HyLIFT-FLEX

»Development & demonstration of flexible & scalable fuel cell power system for various material handling vehicles«

PUBLIC PROJECT END REPORT
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Fuel Cell TowTractor from MULAG with H2Drive ©

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Executive summary

The project has successfully developed and tested a new fuel cell system from H2 Logic in a tow tractor from MULAG.

Based on the project results a positive decision has been taken on continuing commercialisation efforts. Next step will be a large scale demonstration of up to 100 units in a new project named HyLIFT-Europe that is expected to commence in early 2013, with support from the FCH-JU programme.

Main efforts in the project have been the development of a new fuel cell system, named H2Drive® from H2 Logic, and the integration and test in a standard battery powered COMET 3 towing tractor from MULAG.

The picture below shows the developed H2Drive® fuel cell system.

The system size is exactly the same as a standard battery box (DIN measures) and can be easily integrated into e.g. the MULAG vehicle or other electric powered material handling vehicles using the same battery size.

Several R&D efforts on the fuel cell system have been conducted with the aim to reduce cost and improve efficiency, among others the following:

- New air compressor sub-system & control - improving overall system efficiency with ~2,5%
- New simplified air-based compressor cooling sub-system
- New hydrogen compressor sub-system with improved efficiency & reduced cost
- New hydrogen inlet and outlet manifold sub-system - resulting in reduction of more than 50% of all sensor components in the fuel cell system
- New DC/DC converter with an average efficiency of 97% - a 3% improvement
- A new optimized hybrid system that meets the vehicle cycle requirements

In total the R&D efforts have improved the overall fuel cell system efficiency with 10% and helped to reduce costs with 33% compared to the previous generation.

A first prototype of the developed H2Drive® system has been constructed and integrated into the MULAG Towing Tractor.

Only few modifications were made on the base vehicle, among others integration of cabin-heating, displays and motor control.

The picture below shows the vehicle in test operation with H2Drive®.

Several internal tests were conducted at H2 Logic and MULAG before making a first trial at Hamburg Airport in late 2011. The vehicle showed satisfying performance and further tests at other airports are planned to be conducted during 2012.

Dansk sammendrag

Projektet har succesfuldt udviklet og testet et nyt brændselscelle system fra H2 Logic i en lufthavnstraktor fra MULAG.

Baseret projektresultaterne er en positiv beslutning truffet om at fortsætte bestræbelserne på kommercialisering. Næste skridt vil blive en storskala demonstration af op imod 100 stk. i et nyt projekt kaldet HyLIFT-EUROPE som forventes opstartet i 2013 med støtte fra FCH-JU programmet.

Hovedaktiviteten i projektet har involveret udviklingen af et ny brændselscelle system kalde H2Drive® fra H2 Logic, samt integration og test i en standard batteri drevet COMET 3 lufthavnstraktor fra MULAG.

Billedet nedenfor viser det udviklede og færdige H2Drive® brændselscelle system.

Systemet har præcist de same dimensioner som et standard batteri system (DIN) og kan derfor let integreres i eksempelvis MULAG køretøjet eller andre eldrevne arbejdskøretøjer som anvender samme batteristørrelse.

Adskillige F&U aktiviteter er blevet udført på brændselscelle systemet med henblik på at reducere pris og øge effektiviteten, bl.a.:

- Ny luftkompressor system og styring – ~2,5% effektivitetsforbedring
- Ny og simplificeret luftbaseret kompressor kølingssystem
- Ny hydrogen kompressor med forbedret virkningsgrad og reduceret pris
- Nye hydrogen inlet og outlet manifolds resulterende i en reduktion af sensor komponenter i brændselscelle systemet med mere end 50%
- Ny DC/DC konverter med en gennemsnitlig effektivitet på 97%, en forbedring på 3%
- Nyt optimeret hybrid system som matcher køretøjets behovscyklus

Samlet set har F&U aktiviteterne forbedret virkningsgraden for det samlede brændselscelle system med 10% og bidraget til at reducere prisen med 33% sammenlignet med den tidligere system generation.

