Final report

1.1 Project details

Project title	HyLift-Demo
Project identification (pro-gram abbrev. and file)	European demonstation of 3rd generation hydrogen powered fuel cell forklifts
Name of the programme which has funded the project	EUDP-09-I
Project managing company/institution (name and address)	H2 Logic A/S, Industriparken 34b, 7400 Herning
Project partners	H2 Logic A/S, Dantruck A/S, DTU electro
CVR (central business register)	26933048
Date for submission	August 26th 2014

EUROPEAN DEMONSTRATION OF HYDROGEN POWERED FUEL CELL MATERIALS HANDLING VEHICLES

Acknowledgement

This project is co-financed by European funds from the

Fuel Cells and Hydrogen Joint Undertaking under

FCH-JU-2009-1 Grant Agreement Number 256862

1.2 Short description of project objective and results

English version

The purpose of HyLift-Demo project was to conduct a large scale demonstration of fuel cell materials handling vehicles (forklift trucks and tow tractors) and the supporting hydrogen refuelling stations infrastructure. The project succeeded in having more 11 vehicles in demonstration for a total of more than 13.000 hours, and the refuelling station hardware made an impressive 4.400 fills with availability above 99%. Demonstration happed at six different sites, where the largest site was STARK City in Copenhagen.
The project partners made vibration and climate tests on the fuel cell systems and 1000 test refuelings was completed on the new H2Station MH-100 that was developed in the project.

The HyLift-Demo project was the biggest materials handlings demonstration project in Europe to date.

The project was cofounded by FCH-JU, Fornyelsesfonden and EUDP.

Danish version

Formålet med HyLift-demo projektet var at gennemføre en storskale demonstration af brændselscelle systemer i intern transport (gaffeltrucks og tractors) og demonstrere den supporterende brintinfrastruktur og brintstationer. Projektet fik i alt 11 køretøjer i demonstration, og køretøjerne nåede over 13.000 driftstimer og tankede mere end 4.400 gange på brintstationerne med over 99% pålidelighed. Demonstrationen sket på seks forskellige lokationer i Europa, hvor den største demonstration var hos STARK City i København.
Projektpartnerne har gennemført vibrations- og klimatests på brændselscellesystemerne, og der er gennemført 1000 tankninger på den nyudviklede H2Station MH-100.

HyLift-Demo projektet er det pt. Største demonstrationsprojekt for intern transport i EU.

Projektet er samfinansieret af EUDP, Fornyelsesfonden og FCH-JU.

1.3 Executive summary

The overall purpose and ambition of HyLIFT-DEMO was to conduct a large scale demonstration of hydrogen powered fuel cell material handling vehicles, which enables a following deployment and commercial market introduction. The detailed HyLIFT-DEMO project objectives were the demonstration of at least 30 material handling vehicles as well as the demonstration of the corresponding hydrogen refuelling infrastructure at end-user sites. Moreover, the project partnership aimed at conducting accelerated laboratory durability tests and validating the value proposition of the technology fulfilling commercial and environmental targets. Furthermore, objectives were to plan and secure the initiation of Research and Development (R&D) of the 4^{th} product generation. Finally, the project contributed to the establishment of an appropriate Regulations, Codes and Standards (RCS) framework which will enable smooth commercialisation as well as to the motivation of European, national and regional stakeholders by performing adequate dissemination activities.
The project was conducted by a consortium of European partners that for several years have invested significantly in developing and testing hydrogen and fuel cell

technology for material handling vehicles. The technology is now advanced to a 3rd generation level that allows for a large scale demonstration before commencing market deployment. The number of materials handling vehicles being demonstrated in the project was, however, reduced to 11 vehicles due to difficulties in identifying interested end-users for the vehicles. Extensive market analyses have encouraged the partners to focus on the market segments of 2.5-3.5 tons forklifts and airport tow tractors, as these segments provide the strongest value proposition for fuel cell vehicles in the materials handling sector within Europe. It was thought that the demonstration activities could lead directly to a following market deployment with a solid and proven value proposition for the vehicle end-users. Unfortunately this could not be realized and therefore further large scale demonstrations and deployment support will be required.

The fuel cell system was demonstrated in materials handling vehicles from three vehicle manufacturers, representing various market segments and system integration approaches.

The demonstration was handled in fleets of up to 4 vehicles; end-users envisaging larger fleets were preferred. Larger fleets would lead to a more viable business case for the supporting hydrogen refuelling infrastructure, but also to an efficient service and maintenance set up. As well as minimizing the final number of demonstration sites, the project endeavored to place these as close as possible to each other as this lowered costs both for maintenance and for hydrogen distribution. The supply of hydrogen for the sites was from local sources or through commercial subcontracting from local gas suppliers. The refueling infrastructure was owned and operated either by project partners, the end-user, or other local partners or projects.

HyLIFT-DEMO addressed a specific and proven value proposition where hydrogen and fuel cells replace use of diesel / LPG in 2.5-3.5 ton material handling vehicles where batteries cannot provide a satisfying solution. The ambition and driving force of the HyLIFT-DEMO activities and partners were to enable a following deployment and market introduction. Therefore the targets to be reached within the project as well as the demonstration model and relations to end-users were set-up with a future commercial value chain in mind.

1.4 Project objectives

Purpose & objectives
The overall purpose and ambition of HyLIFT-DEMO was to conduct a large scale demonstration of hydrogen powered fuel cell materials handling vehicles, which should enable a following deployment and market introduction initially foreseen to start no later than 2013, now planned to start no later than 2015.

The initial HyLIFT-DEMO project objectives were:

Demonstration of at least 30 material handling vehicles
Conduct 12 - 18 month demonstration of at least 10 units of 2.5-3.5 tons forklifts and at least 10 units of airport tow tractors, but in total at least 30 vehicles.

Demonstration of hydrogen refuelling infrastructure at end-user sites
Conduct 12 - 18 month demonstration of hydrogen refuelling infrastructure at end-user sites throughout Europe where the fuel cell vehicles are to be demonstrated.

Conduct accelerated laboratory durability tests
Perform accelerated laboratory tests on fuel cell systems to validate life time and sensitivity to shock, vibration and climate exposure, reaching 4,000 hours in laboratory.

Validate value proposition & reaching of commercial and environmental targets
Conduct data acquisition from the demonstration operation and validate reaching of performance targets on durability, efficiency and costs for 3rd generation technology.

Plan and secure initiation of R&D of 4th generation commercial products
Ensure that R&D of 4th generation fuel cell and hydrogen refuelling technology is initiated onwards reaching full commercial targets.

Ensure commercial market deployment no later than 2013
Plan and ensure initiation of a commercial market deployment by end of 2013 of hydrogen powered fuel cell material handling vehicles. This involves planning of the companies and development of suggestions for European/national/regional deployment support mechanisms.

Secure RCS for enabling commercialisation
Identify future Regulation, Codes & Standard needs in order to enable commercial high volume certification & use of hydrogen powered fuel cell materials handling vehicles.

European dissemination securing national & regional motivation
Project results and experiences are to be disseminated throughout Europe to the hydrogen and fuel cell industry as well as the materials handling industry. This is to motivate national and regional actors to also initiate development and commercialisation activities within the area.

During the preparation of the 3rd Contract Amendment the HyLIFT-DEMO project objectives were revised as follows. The objectives not mentioned here remain unchanged. The reasons for the required changes were one the hand the difficulties in identifying sufficient end-users for the deployment of 30 vehicles in the available timeframe which was even tightened by the bankruptcy of DanTruck accompanied by the underestimated wish of potential customers to test drive the vehicles before placing an order and on the other hand that due to an electronic hardware dysfunction of the test system during the initial test phase shock and climate tests needed to be cancelled. The aforementioned delays of the vehicle deployment also cause the delays in the initiation of the market deployment.

Demonstration of at least 11 material handling vehicles
Conduct 12 - 18 month demonstration of at least 10 units of 2.5-3.5 tons forklifts and at least 1 unit of airport tow tractors.

Conduct accelerated laboratory durability tests
Accelerated laboratory tests on fuel cell systems to validate life time and sensitivity to vibration exposure, reaching 4,000 hours in laboratory.

Ensure commercial market deployment no later than 2015
Plan and ensure initiation of a commercial market deployment by end of 2015 of hydrogen powered fuel cell materials handling vehicles. This involves planning of the companies and development of suggestions for European/national/regional deployment support mechanisms.

Fuel cell materials handling vehicles demonstration
In the HyLIFT-DEMO project H2 Logic demonstrated 11 units of a 3rd generation fuel cell system in materials handling vehicles from two material vehicle OEMs (after the exit of DanTruck).
H2 Logic had been developing fuel cell systems for the materials handling market since 2003. The technology has now reached a 3rd generation level that had been demonstrated within this project. Within follow-up projects the demonstration efforts is planned to be increased in volume.
Over the years H2 Logic's R&D efforts had been focused on simplification of the fuel cell system by modularisation. The simplification both helped to reduce costs and improve efficiency and the modularisation helped to expand the potential market as the fuel cell system could be integrated and used in a variety of materials handling vehicles.
The fuel cell system consists of a number of base modules that can be configured into different system set-ups enabling either direct integration into vehicles developed entirely for fuel cell operation, or replacement of standard battery boxes in electric material handling vehicles. This approach could achieve volume and reduce costs across several vehicle segments.
The vehicle integrated approach was stopped during the course of the project as a consequence of the bankrupt project partner DanTruck leaving the project in month 9.

Hydrogen refuelling infrastructure demonstration
In the HyLIFT-DEMO project H2 Logic conducted the demonstration of hydrogen refuelling infrastructure at the end-user sites where fuel cell materials handling vehicles were used. Linde contributed with experiences and knowledge from previous activities within hydrogen refuelling infrastructure.
The supply of hydrogen for the sites was through commercial subcontracting tendering from local gas suppliers. The refuelling infrastructure was either be owned and/or operated by H2 Logic, the end-user or other local partners or projects.
The price of the supplied hydrogen fuel for the vehicles is the main parameter affecting the end-user value proposition for using fuel cell material handling vehicles. The higher efficiency of the fuel cell compared to internal combustion engines (ICE)

combined with a sufficient low hydrogen price is to ensure savings on fuel costs that can leverage the extra costs of the fuel cell compared to an ICE. The target for the hydrogen supply was to reach a price level of 7-9 €/kg hydrogen, dispensed at pump.
The hydrogen price consists of two main elements, the costs of hydrogen provision to the site and the dispensing costs. Whereas the dispensing costs are well known due to exact prices on the onsite infrastructure (compressing, storing and dispensing) the costs of providing the hydrogen is greatly depending on the hydrogen source.
The supply option that enables the lowest hydrogen costs is industrial by-product hydrogen supplied by pipeline.
However, trucked-in hydrogen may also enable a sufficient low hydrogen price if the end-user sites are located nearby the hydrogen production and distribution centre. Onsite hydrogen production combined with a local project set-up can also enable reaching the price targets.
Concerning the hydrogen refuelling infrastructure at the end-user sites this had been established by H2 Logic at sites where the hydrogen refuelling infrastructure was not already present. At sites where refuelling was already available, H2 Logic performed a test of the equipment to ensure hydrogen quality and refuelling process compliance with the fuel cell vehicle requirements. This verification process also ensured that 3rd party hydrogen refuelling infrastructure did not influence the results gathered from the demonstrated fuel cell vehicles.
H2 Logic has developed and demonstrated several hydrogen refuelling infrastructure solutions in the past, and thus used HyLIFT-DEMO to assemble a solution fit for materials handling. Linde contributed to the efforts with years of experience within supply of hydrogen and infrastructure, among others from materials handling activities in the USA.
For sites where no hydrogen refuelling solution was already available, the refuelling infrastructure was provided as compact and transportable module that allowed for fast and easy installation on site. Dispensers could be located indoor or outdoor separately from the refuelling module. Within the station hydrogen is compressed to 40-45 MPa and stored onsite, before conducting cascade refuelling through the dispensers. The refuelling infrastructure was designed to supply up to 10 vehicles that are used intensively up to 3 working shifts per day, corresponding to 60 kg per day. Also the storage capacity allows for instant refuelling of at least 3 vehicles. The capacity of the hydrogen refuelling stations varied from site to site depending on the number of vehicles in operation. When the end-user sites were selected H2 Logic and Linde defined the exact hydrogen infrastructure concept for each site based on the available hydrogen supply and the capacity needed for the vehicle fleet at the site.

