Table of content

In this section of the report we will go through all the technical work packages and the tasks involved.

WP2 –R&D specification & evaluation.

The objectives of this work package are:

Specification and planning of R&D and conducting midterm evaluation of performed R&D as well as evaluating if we reached the targets by end of project based on the laboratory testing conducted.

Since this Work Package is more or less the conclusion of the project only the results at the end of the project will be presented.

We have had a lot of challenges during the project and experienced severe time pressure especially with regards to Materials Handling - but in the end we managed to succeed or come very close to the targets we initially set up. So we definitely consider the Liquid Power project a success. In the table on the next few pages the most important Project targets will be presented along with a status at end of project and comments where required.

Project objectives and achievements at end of Project

Project objectives/ targets	**Status at end of Project**	**Extra comments/explanation**
Materials Handling price below €1.800/kW @ 5.000 unit production	Low end – Fuel Cell System, small basis H2 Storage, indoor MH system 10-15kW range is priced at 1.650€/kW High end – Fuel Cell System, large H2 storage, outdoor system – 15kW is priced at 2500kW/kW.	It's required to describe the price as a range instead of a fixed price. One price will represent the basis module which fits some customers and one price that fits the customers known to have the largest set of requirements.
Material handling fuel cell system efficiency 52-55%	**FC System Efficiency** is based on the "high end" balance of plant system. This is expressed by Estimated H2 η to Net Power of 43,6% at Beginning of Life (@288A) to 37,4% End of Life. Without DCDC converter we can at 10 kW output achieve H2 η to Net Power 52.479% Beginning of Life at 150Amps.	

Material Handling Peak power output from fuel cell 10-30 kW	**Peak power output from fuel cell** is with the current 110 cell stack potentially 300 amps. This is limited in our system to 288amps, which with a conservative system efficiency results in an estimated electric power of 20,9kW.	
Material Handling Vehicle breaking energy adsorptive capacity 30 kWh	**Vehicle breaking energy adsorptive capacity** can be obtained almost entirely into the 240 Amp Hour battery.	
Material Handling Peak power output from hybridization 60kW	**Peak Power output from hybridization** with current 240aH battery pack is 35kW for 10 sec. By varying the battery pack other output may be reached.	
Backup Power price below €1.300/kW @ 5.000 unit production	The current system price is marginally higher than the price in 2011. This is primarily caused by the increased dollar rate that has eaten most of the cost reductions achieved in this project. But also a volume purchase agreement we unfortunately couldn't live up to and therefore is less beneficial for us now.	At a volume of >5000 systems per year the focus should be on volume purchase agreements and then it would be possible to get below the 1300 Euro/kW which is the target of this project.
Backup Power fuel cell system efficiency of 45%	52%	Reached through improved power electronics, software and purge intervals.
Backup Power capable of operating in -40 to 50°C	The Cold Climate Kit (CCK) developed has passed 72 hours of operation at -40°C with no performance loss. The high temperature test was just 3°C shy of 50°C but it is believed that the system can handle 50 °C for a shorter time period.	

Backup Power lifetime of +4000 hours of operation and min 1000 startups and shutdowns	DTP have successfully improved the system to operate for 1000 start/stops, this has been tested in this project. The 4000 hours of operation have not been tested, but we have systems in the field that have reached 4000 hours of operation	
Backup Power integrated with SNMP protocol	The SNMP interface has successfully been developed. The module works with both our 1.7 kW and 5 kW backup systems.	
Fuel Processor (FP) – Pressurized system with a target of 6-9 bar	The FP system presently operates at 5,5 bar.	The operation pressure will increase, as the backpressure in the system will decrease by redesign of process details and change of components (e.g. valves)
Fuel Processor efficiency – target > 45 %	Initial results on FP efficiency is 42%	Optimization of operation conditions will result in higher efficiency.
Fuel Processor – Start-up time at ambient conditions, target 60 min	Start-up time from ambient conditions presently about 50 min.	The start-up time will decrease further after optimization of operation conditions.
Fuel Processor – Hydrogen capacity, target 10 Nm^3/h	Present capacity is 6.6 Nm^3/h.	The capacity will increase after optimization of operation conditions (≈8Nm^3/h). The reformer capacity has to be increased in order to reach the initial target.
Fuel Processor – Hydrogen purity, target 99,9500% (main restriction is concentration of CO as CO is the last component in the adsorption order)	Present results regarding hydrogen purity are CO ≈ 30 ppm (on average). At the expense of H2 recovery, the purity can be further improved to CO < 10 ppm.	Target for Hydrogen purity is according to the standard SAE J2719 (CO < 0,2 ppm). Purity can be optimized significantly by increasing the operation pressure (see above).

Fuel processor – Hydrogen outlet price, target 4€/liter MeOH	The target is reached if the MeOH cost is around € 0.25/kg	The MeOH price has varied between 0.20 to 0.45 the last 5 years.
Fuel Processor – Manufacture costs, target (1.000 units) ≈ 1.196 €/Nm^3/h produced H2	Estimated manufacture costs (1.000 units) ≈ 2.434 €/Nm^3/h produced H2	A detailed cost reduction study must be performed to decrease the manufacture costs.

WP3 – R&D methanol reformer for onsite H_2 supply

The objectives of this work package are the R&D of a methanol reforming system with higher outlet pressure, capacity and purity as well as reduced costs providing low cost hydrogen fuel suitable for LT-PEM fuel cells in the addressed markets. This is to be verified by conducting of laboratory testing of the developed components and complete system. In order to reach these objectives we have been through the following tasks:

Task 3.1 Definition of suitable catalyst with improved performance & reduced costs

Concerning the active material within the catalyst formulation there are two catalyst types which are considered for the methanol steam reforming, namely copper-based (Cu) and precious metal-based (PM) catalysts. Main issues for the selection are efficiency, lifetime and costs.
Copper-based catalysts are state of the art for steady state methanol steam reforming systems on an industrial scale. The main advantages are the high activity at moderate temperatures of around 250 – 300 °C and the relatively low costs. The main disadvantages of copper-based catalysts are their high sensitivity for deviations in the operating conditions, their low cycle stability and the high degradation rate. Copper based catalysts can lose about 1/3 of their activity within 1.000 h of operation even under ideal operating conditions. The small temperature range in which the catalyst shows high activity (250 °C - 300 °C) is followed by a range in which the catalyst has a highly accelerated degradation rate (300 °C - 320 °C) and above 320 °C the life expectancy of the catalyst is reduced to a few hundred ours. Another major disadvantage for small-and medium sized units is that Cu-based catalysts are oxidised (CuO) as delivered from the supplier and have to be activated at reducing conditions within a temperature range of about 200 - 250 °C requiring a reducing agent, e.g. H_2. Once the catalyst is activated for the methanol reforming it is pyrophoric (sensitive for O_2). To keep air or oxygen out of the catalyst zone of the reforming reactor an inert purge gas is needed for start-up, shutdown, standby or down-time of the reformer system. Due to these effects much effort has to be taken to precisely adjust the temperature in the complete reactor not only during steady state operation but also especially during transition states (e.g. heat-up).

Precious metal methanol reforming catalysts can be used for various applications especially if high power densities and frequent cycling is required. They show high temperature stability in a range of 200 °C - 1.000 °C and also very high activity for methanol steam reforming without any treatment before utilization. The often-discussed disadvantage of precious metal catalysts is the high and volatile price of precious metals. On the other hand the higher activity and therefore higher space velocity (GHSV) reduces reactor size and the required total amount of precious metal compared to copper-based catalysts. Additionally it has to be taken into account that precious metal catalysts can be recycled after use. More than 98 % of the remaining precious metals can be recovered from catalysts for chemical processes and over the entire product lifetime.
Considering the above stated advantages and disadvantages for the two types of catalysts, precious metal catalysts are the preferred type for developing the methanol steam reformer system for the given application in this project. Especially the required pre-treatment with the resulting sensitivity to oxygen and the small available temperature range argue against copper-based catalysts.
Samples of the suggested precious metal catalyst formulation, provided by Catator, have been tested under defined conditions including steady state operation and cycling operation in a special catalyst test rig at ZBT.

As can be seen in Figure 1, stable results could be obtained. Even after about 750 hours of operation no significant degradation or drop in performance could be detected.