Som en del af projektet er en første prototype af det udviklede H2Drive® system er blevet konstrueret og integreret i MULAG lufthavnstraktoren.

Kun få modifikationer blev foretaget på basis MULAG køretøjet, bl.a. integration af kabinevarme, display og motor styringen.

Billedet nedenfor viser det færdige køretøj med H2Drive®under testkørsel.

Adskillige interne test er blevet gennemført hos H2 Logic og MULAG før den første test blev foretaget ved Hamburg lufthavn i slutningen af 2011. Køretøjet viste en tilfredsstillende drift og yderligere tests er under planlægning i løbet af 2012 hos adskillige andre lufthavne i Europa.

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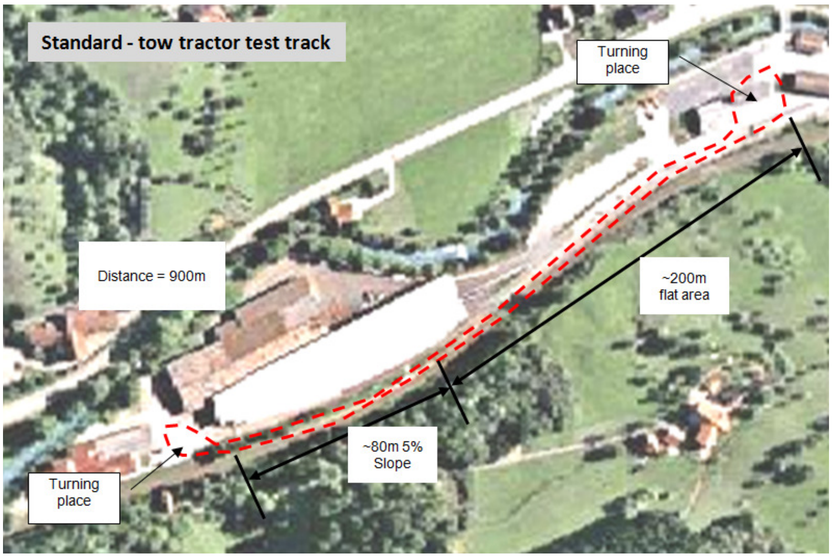
WP1 – R&D & Product Specification & Planning

WP1 involved a specification of the R&D activities in the work packages and conducting of the overall product specifications and targets that were to be achieved.

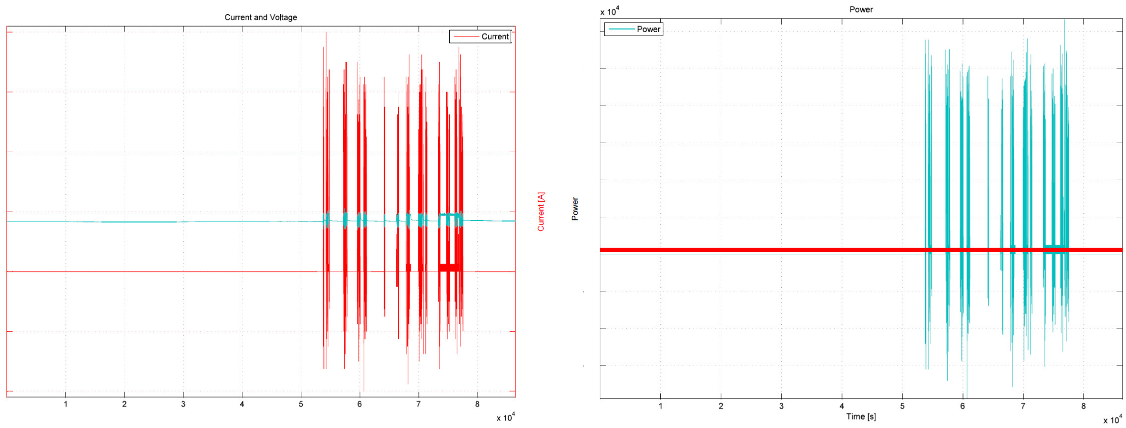
First effort involved understanding the power requirements in a tow tractor environment, with the aim to conduct the overall sizing of the fuel cell system

Data logging was therefore conducted on MULAG tow tractors in the airports of Berlin, Stuttgart and Dusseldorf. Also data logging was conducted on the standard tow tractor test track at MULAG (shown in picture). The test track reassembles the most extreme driving cycles that a vehicle can meet across various airports.