1.5 Project results and dissemination of results

Summary of project achievements in the demonstration preparation phase

- Presentation of DanTruck fuel cell forklift at the CeMAT, one of the world's leading intralogistics trade fairs
- Agreement on detailed demonstration planning comprising a detailed planning of the various interfaces between the project work packages
- Draft version of Report "Overview of existing Regulations, Codes and Standards (RCS) for forklifts and refuelling stations" available
- Successful kick-off meeting in Brussels, 2nd General Assembly meeting in Herning (with DanTruck hydrogen powered fuel cell forklift prototype demonstration) and 3rd General Assembly meeting in Munich
- Monitoring and Assessment Framework (MAF) for the assessment of demo projects for material handling vehicles adapted and finalized

- Appropriate materials handling vehicles for conversion to a hydrogen powered fuel cell drive train could be identified after there was a lack of vehicles caused by the withdrawal of DanTruck from the project in SEP 2011
- In December 2011 the first fully integrated H2Drive system could be certified. Investigations with regard to the advantages and disadvantages of a type approval were ongoing at that point in time
- Performance testing phase for first vehicle prototypes could be finalized successfully
- Because of the new situation with the changed vehicle supplies there was the need of a revision of the time schedule. Afterwards a sound and realistic deployment schedule for all fuel cell materials handling vehicles and the supporting hydrogen infrastructure is available
- In order to improve efficiency and performance of the fuel cell system intense development work was performed in order to identify the optimal hybrid configuration
- Models were developed in order to define an appropriate refuelling method on the one hand to assure refuelling safety and on the other hand to refuel to the highest possible state of charge in the tank at lowest possible refuelling time
- The preparation of both durability and vibration, shock and climate testing were performed
- The cooperation with the material handling vehicle OEMs STILL and MULAG had been intensified and their interest in offering vehicles with a hydrogen powered fuel cell drive train to their customers had been inspired and strengthened
- As the new suppliers of the material handling vehicles could provide services and support all over Europe the area in which the fuel cell vehicle demonstrations could take place was largely widened and therefore the HyLIFT-DEMO efforts to identify appropriate potential end-users had been enlarged accordingly
- In the meantime 10 fully integrated H2Drive system had been manufactured, tested and certified
- Contracts for 6 fuel cell material handling vehicles had been signed. Negotiations for further vehicles were on-going
- EMC testing of the fuel cell system and the vehicles (STILL RX60-25 FC and MULAG Comet 3FC) had been successfully finalized
- The performance testing phases for both the STILL forklift truck and the MULAG airport tow tractor had been finished with good success
- In order to improve efficiency and performance of the fuel cell system intense development work had been performed in order to identify the optimal hybrid configuration

Project achievements in the demonstration phase

In its demonstration phase HyLIFT-DEMO had not fully progressed according to the updated project plan which was necessary because of the withdrawal of DanTruck. As the project was not successful in signing additional contracts with materials handling vehicle end-users the project was not able to reach the initial target of 30 vehicles in demonstration.
Nevertheless, demonstrations could be performed at several end-user sites and in total 11 vehicles, 10 fuel cell forklifts and 1 airport tow tractor, were clocking hours at several locations. Vehicle performance data were collected and processed using the Monitoring and Assessment Framework developed in the EC funded project HyLights and adapted for the specific requirements of materials handling vehicles within HyLIFT-DEMO. Publications of performance data were made. 9 materials handling vehicles were in demonstration operation at real en-user sites, two were in operation for use trials and for fuel cell system performance testing:

- 4 forklifts at Stark / Denmark

- 2 forklifts at Colruyt / Belgium
- 2 forklifts at egetæpper / Denmark
- 1 forklift in Frankfurt / Germany (several potential customers: Hassia, Viessmann, Rudolph Logistics)
- 1 forklift at H2 Logic / Denmark
- 1 tow tractor at MULAG / Germany (trials in Hamburg airport / Cologne/Bonn airport)

Further aspects:
Vibration tests were performed at JRC. Shock and climate testing had to be cancelled because of technical reasons. Durability testing was performed at H2 Logic's premises as showed below.
The mid-term dissemination workshop for European stakeholders, planned for JUN 2012, was postponed and combined with the final dissemination workshop for materials handling stakeholders because of the project's delayed demonstration phase.
The report "Suggestions for deployment support mechanisms" has been finalized in MAR 2013.

Climate tests of MULAG 3FC in Winter @ -13°C.

Overarching project achievements

The HyLIFT-DEMO project conducted the demonstration of hydrogen powered fuel cell materials handling vehicles, while it tried to build the business case to enable following deployment and market introduction. This small scale batch production of these vehicles sought to validate the value proposition as well as commercial and environmental targets by retrieving the data provided by the demonstration operation.
After the revision, the project succeeded to achieve the demonstration of 11 units of 2.5 - 3.5 tons fuel cell forklift trucks and airport tow tractors with an integrated

3rd generation fuel cell system and hydrogen refuelling infrastructure at end-user sites throughout Europe. In addition, accelerated laboratory tests were performed on a fuel cell system to validate life time resistance, planned to reach 4,000 hours in laboratory and ending up finally with 1.200 hours reached. Because of limitations of the test equipment shock and climate testing were required to be cancelled. Climate tests during 2 winters was performed at H2 Logic and customer sites. Vibrations tests had been performed in cooperation with a forklift OEM on internal vibration test track, and had produced very valuable results for further product improvements.

In detail the following results could be achieved in the course of the project:

WP 2 - Demonstration specification & planning

WP Leader – H2 Logic

In second half of 2012, vehicle demonstrations had finally commenced. The following sites were in operation:

STARK K&M City:

- Copenhagen, Denmark
- 4 STILL RX60-25 FC
- Site started 11.2012
- 2 shifts, 5 days per week
- H2 Logic 25 MPa refuelling station

At STARK, the forklifts were working with goods handling in a large hardware store supplying materials for construction. The fuel cell forklifts were replacing the site’s previous diesel powered forklifts and were therefore used intensively for the hard work at the site.

Figure 1: STILL RX60-25 FC taking a break, STARK K&M city

Colruyt Distributiecentrum Dassenveld:

- Halle, Belgium
- 2 STILL RX60-25 FC

- Site started 09.2012 / 01.2013
- 2-3 shifts, 6-7 days per week
- Waterstofnet / Hydrogenics refuelling station

The forklifts at Colruyt were working in a pallet sorting facility and plastic container cleaning facility, where packaging from the company’s stores are recycled.
During December 2012 the two forklifts at Colruyt were returned to H2 Logic for upgrades addressing stability issues learned during the first months of demonstration. The forklifts were returned back to Colruyt immediately after New Year’s 2012/2013 and demonstration recommenced in January 2013.

Figure 2: STILL RX60-25 FC at work, Colruyt Distributieecentrum Dassenveld

egetæpper:

- Herning, Denmark
- 2 STILL RX60-25 FC
- Demonstration starting 07.2013
- H2 Logic 25 MPa refuelling station

Vehicles used for internal distribution of carpets and goods dispatch at carpet manufacturer. Carpet dispatch is every Thursday and Friday, where the 2 vehicles was used intensively.

Figure 3: STILL RX60-25 FC at work, egetæpper carpet dispatch centre

STILL Frankfurt:

- Frankfurt, State of Hessen, Germany
- 1 STILL RX60-25 FC
- Forklift delivered 12.2012
- On road tour from 03.2013
- GHR mobile refuelling station (planned), Linde trailH2 (realized)

The STILL Frankfurt vehicle was used together with a mobile refueller for short trials at potential end-user sites.

Figure 4: Road tour kick-off, STILL Frankfurt

MULAG:

- trials at Hamburg and Cologne/Bonn airports and performance testing at MULAG's premises, Oppenau, Germany
- 1 MULAG Comet 3 FC
- trial vehicle also used for range and power design upgrade in WP9
- H2 Logic H2Station® MH-100 refuelling station

The MULAG Comet 3 FC prototype is used for potential end-user trials at airports, mainly in
Germany and for performance testing at MULAG's premises. To support these activities MULAG had ordered one H2Station® MH-100 hydrogen refuelling station.

Figure 5: MULAG Comet 3FC on trial at Hamburg airport

H2 Logic:

- Herning, Denmark
- 1 STILL RX60-25 FC
- Testing started 04.2012

The first STILL RX60-25 FC built was used for shorter trials at potential end-user sites in Denmark, for testing ongoing system improvements and for operations in the H2 Logic production facility.

Figure 6: STILL RX60-25 FC excessive brake testing, H2 Logic

An overview of all demonstration and trial sites, both planned and already done are shown in **Fejl! Henvisningskilde ikke fundet.**. The follow-up on the planned trial sites will be done in the HyLIFT-EUROPE project.