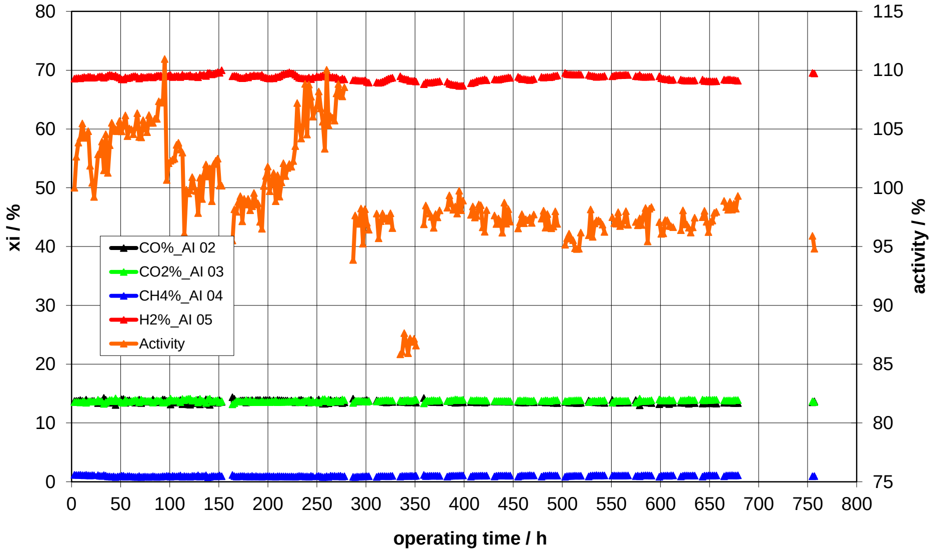


Figure 1: Long term test of selected PM catalyst, steady state (0 – 280 h) and cycling operation (208 – 755h)

Results and conclusions

The choice of a precious metal (PM) catalyst simplifies the design and operation conditions of the developed reformer system. The PM catalyst shows high activity and stability during the performed cycling and life time tests of the catalyst.

Task 3.2 R&D of a pressurized reformer system for onsite H_2 supply

There are a number of reactions to take into consideration in fuel processing. The highest hydrogen yield is obtained when using pure Steam Reforming (SREF) where a mixture of the hydrocarbon feed stock and steam is reacted over a suitable catalyst. The hydrogen concentration is much higher in SREF processes (about 70%) whereas processes including Auto Thermal Reformation (ATR) or Catalytic Partial Oxidation (CPOx) (exothermal steam reforming conditions with addition of oxygen/air) give a lower hydrogen yield. The developed reformer system in this project is based on a SREF-process.

Catator has during the last two decades been heavily engaged in the development of novel catalyst- and reactor systems. The main focuses have been directed to process intensification, i.e. to increase the output of a chemical reactor system per unit volume. The design solutions are especially favorable in cases where the reaction is performed under simultaneous heat transfer, like in combustion and fuel processing.

A cutting edge design must be described by three characteristics in general: low cost, high durability and top performance. The focus of the development work for a pressurized reformer system, called Optiformer, has been on following items:

- It is essential to use ordinary construction materials in order to converge to a realistic price level.
- It is of great importance to avoid thermo-mechanical issues often found in too rigid structures comprising stiff building blocks.
- It is important to provide a highly integrated unit comprising all balance-of plant components like heat exchangers, evaporators, recuperator, etc. in a compact and lightweight architecture.

The Optiformer concept is based on a coil-concept, where a SREF catalyst is inserted into a coiled/helix shaped tube. The basic idea is that there should be a close coupling between the exothermic and the endothermic reactions from a heat-transfer point of view. The Optiformer consists of a number of individual parts tied together in an integral design, as shown in Figure 2 (left).

- Helix shaped coil containing the SREF-catalyst (SREF=steam reforming)
- Central catalytic burner with internal mixer, 2nd cylindrical mesh, diversion plate and ignitor
- Helix shaped tubular arrangement for steam generation
- Exhaust gas recuperation
- Water-gas-shift section (WGS)
- Air cooled and insulated reactor vessel

The commissioned reformer system including all balance of plant components is presented in Figure 2 (right).

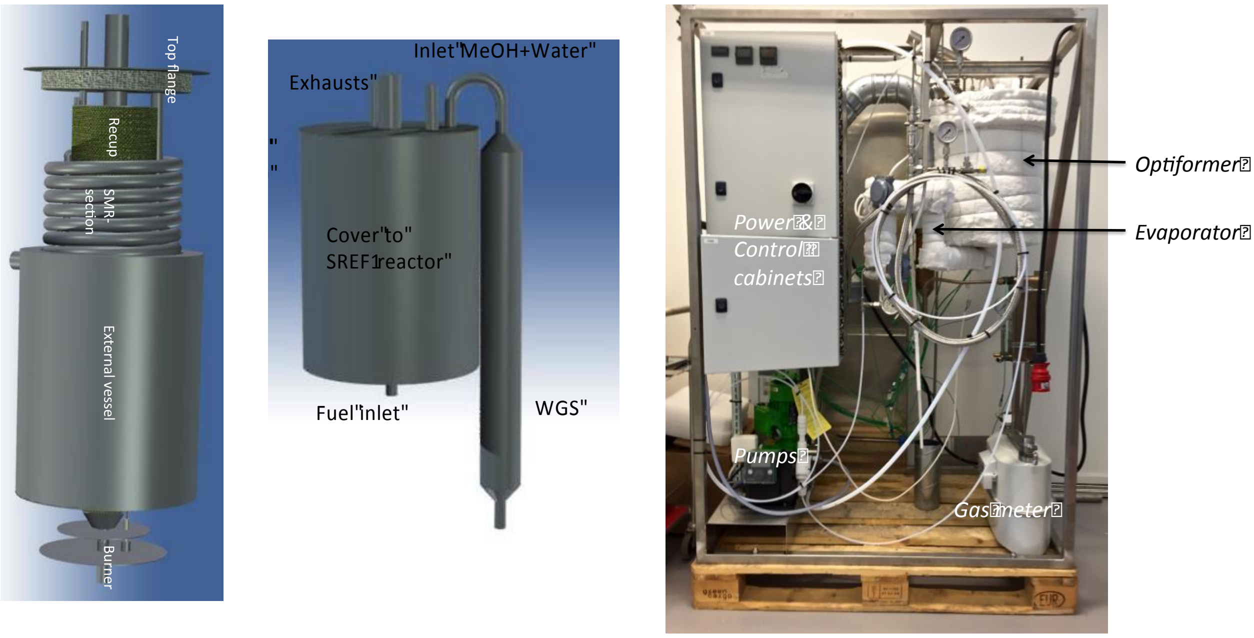


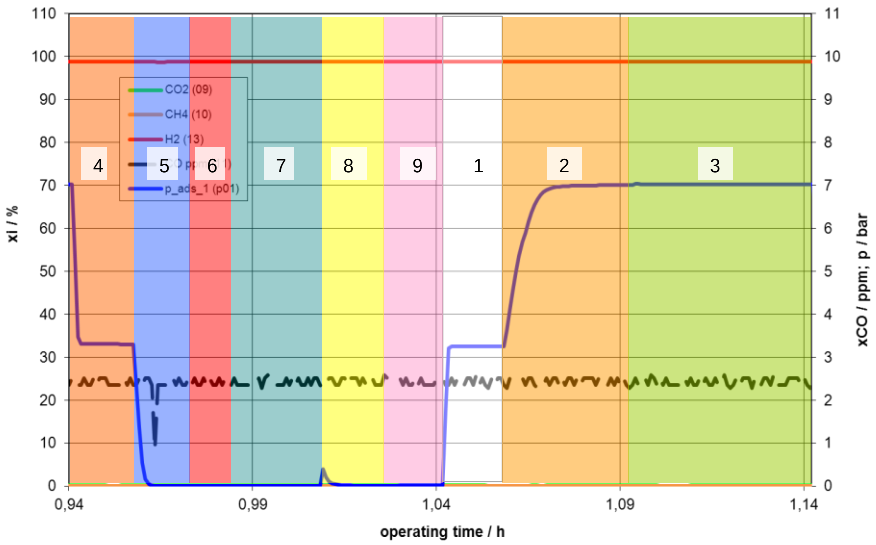
Figure 2: Optiformer unit, design principle (left) and commissioned system (right)

Results and conclusions
The capacity of the reformer unit is 10 Nm^3/h of H2 at an operation pressure of 9 bar (g). The overall dimension of the SREF reactor is ca. ø 312 x l 415 (mm) and its weight is ca. 50 kg. The reformate gas composition is: CO = 3.1 %; CO_2 = 22.6 %; CH_4 = 1.26%; H_2 = 72 %. The reformer system fulfils the main technical targets set in the project.

Task 3.3 R&D of suitable reformate purification unit

State of the art pressure swing adsorption plants (PSA) have typically industrial scale with high outputs up to several 100,000 m^3/h of pure hydrogen and operation pressures in the range of 10 – 30 bar. Medium to small hydrogen production plants as addressed within LiquidPower (10 m^3/h) commonly apply alternative purification technologies like catalytic preferential oxidation or membrane separation which either can only convert single undesired components like CO in the reformate or have to employ very costly materials like Pd/Ag-membranes. Furthermore smaller plants especially small reformers commonly do not operate at elevated pressures. Pressurized reforming as described above now enables the application of the pressure swing adsorption as purification unit.
The main challenge for the PSA development within LiquidPower was to demonstrate a downscale of the PSA technology to the defined output range of about 10 m^3/h (30 kW) and simultaneously to gain the required purity within the given parameter range namely the relatively low pressure in the range of < 10 bar which is limited by the maximum pressure for the pressurized reformer. In order to meet the economic requirements the development focused on the use of commercially available adsorbents, materials and components. Therefore common standard molecular sieves and activated carbon materials have been applied for adsorption. However the functionality had to be confirmed for the non-industrial scale application.