In particular focus for the data logging was the current and voltage cycles and the power consumption. Based the compiled data, requirements for average and peak power delivery of the fuel cell system could be defined. Figure below shows a logging example of a current/voltage curve (left) and a power curve (right).

Tow Tractor data logging | Current/voltage & power curves



With the overall power specification available a more detailed technical specification was developed for the complete fuel cell system. Selected overall technical specifications are shown in the table below:

Make	H2 Logic
Model	**H2Drive®**-10-3-DIN, 80V
Type	LT-PEM fuel cell hybrid system
Avg. power output	~10 kW
Max. power output	~35 kW for 15 sec.
System efficiency	>48% @ 10 kW
Hydrogen storage capacity	~1,5 kg @ 350 bar
Battery storage capacity	100 Ah
Run time on full tank	5-6 hours / 1 working shift
Refuelling time	3-4 min.
Approval	CE marked & TÜV Süd certified
Hydrogen fuel quality	N35 (no CO, CO2 or S)
System dimension (DIN 43536-98 80V, Layout A)	711x1028x738 mm

Based on the overall technical specifications, detailed specifications were conducted for each of the sub-systems and components of the fuel cell system.

The detailed specification of components enabled the formulation of an overall R&D activity plan across the across the WPs. The plan and the specifications were used through-out the project as go and no-go decision tool. If a certain technology, component or subsystem would not meet the specifications or would cause the entire system/product to fail, alternatives would be chosen or developed instead before proceeding. This turned out to be the case for the air compressor to be developed by Svenska Rotor Maskiner AB and the hydrogen storage by DanaTank.

Due to internal restructuring of Dantruck during the project, it was decided not to specify or include the 5+tons forklift trucks in the specifications & R&D. Dantruck later left the project and eventually the company winded down all operations.

WP2 – R&D of air & hydrogen supply components

WP2 involved the following R&D activities:

- Task 2.1 R&D of new air compressor
- Task 2.2 R&D of air humidification direct during compression
- Task 2.3 Investigate opportunities for hydrogen compression

Task 2.1 R&D of new air compressor

Overall objective were to use compressor technology from Svenska Rotor Maskiner AB (SRM) as a basis for developing a new air compressor optimised for use in the H2Drive fuel cell system.

As first step air compressors from different manufacturers were tested and bench-marked on several parameters, among others:

- Total efficiency
- Compressor durability
- Noise & Vibrations
- Heat
- Controlling
- Size

All the compressors where tested at the same operating points.

The benchmark test also included the technology from SRM. Surprisingly the test showed that the SRM technology could not match the best performance of one of the other compressor suppliers. Based on the results SRM decided not to continue R&D activities within the project.

Instead a new compressor supplier was selected, which provided a better efficiency of 2% compared to the existing compression technology.

The new compressor used a standard controller which was not optimized for fuel cell use. To improve the total efficiency of the system, a new controller for the air compressor was found. This controller was capable of direct connection to the bat-teries and thereby resulting in an efficiency increase of the system by ~0,5%.

Task 2.2 R&D of air humidification

Originally the objective was to develop a new water separator system connected to the compression system. In comparison with other compressor technologies/suppliers the technology from SRM could enable this. However as SRM was not chosen as compressor supplier (see task 2.1) efforts were instead focused on optimizing the existing compressor cooling system.

The lower efficiency of the old compressor required a water cooled system. With the new compressor and the higher efficiency air cooling alone would be sufficient.

The old cooling system was a specialised in-house manufactured component due to the cooling requirements. With the new compressor an off-the-shelf air-cooling component could instead be used. Furthermore the new air compressor was mapped resulting in removal of flow measuring components.