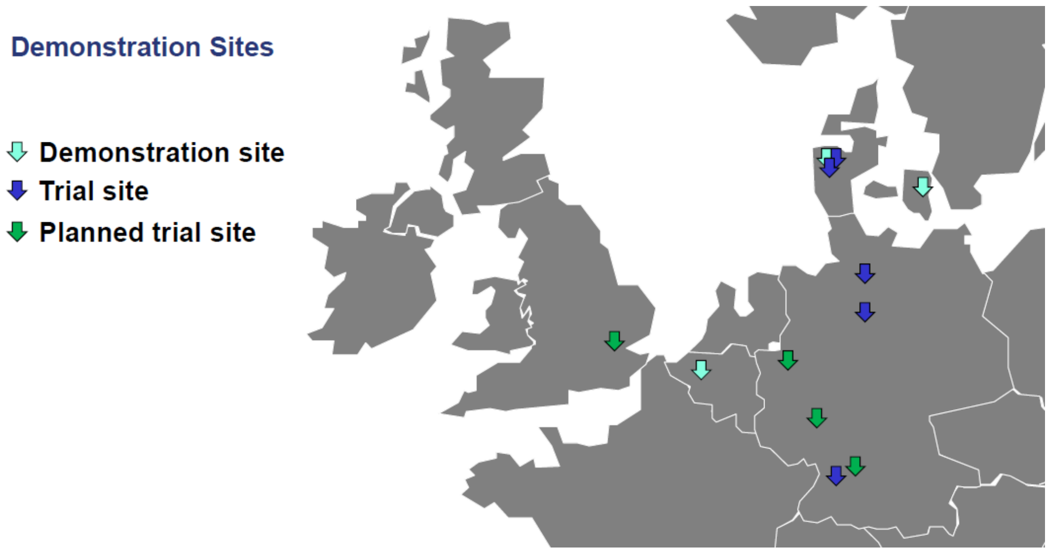
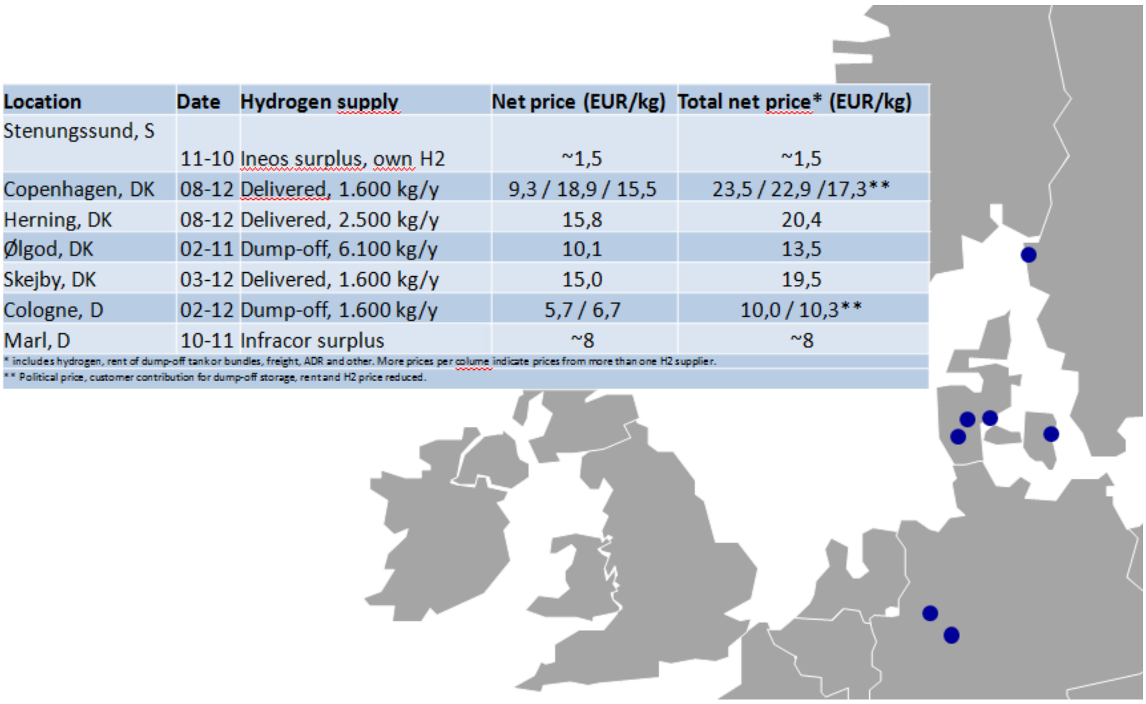


Figure 7: Demonstration and trial sites

With regards to the demonstration planning, the price of hydrogen was also a significant factor in the process of determining the viable sites for sustainable technology deployment. In relation to this, the map of focus regions, developed earlier in the project had been supplemented with a map of actually offered hydrogen prices when planning demonstrations throughout the project. The results can be seen in **Fejl! Henvisningskilde ikke fundet.**.



Location	Date	Hydrogen supply	Net price (EUR/kg)	Total net price* (EUR/kg)
Stenungssund, S	11-10	Ineos surplus, own H2	~1,5	~1,5
Copenhagen, DK	08-12	Delivered, 1.600 kg/y	9,3 / 18,9 / 15,5	23,5 / 22,9 /17,3**
Herning, DK	08-12	Delivered, 2.500 kg/y	15,8	20,4
Ølgod, DK	02-11	Dump-off, 6.100 kg/y	10,1	13,5
Skejby, DK	03-12	Delivered, 1.600 kg/y	15,0	19,5
Cologne, D	02-12	Dump-off, 1.600 kg/y	5,7 / 6,7	10,0 / 10,3**
Marl, D	10-11	Infracor surplus	~8	~8

* includes hydrogen, rent of dump-off tank or bundles, freight, ADR and other. More prices per colume indicate prices from more than one H2 supplier.
** Political price, customer contribution for dump-off storage, rent and H2 price reduced.

Figure 8: Offered hydrogen prices

WP 3 – Safety certification & RCS

WP Leader – H2 Logic

In WP3 the safety certification procedures for fuel cell systems and hydrogen refuelling stations were done according to the manufacturing of the equipment.
In addition to this, procedures for fire and rescue services at hydrogen refuelling stations were developed in collaboration with the Danish Emergency Management

Agency. Although these procedures have been developed based on the Danish context they can also serve as basis for development of similar guidelines abroad. Therefore these guidelines were translated into English, organized by the FCH JU, and are available here: http://www.fch-ju.eu/sites/default/files/DEMA.pdf. Furthermore, local hydrogen refuelling station operators have been trained to identify simple errors and to reset the system safely.

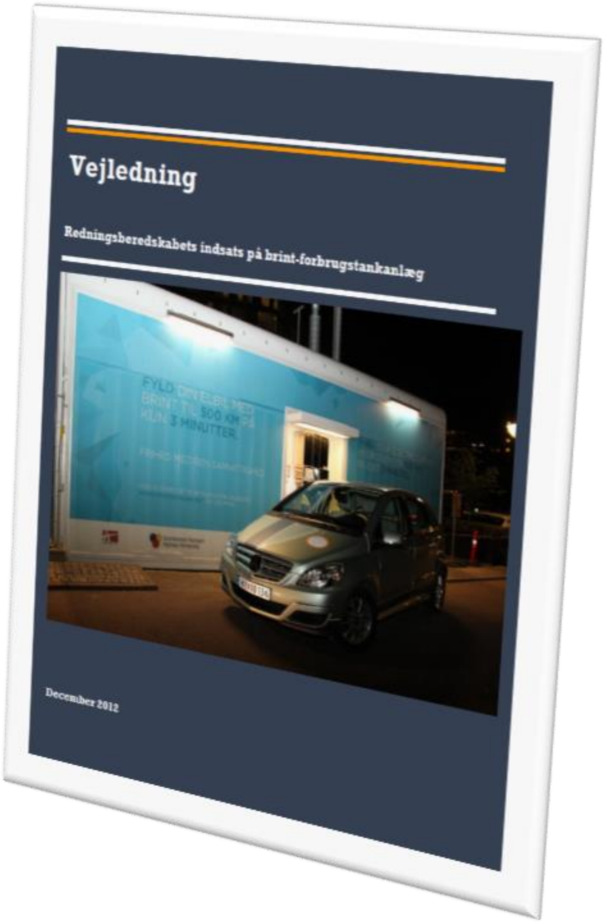


Figure 9: Guideline for fire and rescue services at hydrogen refuelling stations (Danish version)

Furthermore, one deliverable was dedicated to identify gaps in current regulations, codes and standards. The main conclusions here are that the necessary legislation is either in place or under preparation already. However, the RCS specified still need to be validated in order to ensure viable requirements being adopted across the industry.

With regard to safety procedures for materials handling vehicles it has to be taken into account that no education can be expected for end-users. Therefore fuel cell vehicles have to operate in the same way as standard battery / hybrid vehicles do. For maintenance simple instructions have to be prepared and provided. In case of any errors or maloperations the fuel cell system turns into a fail safe mode.

Finally, site evaluations were performed to ensure safe atmosphere in case of an accident. During end-user risk analysis processes specific procedures were determined in order to avoid hydrogen concentrations above 25% LEL in case of an entire storage release.

Figure 10: Leaflets with simple instructions for operation and maintenance

WP 4 - Fuel cell forklift demonstration

WP Leader – H2 Logic

Second half of 2012 saw the first demonstrations of fuel cell forklifts commence.

Status per May 2014:

STARK, Copenhagen, Denmark:

- H2Drive system 1047: 2,418 hours
- H2Drive system 1048: 2,716 hours
- H2Drive system 1049: 2,201 hours
- H2Drive system 1050: 2,222 hours

Colruyt, Halle, Belgium:

- H2Drive system 1044: 723 hours
- H2Drive system 1045: 968 hours

egetæpper, Herning, Denmark:

- H2Drive system 1051: 640 hours
- H2Drive system 1052: 722 hours

H2BZ Hesse, Frankfurt, Germany:

- H2Drive system 1046: 329 hours
- Trials of this vehicle were performed at
    - Viessmann Werke, Allendorf, Germany
    - Rudolph Logistics, Baunatal, Germany

- Hassia, Bad Vilbel, Germany

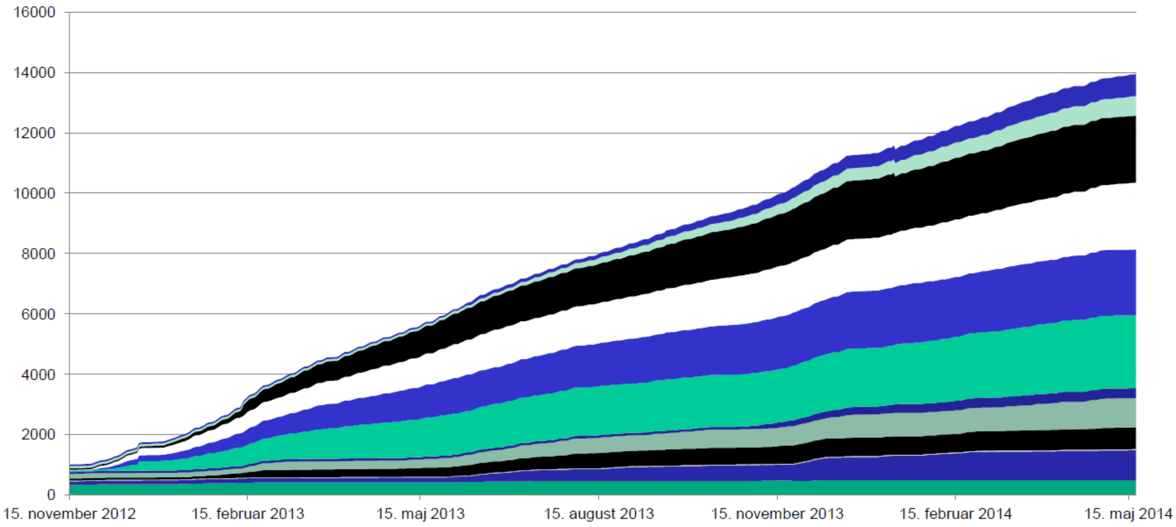


Figure11: Operation hours of vehicles at main demonstration sites accumulating over HyLIFT-DEMO project period

Other HyLIFT-DEMO systems:

In addition to the four main demonstration sites, the following systems were operated as part of HyLIFT-DEMO:

- MULAG Comet 3 FC prototype (developed and manufactured in other project); used for potential end-user trials; 495 operation hours accumulated; system design updated
- 2 DanTruck 3000 Power Hydrogen prototypes 2nd generation; out of operation; 199 operation hours accumulated during system testing
- STILL RX60-30 FC prototype; used for continuous development and improvements, potential end-user trials and as back-up system; 992 operation hours accumulated
- Durability test system; operated in durability test rig; 1,200 operation hours accumulated
- DanTruck 3000 Power Hydrogen prototype 1st generation; out of operation; ~50 operation hours accumulated during system testing; used finally for spare parts provision
- 4 H2Drive systems 1040-1043 (MULAG type systems); systems manufactured but not put into demonstration; eventually used for spare parts.
- Vibration test system; operated in vibration test rig at JRC; out of operation; ~50 operation hours

Figure 12: Operation hours of all other HyLIFT-DEMO fuel cell systems

In total, the fuel cell systems in HyLIFT-DEMO have operated for about 16,000 hours.

