Accelerated Deployment of Fuel Cell Systems

EUDP 64010-0010

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Introduction

This project is based on a joint effort between Dantherm Power and Aalborg University.

The expected outcome of the project was a fully validated and technically mature LT PEM natural gas system with an electrical efficiency of minimum 30% and a combined efficiency above 90%. The lifetime of the system will be in excess of 30000 hours.

Also a complete bill of materials was made - with confirmed bids from component/subsystem suppliers of prices in 2013 for production quantities of 3000 pcs per year.

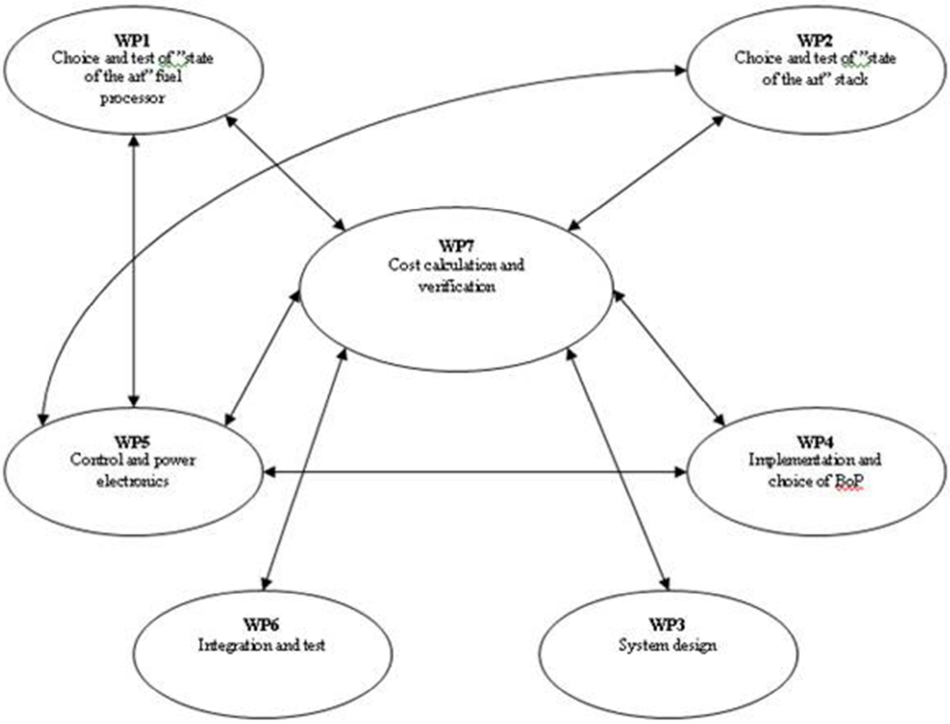
This project has been an important step on the way to reduce the time to commercial market introduction for “made in Denmark” CHP systems. Due to the activities and results in this project it was made possible to introduce LT PEM mCHP systems in the Danish mCHP project by middle of year 2011 and have a fleet of 20 new field test systems installed only 10 months later. The main reason that this accelerated scenario became possible, was that reformer and stack with the right specifications and durability became available for integration into systems during this project.

The fleet of 20 systems have been running stable for the entire demonstration period in the Danish mCHP project with a total of 125.000 hours in total and very good performance with third party measured efficiencies of 35% on electricity and 95% on total efficiency.

Cost reduction goals have not entirely been met, and cost reduction efforts will be continued focus in a next generation mCHP product.

Work packages

The work that has been done, in order to reach the goal of having a fully validated and tested “prototype system” ready for handover to product development after this project, has been following the work packages structure as described below.



Work package structure

The project was made up of 8 WP's – the technical of these are closely interrelated as illustrated in the figure above: The most central WP was WP7. The purpose of this work package was to link the other WP's together and to validate an overall final price for the system by the end of the project, based on economic decisions as much as technical (with direct quotes from suppliers). This work package has been central during the entire project, and been a continuous effort all through the project.

Milestones

Milestones were defined for each WP in order to secure that the project stayed on track. The milestones and actual deliveries can be seen in the table below.

Milestone number	WP no.	Milestone name	Deadline	Means of verification
1	WP1	Fuel processor mapping and running Fuel Processor in lab	Q4 2010	Test data
2	WP2	Fuel cell mapping and running Fuel cell module in lab	Q4 2010	Test data
3.1	WP3	Fuel cell and reformer models updated and calibrated	Q4 2010	Models
3.2	WP3	System model, P&ID, identifying core components and specifications.	Q4 2010	P&ID, steady state model
3.3	WP3	System analysis. completed	Q1 2011	Report
4	WP4	Bill of materials for entire system layout	Q2 2011	BOM
5	WP5	Controls for alpha system and plans for final system including development cost and final system cost for power electronics and embedded controls	Q1 2012	Cost projections for controls and control strategy
6	WP6	Running alpha system prepared for product development phase including CAD drawings, bill of material control manual and test log	Q4 2011	Data report
7	WP7	Verify system cost with regards to choice of fuel processing subsystem, fuel cell subsystem, BoP parts and total system layout.	Q1 2012	Cost break down BOM with suppliers

Milestones

Summary and conclusion

The outcome of this project is a validated prototype LT PEM Fuel cell mCHP system using natural gas as fuel. The mCHP system is validated and technical mature, to the possible extend within the project timeframe. The system key components; stack and FPS, have so far proved 15.000 hours of lifetime in a lab test setup. The suppliers of the fuel cell stack and the FPS specifies a product lifetime >40.000 hours, this is still to be verified in real operation.

20 systems of the Beta design have been in operation in Denmark in the Danish mCHP project, and have accumulated more than 125.000 hours of operation.

The targeted system price including margin and installation of 60.000 DKK in 2013, based on quotes from suppliers at a yearly volume of 3000 systems has not been archived. The result of this project and status in 2013 is a sales price of 89.043 DKK including installation and margin in 3000 units per year quantities.

Most important system degradation parameters has been identified within the project to attain the design goal of 40.000 hours lifetime, the purity of feed stocks to the FPS and stack are proportional to system life as these components are appreciated too expensive to replace. System requirement specifications for natural gas, process air and water have been developed and hereafter individual clean-up units have been developed for acceptable service intervals.

The LT PEM Fuel Cell mCHP system is CE marked and approved for installation in private Danish homes, complying with the Gas Appliance Directive and fuel cell technologies safety standard (EN62282-3-1)

The LT PEM Fuel Cell mCHP system is based on “state of the art” core components, such as a fuel cell stack from Ballard and a fuel processor system (FPS) developed by Tokyo Gas (in the frame of the NEDO program) for the Japanese market.

For the time being, Ballard is in the process of redesigning the FPS to meet the demands of Dantherm Power’s mCHP product – low cost/high volume production and gas compatibility/flexibility.

The Cost breakdown for the system clearly identifies the major cost carriers and identifies where further effort can be made to reduce cost. We see a clear positive trend from the Alpha system to the Beta system in the total cost, although there have been some components that we haven’t been able to cost reduce as we are dependent of a few specialized vendors that need to see high volume production to go into even minor design changes. Alone the cost reduction potential on the inverter can close 50% of the gap down to the target cost for this project.

The outcome of the project has been a fully validated and well proven mCHP system with an electrical efficiency of 35% and a combined efficiency of above 95%.