Task 2.3 Investigate opportunities for hydrogen compression

It was to be investigated if the SRM air compressor developed in tasks 2.1 could be used for hydrogen compression. As SRM technology was not selected, the efforts instead focused on alternative ways to improve the hydrogen compression system.

As a first step hydrogen compressors available on the market were investigated with regards to a number of design parameters among others:

- Deliver a high enough recirculation flow at all currents
- Suitability for wet hydrogen
- High efficiency
- Volumetric size

The conclusion of the investigation was that none of the compressors available on the market could meet the requirements.

It was therefore decided to aim for a new hydrogen recirculation strategy and to develop a new compressor together with a supplier. The new setup of compressor gave a higher system efficiency and better operation suitability. Also the system proved to be cheaper and more robust. A strategy for operating the new hydrogen compressor setup was also developed.

WP3A – R&D of H2 manifold with integrated BoP

The objective of WP3A was to develop and construct a new hydrogen manifold that enables integration of the balance-of-plant components (BoP) into one manifold.

As a first step the original fuel cell balance of plant (BoP) system and components were evaluated, in particular with regards to sensors. The effort revealed that many sensors were obsolete and could be removed because of improved knowhow about the system and simplification of controls. Also each sensor function was thoroughly investigated to see if each could be used for other functions than it was original used for or if it simply could be removed.

This evaluation exercise resulted in:

- Removal of 80 % of the sensors in the cathode module
- Removal of 66 % of the sensors in the fuel cell module and various components
- Removal of 50 % of the sensors in the cooling module and removal of 75 % of various components.
- A new designed safety controller also enabled removal of dual sensors

In total the removal of the sensor components resulted in cost and space reduction which again has improved the physical footprint of the system.

Based on the BoP component set-up (with fewer components), new manifolds were designed, with the aim of integrating as many components as possible.

On the new inlet manifold the number of transmitters has been reduced, and the construction has been simplified which have helped reducing cost of production.

The new outlet manifold is more complex due to an integration of many components. The hydrogen channels in the manifold are more integrated with the other components in this loop. This resulted in a reduction of hydrogen fittings, at the same time provides significant space and cost reduction.

Prototypes of the new inlet & outlet manifolds were made and tests conducted via implementation in an H2Drive fuel cell system. The tests lead to a review of the design that resulted in an even more robust system with fewer ports and less size which again lowered the price.