In the case of the hydrogen powered fuel cell forklifts the following conclusions can be drawn from operational experiences:

- Users are excited about performance and technology
- Operators are concerned with regard to vehicle availability
- Owners are evaluating costs versus branding gains

In the case of the airport tow tractors the conclusions are:

- Users were experiencing performance and range issues which requires a design update still to be done

For the H2Drive system it can be concluded:

- The system could achieve an availability >95%
- Service costs turned out to be higher than initially expected
- Hydrogen components still show several stability issues

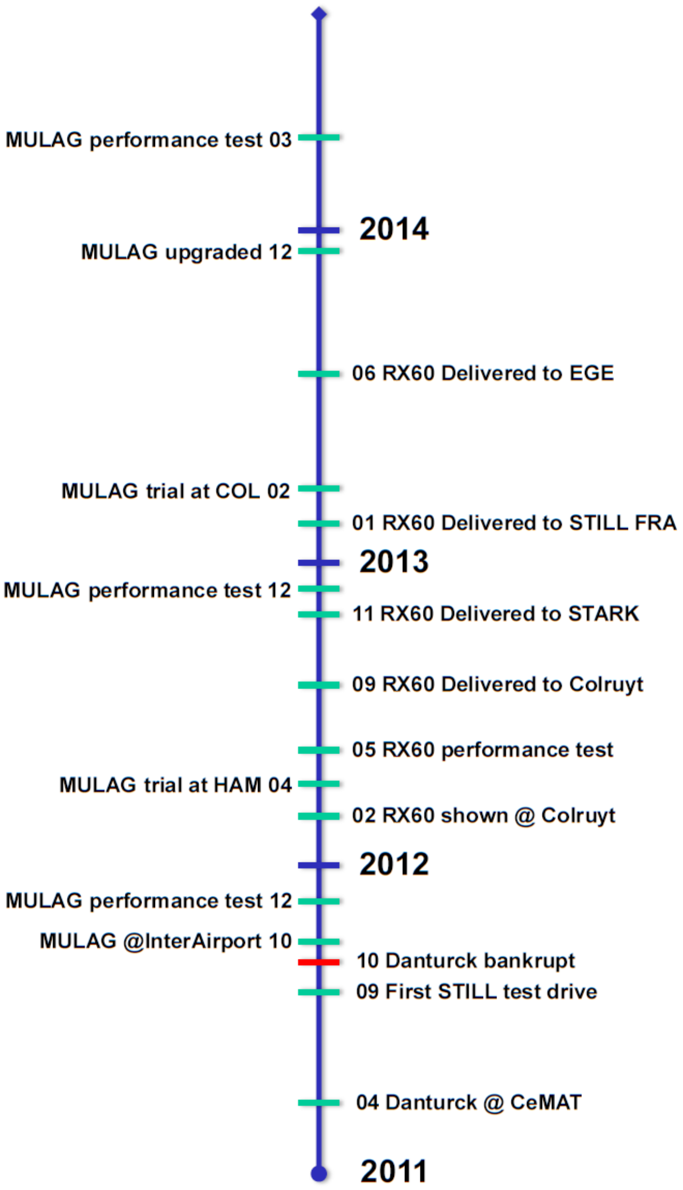


Figure 13: HyLIFT-DEMO vehicle time line

Figure 34: Fuel cell forklift at STARK Copenhagen

The first months of operation have produced a large amount of learning and both software and hardware had received updates to improve stability. Therefore, the two systems at Colruyt were returned to H2 Logic in December 2012 for a major update and reintroduced into operation again in January 2013. The impact of these updates could be sensed by increased operation stability which in consequence influenced the measured vehicle availability and the amount of operation hours. The updates were then consecutively also implemented in all other systems in operation.

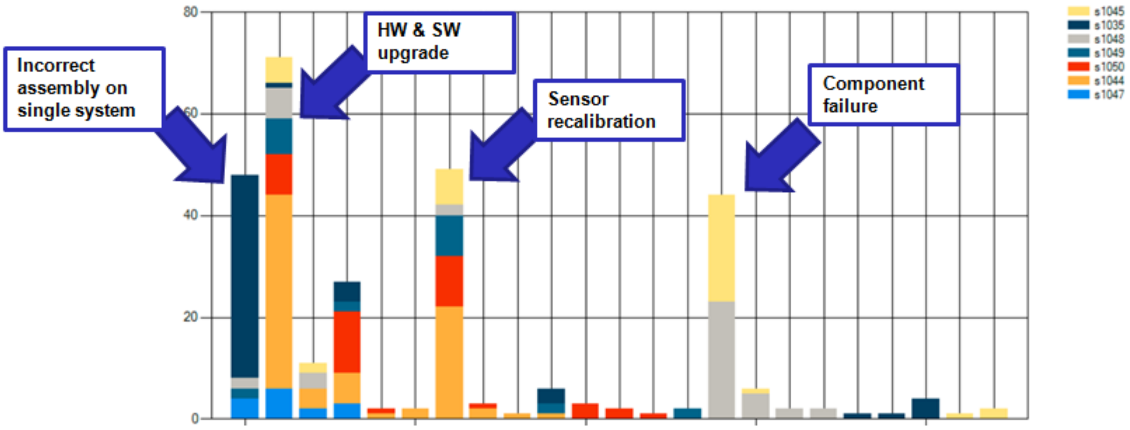


Figure 4: H2Drive error statistics

Figure 4 shows an error statistic from the early part of the demonstrations. Four main issues draw attention and have set the prioritization of the continued maturation of the H2Drive fuel cell systems.

WP 5 – Hydrogen infrastructure demonstration

WP Leader – H2 Logic

Within the second half of 2012, the first H2Station® MH-100 was manufactured. In early 2013 the hydrogen refuelling station (HRS) underwent thorough tests to verify performance, stability and durability. 1.500 test refuelling were successfully validated. After testing was completed, MULAG had placed an order for an MH-100 HRS to support continued end-user trials of the Comet 3 FC tow tractor.

Figure 5: H2Station® MH-100 (35MPa)

At demonstration sites, the vehicles were refuelled by either 3rd party refuelling stations procured or rented by the end-users or other parties separately or by the fleet of available 25 MPa HRSs from H2 Logic:

STARK, Copenhagen, Denmark: H2 Logic Mini 25 MPa; number of refuellings made: 3,689 (04/14)

Colruyt, Halle, Belgium: HRS provided by WaterstofNet; no information available

egetæpper, Herning, Denmark: H2 Logic Mini 25 MPa; number of refuellings made: 634 (04/14)

H2BZ Hesse, Frankfurt, Germany: H2BZ Hesse organized a mobile hydrogen refuelling solution outside the HyLIFT-DEMO project

MULAG, Oppenau, Germany: H2 Logic H2Station® MH-100; number of refuellings made: 11 (04/14); Linde refuellers used for trials at Hamburg and Cologne/Bonn airports

- **25-100 kg/day | 35MPa fast-fill**
- **Cost optimized refueling for material handling vehicles**
- **Designed with low investment & installation costs**
- **Easy & fast installation in only 2 days**
- **Capacity configurable to vehicle tank & fleet type/size**

Average daily capacity *Base configurations*		**25 kg/day** *@1MPa inlet*	**60 kg/day** *@2.5MPa inlet*	**100 kg/day** *@5MPa inlet*
1st hour instant capacity *1.6 kg tank size*	*No. of refuelings*	*2-4*	*3-5*	*5-6*
	Hereof back-to-back	*1-2*	*1-3*	*1-3*
Refueling pressure, protocol & pre-cooling		*35MPa | OptiH-fill™ | Active pre-cooling*		
Hydrogen supply		*External hydrogen source 0.5-20MPa inlet pressure*		
Integration & transportability		*All equipment integrated into one transportable module*		
Local site works required		*Power connection & flat foundation for station & vehicle*		
Installation time		*2 days*		

Figure 6: Specification of H2Station® MH-100

In the case of hydrogen refuelling stations for material handling vehicles the following conclusions can be drawn from the HyLIFT-DEMO experiences:

- A first unit was built and ~1,500 refuellings could be performed at H2 Logic's premises
- The OptiH-fill protocol could be validated with intensive testing for 1.6 kg type 3 tanks
- Users were gaining confidence with use and operation of the hydrogen refuelling stations. Especially trained users committed to daily usage
- Utilisation of trucked-in hydrogen was an issue: site procedures caused premature exchange of bulks while the hydrogen returned to the supplier has not been refunded
- Availability of +99% was successfully shown in the hyLift-Demo project, showing the readiness of the H2Station® technology.

Hydrogen refuelling station performance in HyLIFT-DEMO

The following conclusions can be drawn from the HyLIFT-DEMO HRS operations:

	Start Mass (Avg)	End Mass (Avg)	Used Mass	Utilization
Cologne, 35MPa Linde HRS	0,84	1,63	0,78	**50,0%**
STARK, 25MPa, H2 Logic old HRS	0,39	1,10	0,71	**65,1%**
H2Station MH-100	0,77	1,65	0,89	**56,5%**
Colruyt, 35MPa, Hydrogenics HRS	0,72	1,45	0,73	**46,5%**

Figure 7: Calculation of vehicle tank utilization rate

- 15% of hydrogen tank capacity is not used (below 3.5 MPa)
- 35MPa HRSs normally refuel to ~90%, H2Station MH-100 refuel to 95-100% SOC
- Operators tend to make opportunity refuelling, when they have a natural break in operation or they drive the vehicle until the "refuel" light becomes red.
- Improvement of the tank utilization rate is depending on training of drivers and experiences

Refuelling at STARK in Copenhagen

WP Leader – SINTEF

Work package 6 foresaw the conduction of demonstration monitoring / validation as well as of accelerated tests to be performed by experienced organisations. SINTEF has extensive laboratory equipment and experience in accelerated durability tests and JRC on shock, vibration and climate tests. The data parameters collected and monitored were defined with inspiration from the HyLights MAF Handbook I (demo project level) that was developed by project partner LBST in agreement with the HyLights industry partners.

<u>Monitoring and Assessment Framework (MAF)</u>
H2 Logic and LBST have developed a data acquisition and analysis system for the handling of the key performance indicators to be collected from the demonstrated fuel cell material handling vehicles and hydrogen refuelling stations. In the course of the project but before its practical use LBST improved the system based on its experiences made in the H2moves Scandinavia project and thereby could solve some minor issues. However, the finalisation of the MAF took place in due time (before first vehicles enter into the demonstration phase) and allowed for a smooth and efficient data gathering and handling during the demonstration phase. According to the performance indicators defined within HyLights MAF Handbook I, four EXCEL templates were prepared to collect real life data and lab data for both HRSs and material handling vehicles. In the figure below, an example for a sheet from 1 of the 4 EXCEL files is shown.

