development of an ejector for high pressure hydrogen, since this had not been done before. The work was carried out in the following order.

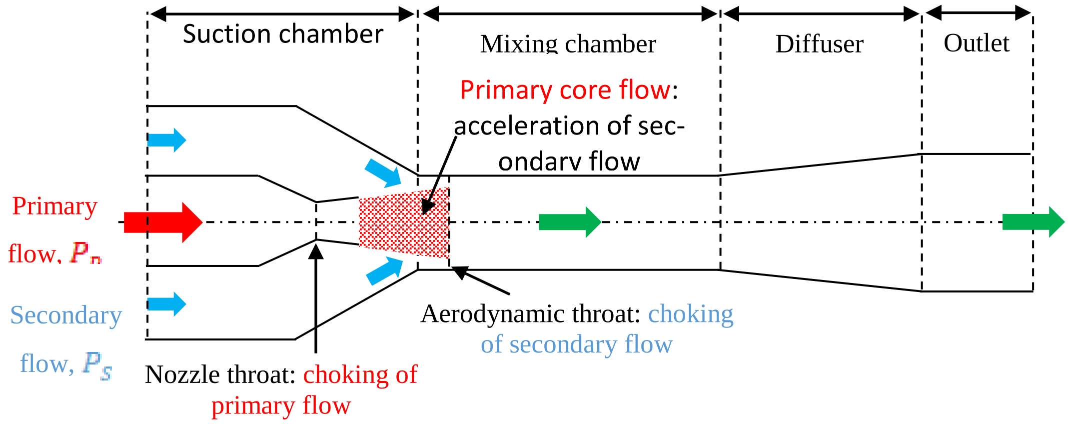
1. Literature review and first version of a CFD model of an ejector projected from other applications in literature.
2. A 1-D Matlab model was developed and verified against the CFD model, the Matlab model enabled calculation of the coefficients and optimization for the ejector.
3. A dynamic model of the ejector was constructed and implemented into the dynamic simulation library “Hydrogen fueling”.
4. Different cases of hydrogen fuelings using and ejector as reduction valve were analysed to see the performance for different hydrogen fueling stations setup.
5. A machine drawing were made and a prototype manufactured.

<u>1. Literature review and first version of a CFD model of an ejector</u>
It was found that ejectors for high-pressure (50-1000 bar) hydrogen was a novel technology with no prior references found in literature. Prior studies with ejectors for hydrogen only considered ejectors for low-pressure hydrogen used for fuel cells

(1-2 bar). The only higher pressures ejectors reported in literature were for CO2 refrigeration facilities. A CFD model of an ejector were made using geometry from an low pressure hydrogen ejector and the model was validated against the low pressure hydrogen ejector. The findings are reported in the paper: A first study of the potential of integrating an ejector in hydrogen fueling stations for fueling high-pressure hydrogen vehicles [1].

2. Matlab 1-D model and parameter analysis of the geometry of the ejector

A 1-D matlab model of the ejector was made. The 1-D model was fitted and verified against the CFD model. The matlab model was used to analyse the importance of the parameters of the geometry. It was fond that the area ratio was the most important factor of the geometry and that the nozzle diameter is the primary design factor for the flow rate. The area ratio determines the entrainment ratio and working time, thus optimizing the area ratio with respect to entrainment ratio will results in an optimized performance of the ejector. The 1-D model was also used to calculate the coefficients that are used in the quasi steady state dymola model. The 1-D model is limited to the specific pressure ranges of the CFD calculations and the geometry used in the CFD model, except the area ratio. A sketch of an ejector with its geometry is shown below



The findings and description of the 1-D matlab model are reported in: Numerical optimization of a novel gas-gas ejector for fuelling of hydrogen vehicles [2].

3. Dynamic model of an ejector

The existing Modelica/Dymola library “Hydrogen fuelling” was updated with an ejector model based on the coefficients retrieved from the 1-D matlab model. With an intergrated model in Dymola, it was possible to integrate the ejector into different hydrogen fueling stations designs and do dynamic simulations, showing the performance of the ejector when primary pressure, secondary pressure and outlet pressure changes over time. The models can be found in the open source Dymola library developed at DTU for hydrogen fueling: Hydrogen fueling [3].