Where we are today compared with the expected:

- Performance test data on the mCHP system have been verified by DGC (Danish Gas Technical Center) and the performance is better that the project goals.
- Lifetime has reached 15.000 hour and systems are still operating. 30.000 hours will take another 20 months to reach, but lifetime expectations on both reformer and stack supports that this should be achieveable with the systems developed in this project.
- A complete BoM with confirmed prices from suppliers has been established for 3000 units per year. The result is around DKK 85.000 against the target of DKK 60.000 installed. This cost target results have not been met yet due to the continued complexity of the systems design and challenges on bringing down the cost on reformer and stack to the target level.

Next steps:

- Based on this project a direct follow on project with focus on reformer tolerance to more fuel qualities and continued focus on cost reductions has been defined. This project is again between Aalborg University and Dantherm Power, and includes participants from US with financial support from South Africa. This project has been granted support from EUDP under the name “USDan”.
- As a spinn off project, the system simulation and failure mode analysis tool from Aalborg University has been included in an ongoing EU, JTI project called D-Code where this tool solves challenges that already engaged universities were not able to solve.
- As a follow on to the D-Code project a new EU, JTI project called Sapphire has been established and granted to fine tune the models for real use as onboard failure diagnostics on mCHP and other reformate systems.
- Going forward the focus is to achieve lower prices on stacks and reformer from world leading suppliers combined with increased lifetime! For the following generation of products, the 1300 series stack from Ballard has been chosen based on its cost reduction potential, and Ballard and Dantherm Power is working on a cost optimized and more fuel tolerant reformer from Ballard UMD - based on the concept from the Tokyo Gas CE-4 reformer.

List of publications

During this project the publications listed below were produced.

Following newspaper articles have been registered so far:

Gasteknik, no. 6, 2012, page 18-21
FiB, no. 14, September 2012, page 20-21
Den grønne løsning på el og varme, NordJyske, Annoncetillæg, March 10th 2013, page 6
Demoprojektet i Varde indtager private hjem, DEBRA Energinyt, September 3rd 2012, page 6-8
Alternativ varme testet i Varde, Boligavisen Varde, May 7th 2013, page 2

Following scientific papers have been made:

Numerical analysis of charge transfer based condition monitoring for PEMFC, Hans-Christian B. Jensen, Søren Knudsen Kjær, Søren Juhl Andreasen. Aalborg University, Department of Energy Technology, Pontoppidanstræde 101, DK-9220, Aalborg, Denmark

Failure mode and effect analysis on Fuel Cell, Aalborg University, Department of Energy Technology, Pontoppidanstræde 101, DK-9220, Aalborg, Denmark

Milestones

Milestone number.	Description	Deadline	Status
1	Fuel processor performance and durability test	Q2 2011	9850h test finalized, Q2 2012
2	FC performance and durability test	Q2 2011	6200h test finalized, Q2 2012
3.1	FC and fuel processor model updated	Q2 2011	Done
3.2	System model, P&ID specification and selection of critical components	Q2 2011	Component specifikation done on critical components Specifikation of P&ID done by Q2 2011
3.3	System analysis finalized	Q2 2011	Modelling of thermal integration and heat storage donet
4	Bill of Material (BoM) for complete system	Q3 2011	Done
5	Controls software done and and power electronics selected. Plan for PCB version of the controller	31. October 2012	Software has been finalized and inverter has been selected and integrated. Plan for conversion to PCB has been laid out.

6	Alpha system lab test and CAD work and Bill of Material (BoM) completed	Q1 2012	CAD design and BoM has been finalized
7	Verification of system performance og components	31. October 2012	The prototype has been tested and validated, and cost analysis is done.

Milestone results

Work and results during the project

In the following the work and results during the project are described work package by work package, as the work progress and generation of results has been following the lines defined from the beginning of the project.

WP1: Choice and test of ”state of the art” fuel processor

The fuel processor for this project was chosen based on years of testing of fuel processors and catalysts at Dantherm Power and Aalborg University.

Given the opportunity of buying the CE-4 fuel processor from Tokyo Gas, which has been proven in the Japanese field trial program, the choice was very clear.

The CE-4 specifications are attached in the following table.

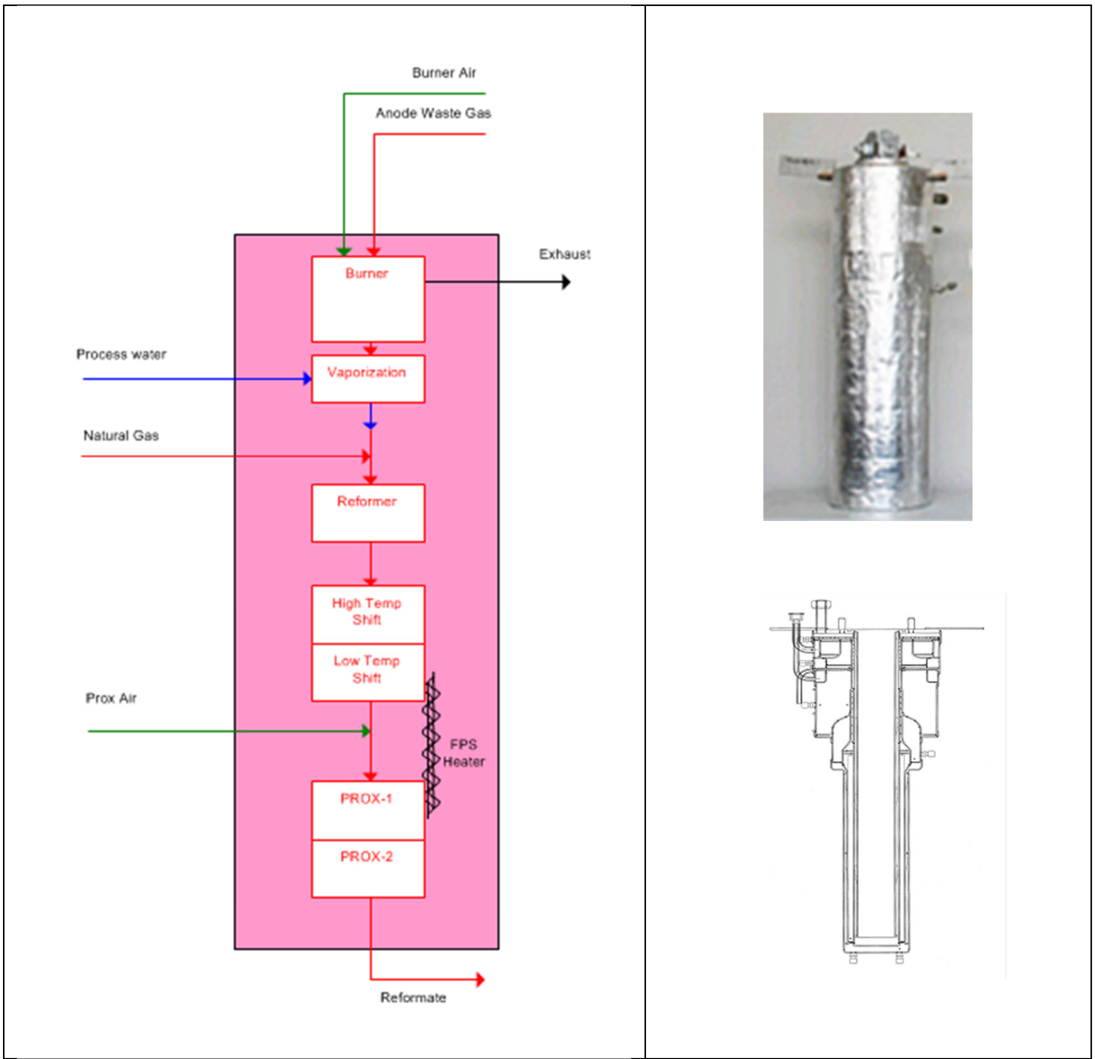
FPS-CE4 Specification (Nominal)