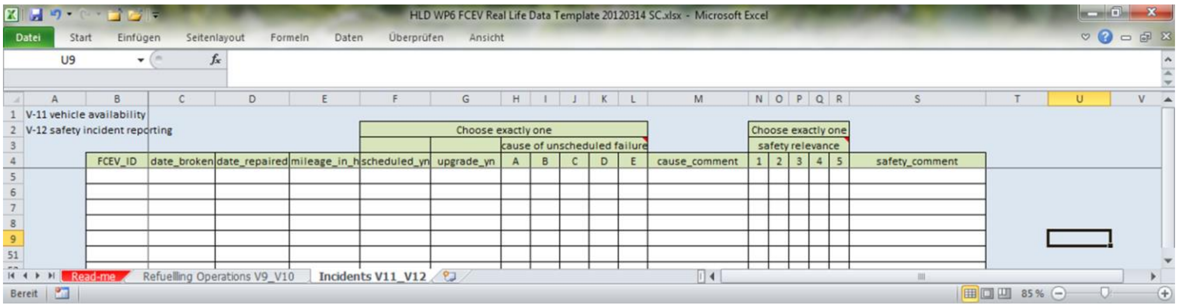


Figure 8: Example of EXCEL sheet for collecting data

Data collected with these templates were sent via email to LBST in defined periods. At LBST, the data sets were consolidated in an ACCESS database. The automatic data import has been significantly improved and simplified within the first project phase. Additionally, selected key figures could be inserted manually in a convenient way, as shown in the figure below.

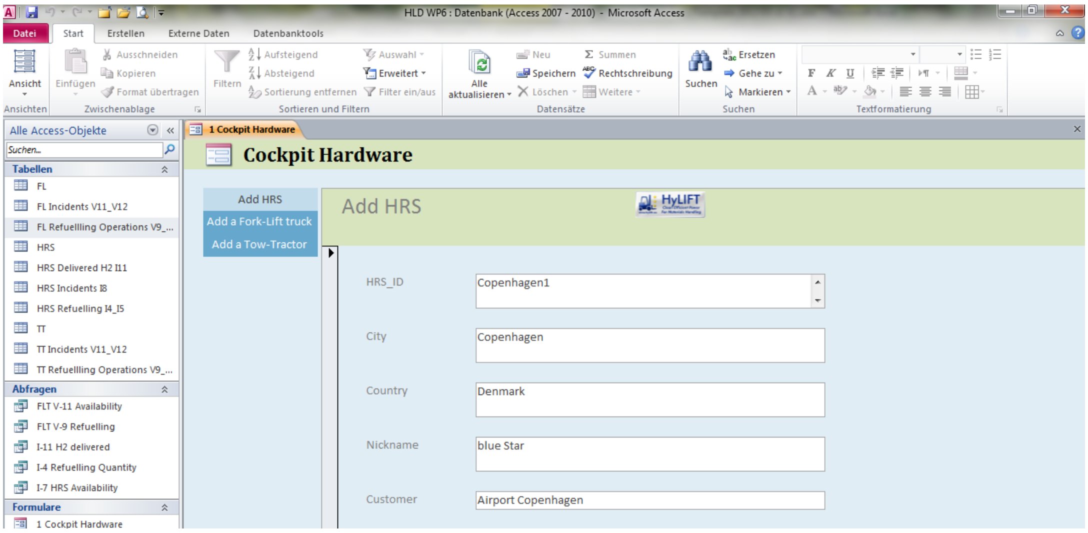


Figure 9: ACCESS graphical user interface for manually entering new hardware specifics

The structure of the data base is as shown in the figure below. Both, the lab data and the real life data were collected here. The data sets are linked to each other to ensure consistent data sets. E.g. when the data set from a refuelling process is added, it is checked whether the FCEV ID actually does exist. By importing the data sets from EXCEL sheets into ACCESS, it is ensured that the data format of each individual cell is correct; otherwise ACCESS aborts the importing process.
The templates for collecting data for ForkLift Trucks (FLTs) and Tow Tractors (TTs) are identical to the greatest possible extent. There are only few exceptions; one of them is the lifting speed which is only relevant for FLTs. However, data for FLTs and TTs are collected in entirely separated tables in the ACCESS database, as different patterns of usage are expected.

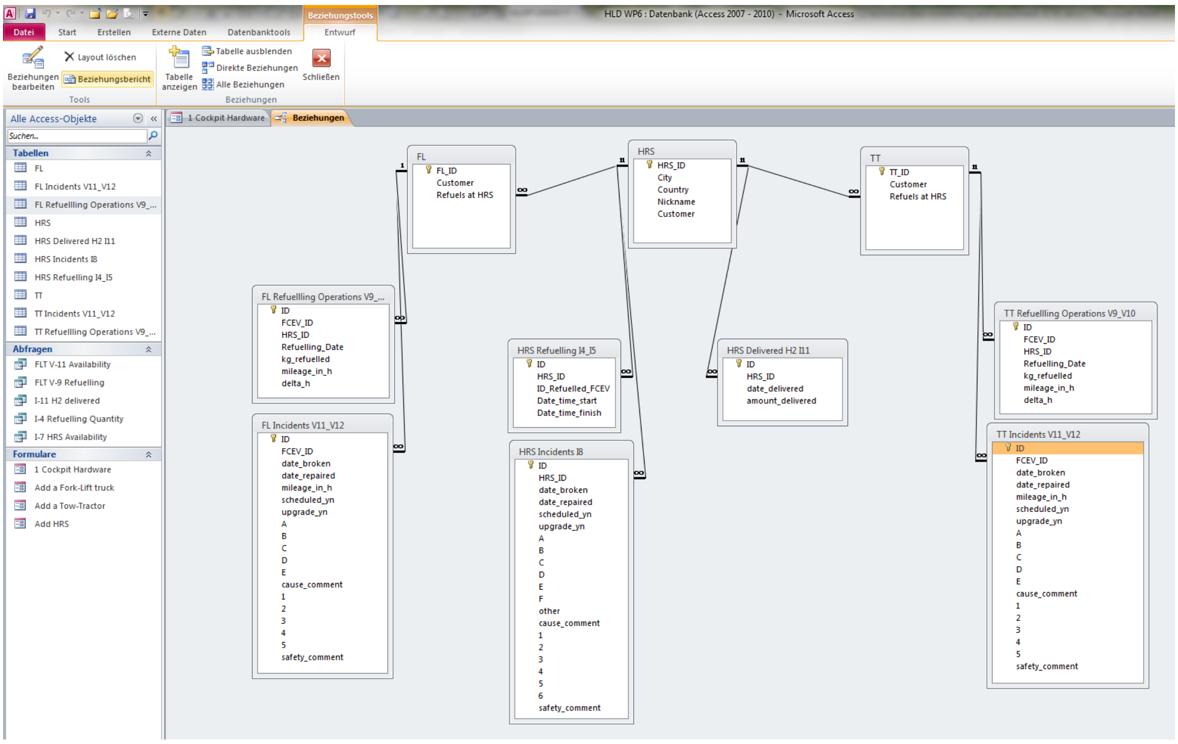


Figure 10: Structure of ACCESS database for consolidating collected data

Data collected from real life operations were processed automatically. EXCEL sheets were set up to generate the graphs, an example is shown in the figure below. The table on the left side is linked to the ACCESS data base. It can be updated with one mouse click, which leads to a new calculation of the histogram shown on the right side.

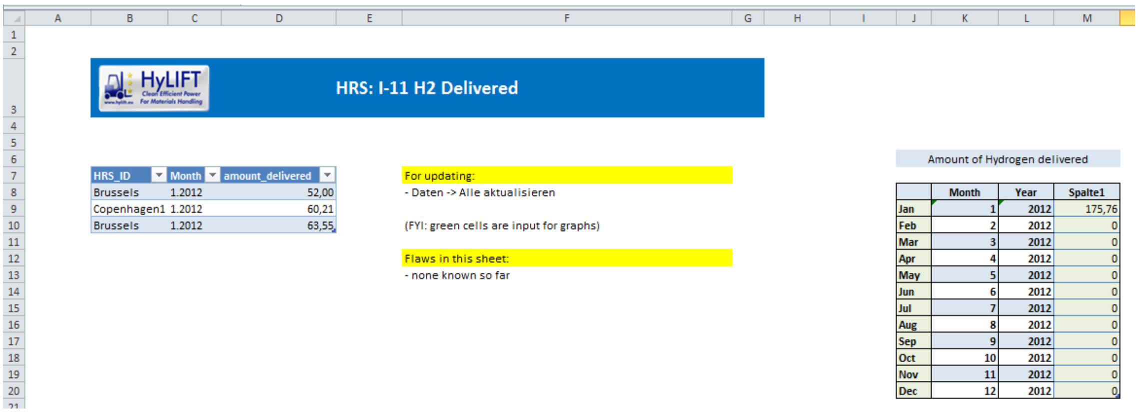


Figure 11: Automatic data evaluation in EXCEL (dummy data)

The corresponding graph is part of the "dashboard" sheet shown in the figure below.

All graphs generated within data evaluation follow the same design scheme to simplify usage in presentations and publications.

First ideas regarding the utilisation of the results of this data acquisition and analysis were collected and developed in order to make best use of the information gathered and processed.

Figure 12: Dashboard in EXCEL evaluation sheet (dummy data)

<u>Monitoring of demonstration</u>

The demonstration of the 11 fuel cell vehicles and the 3 HRS in the project was monitored by H2 Logic during the project. Modems were installed in the H2Drive systems and the H2Stations and live data were sent to a server at H2 Logic with operation, failures and statistics information. Screenshots of the KPI (key performance indicator) website for H2Drive are shown below.