4. Different cases of hydrogen fuelings using and ejector as reduction valve

Two kind of fueling concepts with the ejector were analysed using the dymola hydrogen fueling library. The first one for high pressure cascade fueling of vehicles, 50 bar -900 bar. The second considered emptying the trucks delivering hydrogen at lower pressures, 10 bar – 500 bar. Different cases for each scenario were set up varying the number of pressure levels in the cascade fueling and the pressures in the delivering trucks. The use of ejectors in the hydrogen fuelling station showed a reduction in the energy efficiency of compression, by lowering the amount of hydrogen extracted from the high pressure. Increasing the number of tanks in the cascade system reduces the energy consumption, due to the lower compression losses using regular expansion valves tank of the cascade system. The results show that a reduction of 6.5% of energy of compression can be achieved with two pressure levels. Increasing the amount of pressure levels decreases the possible reduction in energy compression [4]. The analysis of using an ejector to empty the trucks showed that the use of an ejector allows increasing the mass of hydrogen coming from the lowest pressure tank of the fuelling station by more than 70%, which corresponds to a mass increase of 1.56 kg. However, it is shown that the pressure drop between the fuelling station and the vehicle's tank lowers the benefits of having an ejector, by reducing the working time of the ejector [5].

5. A machine drawing were made and a prototype manufactured.

An ejector for emptying trucks was designed using the results from the 1-D matlab model and Dymola simulations [6]. The ejector was manufactured, but unfortunately no experiments has been carried out yet, it is expected to be done in first quarter of 2021.

5.1.2 Development of innovative MC and direct fueling method

This section analyzes the SAE J2601-1 MC method fueling protocol. The MC method should in theory allow for higher fueling rates and higher end SOC. The objective was to quantify the difference between the two approaches and to determine the advantages of switching from the well-known Table Based Approach to the novel MC Method Approach.

The analysis's focus was on H70 Class vehicles and followed these steps:

1. Development of a numerical simulation model
    a.The model includes vehicle thermodynamics, hydrogen flow restrictions, control valves and al-low incorporation of any refueling protocol.
2. Benchmark of the MC method with respect to the table based protocol
    a. Investigated parameters:
        i. Fueling time
        ii. Precooling requirements
        iii. Non-comm SOC
        iiii. Energy consumption
3. Determination of the optimum station control approach using the MC method

4. The impact of the compressed hydrogen storage system on the fueling station.

<u>1. Simulation Model</u>

Two simulation models was developed one in MATLAB® and one in Dymola. The Matlab model was segregated into several sub models, which can be combined to simulate the entire Hydrogen Refueling Station (HRS). The main sub models are the thermodynamic vehicle Compressed Hydrogen Storage System (CHSS) model, HRS cooling system model and the hydrogen com-pressor model. The Dymola model of the MC was integrated into the "Hydrogen fueling library" [3] enabling the library to simulate both table based and MC fuelings corresponding to SAE J2601. For both model the vehicle CHSS model is most essential since the CHSS temperature during fueling is a key performance and safety parameter. The developed thermodynamic CHSS models are validated through com-parison with actual refuellings.

The simulation models are tools which is usable in the following MC analysis and future HRS development.

<u>2. Benchmark</u>

The MC method allow faster refuellings compared to the table based approach, regardless of initial pressure, am-bient temperature and fuel delivery temperature. The HRS precooling requirement could be reduced to -31°C when using MC, while maintaining the same fueling performance as table based. Lowering the precooling requirement will reduce the energy consumption per refueling.

It is found that MC and TB will terminate at similar non-comm SOC's. Higher non-comm SOC was expected when using the MC, but actually the two methods will terminate at a SOC within +/-2 % of each other. Furthermore, the equation based target pressure method, is not found to be advantageous compared to the table based target pres-sure method, which both are options in the MC method. One of the comparisons between the table based method and MC method can be seen in the table below.