Input	Maximum output
Material gas(NL/min)	4,1
Fuel(NL/min)	0,0
Combustion air(NL/min)	18,0
Combustion air ratio	1,3
Selective oxidization air, stage 1(NL/min)	1,3
Purified water flowrate(CC/min)	10,0
S/C	2,7
Pressure	
FPS inlet pressure of gas to be reformed(kPa)	30
FPS outlet pressure of reformate (kPa)	29
Process water inlet pressure(kPa)	71
Reformate	
H2	73%
N2	5%
CH4	2%
CO2	20%
CO(ppm)	0
Flowrate of reformate(NL/min)	21,2
Thermocouple data	
Burner temp.[B](℃)	770
Burner temp. symmetric[BB](℃)	770
Reformate catalyst outlet temperature[G](℃)	680
Outlet temp of PWPROX[E2](℃)	110
Inlet temp of high temp shift-conversion catalyst[JJ](℃)	360
Low temp shift-conversion catalyst inner-2[Ka2](℃)	270
Low temp shift-conversion catalyst outer-2[Kb2](℃)	210
Inlet temp of PROX-1catalyst[L](℃)	160
Reformate outlet temp[Ref](℃)	90
Exhaust gas outlet temp[Exh](℃)	90
Performance	
Produced hydrogen flow rate(NL/min)	16,0
Methane inversion ratio	91%
Hydrogen generation efficiency(HHV)	83%
Hydrogen generation efficiency(LHV)	78%
Thermal efficiency(HHV)	88%
Thermal efficiency(LHV)	84%
Expected hydrogen utilization ratio in the STACK (The rest of reformate is returned to the burner.)	75%

Fuel processor (reformer) specifications

During this project Tokyo Gas has been very helpful providing very much help on integration of the reformer into a system, and also providing support on the reformer concept in order for Dantherm Power and Ballard to be able to work on further cost reductions and improvements on specific performance parameters like fuel quality tolerance, start-up time, etc.

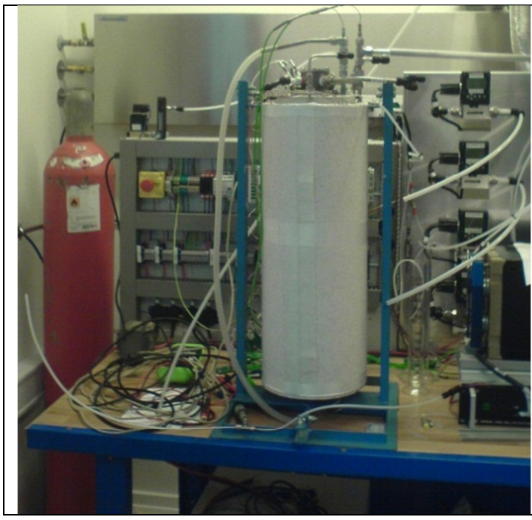
The fuel processor is using the steam reforming principle. The basic principle of operation is shown in the following sketch along with picture and a sectional drawing of the fuel processor.



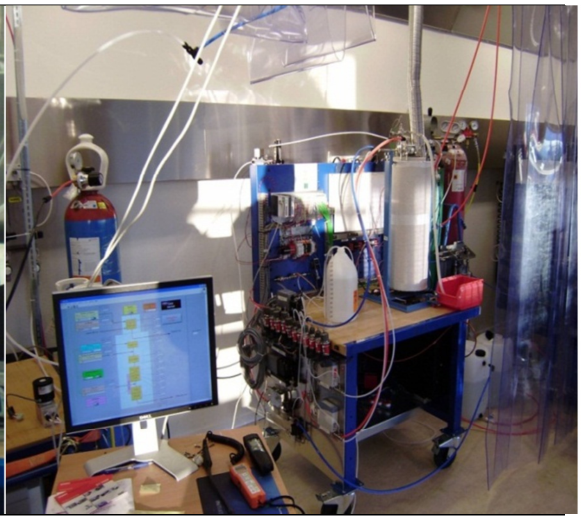
Fuel processor (reformer) design

The initial testing of the reformer was done in a dedicated test stand with analysis of fuel feed and reformat quality. After obtaining good results in accordance with the specifications, the reformer was built into test stands to emulate a system setup.

Two test stands have been built at Dantherm Power, to step by step learn the integration of the fuel processor, and afterwards to perform testing of both sub-components and system.



OB1 Teststand



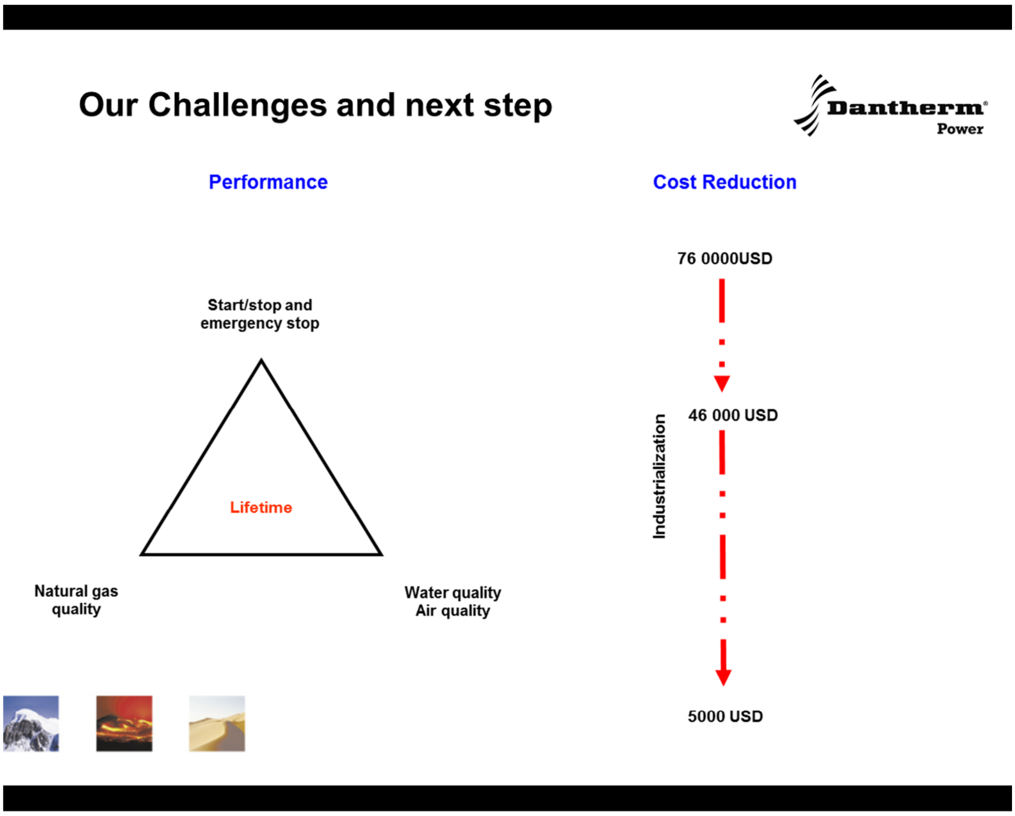
OB2 test stand

The OB1 test stand is testing fuel processor and fuel cell stack, individually or combined, using mass flow controllers.

The OB2 test stand is testing fuel processor and fuel cell stack combined using real BoP (Balance of Plant) components . As such the OB2 test stand mirrors the full fuel cell system, just on a table rather than in a box. OB2 has been used to qualify components for the system before building the real Alpha prototype.