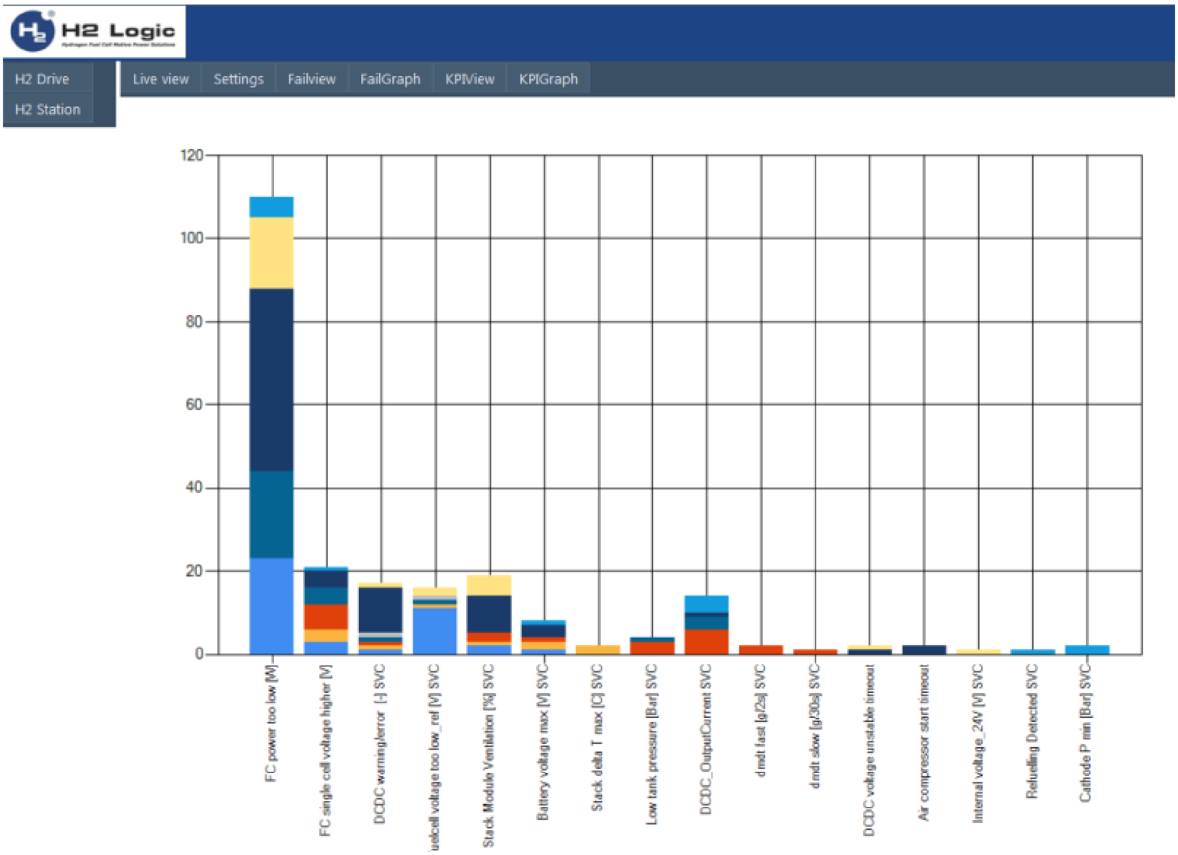
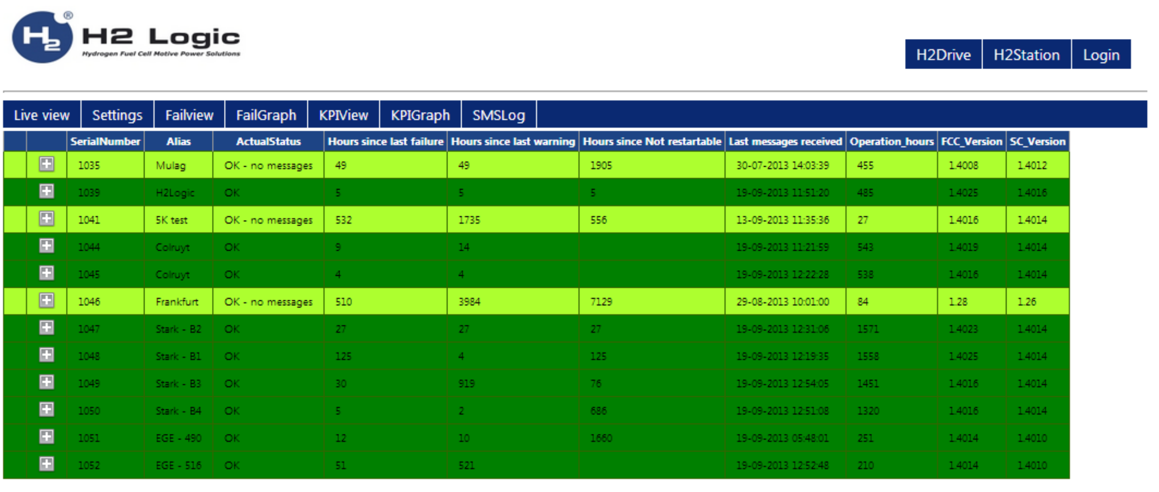


Figure 13: Monitoring of key performance indicators



		SerialNumber	Alias	ActualStatus	Hours since last failure	Hours since last warning	Hours since Not restartable	Last messages received	Operation_hours	FCC_Version	SC_Version
	⊞	1035	Mulag	OK - no messages	49	49	1905	30-07-2013 14:03:39	455	1.4008	1.4012
	⊞	1039	H2Logic	OK	5	5	5	19-09-2013 11:51:20	485	1.4025	1.4016
	⊞	1041	5K test	OK - no messages	532	1735	556	13-09-2013 11:35:36	27	1.4016	1.4014
	⊞	1044	Colruyt	OK	9	14		19-09-2013 11:21:59	543	1.4019	1.4014
	⊞	1045	Colruyt	OK	4	4		19-09-2013 12:22:28	538	1.4016	1.4014
	⊞	1046	Frankfurt	OK - no messages	510	3984	7129	29-08-2013 10:01:00	84	1.28	1.26
	⊞	1047	Stark - B2	OK	27	27	27	19-09-2013 12:31:06	1571	1.4023	1.4014
	⊞	1048	Stark - B1	OK	125	4	125	19-09-2013 12:19:35	1558	1.4025	1.4014
	⊞	1049	Stark - B3	OK	30	919	76	19-09-2013 12:54:05	1451	1.4016	1.4014
	⊞	1050	Stark - B4	OK	5	2	686	19-09-2013 12:51:08	1320	1.4016	1.4014
	⊞	1051	EGE - 490	OK	12	10	1660	19-09-2013 05:48:01	251	1.4014	1.4010
	⊞	1052	EGE - 516	OK	51	521		19-09-2013 12:52:48	210	1.4014	1.4010

Figure 14: Fuel cell system data logging interface

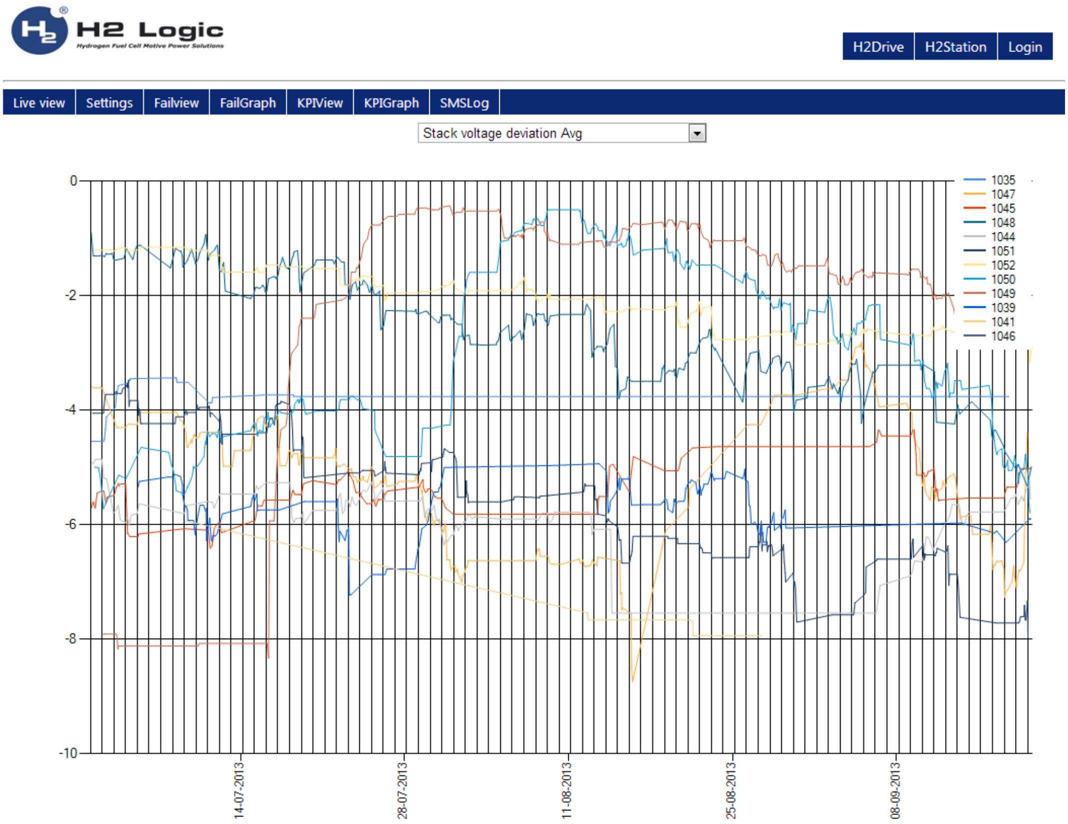


Figure 15: Example for operation data logging (average stack voltage deviation)

The operation data were also collected from the SD-Cards in the H2Drive and data were then shared with LBST for the MAF.

From November 2012 to May 2014, real life data from the HRSs and material handling vehicles (MHVs) were collected from H2 Logic and sent to LBST in customized EXCEL files. At LBST, these data were consolidated in an ACCESS database. Using Microsoft Query to access this data, it was evaluated with the Pivot functionality of EXCEL. Therefore it was possible to nearly fully automatically evaluate the data. HRSs and MHVs were still in operation in June 2014, but as all work on the individual WPs needed to be concluded in June towards the end of the project, it was not possible to consider the data from the final month. Three final reports were prepared in June 2014:

- Public presentation to be published on the HyLIFT-DEMO website
- Project internal presentation for project partners and FCH JU
- Confidential presentation to which only LBST, H2 Logic and FCH JU have access

For benchmarking, publically available data from NREL were compared with the results from HyLIFT-DEMO.
A selection of significant results from the data evaluation is shown in the following graphs:

For detailed data evaluation, data was available for the following HRS and MHVs:

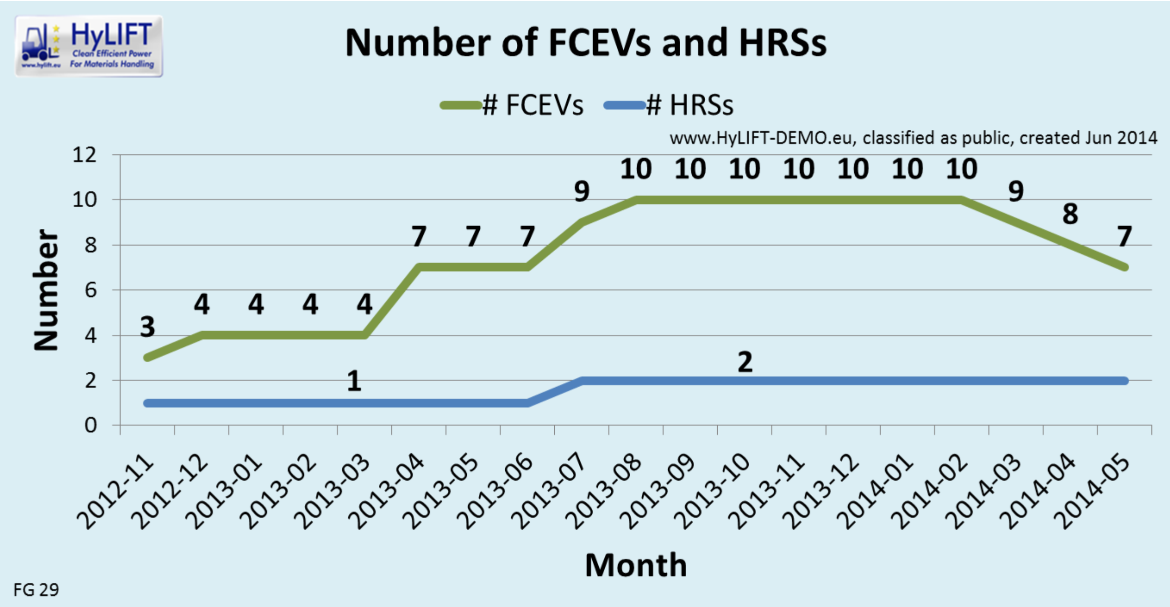


Figure 16: Number of fuel cell electric vehicles and hydrogen refuelling stations in the HyLIFT-DEMO project

Throughout the project, the FCEVs were operated for more than 12,413 hours. This corresponds to more than 2,200 work shifts.