	MC method	Lookup Tables method
Fueling Duration (s)	178.97	248.97
State of Charge (%)	98.74	98.39
Mass Dispensed (kg)	5.12	5.10
Theoretical Mileage (km)	497	495

In general the MC method uses more energy than the look up table method, this is due to a higher mass flow rate that results in larger pressure losses, the only excep-tion is when it is 40 C ambient temperature, as the fuelings proceed so slow that the pressure losses becomes less significant than the cooling demand.

Scenario - Method	Overall duration	Energy Consumption
Base Case - MC	449.87	3.77
Base case - L.T.	470.35	3.52
Hot Case - MC	915.87	4.26
Hot Case - L.T.	1053.11	4.56
Cold Case - MC	319.92	2.15
Cold Case - L.T.	407.81	2.11

The findings are reported in the paper: Overall efficiency com-parison between the fueling methods of SAEJ2601 using dy-namic simulations [7].

3. Optimum fueling approach

The MC method fueling protocol could be implemented on stations already in operations. If no changes were made to the station software, the dispenser would target a T40 refueling and vehicles will be filled faster. This will leave the station OPEX unchanged and the benefits of MC method will only affect the HFCV owners.
An alternative approach is proposed, where the station module can operate within a wider range of fuel delivery temperatures, while maintaining a fueling performance similar to the table based protocol. When the station is not fueling vehicles, the dispenser is regulated to maintain a temperature of -20°C, reduction the energy consumption compared to the regular dispenser temperature of -37°C. Once a refueling begins the station cooling system will rapidly cooldown of the hydrogen and the fuel delivery temperature will approach -31°C temperature. If the cooldown from -20°C to -31°C is complete within the first 60 seconds, then the HFCV owner will only experience an change in fueling time of -6 to +21 seconds. The purpose of the MC method is to allow the station to optimize the fueling using real time measurements. The strict fuel delivery temperature categories from the table based approach are eliminated. Using MC method the station can fill vehicles with greater variance in delivery temperature, while maintaining a high performance and safe refueling. This is deemed a key improvement when switching to MC method.
An optimum fueling approach has been investigated where the fuel delivery temperature is increased. By increas-ing the fuel delivery temperature, the overall cooling requirements are reduced and thereby minimizing energy consumption. This adjustment will result in limited changes in fueling times, but the station operator will experi-ence a station operating at a lower OPEX.

4. The impact of the compressed hydrogen storage system on the fueling station

The dynamic model of the CHSS were used to analyse the effect of the pressure loss in the CHSS on the fueling procedure. After the hydrogen leaves the fueling station, the station operator and manufacturer has no control of pressure losses. The analysis therefore considers how the pressure loss in the CHSS affects the fueling. The study showed that if there are no pressure losses in the vehicle the final temperature in the CHSS is constant no matter the APRR. If there are pressure
losses in the CHSS the lower the APRR the lower the temperature increase, as the pressure loss is directly related to the mass flow rate which is decreased by lower APRRs. The study shows the importance of limiting the pressure loss in the vehicle in order to obtain faster fueling times increasing the APRR without compromising the boundary conditions. The study also shows the importance of cooling hydrogen at the station outlet, showing that the minimum temperature increase in the CHSS is around 75 C with cooling to -40 C and that the minimum temperature in the CHSS increases to 180 C if there is no cooling present. The findings are reported in the paper: Dynamic simulation of the effect of vehicle-side pressure loss of hydrogen fueling process [8].

5.1.3 References

[1] Chuang Wen, Brice Rogie, Martin Ryhl Kærn, Erasmus Rothuizen. A first study of the potential of integrating an ejector in hydrogen fueling stations for fuelling high pressure hydrogen vehicles. Applied Energy 2020, vol 260, 113958.

[2] B. Rogie, M. Ryhl Kærn, C. Wen, E. Rothuizen. Numerical optimization of a novel gas-gas ejector for fuelling of hydrogen vehicles. Int. J. Hydrogen Energy 2020, vol 45, 21905-21919.

[3] Erasmus Rothuizen. Dymola library. "Hydrogen Fueling Station" 2020. https://doi.org/10.5281/zenodo.4436147

[4] B. Rogie, C. Wen, M. Ryhl Kærn, E. Rothuizen. Optimisation of the fuelling of hydrogen vehiclesusing cascade systems and ejectors. Int. J. Hydrogen Energy 2021, In press.