H_2-purity will be evaluated by measurement of carbon monoxide CO as the leading component[1] within the expected products. Further performance indicators are the recovery rate as well as the productivity.
The consortium agreed to add the development of a small scale stand-alone PSA-system with comparable settings in the range of 0.35 kW (H_2 output) to the original project plan. Based on this small scale PSA-system required components have been identified, initial laboratory tests have been performed and the PSA-process steps have been validated. The characterization took place with predefined synthetic reformate gas at this stage of development.
The PSA utilizes a four bed set-up according to the so called *Lofin PSA process*. Combining the four separate batch operations in an appropriate adsorption cycle comprising up to 9 discrete steps like pressurization, adsorption purge and regeneration enables a continuous hydrogen production. The steps, a typical pressure curve for one adsorber as well as the resulting gas composition for the complete small scale PSA are presented in Figure 3. It can be noted that within one full cycle (about 12 minutes) a stable H_2-purity with CO < 3 ppm can be achieved at 7 bar adsorption pressure (step 3).



1	Pressurization 1
2	Pressurization 2
3	Adsorption
4	Depressurization 1
5	Purge (active)
6	Blow Off
7	Pause
8	Regeneration
9	Pause

Figure 3: Adsorption cycle for one column, gas composition and pressure as a function of time

Summarizing the results from the small scale PSA system shows that parameter changes of pressure, load and cycle time affect the performance of the PSA-system. Increased pressure is advantageous for the purity and the productivity. Increasing the load results in a downgraded purity but has advantages for the recovery and productivity. Whereas cycle time elongation affects the purity negatively, the recovery positively and has no impact on the productivity. System optimization is therefore mainly a trade-off between high purity and high recovery.
The main findings from the small-scale test unit were used as input for the design of the full scale PSA unit. The general dimensions as well as the proportions of the adsorbent layers have been transferred. The P&I-diagram has been fixed and balance of plant component specifications have been determined. An accompanying work package was the detailed elaboration and documentation of a possible path of a CE conformity assessment which has to be performed by a third party on the way to commercialization.

Results and conclusions
The resulting main design specifications of the PSA system are presented below and in Figure 4.

- Nominal output: P_{H2} ~ 30 kW, V_{H2} ~ 10 m³/h
- Design pressure: $p_{max,g}$ = 12 bar

[1] According to ISO 14687-2 „Hydrogen fuel – product specification, Part 2: Proton exchange membrane (PEM) fuel cell applications for road vehicles" CO serves as leading component (canary species) for the evaluation of the purity of H_2 derived by steam reforming and PSA

- Volume: 4 * 110 l = 440 l
- Weight adsorber columns: 4 x 240 kg = 960 kg
- h*w*d of the rack: 3.0 m * 1.8 m * 1.2 m

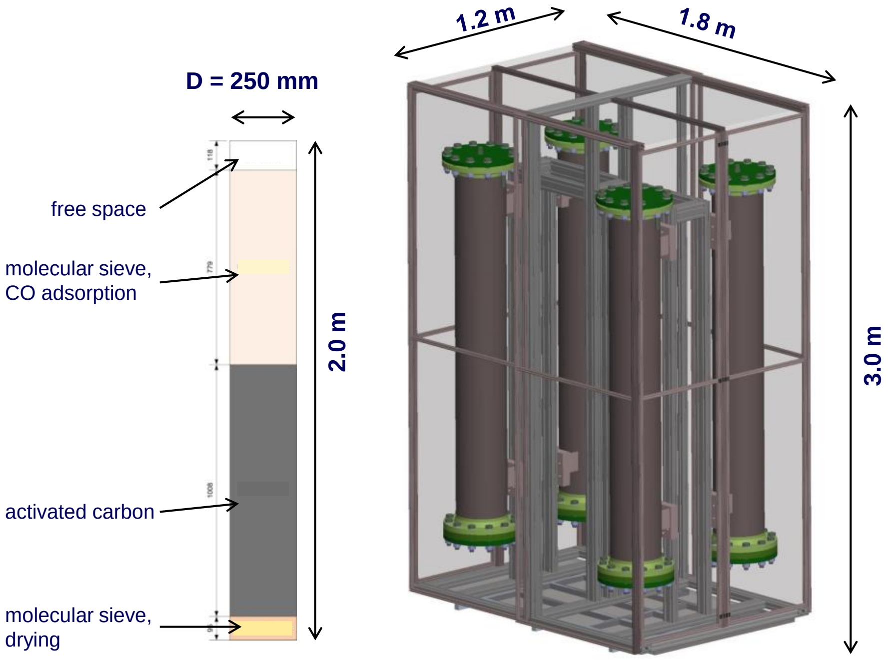


Figure 4: PSA set-up, adsorbent layers and column-arrangement

The PSA-system has been assembled at the ZBT laboratory and mounted into a designated housing. The set-up is dominated by the four adsorption columns (flange design, stainless steel tubes). Furthermore numerous industry standard valves and instruments have been installed at the top and the bottom of the columns to facilitate the cycling operation, see Figure 5.

Figure 5: View of the full scale PSA system (left), bottom valves (right)

Task 3.4 Construction of laboratory test system and conduction of tests

The two developed sub-systems have been integrated to a complete fuel processor system as presented in Figure 6. Main efforts of this integration work have been the preparation of the infrastructure, the implementation of all mechanical and electrical interfaces, the development of the system control, the development and implementation of an appropriate safety concept with focus on explosion protection at the designated site as well as the stepwise functionality test of all safety devices, components and subsystems. The fuel processor system is approved to be in operation according to the German industrial safety regulations including ATEX directive, pressure equipment directive, gas appliance directive et cetera. The semi-automated sequence control enables systematic characterization especially of the PSA operation in order to check the system performance against the idealized small scale PSA results and overall targets.

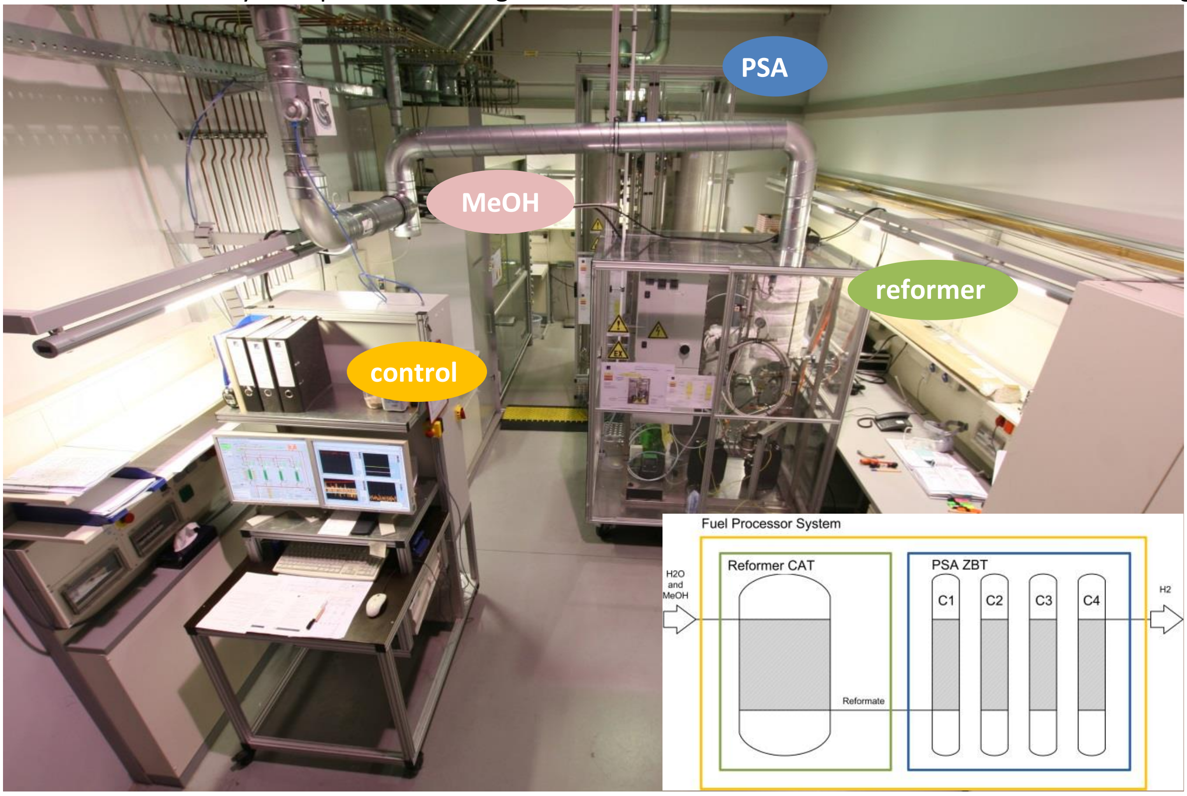


Figure 6: Fuel Processor System subsystem boundaries and set-up in the ZBT laboratory

Results and conclusions

Characterization of the fuel processor system included the determination of the start-up time, check of the reformate gas (composition, volume flow, stability) and finally the performance of the purification unit indicated by the hydrogen purity, recovery and productivity. As the degree of freedom for the coupled system is restricted in some points the described trade-off between high purity and high recovery has been addressed mainly by varying the adsorption cycle time. Figure 7 shows typical cycling operation of the PSA in combination with the methanol reformer. In contrast to the idealized small scale measurements it could be seen that operation and result parameters like pressure, gas-composition and flow were subject to significant fluctuations. Additionally the pressure drop in the process chain has been higher than predicted thus the outlet pressure of the PSA is in the range of 4 to 5 bar and the adsorbent capacity could not be fully utilized. Nevertheless a CO fraction of 25 - 50 ppm and an average H_2-volume flow of 110 l/min corresponding to around 20 kW could be measured in the purity-recovery-optimum operation which leads to a recovery of about 57 % and a productivity of 0.26 $l_{H2}/(min * l_{ads})$.