Figure 17: Cumulative operation hours of vehicles in the HyLIFT-DEMO project

Over 12 consecutive months, the availability of the vehicles was 95.01% on average.

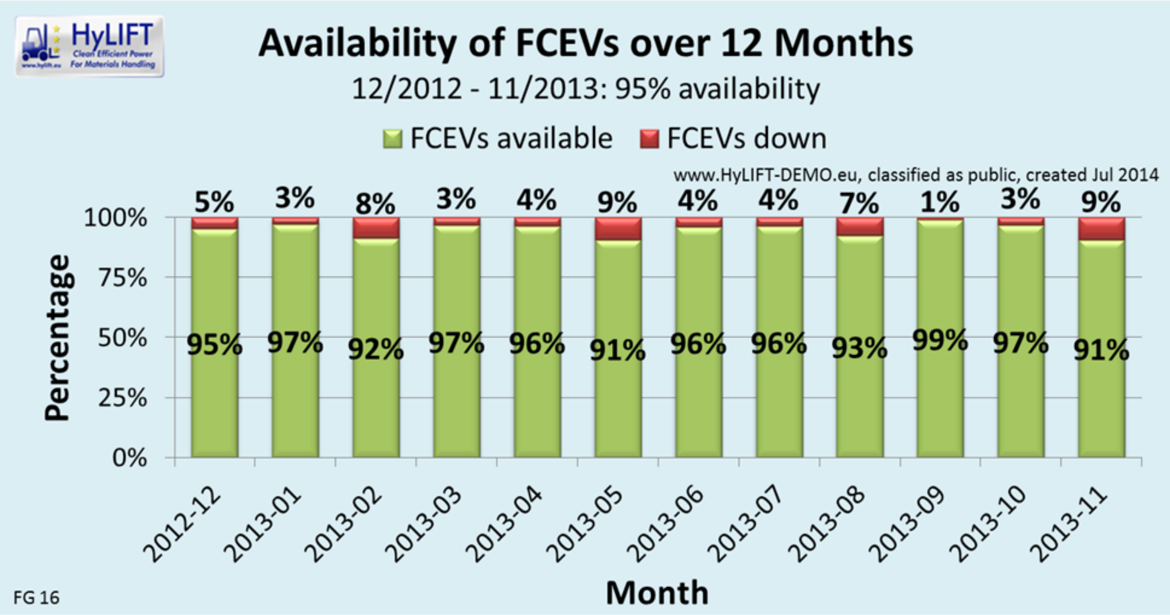


Figure 18: Availability of vehicles in the HyLIFT-DEMO project

The HRS availability throughout the project is 99.5 %.

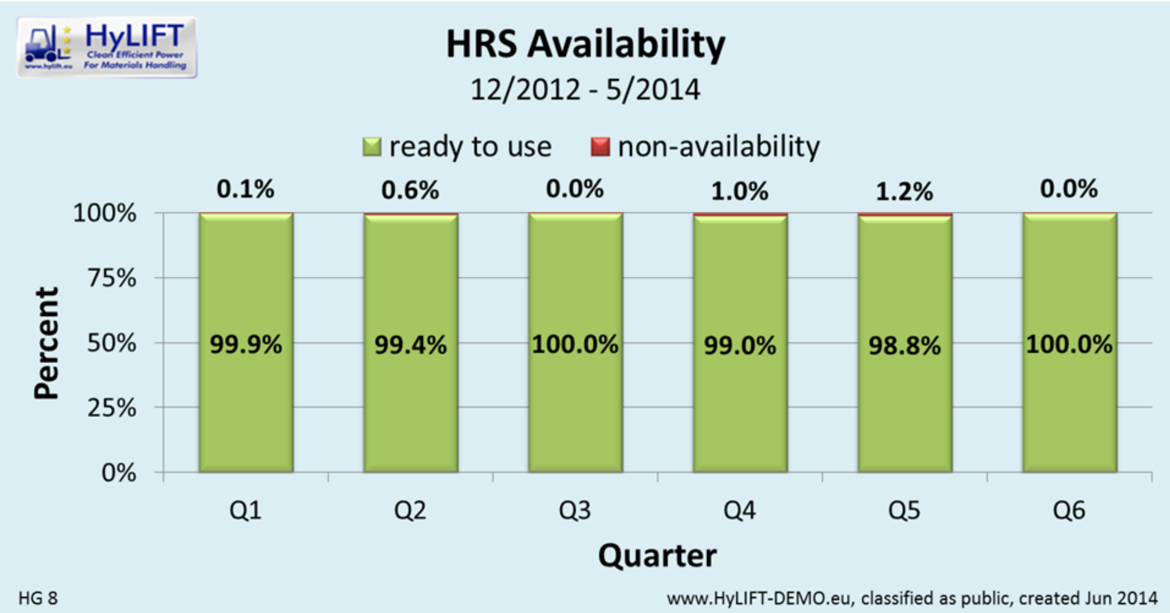


Figure 19: Availability of hydrogen refuelling stations in HyLIFT-DEMO

94% of all HRS down-times were repaired within 24 hours.

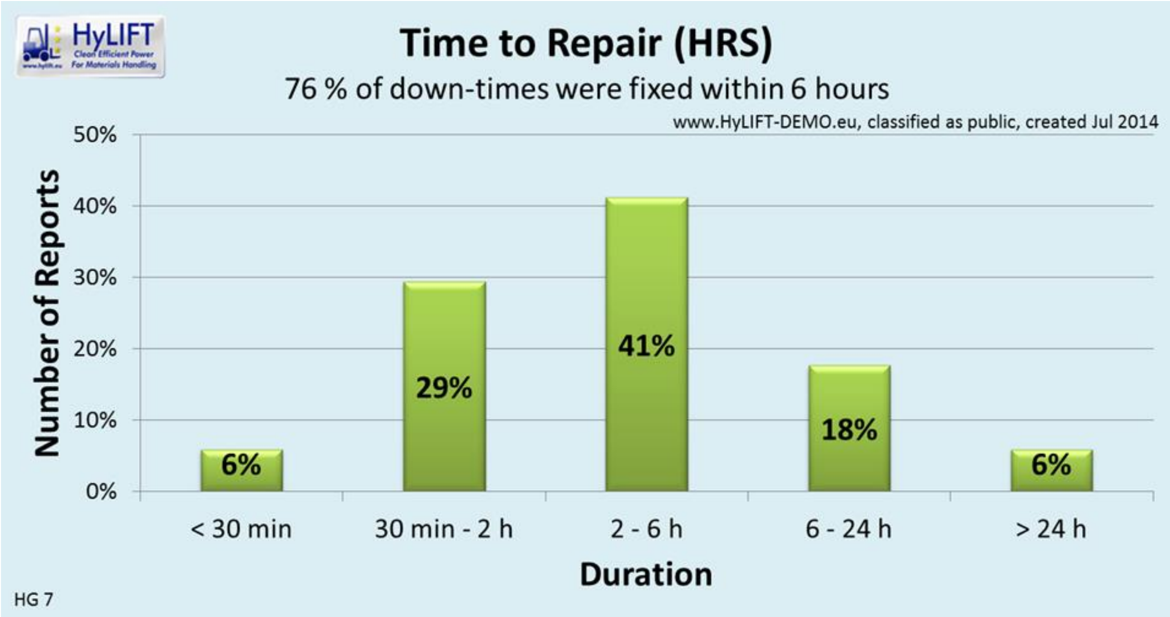


Figure 20: Time to repair of hydrogen refuelling station in HyLIFT-DEMO

When comparing data from HyLIFT-DEMO with NREL data, most results are comparable. One example is the average duration per non-availability which is slightly better for HyLIFT-DEMO.

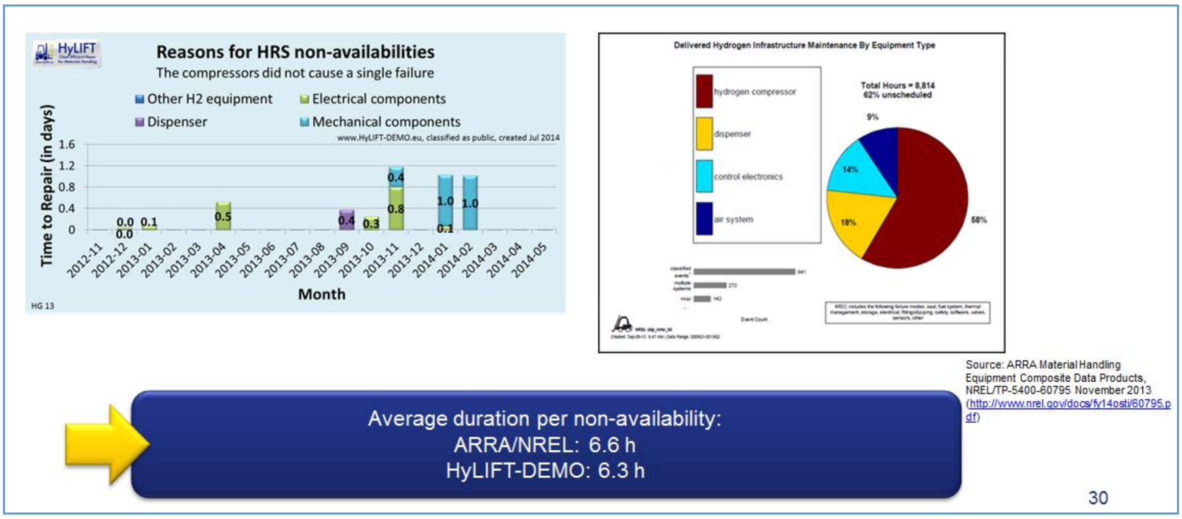


Figure 21: Comparison of average duration per non-availability between NREL and HyLIFT-DEMO

<u>Long-term testing</u>

This task was unable to meet its specified objective of 4,000 hours of fuel cell system testing. Several problems have beleaguered the system testing rig: a burst hydrogen line from the electrolyser to the purification unit in January 2013, a pump failure in the refuelling station that was providing the compression for the system in March 2013, and another burst hydrogen line in the purifier in May 2013. In summer 2013 the limited cooling capability of the container housing the equipment (including a 40 kW alkaline electrolyser) hampered operation. Later, issues with control of the refuelling procedures surfaced and caused further delays, since without automated refuelling the system could be run only a few hours at a time; in particular, some safety safeguards designed for manual operation had to be worked around.

Figure 22: Durability test rig

The rig was finalised in spring 2014, but the limited time available until the end of the project made it impossible to achieve 4,000 hours testing; the system had until then logged 1,200 hours in total. At the same time, it was known that several forklifts had been operating in field tests for up to 2,500 hours at the Copenhagen site. The issue was presented to the coordinator and discussed with the project manager at FCH JU, and at the General Assembly meeting of 20 May 2014 it was decided that the long-term testing activity would be discontinued, as monitoring of forklifts in real operation provided already more data than what could be provided by the test rig. The operation of the test rig was demonstrated live at the same General Assembly meeting via remote desktop. The delays had no impact on other activities of the project, as no other activity depended on it. A significant result of the activity was a direct consequence of some of its difficulties: it was noticed that the H2Drive system, when subjected to the load profile specified in the course of the project, would regularly trip because of undervoltage or overvoltage. Since this problem did not occur in the forklifts deployed at the demo sites, it was concluded that the prescribed test protocol cannot be representative for real operation conditions.