Both test stands have been running almost continuously since early 2011 to reveal life time limitations on components. OB1 has been focusing on stack and fuel processor lifetime whereas OB2 has also included BoP component lifetime issues along with the impact from these on stack and fuel processor.

The learning from running the initial tests on OB1 and OB2 test benches has been that fuel purification, water purification and controlling of start stop (especially emergency stop) processes are major contributors to reformer durability. These areas have been focus areas along with the continuous cost reduction efforts, as illustrated in the figure below.



Focus areas

Desulphurization

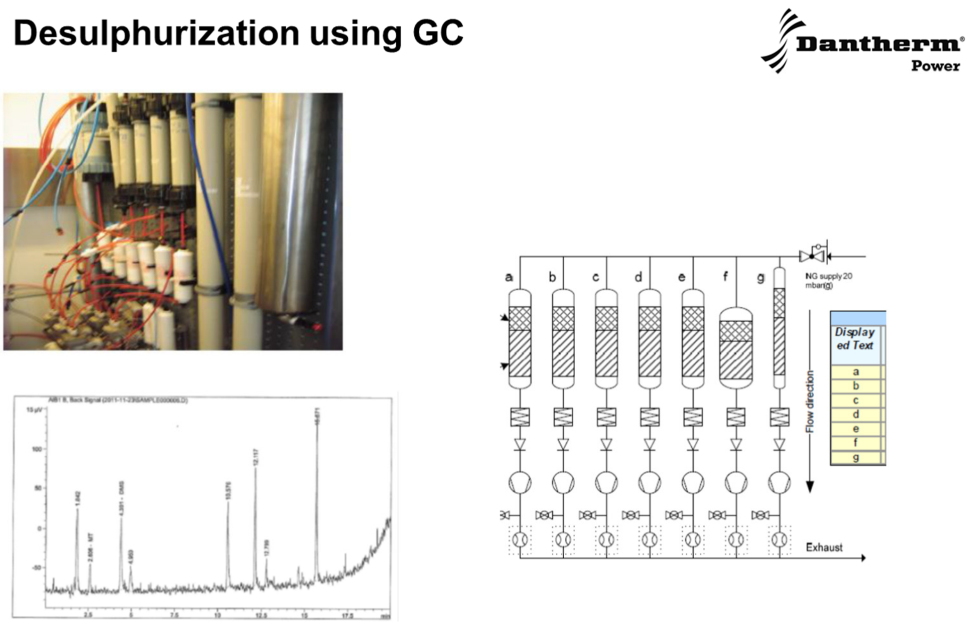
The sulphur content and the sulphur composition in natural gas varies a lot from country to country, depending on the source of the natural gas. Sulphur removal is a barrier to the successful deployment of the Danish mchp or any product using the steam reformer technology.

In this project a lot of effort has been focused on the right selection of desulphurizing catalyst for the systems.

Compared to early desulphurizing systems, major milestones have been achieved by selecting the best available desulphurizing catalyst in the right setup through the ex-situ DOE:

- Reducing of capital cost by 80%
- Reduction of assembly cost by 80%
- Reduction of the size by 30%
- Increasing the lifetime by 40%.
- Reduction of sulphur slip by a factor of 10.

On the following figure, the test setup for testing desulphorizing catalysts is shown. The fuel feed is Natural gas from the North Sea, and the reformate quality is measured using a GC (Gas Cromatograph).



Desulphurization testing

Process water quality

Water quality for the steam reforming has shown to be a very critical point for ensuring durability of the reformer. The first tests on OB1 and OB2 were done using tap water with DI filters. After several attempts where the reformers were damaged, the decision of reusing the condensate from the system was taken. As the water produced in the fuel cell stack is of constant quality. The challenge is to get the water condensated in the exhaust and collected for use in the reforming process. A special condensation system was developed and has shown to work very well under the conditions specified for the system. If temperature exceeds 30C the condensation concept is getting more difficult to manage, but that is not an issue for indoor mCHP systems in Northern Europe.

The required process water quality for the reformer is shown in the table below.

Process Water quality

Fluid	DI water
Flow	15 ml/min
Lifetime target	5000 hour
Temperature	0 - 60˚ C
Contaminents (inlet DI)	
Conductivity	8 µs/cm
PH	5
Silica(SiO_2)	12 µg/L (assuming measured silicium forms Silica)
Sulphur (S)	0,1 µg/L (4 mg/45000h)
Anions	47 µeq/L
Cations	34 µeq/L
Requirements (Outlet DI)	
Process water conductivity (target)	< 0,1 µS/cm at 25˚ C
Silica(SiO_2)	2,77µg/L (100mg/40000h)
Sulphur (S)	0,083 µg/L
Anions	Not specified, 1% of inlet = 0,47 µEq/L
Cations	Not specified, 1% of inlet = 0,34 µEq/L

Water quality requirements for fuel processor

Regarding water treatment, we have screened all major commercially available ions exchange resins regarding to their respective capacity. We also identify that either CO_2 or VOC were responsible for the deactivation of the resin. Adding a small degasser to the water system was allowing to increase the lifetime of the resin by a factor of 12.

Ion exchange resin testing

Controls

Controlling the startup and shut down process for the fuel processor has been one of the most time consuming tasks. Tokyo Gas has been very helpful getting the control algorithms defined, but lots of testing has had to be conducted to get the process working sufficiently well to avoid sacrificing lifetime during startup and shutdown – especially emergency shutdown.

Testing

During the project the OB1 Teststand has been running for 9.850 hours with fuel processor and fuel cell stack. The OB2 teststand has been running for 6.200 hours with both fuel processor, fuel cell stack and BoP components.

All tests have been performed on methane and Danish natural gas (North Sea quality)

Catalyst improvements needed

The nitrogen tolerance of the CE4 reformer is 0,6% which is sufficient for natural gas coming from the Danish North Sea, but not sufficient for large parts of Europe.

In order to use the CE4 reformer more broadly in Europe in future, it is nescessary to change the catalyst to a different version with higher nitrogen tolerance.

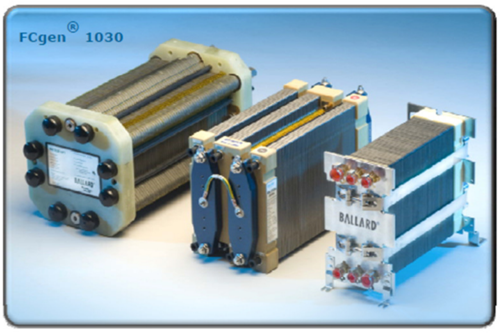
The plan for development of a next generation fuel processor is settled, and initial tests with a CE6 reformer with higher nitrogen tolerance have been done with good results.

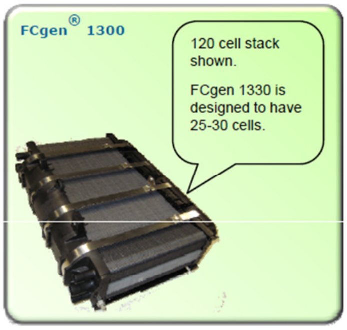
WP2: Choice and test of ”state of the art” stack

The choice of fuel cell stack for this project is based on many years of fuel cell stack testing at both Dantherm Power and Aalborg University. With the successful deployment and durability of hundreds of systems in Japan using the CE4 reformer with the Mk 1030 stack from Ballard Power Systems, this would be the obvious choice.

Dantherm Power has been working with earlier versions of the 1030 stack with very good results, and the continuation engineering on the 1030 stack to reduce costs and durability even further shows good potential in this stack.