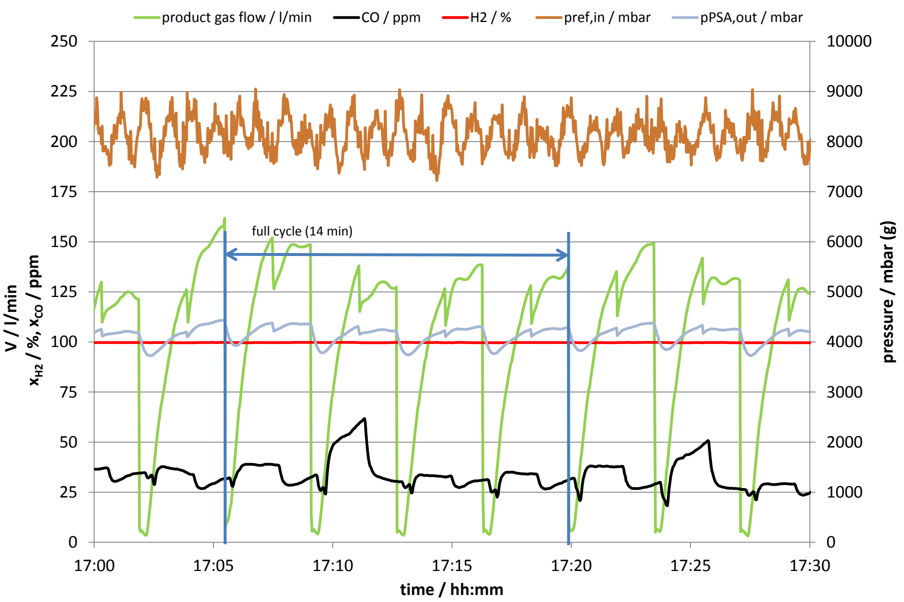


Figure 7: Purity-recovery optimum, volume flow, pressure and gas composition as a function of time

The reformer operation revealed optimization potential with regard to pressure and temperature fluctuations. An optimized temperature control would enable an independent stable long term operation of the reformer. Reducing the pressure drop in the process chain by eliminating and redesigning components enables the utilization of the adsorbent capacity which finally enhances the hydrogen purity. In order to enhance the hydrogen recovery the inevitable H_2 losses caused during pressurization and purge steps have to be minimized. Therefore the alignment of the subsystem-capacities seems to be a key factor. As the absolute volume of the PSA is too high for the maximum reformate production rate either the reformer capacity can be increased by a factor of around 1.2 or the PSA has to be downsized vice versa. Finally continuous hydrogen flow and stable PSA outlet pressure can be obtained by the use of a suitable hydrogen buffer tank as a source for hydrogen in the steps pressurization and purge.

Task 3.5 Continuous manufacturing & cost evaluation

The target in the project was an outlet price for produced H_2 of around 4 €/kg. The subsystems have been evaluated separately by means of cost groups. Numbers have been added for the complete fuel processor system with the result that at the current state of development and assuming that up to 10 units will be produced per year the specific capital expenditure (CAPEX) will be in the range of 4000 €/(m³*h). The economy of scale has been evaluated which leads to a price reduction of about 40 % for a volume of 1000 units per year. Though the cost estimations show that the CAPEX is quite high it is yet possible to produce pure hydrogen with a competitive price. It could be found that CAPEX only corresponds to about 20-30 % of the outlet price for H_2. The dominating share is the price of the fuel methanol as main operational expenditure (OPEX) which varied from 0.24 to 0.45 €/kg in the last 3 years. The target can be reached if the price for methanol is in the range of 0.25 €/kg even for a high CAPEX as can be observed in Figure 8.

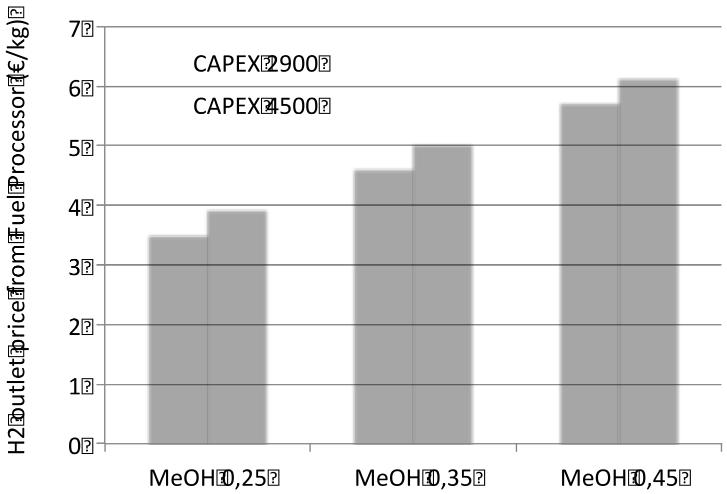


Figure 8: H_2 outlet price as a function of CAPEX and OPEX

Conclusion WP3

The technical target in the project was the development of a fuel processor system that can operate at a high pressure (target 7-9 bar) and with a high capacity (target 30 kW H_2) and with a production of pure hydrogen (target 99.9 % H_2). The functionality of the full scale laboratory test system has been demonstrated. The evaluation of the results shows plausibility with theory and with idealized small scale PSA system tests. Although the defined targets could not be reached in every point especially pressure and capacity this work package terminates with a successful demonstration of a methanol fuel processor system of the 20 - 30 kW class. Significant optimization potential has been described in order to reach the defined targets with a next generation fuel processor.
Finally the cost evaluation shows that the operational expenditure has the dominant influence on the hydrogen price and that a target of 4 €/kg can be reached with the current system set-up assuming that the methanol price is in the range of 0.25 €/kg even with relatively high capital expenditure.

WP4 - R&D fuel cell system for back-up-power & telecom

The objectives of this work package are:
R&D of a new generation fuel cell system for backup power with significant cost reductions, scalability, lifetime and efficiency improvement thus reaching full commercial targets. This is to be verified by conducting laboratory testing of the developed components and several systems under various external conditions

Task 4.1 R&D of fuel cell module & Balance of Plant components (BoP)

The existing fuel cell system consist of the following main components.

- Fuel cell unit
- Controller unit
- Bridge Power Unit
- Valve block

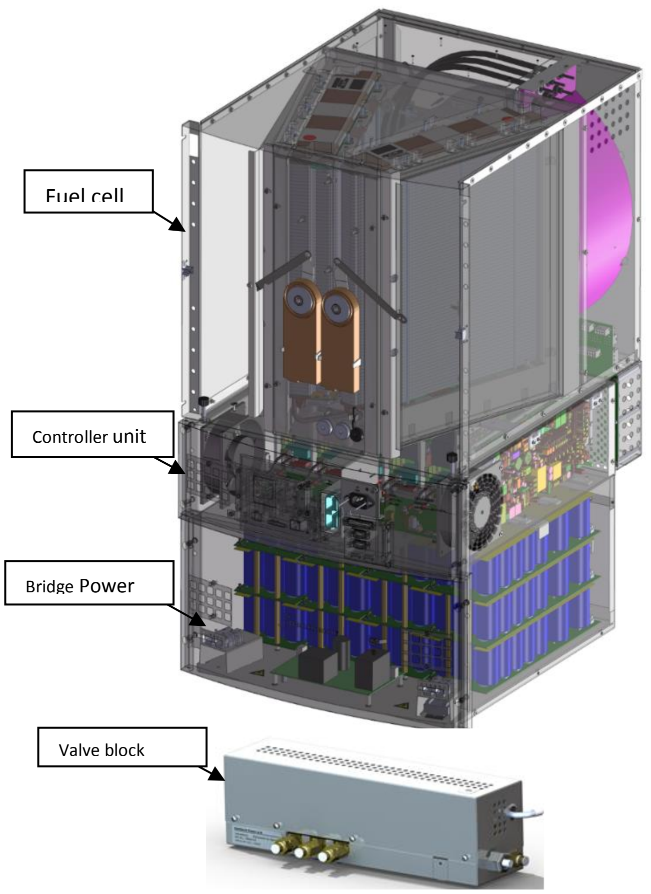


Figure 9 Fuel Cell system design for back up applications

The components used in the systems are reused in as many subsystems as possible. Although this might mean over dimensioned components in some subsystems, it opens the possibility for buying cheaper items due to extended volume.

Keeping the same mechanical platform on all scalable products will reduce stock expenses and make it easier for customers to upgrade the product.

The fuel cell stack is in the scope as the most expensive component in the system. But there are other expensive components that also are scaled. Primarily the DCDC converters and the bridge power module.