<u>Vibrational tests</u>
The vibrational tests suffered several delays initially, but could be completed finally. The task showed that the H2Drive's compressor was very vulnerable to vibrations at low frequencies (10 to 30 Hz) and all directions. Other vulnerable components were the tank valve, the DC-DC converter and the receptacle. By the end of the vibrational tests, the battery had heavily damaged the unit, which had to be shipped back to H2 Logic before further tests could be performed.

<u>Validation of attainment of pre-commercial targets</u>
The validation of the customer acceptance was happening throughout the project. Through the project it became clear that there are different interests among the stakeholders within a customer company.

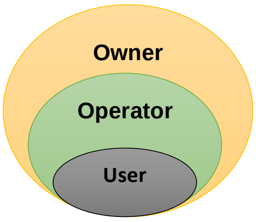


Figure 23: Various stakeholders within a customer company

Owner: The person responsible for the costs of the fuel cell forklift truck; concerned about green branding and HSSE (health, safety, security and environment); responsible for additional costs of fuel cells compared to conventional technology

Operator: The fleet manager that has the responsibility to move goods with forklift trucks; concerned about performance, reliability and operation costs (service, fuel and time wasted to refuel or service trucks)

User: The drivers of the trucks; concerned about the power, the noise and vibrations of the trucks, and the operation time between each refuelling

The User targets were met in the HyLIFT-DEMO project. The power of the trucks is better than that of batteries, and the drivetrain is as easy to use as batteries. The refuelling is easier than battery change or charge, which is positive from the User's point of view.
The Operator targets have to some extent been met. The operation costs at STARK is an example of not meeting the targets, since fuel consumption was about 30 % higher than expected. The detailed analysis showed that the reason was that users run the electrical heater 24/7. The performance of the trucks at the egetæpper demo site was acceptable; Colruyt and STARK experienced downtimes higher than they would accept for a commercial product.
The Owner target was overall met. Zero emissions, HSSE improvements and the CAPEX of the project were in line with expectations. However, reports from Operator to Owner tend to make the Owners consider the demonstration as semi-successful.

Recommendations for future large scale demonstrations are quite clear: focus on the Operator.

- Improve reliability of the fuel cell systems and trucks
- Reduce the price of fuel cell systems by up-scaling of production
- Enable large sites with high utilisation of the HRS → lower H_2 prices
- Include gas companies for the supply of H_2 from the very beginning of the project

WP7 - Securing & planning commercialisation

WP Leader – H2L

Securing and planning of commercialisation for hydrogen and fuel cell technology in the materials handling sector turned out as one of the most difficult tasks in the course of the HyLIFT-DEMO project as technology is still too immature for immediate full commercial deployment in the next step. Instead, further large scale demonstration projects such as HyLIFT-EUROPE and HAWL as well as appropriate deployment support mechanisms are urgently required.

Nevertheless, the project managed to collect some focal points to be dealt with in the further approach of fuel cell materials handling vehicle commercialisation. The summarized focal points to be addressed are:

- End-user sensitivity to the hardware costs
- Requirements to service platform (local, 3rd party, fast reaction, etc.)
- Viable hydrogen supply solutions
- Scale up from small start-up fleets to large fleets
- Cost reductions (total cost of ownership - TCO)

The main technical objectives to ensure commercial viability for both fuel cell systems and hydrogen infrastructure are already starting to firm up.

- Fuel cell system:
  - Reliability: 98%+ availability ➔ ongoing
  - Reproducible manufacturing quality ➔ starting
  - Cost reductions through re-engineering and scale-up ➔ awaiting
  - Target price for 10 kW system: <25,000 € ➔ possible

- Infrastructure:
  - Reliability: 99%+ availability ➔ ongoing
  - Min. refuelling to 95% nominal capacity ➔ ongoing
  - Target price for 20 kg/day HRS: <200,000 € ➔ possible
  - Hydrogen delivered at ~6 €/kg ➔ onsite / delivered

<u>Business case considerations small versus large fleets</u>

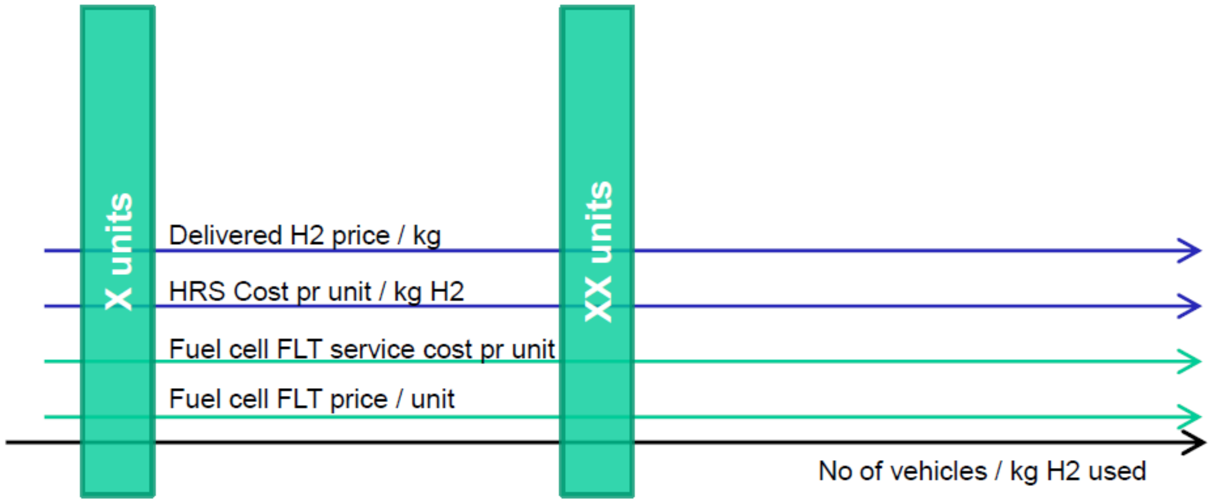


Figure 24: Customer interest in fleet growth

- X units … then evaluation of economics after period of 1-2 years
- XX units … then evaluation of economics after period of n years

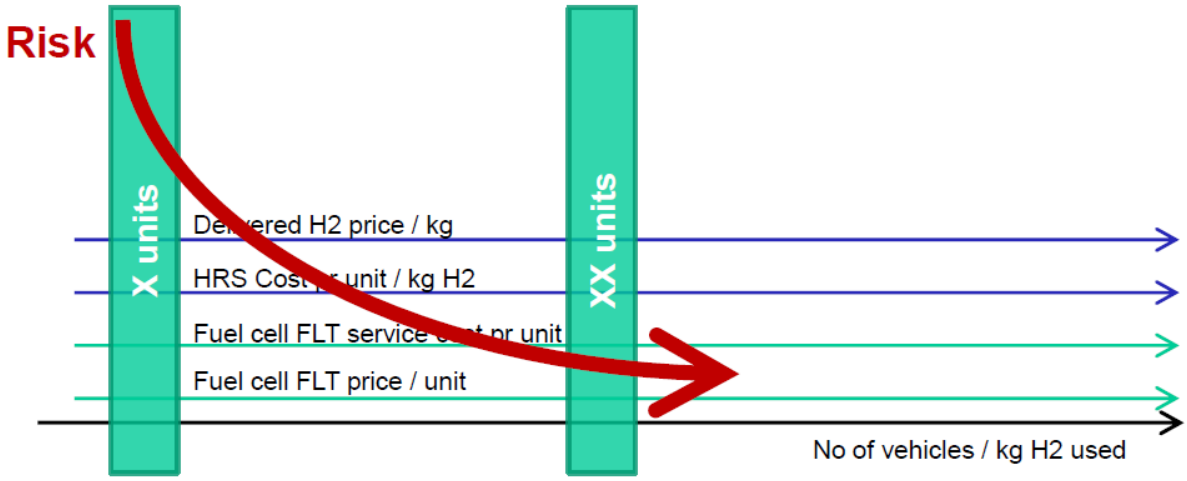


Figure 25: Financial risks drop by number of units in operation

- Risk on forklift trucks can be covered by public financial support
- Risk on hydrogen and hydrogen refuelling stations is not covered by public financial support

Considerations for planning the commercialization of fuel cell materials handling vehicles in Europe:

- The risks associated with market initiation of fuel cell technology in the materials handling sector was shown by Plug Power in the USA
- A similar approach is currently happening in Europe
- The risk handling at the beginning of market deployment is impossible for SMEs
- The public funding can be a good support and give good IRR in the long run, but taken such risks is typically a task for large companies
- The potential for large fleets can be exploited if other (smaller) FLT sizes are taken into account as well, but then the technology to be outrivaled is no longer ICEs but batteries
- In the HyLIFT-DEMO follow-up project HyLIFT-EUROPE this becomes already clear now, and the set-up of the project has to be changed after recognition of this matter

1.6 Utilization of project results

The activities from the HyLift-Demo project are valuable knowledge and experiences for the partners. For the main Danish partner, H2 Logic A/S, the outcome are two folded.
The activities within H2Station (hydrogen refuelling stations) have shown to be performing to a level expected from a commercial product. Availability of 99,7% is state-of-art and has been widely recognized. The product, H2Station MH-100 is a direct outcome from the project, and this product is already on sales for materials handling customers around Europe. The next steps for H2Station MH-100 will be maturation and cost reduction activities.
The activities within H2Drive (fuel cell systems for materials handling) has shown to be close to a commercial target with respect to performance, but it is also reconized that activities within cost reduction are required. H2 Logic A/S has in June 2014 decided to focus its activities on H2Station development and production. H2 Logic has established a consortium that will continue and commercialize the H2Drive activites. The consortium consists of Dantherm Power A/S and Taiwanese company, M-Field. Dantherm Power has experiences with cost reduction of fuel cell systems from the backup power business, and will use these experiences to make similar activities within H2Drive.

1.7 Project conclusion and perspective

The overall conclusion of the HyLift-Demo project is that the project was a success. The project partners managed to get fuel cell systems and supporting hydrogen refuelling stations in real life operation for thousands of hours, and the project proved the benefits of using fuel cells in materials handling.
The project also conclude that introducing fuel cells in materials handling will only be a commercial success if the complete TCO is cheaper that comparable diesel/LPG trucks. It is also experienced through the project, that costomers benchmark more towards battery operated trucks than Diesel/LPG, and this makes the fuel cell target even more challenging.
Experiences from the hydrogen refuelling stations are that the technology is performing and becoming mature. The challenge is however that a sufficient number of materials handling vehicles are required to justify the investment in the refuelling station.

The HyLift-Demo project is co-funding by EUDP, Fornyelsesfonden and FCH-JU. The co-funding was a rather new activity, and it has shown to require multi fold of administrative work to support all funding authorities. The reporting periods are not aligned, the requirements when changes are made are different, and cost statements has to be made in different ways for the authorities. Co-funding of 2 programs might be recommendable, by co-funding rom 3 authorities are not recommended for future projects.