[5] B. Rogié, 2020. Internal report: Hydrogen Fuelling stations using two large size tanks.

[6] B. Rogié, 2020. Internal document: Ejector prototype.

[7] C. G. Chochlidakis, E. Rothuizen. Overall efficiency comparison between the fueling methods of SAEJ2601 using dynamic simulations. Int. J. Hydrogen Energy 2020, vol 40, 11282-11854.

[8] E. Rothuizen, B.Elmegaard, M. Rokni. Dynamic simulation of the effect of vehicle-side pressure loss of hydrogen fueling process. Int. J. Hydrogen Energy 2020, Vol 45, 9025-9038.

5.2 Dispenser accuracy optimization & test methodology

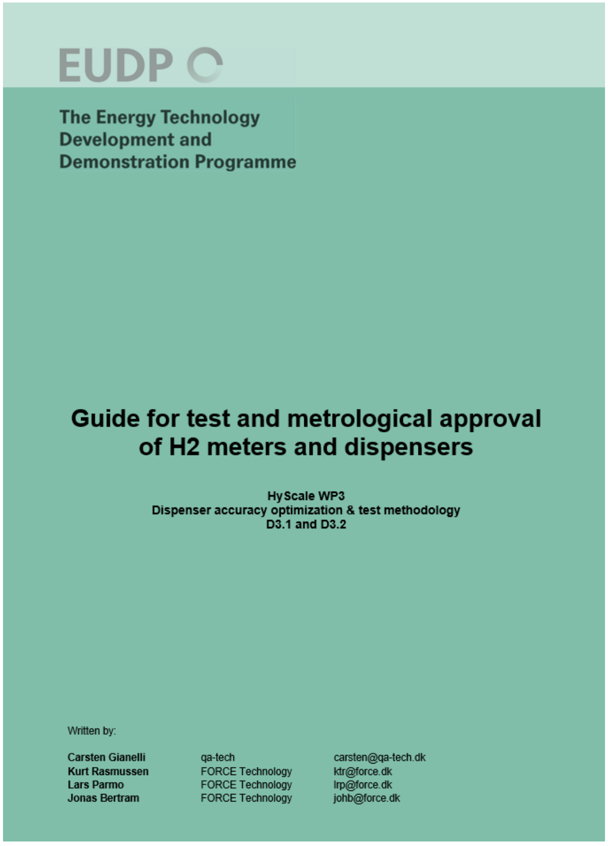
One of the tasks in HyScale has been to lay the pioneering groundwork for achieving type approval of a hydrogen dispenser metering accuracy.

For approval of a hydrogen refuelling station (HRS) OIML recommendation R139 are widely accepted. Approving of a hydrogen dispenser in the US is based on national rules which are widely based also on the OIML R139. The Hyscale partners already achieved US approval on a hydrogen dispenser back in 2016. In Europe however, prior to the Hyscale project, no experiences on hydrogen dispenser certification existed.

OIML R139 only specifics accuracy targets for hydrogen dispensers, but does not detail how certify hydrogen dispensers. One of the efforts in the project was therefore to develop a test methodology for accuracy approval.

This resulted in a comprehensive guideline document on test and metrological approval of hydrogen dispensers. Figure to the left shows front page of the guideline. The full guideline is attached to this report.

The guideline was formulated in parallel with development of a new mass flow test device and conducting of accuracy tests within the project.