In order to decide which scalable product sizes that are optimal/necessary in order to fulfill customer requirements at the lowest possible cost, the following 3 Points will be described in the next paragraphs:

- DCDC converter optimal numbers contra fuel cell size
- Fuel cell optimal sizing and system configuration
- Bridge power size

DCDC converter optimal numbers contra fuel cell size
The power capability of the systems that can be realized based on the FCgen®-H2PM 5.0 kW/48V platform are determined by the fact that the DCDC converters can deliver 1kW output power each, down to a voltage input limit of 30VDC. Also the systems parasitic power must be drawn from the DCDC converter's output, which reduces the net power output capability of a system.

Fuel cell/system sizing:
After having heavily analyzed and discussed the different possible fuel cell sizes/system sizes possible while taking into account limitations from the DCDC converters and the needs of our current and potential customers – we ended up deciding at 3 different fuel cell sizes:

66 cells fuel cell with a “nominated” output of 2,5 kW
46 cells fuel cell with a “nominated” output of 1,6 kW
34 cells fuel cell with a “nominated” output of 1 kW

Bridge power
The bridge power is used to deliver a supply to the output power, as the stack starts up. The startup phase might last for a few minutes and the bridge power module shall be able to supply the grid with power while the stacks heat up to maximum power.The solution is to remove some of the ultra-caps from the assembly so the capacity can match the power required. Experience shows that 12 of these ultra-cap units (Figure) are needed to cover 5000 watts startup time. Experience and interpolation determine the amount needed for each system size.

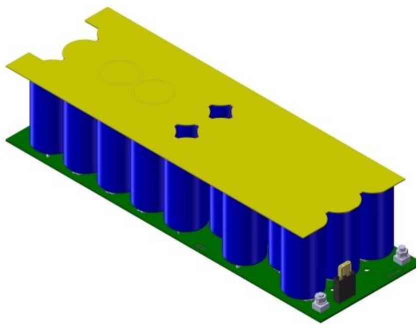


Figure 10 ultra-cap module

Task 4.2 R&D of fuel cell system controller

The first idea was to develop a new fuel cell system controller where the control strategy is optimized to protect the stack from unwanted operating conditions under the most difficult ambient conditions and operating modes. Still at the same time the controller will enable maximum performance out of the stack in order to save the number of cells needed in the fuel cell stack. The new control system should incorporate failure diagnostics and preventive maintenance enabled by remote monitoring capabilities in order to ensure highest possible reliability. After the preliminary work to map requirements for the new CPU and auxiliary CPU components the conclusion is to keep hardware and major part of the software (File-system is replaced). This is due to testing time, experience about hardware complications, and the amount saved per unit. Instead work was done on reworking and optimizing software to improve stability and gain memory space to be able to add improved functionalities and add Simple Network Management Protocol (SNMP) communication protocol.

Task 4.3 R&D of DC/DC converter

The DC/DC converters ability to handle the lower voltages at a good efficiency have been tested and approved. The solution by removing 1-4 DC/DC converters is the most obvious when scaling the fuel cell systems. The configuration of the DC/DC managed the current drawn from stacks have been changed with success. This has resulted in more power drawn from the stack with good performance rather than drawing the same amount of power from both stacks. This will significantly improve the lifetime of the overall system.

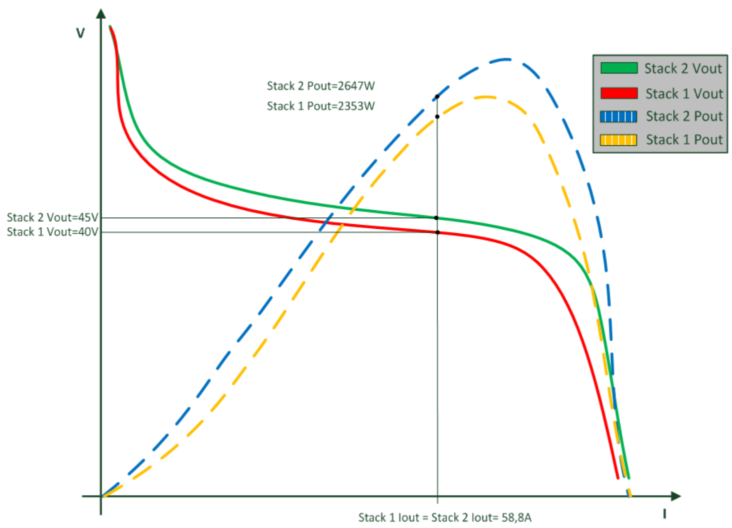


Figure 11 Current share allows the DC/DC to draw more power from the stack with best performance

Task 4.4 Laboratory prototype construction, test planning and testing

Four out of five of the scaled down systems designs where build as prototypes. One of them is the one shown in figure 12. The prototype shown is the 3.2kW system configuration.

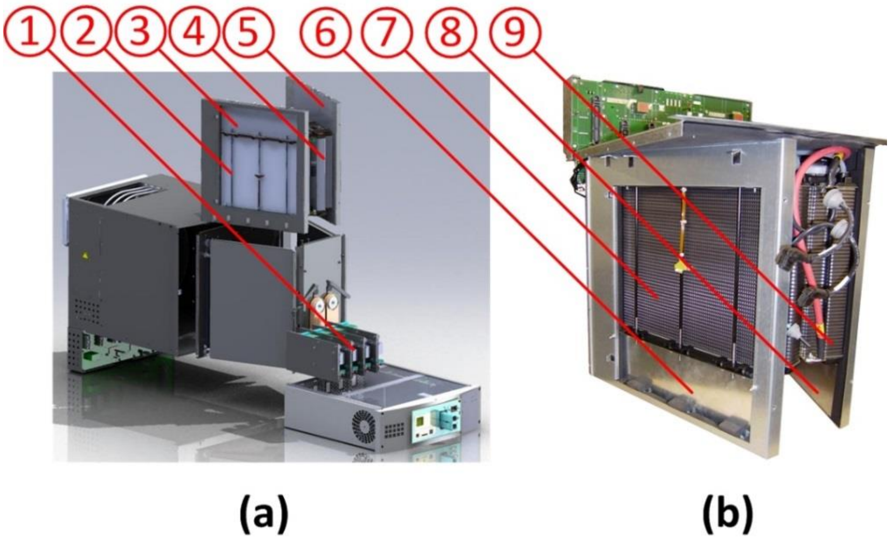


Figure 12 (a) 3D representation of the 3.2kW system configuration. (b) Picture from the build-up of the 3.2kW prototype. 1: 4xDCDC converters. 2: FC Stack 1 (56 cell). 3: Blind-plate allowing for a smaller stack 1. 4: FC Stack 2 (56 cell). 5: Blind-plate allowing

In the 3.2kW configuration two 56 cell fuel cell stacks are installed in the fuel cell module. In order to facilitate the usage of a smaller fuel cell stack, blind plates compensating for the smaller stack height had to be constructed. In the controller, the power from the stacks is conditioned by four 1kW DCDC converters – two converters operating in parallel from each stack. This is illustrated on **Fejl! Henvisningskilde ikke fundet.**.

Testing:
The fuels cell systems have in this project undergone extensive testing in extreme condition.
Two standard 5.0 kW systems have been put through the following tests.

- 1000 start/stop cycles combined with sufficient operation hours to reach 10% degradation
- Operation under cold and dry conditions with different user profiles
- Operation under hot and dry conditions with different user profiles

The first system performed the 1000 Start/stop test. The system managed 988 cycles before it reached 10 % degradation. The total operation time for the system was 494 hours. This is much lower than the lifetime expectancy for normal operation. The goal was 1000 cycles and it is believed that the system could have reached this goal. After the test the connection from the hydrogen bottles to the system was inspected and a heavy amount of corrosion were found in the inlet valve 13. This explained the sudden drop in performance, and why the system did not reach over 1000 star/stops before 10 % degradation.

Figure 13 Contamination in H2 Valve block

Despite the contamination the test was a success and it is believed that without the contamination the system would have been able to go beyond the 1000 cycles before 10 % performance degradation.

For the climate test dry/cold and hot/dry our new test facilities were used. With this setup we have been able to test with temperatures down to -40°C and up to 50 °C. The tests were a success and the system limits without a Cold Climate add-on were found through these tests. Operation in these condition have been improved through these tests.

The results will not be shown in this report as they are considered confidential.