On the following picture the history and a future outlook of the 1030 stack is illustrated.





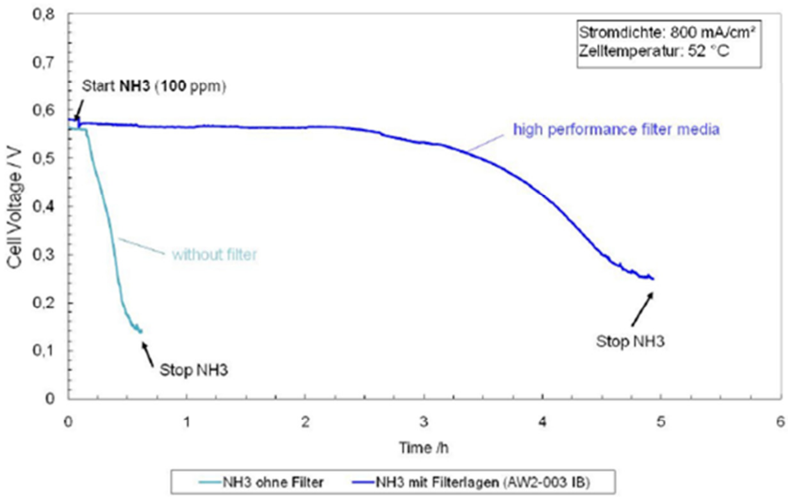
	FCgen® 1030 Series		
	AP1	AP2	V3
Launch	2002	2005	2008
Weight	26 kg	20 kg	12 kg
Durability	>5000	>15 K, 3 yrs	>40K, 10 yrs

FCgen® 1300 Series
1330 (in development)
2012
7 kg
>40 to 60K hrs, 10 to 15 yrs

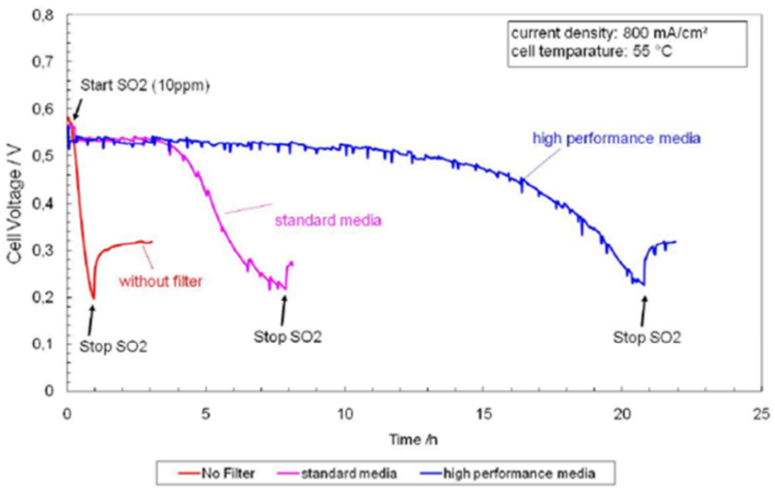
Fuel cell stack – history and future outlook

As mentioned under WP1, the OB1 and OB2 test stands have been running durability testing under different conditions with good results. Main tasks regarding fuel cell stack integration have been the air quality and the control algorithm development.

The impact from bad air quality has been assessed through accelerated tests with Ammonium and SO2 in the air flow. Some of the results are captured in the graphs below.



Impact on stack performance from NH3 with and without air filter



Impact on stack performance from SO2 with and without air filter

Based on the testing the air filter solutions have been selected.

The reformate quality from the reformer has not been a challenge as the shift and PROX clean up always protects the stack.

First stack tests were done in a standalone set-up where the H2 and N2 mixture was controlled.

Next stack tests were done using bottled gas simulating reformate quality from the reformer.

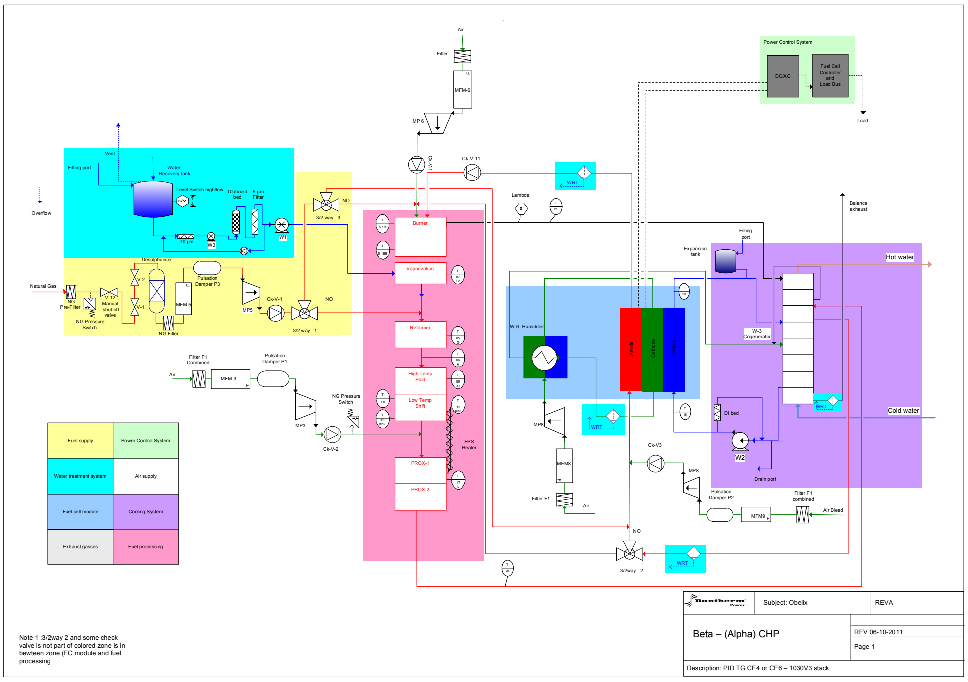
Third step was the testing in the OB1 and OB2 test stands where mass flow controllers were used on OB1 and complete set of Balance of Plant components used on OB2.

All tests were successful and no surprises were found on stack performance under different conditions and when integrated with system components. The results from the 20 unit field trial without stack failures speaks its own language of a very robust design.

WP3: System design

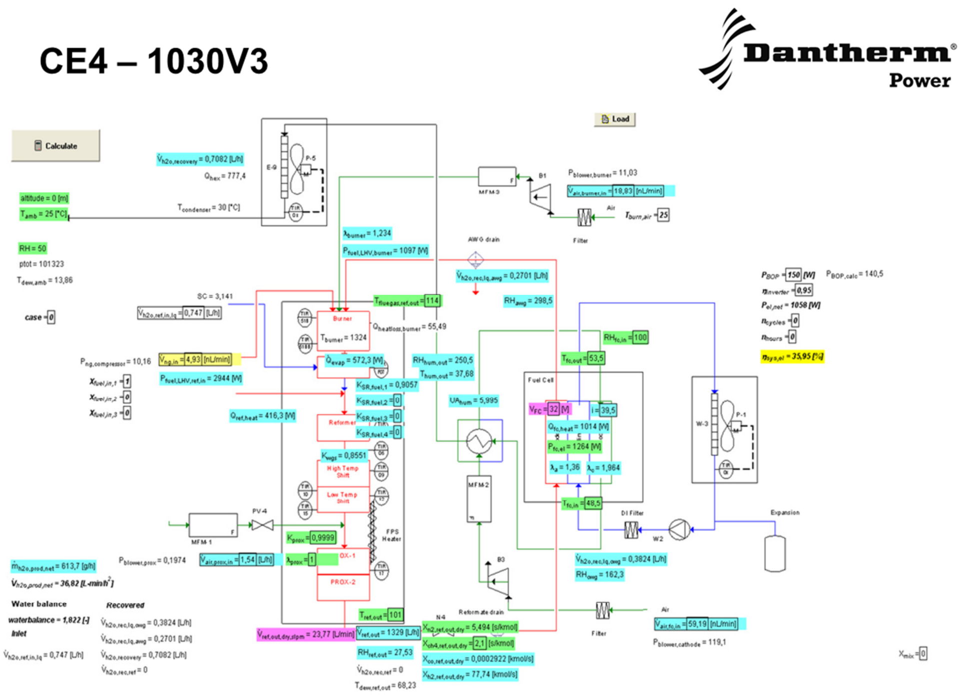
System design has been an iterative process based on experience from previous system designs, learnings during the project, recommendations from Tokyo Gas and possibilities of getting right components at the right price – still with the goal of building in ease of assembly and durability in the design from the beginning.