EUDP

The Energy Technology
Development and
Demonstration Programme

Guide for test and metrological approval of H2 meters and dispensers

HyScale WP3
Dispenser accuracy optimization & test methodology
D3.1 and D3.2

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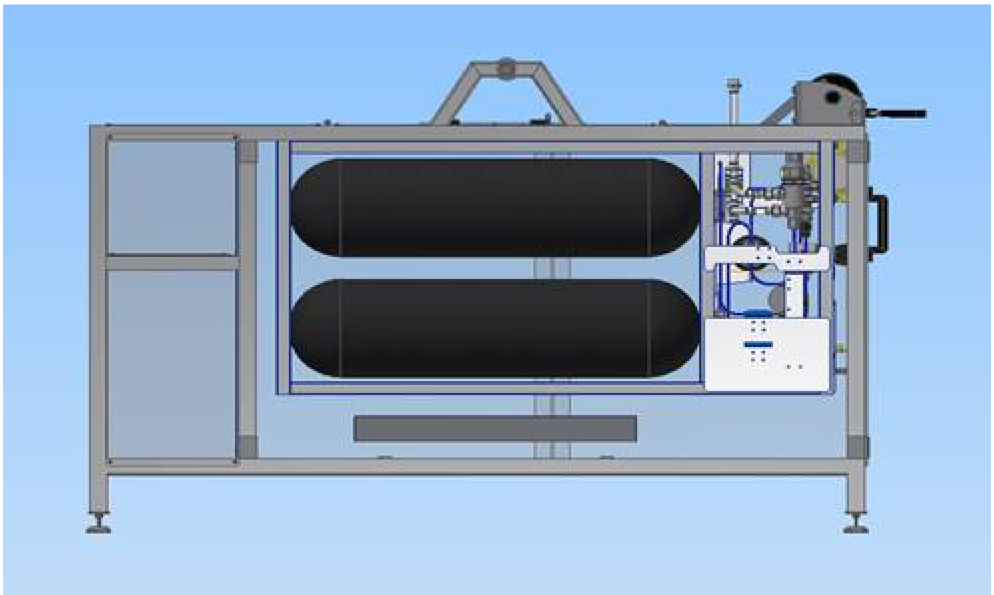
The mass flow test device equipment being used for the certification and performance test. The test device was developed so it can be used the certification and accuracy performance test of hydrogen dispenser. The device consists of the following modules:

- Frame with 2 x Type 3 cylinders of 58L each (equals 2x2,3kg H2 tank) each equipped valve block.
- Valve panel including manual valves, pressure gauges, check valves and relief valves, and hydrogen detector
- A SARTORIUS, Combics 3 scale

The device is a fully manual system but needs electrical power for pressure, temperature and hydrogen transmitters and display readings. It can fil and empty semi automatic. The weight is placed in the bottom of the test equipment. (see illustration below illustration). The design further ensures the system are infected as little as possible by surroundings weather and moist.



Within the HyScale project several test where performed with the new device:

- Initial Tests to identify the accuracy class
- Performance test to fill a tank fully where the relative error below 1% fueling where in the range from 1-2kg dispensed.
- Tests on Systems with a Sequential Control Device where bank switching during a fueling sequence functions properly and can be completed still keeping the accuracy range from 1-4kg with an relative measured below 1%
- Tests on Minimum Measured Quantity accuracy when transferring no less than the 1.0 kg, and stopping the fueling as close as possible to full charge of the tanks
- Zero Stability Test – to test the zero stability of the mass flow metering system

Also in order to fulfill the OIML 139 requirements an Influence and Disturbance tests of a Calculator and Indicating device mounted inside the dispenser had the be performed. The tests were carried out according to OIML R 139-2 “Compressed gaseous fuel measuring systems for vehicles – Part 2: Metrological controls and performance tests”. All test results obtained show that the Calculator and Indicating device mounted inside dispenser, comply with the requirements of OIML R 139.

Below is shown a picture of the test device in use.

Overall the tests were successful and validated that the gravimetric calibration is metrological adequate. This also resulted in issuing of the first third-party verified hydrogen dispenser certification in Europe, see copy of certificate below.

CS OIML Certification System

FORCE Certification

OIML Member State	**OIML Certificate No.**
Denmark	R139/2018-B-DK2-2020.01

OIML CERTIFICATE ISSUED UNDER SCHEME B

OIML Issuing Authority

Name: FORCE Certification A/S
Address: Park Allé 345, 2605 Brøndby Denmark
Person responsible: Kurt Rasmussen

Applicant

Name: NEL Hydrogen A/S
Address: Vejlevej 5, 7400 Herning Denmark

Manufacturer

Name: NEL Hydrogen A/S
Address: Vejlevej 5, 7400 Herning Denmark

Identification of the certified type *(the detailed characteristics will be defined in the additional pages)*

MM-001

Designation of the module *(if applicable)*

Metering module to be used in a NEL 70 MPa hydrogen refuelling dispenser for light duty vehicles.