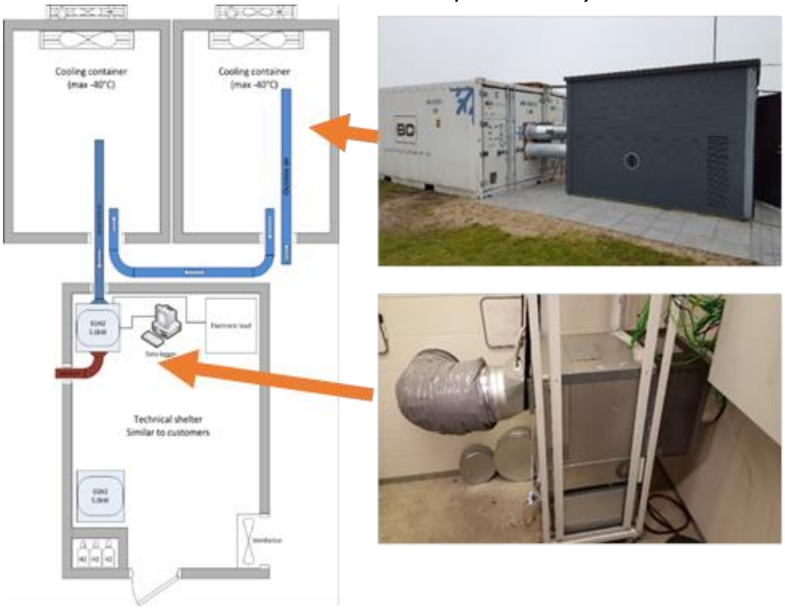


Figure 14 Climate test facilities

Task 4.5 Continuous manufacturing & cost evaluation

The possibility of scaling the systems to the customers' needs have the following cost saving potential:

Scaling Bridge Power to chosen scalable stack sizes

3.2kW system	
Reduction compared to 5kW system	36%
2,5kW system	
Reduction compared to 5kW system	50%
1,6kW system	
Reduction compared to 5kW system	68%

With the focus in this project on scaling the systems from 1 – 5.0 kW by creating stacks with fewer cells, less DC/DC converters and smaller bridge capacity for customers with les power demand the cost of the system is reduced by comparing it to a customer buying a 5 kW system with the need of only 3.2 kW. With the RD efforts on creating scalable systems that would work this way, our FC system controller had to be reworked and software had to be modified. With this the handling of especially current share between the two stacks was improved. This helped improve our reliability and lifetime of the fuel cell system in total. The upgraded FC controller also improved the CAN communication making it ready for communications with and SNMP module. Which is an increasing demand from our customers. The work done has not directly reduced the cost of the system but is has definitely improve the lifetime, reliability and performance in extreme conditions.

Conclusion on WP4

The target of creating scalable fuel cell systems for backup applications have been reached. Several working prototypes have been constructed and successfully tested. The prototype build of a 3.2 kW system is still in operation as a backup unit today.
To be able to scale the systems the fuel cell controller software had to be reworked. This made it possible to implement a “current share” feature which helped improve the performance and lifetime of the fuel cell system. The improve controller also made it possible to develop Simple Network Management Protocol (SNMP) application for the system. The SNMP application is now released and can be purchased as an add-on for all our backup applications.
The extensive climate testing helped improve how the backup system operates in extreme cold/ dry but also in hot/dry conditions. The work done in WP4 is definitely a success. It has not directly reduced the cost of the system, but it has improved the lifetime and performance which is critical factor with backup systems.

WP5 – R&D fuel cell system for material handling vehicles

The objectives of WP5 is to conduct R&D of a new generation fuel cell system for material handling vehicles. R&D efforts will focus on the fuel cell module including BoP, control module and hybrid module. The developed components and complete system is to be laboratory tested to validate reaching of technical and market targets.

Task 5.2 R&D of fuel cell control module

During the development of the project different controllers have been used and evaluated. The automotive controllers have shown the most promise. Dantherm Power has used a controller from German Bosch which is an expensive option during the test period. The controller comes with a well-tested hardware setup that is sturdy and can operate in the harsh conditions within an IEC vehicle.
There are a couple of automotive controllers that has been evaluated one was the Bosch controller and the other was the STW controller. They are both robust and made for use in a vehicle. Bosch has a “half-ready” platform for fuel cell systems, which can be used. It will save a lot of time, but Dantherm Power will also be dependent of the Service team from Bosch. Dantherm Power sees both suppliers as future supplier of controls units for Fuel Cell Systems. Dantherm Power will choose one of the two and use the other as a second source.
Self-diagnostics is an integrated part of the controller setup used for ICE vehicles. This allows the same software routines that is used to monitor the IEC engine to also monitor the fuel cell system components during the operation. This gives a good level of security for the operation of the fuel cell module. .
If we compare STW and Bosch with the H2L controller, it is clear that STW and Bosch are on a different level of maturity. Therefore there is a good and natural progression from task 5.1 to 5.2. The controller is designed to be installed in a motive system, as cars, trains and boats. STW and Bosch have a fully tested product and the documentation of the product is well described, which makes it easier for technicians to troubleshoot.
Generally the automotive controllers have an advantage in terms of robust hardware design. In the end the software environment and the possibilities and limitations related to the safety designs and software processes will determine which of the automotive controllers are best suited for certain vehicles.
The use of automotive controllers seems the most suitable choice for further development both within materials handling systems as well as road and non-road use of the fuel cell modules which is enabled via the controllers.

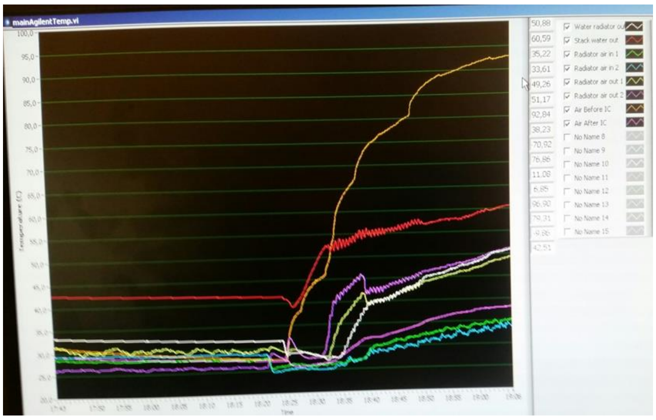
As with the ICE controllers it's relevant to start a broader adoption of automotive components. There are a lot of similarities between the ICE drive trains in the automotive industry and the fuel cell systems. They both require oxidant, cooling and gas/fluid for the conversion to kinetic energy in a motor.
Relevant components that more or less can be directly adapted from the automotive industry are air compressors or turbos, temperature sensors, mass-flow meters, fuel injectors and energy managers.

Conclusion

The automotive controllers have shown a great adaptivity to the fuel cell systems. This allows for a swift initial integration into a test bench system where the control logics and the general functionality of the controller, in this case the BEG controller was tested. The use of the automotive controller is for sure a platform that will be used going forward in Dantherm Power.

Task 5.3 Heat and water management subsystems

There are different factors in the heat and water management that has to be taken into account. The air temperature of the cathode will affect the humidifier so therefore it's natural to look at both these components.
To investigate which influence the intercooler has on the temperature of the air. External to the system controller, some temperature sensors Thermocouples Type K are added and logged with the Agilent 34970a, viewed with a Labview graphic user interface.



The orange curve with the highest end value is the air temperature before intercooler displaying 92degC. It will reach above 100degC. The purple curve displaying 38degC is the air temperature after the intercooler. This is with fans on both the pump and on the intercooler. The thermographic camera on the pump showed that the hottest part of the pump was the end cap of the air compressor part, where the inlet and outlet connection port is located. The high temperature is caused by air compression. A law of physics that cannot be ignored, so the air needs cooling before entering the humidifier, one way or the other.

The other picture shows the intercooler for the cathode string with an extra fan mounted to force the air through.
The temperature before and after the intercooler is measured to investigate if the intercooler could be smaller in dimension or could be left out completely

Work related to the humidifier has been centered on the cost reduction method, but has enabled and of course taken into account the functionality of the humidifiers.

Task 5.4 Construction of laboratory test system and conduction of tests

The tests are divided into 2 paths;
One being tests of the stack module with components developed in T5.1-T5.2 with the needed submodules to operate the stack itself. The purpose with this procedure is to make the test system as simple as it can be, so the test team has a system that is easy controllable, where the load from the FC stack could be regulated directly on the electronic loads. The controller used in this setup was a purpose build controller developed and purchased at an external partner.

Second path being the exact same setup as before mentioned, but adding the DCDC converter between the FC stack and the battery. Now the Battery Management System is going active and it is more complex to regulate the power drawn from the stack, because of the capacity of the 80V 240Ah battery in between.
The reason that the test system was split up like this was to ensure that the basis fuel cell module and components had proven functionality and that the complexity of adding the DC/DC to the equation would be isolated from the results.
Some work has been performed on the integration of a different heat management system as the initial system did not have the cooling capacity to leverage the full cell count of the fuel cell module. The initial system had a 110 cell PEM fuel cell stack but only had the cooling capacity to leverage approximately 50 % of the power the system could produce. Therefore the testing showed the need to develop a better cooling circuit.

The picture to the left is the stack module, the FC stack is laying in the bottom and on top of that the aluminums plate with the valves, sensor and pumps needed, is mounted.
To the right the laboratory test system is in the test facilities at Dantherm Power. The DCDC converter is not mechanically mounted in the system at this point because the test team needs easy access. The orange wires are going to it in the right side of the picture. This is a typical test situation with a lot of measurement equipment, needed for analyzing and interpretation of the systems behavior.

Conclusion

The system components carried over from the initial phases of the liquid power project has proven them self to be sturdy and reliable. Some work has been performed on the integration of a different heat management system as the initial system was under dimensioned by a 50% and therefore were not able to fulfill the initial target of about 10-30 kW output power from both the FCM including DC/DC and the battery system. The new and improved cooling system allowed the system to deliver max power from the stack, which in the case of this HTPEM stack means about 21kW net power, from FC stack only.