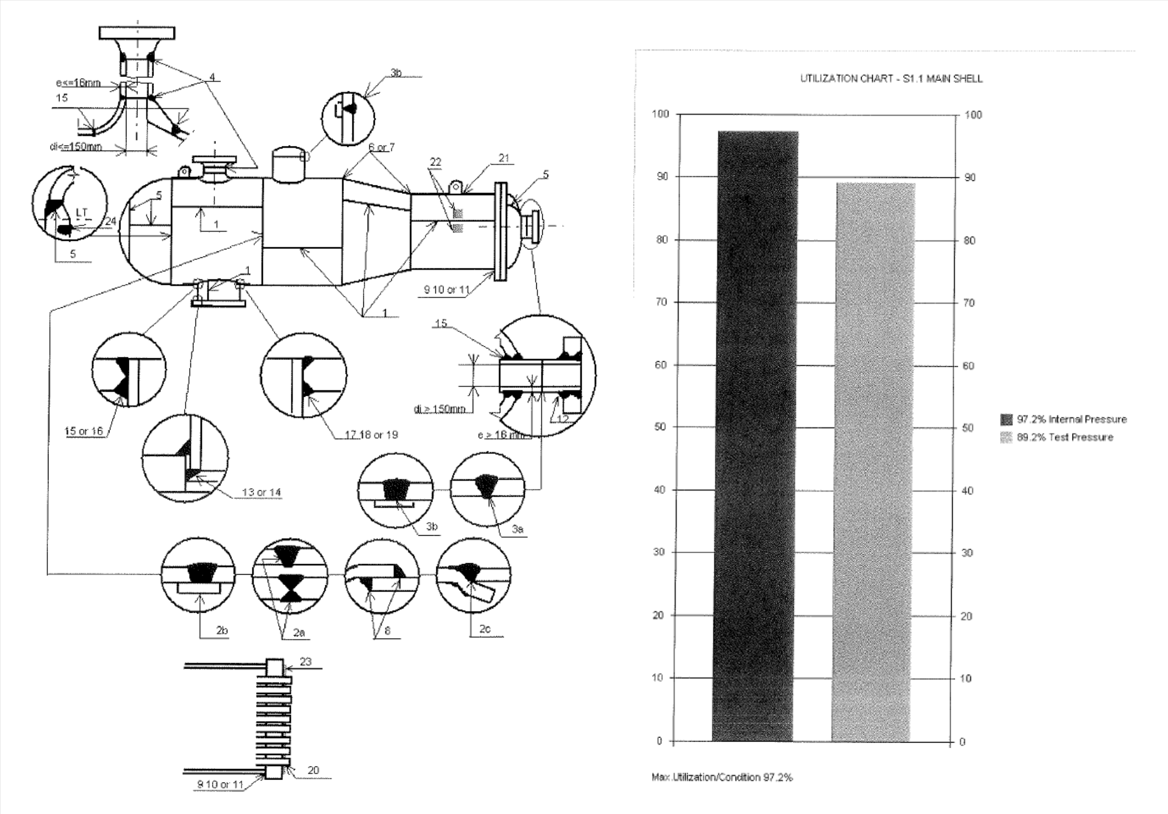
WP3B – R&D of hydrogen storage vessel

The objective of WP3B was to develop and construct a new 350bar low cost and flexible hydrogen storage vessel based on existing storage technology from DanaTank A/S. This could help reduce cost of the onboard storage in comparison with present use of available storage vessels on the market.

A design process was conducted by DanaTank focusing on the following topics:

- Calculation of material thickness to enable higher working pressure
- Specification of test cycles
- Develop design suggestions for vehicle integration

The figure below shows the final design for a 35MPa storage vessel.



A manufacturing and costs evaluation was made of the design. This showed that at a sufficient high volume the vessel would be more cost competitive compared to available vessels on the market. However the volume level required would not be reached within the coming 3-4 years deployment of fuel cell vehicles.

Also extensive deep-cycling tests would need to be made in order to test the stress levels of the materials when used onboard a vehicle.

It was therefore decided not to continue with the design and test of a prototype.

WP4 – R&D of fuel cell hybrid system

WP4 involved the following R&D activities:

- Task 4.1 Specification of overall system design
  A detailed specification was conducted based on WP2 and results/input from WP3, WP4 and WP5.
- **Task 4.2 Development of hybridization & power management module**
  A detailed reporting is provided in later sections
- Task 4.3 Development of overall control system module
  A new system control strategy was developed to obtain better system life-time and better power management. The new layout of the system and the new components resulted in new control strategies to control pressure, flows, temperatures and power management.
- **Task 4.4 Development of system packaging design**
  A detailed reporting is provided in later sections
- **Task 4.5 Construction of fuel cell hybrid system prototype**
- *A detailed reporting is provided in later sections*

In total the R&D were to results in the construction of a new prototype fuel cell system ready for integration into a towing tractor in WP5.

On the following pages are provided a detailed report of the tasks 4.2, 4.4 and 4.5 which were the main tasks in WP4.

Task 4.2 Development of hybridization & power management module

This task involved development of a new DC/DC and a hybrid system.

DC/DC

A new buck-boost DC/DC converter was developed with outstanding efficiency up to 98% and in average 97%. The higher efficiency removed the need for liquid cooling and an air fan could be used instead, thus helping to simplify the system. In total an efficiency gain of ~3% was achieved compared to the old DC/DC system.