The system P&ID is shown in the following figure.



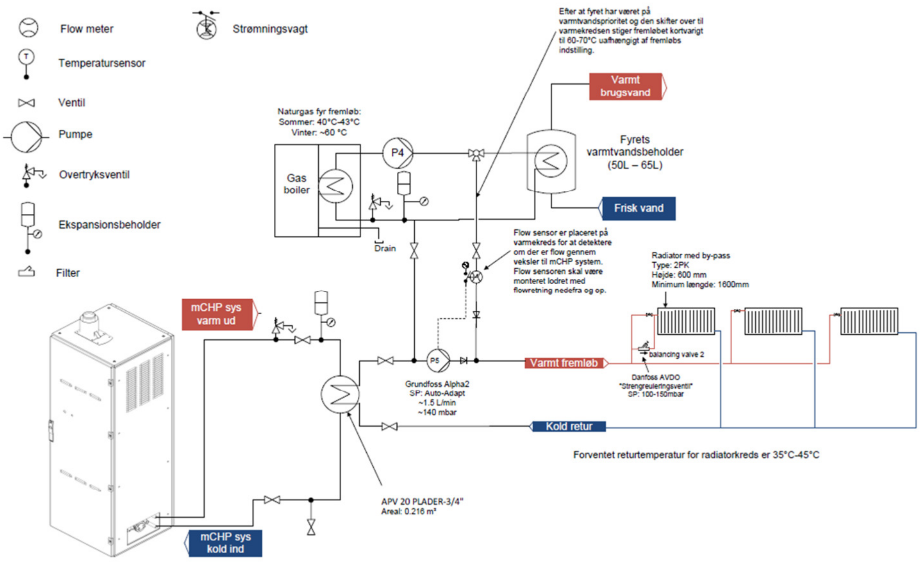
System P&ID

In order to speed up the design process and make sure that selected components for the system design are matching, Dantherm Power has developed a system model that simulates all components and the impact on the system by changing components. This system model is a very strong tool for fuel cell system design. In the figure below a steady state simulation is illustrated for the Bets system.



System simulation

The fuel cell system has to be integrated into the heating system in the house. On the following figure the P&ID of the heat integration is shown.



P&ID of system heat integration

The fuel cell system is integrated with the heating system of the household. The existing boiler makes sure to cover the peak heating demand, whereas the base demand is taken care of by the fuel cell.

The heat integration strategy has been modeled at Dantherm Power, and we have different opportunities depending on the actual application. If large fluctuations on electricity production are seen in the public grid, it is possible to match the fuel cell system heat integration to a situation where extra electricity production going back to the grid is needed. So far the heat integration is matching local neds in the household, but flexibility has been built into the systems.

The fuel cell system also has to be integrated into the electrical system of the house. For that purpose a special designed inverter has been chosen. This inverter connects to the variable DC-bus of the fuel cell system and hooks up to the grid in the household. For more information, please refer to WP 5. The fuel cell system covers the yearly electricity demand of the household (usually around 4500 kWh per year) and has the ability to be externally controlled as part of a smart grid setup or as a virtual power plant.

HAZOP on system safety has been performed and the system has been CE-marked.

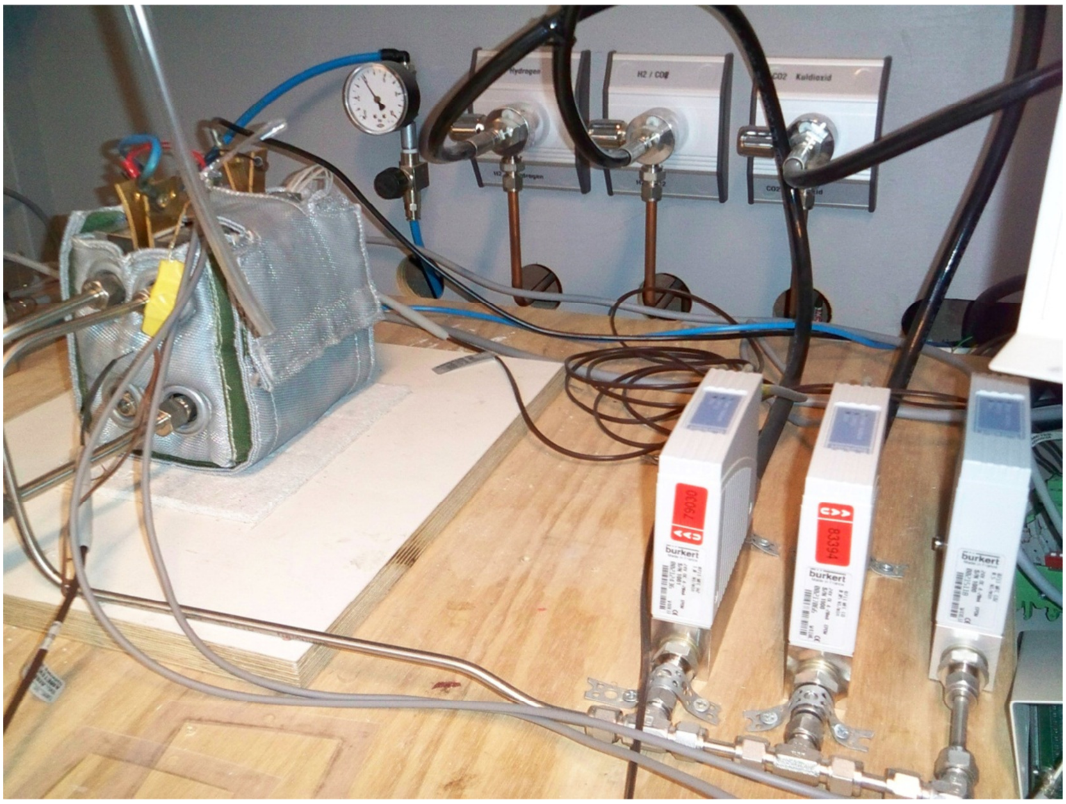
System reliability and fault detection

The work at AAU focused on two different theoretical methods for fault detection and isolation. One method did not lead to useful results within the timeframe of the project whereas the other showed good potential but also needs further development. The objective of both methods was to improve the stability and lifetime of fuel cell systems. Some of the development work was focused on the HTPEM technology as the required experimental input data was not available for LTPEM. The methods and results can however be transferred to LTPEM with a minor effort when experimental data becomes available.