Task 5.5 Continuous manufacturing & cost evaluation

The cost reduction report is based on the initial cost price calculation that has been transferred from H2Logic A/S as part of the purchased materials handling intellectual property (IP) portfolio.
The cost reduction of the new version of the H2Drive will be achieved through a range of activities and action points.

- Identification of key cost reduction options
- Direct Material Cost
- Direct Labor cost
- Sourcing components
- Design changes
- Certification changes

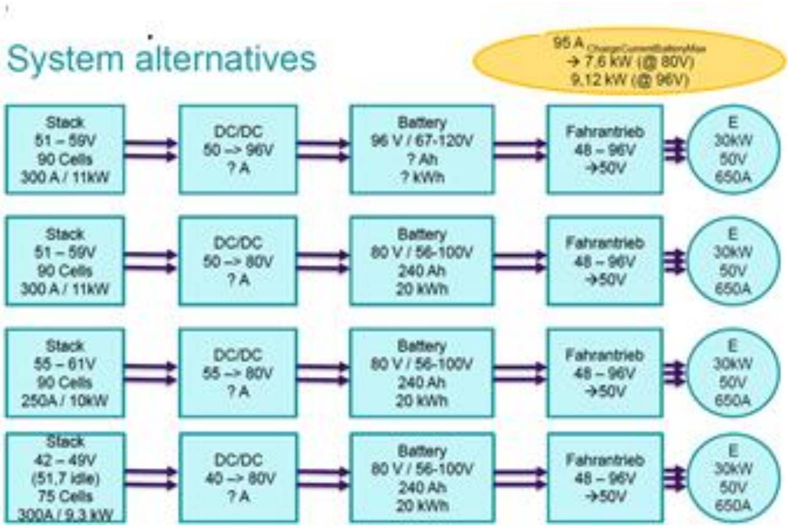
By the joint efforts, based on the main tasks re-engineering, volume production, sourcing, production and changed certification process the cost target was reached. We will not describe this point further as we consider this confidential.

Task 5.6 Development and test of alternative hybridization system

The typical materials handling system is a system consisting of fuel cells, batteries, DC/DC converters and, in some cases, resistors used for the absorption of the regenerated breaking energy or kinetic energy from the lifts. An alternative solution, using either lithium-ion batteries, super capacitors or a mix of the 2 technologies, will benefit the BoP on both cost reduction and durability.

Studies around the battery size and voltage have been carried out in the Liquid Power project. We have studied several voltages levels in corporation with a vehicle manufacture of material handling systems. The starting point was the 80 Volt battery.

Step 1: Broad approach to identify suitable DC/DC converter solutions out of a series of possible combinations, in order to meet fixed customer output requirement.



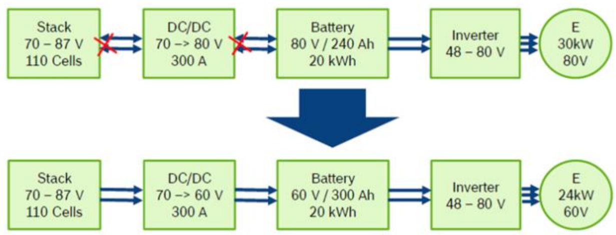
We investigated a 96Volt battery together with a 90 cells fuel cell stack. In such a configuration, we could use a simple step-up converter. But this would lower the power output of the stack, and make the fuel cell stack operate at higher average load compared to the Max limit of the fuel cell stack.

Step 2: Select most promising solution for further analysis and testing with respect to alternating DC/DC conversion (allowing different battery types) and fixed fuel cell stack design.

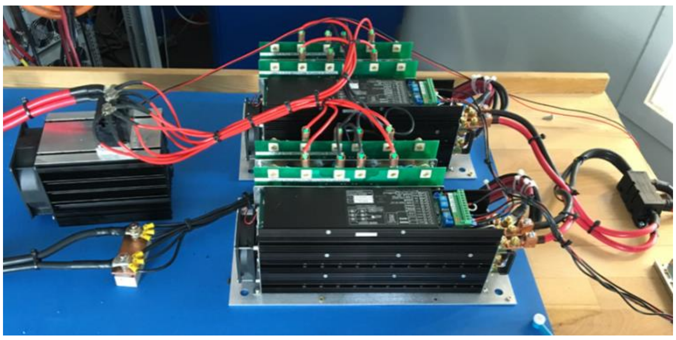
In an attempt to make the design of the DC/DC converter simple, the voltage of the battery was lowered from 80Volt to 60Volt. With 60Volt, a simple stepdown converter technology could be used.

In the end, the vehicle manufacture could not handle 60Volt on the electric drive motor.

The status now is that we are back on the 80Volt using a bi-directional converter technology.



Step 3: Select DC/DC design for prototype test bench system and preparation of hybridization tests with different battery types.

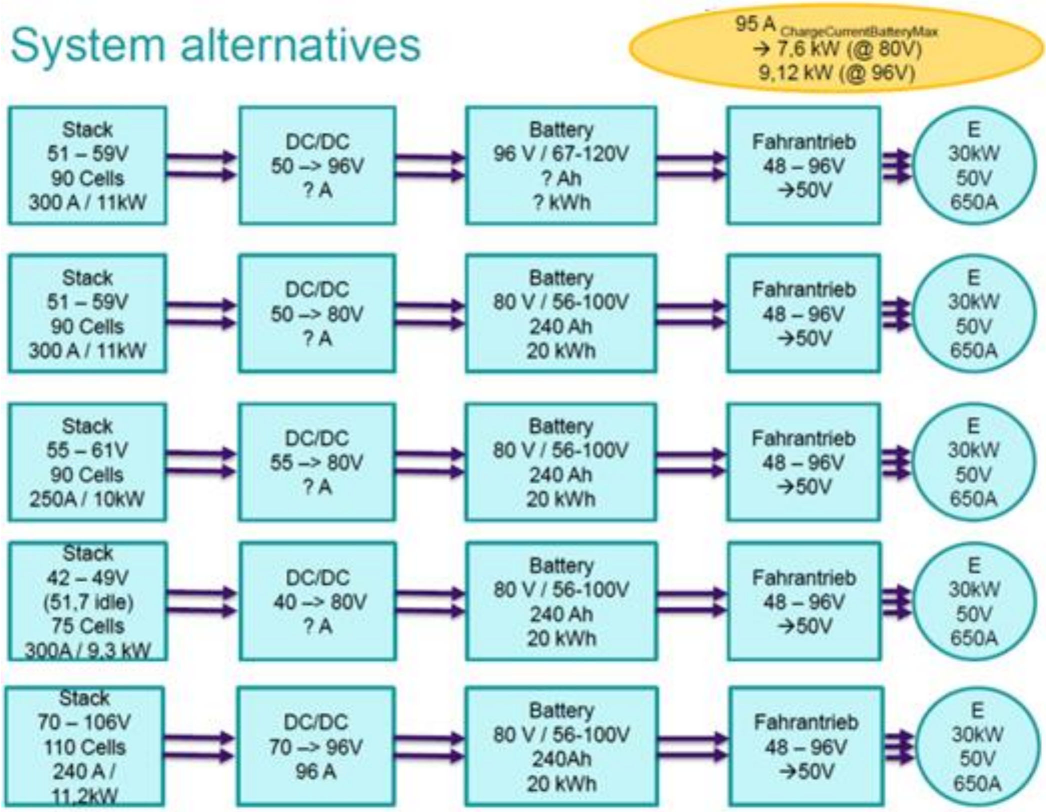


A step-down converter meant for the 60Volt battery. Wired up and functionality tested with power supplies mounted instead of the fuel cell stack and electronic loads on the output side instead of battery.

During the design stage, several stack and battery sizes were discussed, in order to ensure a cost reduction on the DC/DC converter and FC stack. If the converter could be a simple step up design, instead of a mix where the input and output is crossing each other, then the cost would be lower. However, the power output from the stack would not be high enough if a 90 or 75 cells stack is used.

The first and second suggestion of system alternatives, with a 90 cells stack, are actually stating an output of 11kW, but to do this the current draw is 300A, which is maximum capable current. This will course the stack to wear out prematurely. In the third and fourth suggestion, using a 90 and a 75 cells stack, the power output is not sufficient to power a tow tractor application.

An 110cells stack is needed for the demanded power output, used together with an 80V battery pack, then the DC/DC converter needs to handle both the step up and step down functionality. This would make the DC/DC converter more expensive, but this is the best choice.



Conclusion

The use of an alternative controller setup and early development of the hybridization setup have been very successful in the sense that they showed a much more stable and adaptive solution than experienced with the previous platforms in the Liquid Power project. In conjunction with an automotive controller and the right battery setup the flexible and adapted DC/DC will enable an optimized FCM system for the purpose build vehicle.

WP6 – Dissemination & planning R&D and commercialization

The objectives of this work package are to disseminate project results on a European level as well as planning and securing a following exploitation of project results by planning commercialization activities & securing patents. In addition, this work package supports the R&D activities in WP3, WP4 and WP5 by helping to both identify patent opportunities.