The new DC/DC has a modular design with enables a flexible scaling of power output, thus matching future systems with varying rated power. The design also enables a more optimal control resulting in higher efficiency in a wide range of power outputs. The modular design also enables continued operation if one module fails.

Hybrid system

For the hybrid system extensive evaluation was conducted with regards to selection of battery technology. This was done by contacting various suppliers of batteries and discussing their maturity and usability in the fuel cell system.

As only a small battery capacity was needed but a very high power output, it would not be possible to use standard forklifts batteries. The small capacity was needed because of battery volumetric size and because the battery energy was only partly needed when the fuel cell system was running.

In advance of the project extensive evaluation of lithium-ion batteries had been conducted. This showed that controlling this type of batteries at the relative high currents compared to the battery pack capacity was very difficult. This had to do with battery safety, battery management system and balancing of individual battery cells. Furthermore it was a quite expensive technology.

Despite of the small battery capacity required, the use of super capacitors was evaluated not to provide sufficient energy. Capacitors also proved to be an expensive technology especially per energy capacity.

Lead acid batteries were therefore chosen as battery pack due to stability, space and cost. Lead acid is very well proven technology, but it has its limitations. Therefore, a new control strategy for the battery system was developed with the aim to handle fast transients. A power resistor was also included enabling the vehicle to drive down hill (regenerating) even when the batteries are fully charged. An evaluation of different lead-acid batteries was also conducted, with the aim of ensuring highest possible energy per volume and the ability to handle high C-rates.

The design and final packaging of the hybrid system however became a challenging task due to selection of standard lead-acid batteries. This did not leave much space for the fuel cell components. But after various iterations and optimizations the components were all packed in a box equivalent to the battery size. This system integration design is further elaborated in the following section.

Task 4.4 Development of system packaging design

Based on the R&D results from WP2, WP3 and the WP4 tasks a new system packaging design was developed. The aim was to ensure a fit into the tow tractor in WP5, where the requirement provided was the dimensions of a standard battery box. The battery box size and design gave some challenging constrains for the fuel cell packaging, in particular with regards to integrating all fuel cell components. However after several design iterations in 3D a system packaging design was concluded.

Task 4.5 Construction of fuel cell hybrid system prototype

Based on the system design from task 4.4 a first prototype system was constructed. The prototype was used for vehicle integration and tests in WP5. During the manufacturing several design modifications were made with the aim to optimize future manufacturing.

The picture below shows the finished H2Drive system prototype.

WP5 – Vehicle integration & field test

The objective of WP5 was to integrate the H2Drive fuel cell system in a towing tractor from MULAG and conduct field test at a German airport to verify reaching of performance targets.

The existing battery powered MULAG COMET 3 towing tractor was selected as base model. Firstly an evaluation was made, with regards to necessary vehicle changes in order to integrate and connect the fuel cell system. Despite the fuel cell system matching the physical size of the standard battery box, a few modifications were necessary on the base towing tractor.

Among others a service charger and air venting surface had to be integrated into the vehicle chassis design. Also cabin heating were to be integrated with the fuel cell enabling utilization of the waste heat.

The motor control was also modified to fit with the hybrid system, and a display for the fuel cell system integrated inside the vehicle (shown in picture below).

The first actual integration of the fuel cell system also resulted in a number of design revisions of the integration.

Before commencing of tests at airports an internal performance test was conducted both at H2 Logic and at MULAG. This lead to a number of system optimizations before releasing the vehicle for airport tests.

The pictures below show internal vehicle tests at both H2 Logic and MULAG.

MULAG Comet-3-FC with H2Drive®
9,5T towing test at @ H2 Logic

MULAG Comet-3-FC with H2Drive®
Performance test at standard test track at @ MULAG

In late 2011 (before project end) the first field test was conducted at Hamburg Airport. The vehicle showed satisfying performance. Further tests at other airports are planned to be conducted during 2012 after project end.