This OIML Certificate attests the conformity of the above identified type (represented by the sample(s) identified in the OIML type evaluation report) with the requirements of the following Recommendation of the International Organization of Legal Metrology (OIML):

OIML R 139-1, Edition (year): 2018

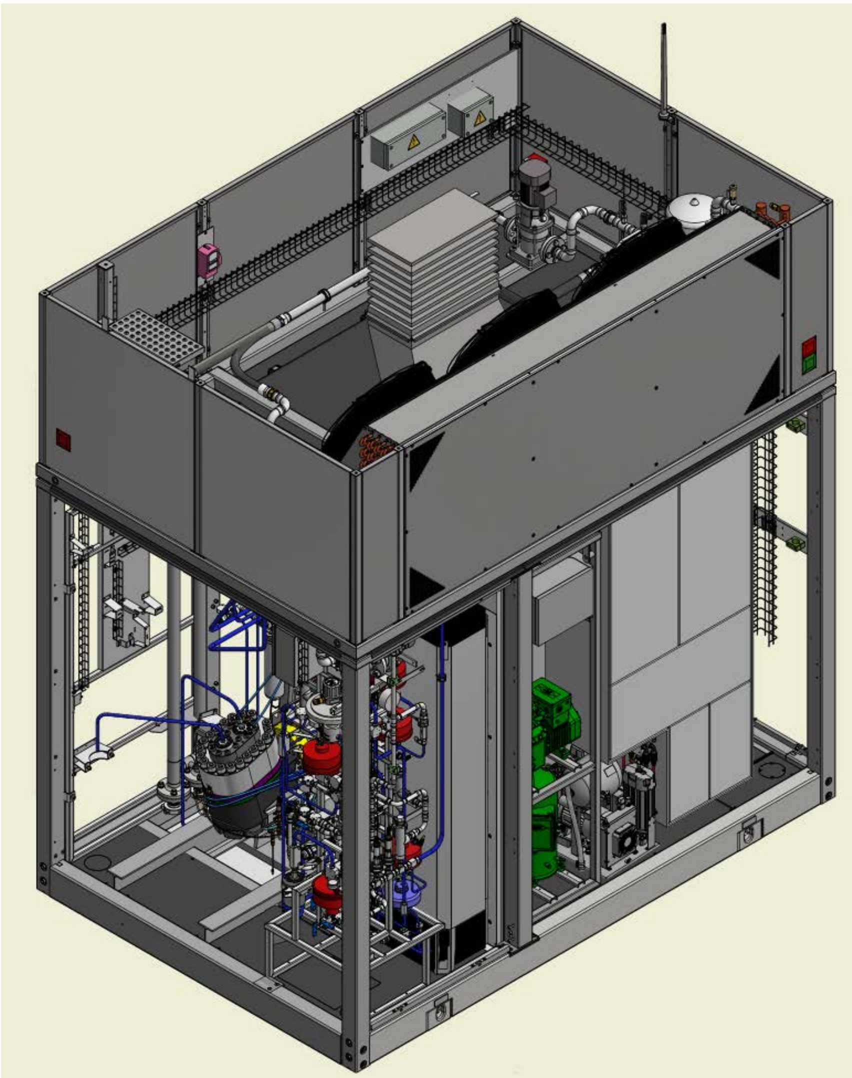
For accuracy class (if applicable): 2

5.3 Station Module capacity scaling

HyScale has also involved the design for a prototype of a new 3rd gen. HRS. This has involved various efforts on both scaling components and sub-systems to enable connecting of two dispensers as well as integrating the various development results from HyScale. Also new compressor and cooling technologies from previous EUDP funded projects was integrated into the 3rd gen.

The picture below shows the 3D layout of the developed Station Module, which integrates the various sub-systems and components.

New hydrogen valve panels has been designed that both integrates the compressor and cooling and connects to two dispensers for LDV and HDV fueling. Despite scaling the valve panels two service to dispenser, efforts have at the same time focused on avoiding the actual physical size of the valve panels to increase. This was done both to reduce size of the overall Station Module, and avoid increasing costs from a too advanced valve panel.