Task 6.1 Planning of continued R&D

During the course of this project new areas have been identified, where additional R&D activities are needed to secure a successful commercialization of the individual applications. The three applications in this project are each at very different maturity levels at the end of the Liquid Power project. Whereas Back-up Power products are closest to a commercial market (TRL 8-9), the Material Handling platform still has ways to go (TRL8-9), and the Fuel Processing System (TRL 4-5) is still quite far from the commercial market.

For back-up power products and material handling systems the principle target with R&D activities going forward is in cost reduction and lifetime improvements. The challenge for the fuel processing system is to generally mature the concept. Hence, most R&D activities in this report focus on the R&D topics for Fuel

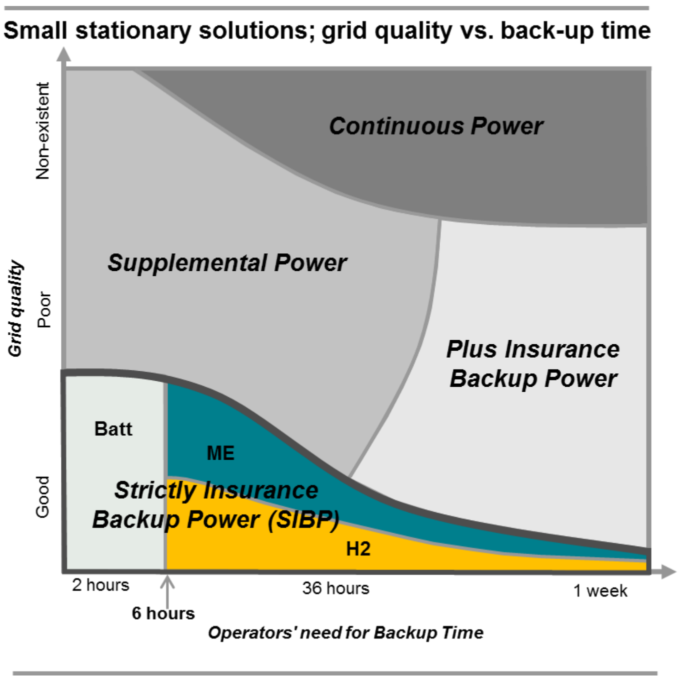
Processing Technologies going forward, targeting robustness, performance and reliability. The overall R&D steps for the FP system to move towards commercialization are outlined below:

1. Optimization reformer operation – to reduce instabilities from temperature fluctuations
2. Optimization purity – stabilize reformate quality and volume
3. Optimization recovery – enhance system flexibility for best recovery vs. purity compromise
4. Minimizing flow and pressure fluctuations – develop H2 buffer tank subsystem
5. Evaluation of lifetime – develop automated control system and safety concept
6. Cost reduction – optimization of manufacturing cost and component cost
7. Capacity - Scale-up to meet customer needs and settle on 3 standard capacity sizes for commercial introduction

Patenting opportunities have been investigated in this project for the developed technologies in WP3, WP4 and WP5. All technologies have been found to be commercially available technologies. The development and challenge in this project have been to design or re-design a more robust, more reliable, more customer specific unit or product. No patenting opportunities have been identified.

Task 6.2 Planning commercialization & product maturation

This task focuses primarily on the commercialization of the back-up system and material handling system, as they are the solutions closest to enter the market. Since the reformer and PSA are still in the development phase, the planning of commercialization is too early. However, the market possibilities are investigated to argue the relevance of continuous development in this area.
Fuel cell based back-up power products are commercially up against current mature back-up power products on batteries or diesel generators. In certain market segments these current technologies used today have their shortcomings – batteries on short backup availability, short lifetime and environmental concerns regarding lead pollution and diesel generators being unreliable, requiring significant maintenance and generating both noise and heat and polluting emissions.
The following figure illustrates the commercial field where small stationary fuel cell systems are playing a competitive role, when these are used from backup power up to continuous power.



The customer segments with immediate relevance for fuel cell back-up power are:
• Telecommunication – the need for reliable communication, especially for segments with users having special requirements (government, hospitals, banks etc.)

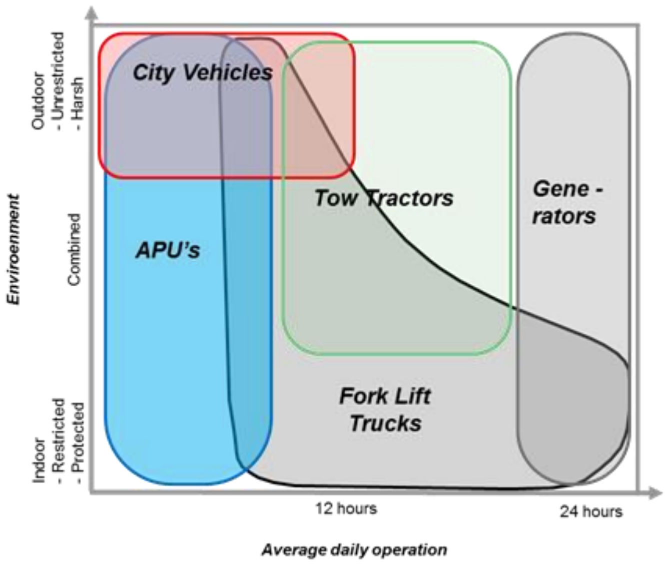
• Fiber broadband – the Fiber to The Home (FTTH) and Fiber to The Business (FTTB) segment where demands from the users can be very high
• Tetra – the special encrypted networks usually used by police, ambulance services, fire departments etc.
• Railways – the communication network along railways which is backbone for both data, cell phone network and lately also signaling

With marketing plans at hand for these early customers and the production facilities in place, the Scandinavian market is the first area, where the back-up power products of this project are introduced to customers and demonstrated in smaller trial projects for customer testing.

The material handling platform is targeting the following applications, where more and more electrified transport solutions for specialized services, reliable, robust and cost-efficient solutions are needed:

• Indoor material handling
• Urban material vehicles
• Underground vehicles
• Range extension to battery electric vehicles
• Airport vehicles

For these purposes the current technologies used today have their shortcomings – batteries on availability, short lifetime and environmental concerns regarding lead pollution and diesel engines generating both noise and polluting emissions, along with high temperatures.
The Small Motive segment is broken down into daily "Drive cycle". The daily drive cycle tells about the hydrogen logistics challenge – the higher the use gets, the more critical the hydrogen logistics gets. On the other hand, the higher the use of hydrogen, the higher is the potential for CO2 savings.



For fork lift trucks and tow tractors, the main focus is cost savings, and as such the most relevant applications are high daily use in areas with restricted exhaust emissions, where batteries have challenges. For city vehicles and APU's, the main driver is often CO2 and in general emission reductions that are in focus, so these applications can be just as relevant for low and for high usage applications.
The first segment, where sales expectations are getting clear and concrete, is within the fork lift truck segment, where there is a good foothold with prototypes since 2010. Due to the need for technology improvements and cost reductions, and due to long sales cycles within this segment, the sales are expected to take off around in early 2018. This timeline also allows for more cost reductions also in the fueling infrastructure, which are of vital importance for the success of this product.

Task 6.4 Dissemination of project results & networking

Results from the different technologies have been disseminated differently due to the different technology maturity levels and different audiences for networking.
Most active dissemination with commercial focus has been conducted for Back-Up power and material handling systems.
In Scandinavia meetings have been held with the biggest telecom and broadband industrial players, where the back-up power product and project results have been presented. These industrial customers are large and the decision process to change to a new technology of such strategic importance as back-up power supply takes a long time. Therefore, several visits are needed and products are offered for customer testing.
Similar activities have been conducted for Material handling systems. However, the target group is vehicle manufacturers and not end users, as is with back-up power products. The most relevant European based material handling manufacturing companies have been approached. The project results have been presented and good contacts have been established for further dialogue on how to proceed towards further cost reduction and optimization of fueling infrastructure. The cost challenges of the latter seem to constitute a general barrier for customers interested in fuel cell based material handling technologies.
This is reflected in the vehicle manufacturer's interest in the technology only, if the fueling infrastructure can be solved cost effectively for the end customer.

Conclusion WP6

Whereas the project results from the fuel processing system have primarily been disseminated and shared in scientific groups for educational and knowledge sharing purposes, the results from back-up power and material handling have proven ready for early customer introduction with commercial relations in sight.
Back-up power results and products are presented to end customers, who are engaged in testing these new products. The back-up products meet the customer expectancy for technological competiveness with traditional technologies in select, early markets. This is proving that the technology is headed in the right direction and with additional improvements and cost reductions constitutes a realistic and beneficial alternative to battery or diesel generation in difficult sites.
Material handling products need further technological improvements and severe cost reductions to be truly competitive to battery or diesel products. In addition, the main challenge according to the manufacturers of vehicles is the reliable and cost efficient fueling infrastructure.
This underlines the strong relevance and need for further R&D activities to develop and mature a cost-efficient, robust and reliable and scalable fuel processing systems, which can both serve a vehicle fleet locally with hydrogen as well as centrally produce fuel for public fueling station.