Most of the work focused on model based fault detection and isolation using parity space theory applied to well-known and generally accepted fuel cell models. The method was shown to be applicable in theory and through simulations (AAU appendix 1). Unfortunately, it has not been possible to make these results applicable in practical fuel cell systems. Without useful results from the parity space theory it was not possible to derive new methods for model based fault detection and isolation. However, Failure Mode and Effect Analysis (FMEA) (AAU appendix 2) can be used for traditional fault detection and isolation. This method was not developed to a stage where it can be demonstrated in real system. This would require a more precise model based on detailed experimental characterization of the fuel cell stack and other system components. This could not be completed within the time and budget of this project.

The possibility of estimating the amount of CO in a reformate gas was also investigated as this significantly influence lifetime and performance of a fuel cell, LTPEM in particular. It is possible to measure the CO concentration using a gas analyzer; however, this is a very expensive solution that is not feasible in a commercial fuel cell system. The possibility to estimate the CO concentration using online methods based on the fuel cell itself is therefore of interest. In this project the use of electrochemical impedance spectroscopy was explored. Instead of the traditional approach that uses the entire frequency spectrum, this work only uses a single frequency as this could make the hardware implementation cheaper. The relation between CO, CO_2, temperature, internal resistance and impedance was mapped. Based on this map impedance measurements, that can be made relatively easy, can be used to estimate the mentioned properties including CO concentration. This model differ from the one mentioned above as it is entirely based on a black box model of the fuel cell

To demonstrate the applicability of the model it was tested on a single cell test setup as the one shown on the photo below. The results from this test have been presented at the FDFC2013 conference in Karlsruhe and published in a conference paper. Overall, the results from this work are promising but further work is needed before it can be implemented in commercial fuel cell systems.



Test setup for the fault detection system at AAU

The fault detection system to improve both system reliability and system durability is a novel methodology that still needs some development before being implemented. This work is ongoing between AAU and Dantherm Power, and it is expected to show big benefits on future generations of fuel cell systems.

WP4: Implementation and choice of BoP

Based on P&ID design, system simulations and test bench setup, we have chosen all components for the fuel cell mCHP system.

All BoP components have been tested in OB2 test stand for functionality, reliability and durability.

Below is a part of BoM for the complete system. For confidentiality reasons only the heat storage, exhaust and inverter is shown.

83	**Heat storage**			
84	Circulation pump heat storage	W-4	RD12Z	IWAKI
85	Integrated HEX	HEX-4(b)	Custom	Hobro rustfri
86	Integrated HEX	HEX-3(b)	Custom	Hobro rustfri
87	Integrated HEX	HEX-2(b)	Custom	Hobro rustfri
88	Integrated HEX	HEX-1(b)	Custom	Hobro rustfri
89	Overtemperature cooling water	T25	PTC switch	
90	Water temp to heating system		pt1000	
91	Water temp from heating system		pt1000	
92	Water flow heating system	MFM-W4	Shark 478 US-VMT	Hydrometer
93	**Exhaust**			
94	Integrated HEX	HEX-1(a)		Hobro rustfri
95	Integrated HEX	HEX-4(a)		Hobro rustfri
96	**System cabinet**	**PID ID**	**Product name**	**Manufacturer**
97	Cabinet			
98	Cabinet temperature	TS-C1		
99		TS-C2		
100	Cabinet gas sensor	GS-C1		Neodym
101	**PID ID**	**Product na**	**Manufacturer**	**Type**
102	EBC-E1	CT10280	Milton	ø125 stainless steel white flange mounted
103	EBM-E1	custom produced		fange welded on CT60014 w. G1" hose connection for
104	EBP-E1	CT60016	Milton	ø125/80mm 1m stainless coaxial exhaust pipe
105		CT60023	Milton	ø125/80mm stainless steel
106	PS-E1	GW10 A6	Dungs	10mbar(g)
107	**Power control system**	**PID ID**	**Product name**	**Manufacturer**
108	Inveter	DC/AC	Hydroboy	SMA
109	**Exhaust**	**PID ID**	**Product name**	**Manufacturer**
110	Exhaust connection	EBC-E1	CT10280	Milton
111	Exhaust manifold	EBM-E1	custom produced	
112	Exhaust pipe	EBP-E1	CT60016	Milton
113	Top rain cover and roof through pipe		CT60023	Milton
114	Ventilation for process water tank	EBV-V1		

Part of System Bill of Material (BoM)

WP5: Control and power electronics

The control software has been developed in Labview as a generic platform for controlling fuel cell systems. Spcific algorithms hhave been developed for the Beta system, and the controls platform is continuously being updated with experiences from the field and from internal testing.

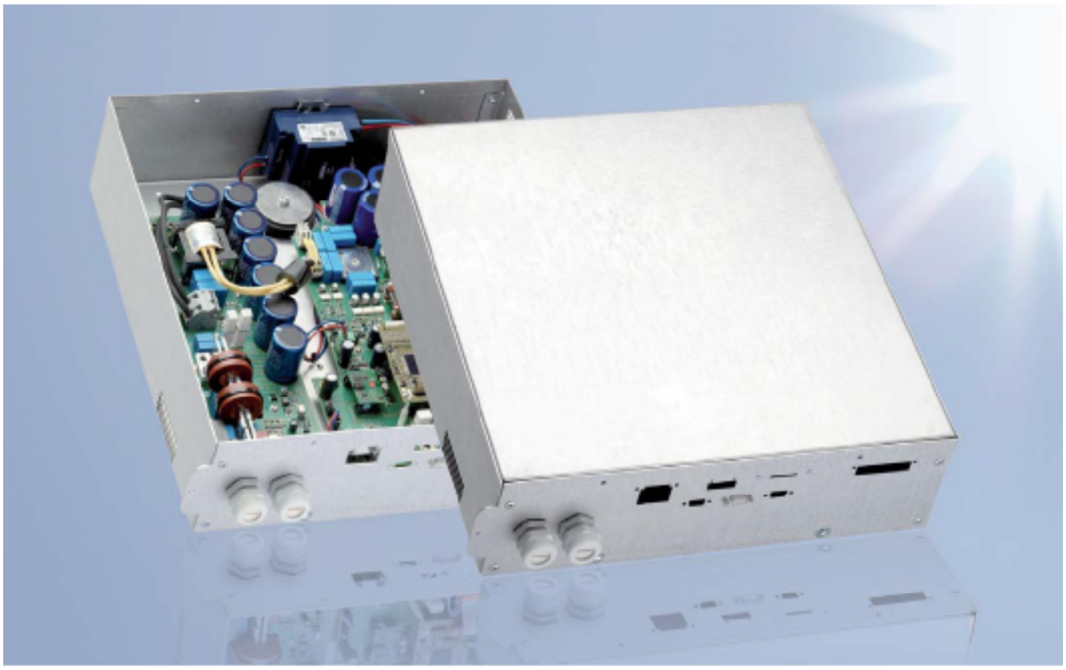
The controls hardware has been chosen as an industrial pc platform with IO from Beckhoff.

The PC based Labview software and Beckhoff IO is transferable to embedded hardware on an already developed IO platform from Dantherm Power as soon as the system design is ready for mass production and production volume justifies this.

The flexible hardware platform makes it possible to make changes and upgrade the system controls with new features in a flexible way. This hardware platform makes it possible to implement the failure prediction algorithms and hardware that is being developed with Aalborg University as soon as it is ready for implementation. Also other upgrades for different flexible heat integration setups can rather easily be implemented as long as the hardware is not embedded.

The Power conversion from fuel cell DC output to AC grid connected power is managed by an existing inverter from the German company SMA. The inverter from SMA has been tested in the laboratory and has shown good performance also in the field trial.