MULAG Comet-3-FC with H2Drive®
Performance test at Hamburg Airport

WP6 - Planning commercialization & dissemination

Objective of WP6 were to plan and prepare a following commercialization of the fuel cell systems after project end. This included the following sub-tasks:

- Task 6.1 Production integration investigation & planning
- Task 6.2 Service platform considerations
- Task 6.3 Sales strategy & shaping of value proposition & product set-up
- Task 6.4 continuous dissemination throughout the project

A short reporting of each task is provided in the following sections.

Overall significant efforts have been spent on analysing and preparing the business platform for continued efforts on fuel cell powered tow tractors. Detailed TCO calculations have been made in collaboration between MULAG and H2 Logic. This has shown a very strong and near term commercial potential.

Decision has therefore been taken to move to the next step, which is a large scale demonstration project. European funding was therefore applied for in August 2011 on demonstration of up to 100 units in a project named HyLIFT-EUROPE. In late 2011 the project was selected for funding negotiations which are still ongoing. Expected project start is in early 2013. The large scale demonstration can help increase volume and contribute to cost reductions onwards reaching a competitive market price through further supported market deployment.

Task 6.1 Production integration investigation & planning

Production considerations of both the modified MULAG vehicle and the H2Drive® from H2 Logic have been conducted. Necessary interfaces between vehicle and the H2Drive® has been documented and processed at MULAG and H2 Logic.

These preparations have been conducted with the aim of enabling volume production for the following large scale demonstration, as elaborated elsewhere.

Task 6.2 Service platform considerations

Part of the preparations for large scale demonstration also included considerations on service platform. Given the very simple interface between the vehicle and the H2Drive® the service interfaces are correspondingly very clear.

MULAG conducts service of the base vehicle with the same service platform as today. MULAG service personnel is also trained in conducting simple service of the H2Drive®, in particular in conducting simple fix of errors or break-down in field. Regular and scheduled maintenance as well as advanced service in-field is conducted by H2 Logic personnel. In total this enables a very lean service set-up where as much as possible of the existing MULAG service platform is used.

Task 6.3 Sales strategy & shaping of value proposition & product

Detailed Total Cost of Ownership calculations for the fuel cell tow tractor have been conducted. Despite the vehicle/fuel cell cost (CAPEX) will be higher than e.g. LPG/diesel powered vehicles the higher energy efficiency reduces fuel costs (OPEX) and facilitates the achievement of competitive Total Costs of Ownership (TCO).

The TCO takes into account all expenses of owning and operating a material handling vehicle and is therefore the main selection criteria for end-users, thus fuel cell vehicles must be cost-competitive on a TCO basis. The calculations were made for vehicles with an average operation level and average fuel consumption (based on vehicle manufacturer data).

The calculations showed that a supported large scale demonstration will enable fuel cell vehicles to match the TCO of LPG powered heavy-duty forklifts and reach TCO in between diesel and diesel-hybrid powered airport tow tractors. Within airport tow tractors there is a trend towards switching from diesel to diesel-hybrid in order to reduce the overall emissions footprint of airport operations. The 2015+ targets for fuel cell vehicles are to reach a TCO level that is fully competitive with diesel without any public support. The calculations also showed that batteries always have the lowest TCO, but the majority of vehicle-users still choose LPG/diesel due to the inconvenience of batteries.

Task 6.4 continuous dissemination throughout the project

Dissemination of the project results throughout the project has mainly focused on potential end-users at Airports.

Meetings have been held with several airports in Europe. Main purpose of the meetings has been to plan a test-trial of the MULAG tow tractor and ensure their interest for joining the later large scale demonstration project (HyLIFT-Europe).

In total support letters for joining the HyLIFT-Europe was secured from 13 organisations that are potential customers for the MULAG tractor. The organisations cover various airports and industrial companies with a combined fleet of 1.500 vehicles.

To support the dissemination a product brochure has also been made of the MULAG COMET-3-FC vehicle: http://www.h2logic.com/h2drive/mulag_comet3fc-tow-tractor_ENG_web.pdf

Also the vehicle was exhibited at the InterAirport exhibition in Munich. The picture to the left shows the exhibition booth, with the fuel cell tow tractor to the right.