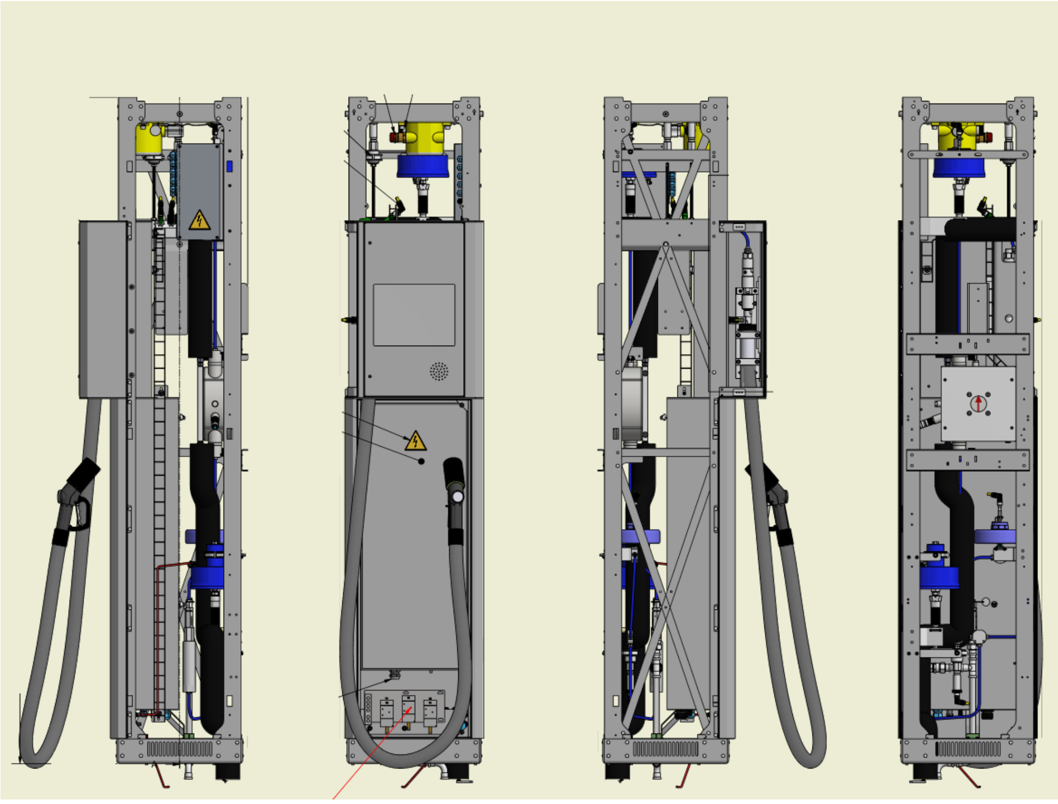


Besides of the valve panels the Station Module also includes a new enclosure that combines several sub-modules:

- <u>H2 compressor:</u> new skid and foundation that allows for a larger motor (scaled capacity)
- <u>Cooling compressor:</u> new rack that allows for larger and one additional compressor
- <u>Cooling heat exchanger:</u> new rack for a bigger and one additional HEX compartment

A new dispenser for HDV fueling was also developed as part of HyScale. The design is very similar to existing dispenser for LDV, in order to achieve synergies – however with few components and adaptions to reflect a different fueling pressure and capacity for HDV.

Picture below shows the new dispenser design.



5.4 Hydrogen Fueling Station prototype construction

A prototype of the 3rd gen. HRS has been designed constructed at the NEL facilities in Herning as part of the project.

The picture below shows the complete HRS installation covering the following sub-modules:

- Hydrogen Supply Storage at 20MPa
- Hydrogen Fueling Storage at 45MPa and 95MPa
- Storage Valve Panels
- Station Module

The prototype is constructed behind external walls and in a wide yard, to provide flexibility for future expansions and adaptions. This way the prototype can also service as basis for new developments in the future.

The HRS is connect to two dispensers placed outside of the test yard, in an area with public access. Picture below shows the two dispensers placed side-by side. The co-location allows for both LDVs and HDVs to be fueled at the same location.

The LDV dispenser is open to the public as a demonstration station, and will thus continue to generate test results beyond the project period.

5.5 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.

Also DTU-MEK have published the following research articles with results from the project:

- *"A first study of the potential of integrating an ejector in hydrogen fuelling stations for fuelling high pressure hydrogen vehicles"* Applied Energy 260 (2020) 113958
- *"Numerical optimization of a novel gas-gas ejector for fuelling of hydrogen vehicles"* International journal of hydrogen energy 45 (2020) 21905-21919
- *"Overall efficiency comparison between the fueling methods of SAEJ2601 using dynamic simulations"* International journal of hydrogen energy 45 (2020) 11842-11854

In addition a master thesis at DTU-MEK has been completed as part of the project with the following title: *"Hydrogen Fueling Methods - Overall efficiency comparison between the MC method and the Lookup tables method for the optimization of hydrogen fueling, using dynamic simulations".*

6. Utilization of project results

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

The HyScale results on the 3rd gen. hydrogen fueling technology has successfully been commercialised, by Nel Hydrogen (outside of the project) and with new additional R&D and demonstration efforts ongoing for further expansion into the Heavy Duty Vehicle (HDV) market.

Nel Hydrogen introduced the 3rd gen. hydrogen fueling technology in during 2020, now offering to fuel both LDVs and HDVs at the same fueling station. The technology has been integrated into product offerings for the market and sales efforts underway in Europe, US and Korea.

To further expand into the HVD market, EUDP funding has been secured for a new development project, HyTon, which is to design a new compressor with a daily capacity of 1,5 tons of hydrogen sufficient for fueling of HDVs at large-scale. The project was commenced in 2019 and will elapse until 2022. The market experiences from the HyScale HDV dispenser will feed into the HyTon project on a continuous basis.

Since commencing of the HyScale project in early 2017 the number of average employed persons (as stated in annual final report) at NEL in Denmark has grown from 95 (2017). At the time of this report issue, NEL employees 150 persons, with an expected conservative outlook of a 10% increase per year going forward, thanks to among others the results of HyScale. With regards to annual revenue of NEL in Denmark this has grown from 72 million DKK in 2017 to 200 million DKK in 2020 with an expected conservative outlook of a 20-30% increase per year going forward, thanks to among others the results of HyScale. Almost 100% of the revenue generated by NEL in Denmark is export to Europe, USA and Korea.

7. Project conclusion and perspective

HyScale has successfully managed to develop various subsystems and components for a new third generation (3. Gen) Hydrogen Refueling Station (HRS) that can fuel both Light Duty Vehicles (LDVs) and Heavy Duty Vehicles (HDVs) vehicles.

Various fueling control optimization efforts have been conducted, covering among others, development of a new innovative hydrogen regulation valve and fueling control strategies. The technical results have been published in four scientific articles, as well as one master thesis conducted.

HyScale has also made the pioneering groundwork for achieving type approval of a hydrogen dispenser metering accuracy. A new comprehensive guideline document on test and metrological approval of hydrogen dispensers have been developed, as well as supporting mass flow test device equipment. This was applied to the hydrogen dispenser developed in HyScale, and enabled achieving of the first third-party verified hydrogen dispenser certification in Europe according to OIML R139.

A prototype of the 3rd gen. HRS has been constructed at the NEL facilities in Herning as part of the project. This involved various efforts on both scaling components and sub-systems to enable connecting of two dispensers as well as integrating the various development results from HyScale. Also new compressor and cooling technologies from previous EUDP funded projects was integrated into the 3rd gen.

NEL has conducted product maturing activities of the 3rd gen. technologies, which has enabled integration into the H2Station® hydrogen fueling station product portfolio. Offerings for the market and sales efforts are underway in Europe, US and Korea.

Since commencing of the HyScale project in early 2017 the number of average employed persons at NEL in Denmark has grown from 95 to 150 and annual revenue increased from 72 million DKK to 200 million DKK. Annual revenue is expected to grow 20-30% per year going forward, thanks to among others the results of HyScale.