The specifications of the inverter are sown in the data sheet below.



HYDRO BOY HF

High yield devices in lightweight housings

The new Hydro Boy generation: The 1524HF and 2524HF devices are equipped with modern high frequency technology and thus ensure a very high efficiency. By reducing the weight and size of the coil components, these inverters have become particularly lightweight and easy to use. Thanks to the modular design of the power electronics, the Hydro Boy Inverters also adapt flawlessly to external conditions. Thus combining the state-of-the-art SMA technologies and the highest efficiency in a 19" rack.

Technical Data
Hydro Boy 1524HF / Hydro Boy 2524HF

DC input	
Input voltage	25 V - 70 V
Continous input power @ 30 °C HB 1524HF / HB 2524HF	1500 W / 2500 W
Maximum input current HB 1524HF / HB 2524HF	60 A / 100 A
AC output	
Maximum AC power @ 30 °C HB 1524HF / HB 2524HF	1150 W / 2300 W
Output voltage (Range)	230 V (184 V - 264 V)
Frequency (Range)	50 Hz / 60 Hz (45 Hz - 65 Hz)
Maximum Efficiency	> 93 %
Interfaces	
CAN	Yes
RS485 or RS232	Optional
General Data	
Width x Height x Depth (in mm)	approx. 444 x 130 / 160 x 454
Protection rating	IP20
Weight HB 1524HF / HB 2524HF	approx. 15 kg / 17 kg
Ambient Temperature	0 °C ... +70 °C

SMA inverter specification

WP6: Integration and test

All BoP components have been integrated in a system design for the Alpha prototype. Testing under a number of different operating conditions has been performed with good results. Below the Alpha prototype system is pictured.

Alpha system

Based on the Alpha system an improved system design has been developed with a number of improvements for assembly and durability, but also based on the learnings of the simple functionality of the system. This new Beta system has been documented for production and one system has been built and installed in the Dantherm Power facility for durability testing.

The system has been CE-marked before the next 20 systems were built for the Danish mCHP project.

The Beta product specification is seen below.

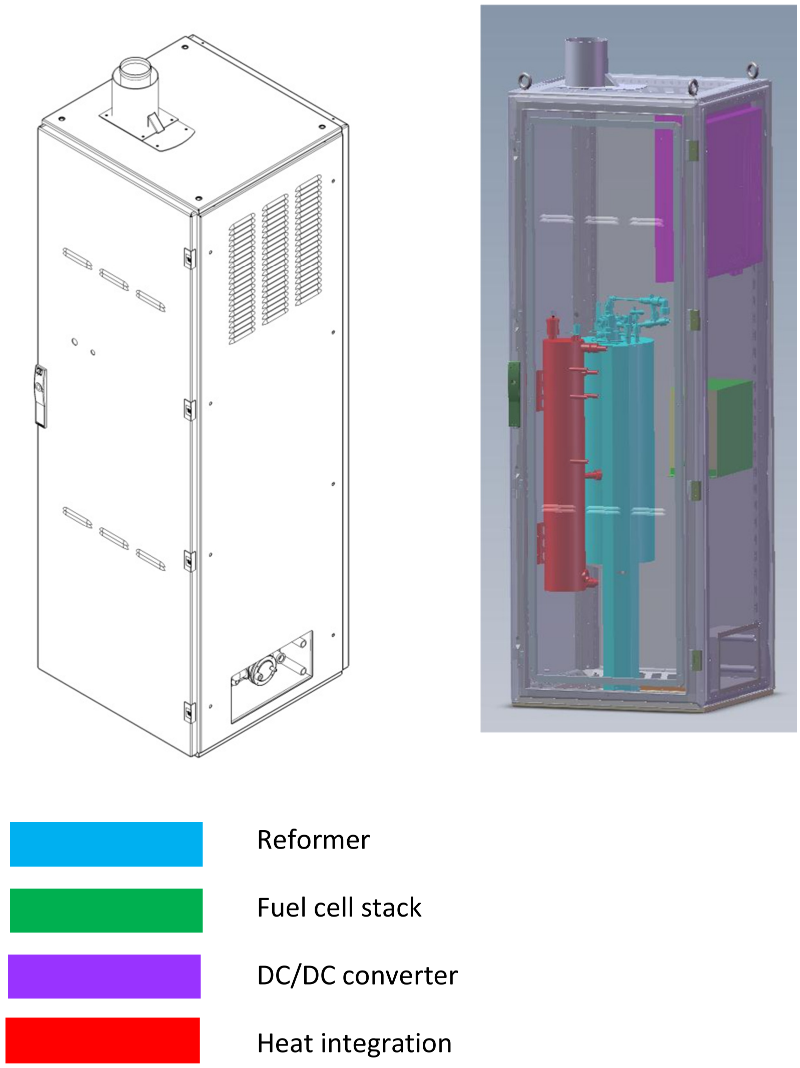
Product Specifikation - Beta

AC Output	Rated output : > 900W Turn down limit :<400W AC Specs: 240VDC 50Hz
System performance	Electricity : 35%LHV Overall (heat + electricity) : 95%
Durability	40 000 hours – (5000 hours for the Beta Danish phase µCHP)
Fuel	Danish NG N2 <0,5% (CE4) Sulphur 4,2- 10,9 mg/Nm^3[S] BTX <100 ppm
Start-up time	60-90 min
Temperature	Cogenerator 35-65°C temperature regime Stack 57-67°C
Maintenance frequency	Once a year
System size	HxWxD 1800x600x600mm, inverter implemented inside cabinet
Installation	Indoor, residential or light industry, Denmark, CE marked
Main Components	1030 V3 - CE4 - SMA Inverter, DP Cogenerator, NOK 1000 fibers
Exhaust	Balanced 12m metal, mounted with two screws ø60/100
System control	Heat following and VVP (DONG powerhub, option: smart grid interface(IEC 61850))

Beta product specification

System layout

The layout of the system is illustrated on **Fejl! Henvisningskilde ikke fundet.**. To the left the exterior and system connections are presented. To the right, the main components location inside the system are indicated. Color identification for the main components can be found in the table below.



CAD illustration of Beta system layout and identification of main components

The final Beta system installation is seen below.

Examples of installations

Installation in technical room of the home

System #8 installed in private home in room containing all central heating installation, electronics, and network.

Home details: Built 2006, 293m2, floor heating

Beta system installation

The system has been tested by DGC (Danish Gas Technical Center) as a formal third party test, and the results are seen below.

FC mCHP technology
Our results from 3rd party approval

Parameter	LT PEM Alpha	LT PEM Beta
Source data	*DGC Jan 2010*	*DGC Nov 2010*
Fuel	Fuel G20 (Methane)	Fuel G20 (Methane)
AC 230 V output, gross (W)	1090	NC
Power Consumption (W)	220	NC
AC 230 V output, Net (W)	870	900
Fuel (G20) input (nm^3/h)	0,292	0,268
Fuel input (W)	2910	2677
Cooling water flow (kg/h)	31,8	34,5
Return temperature (° C)	25,6	25
Forward temperature (° C)	67,3	62
Thermal output (W)	1540	1468
Gross electric efficiency (%)*)	37,5	NC
Net electric efficiency (%)*)	29,9	33,6 (35% at BOL – field)
Thermal efficiency (%)*)	53	54,9
Overall efficiency, net (%)*)	83	88,5 (100 in the field)
Flue gas temperature (°C)	33,3	34
O_2 in flue gas (%, dry basis)	9,5	9,9
Condensate drain (kg/h)	0,33	*0,34*
NO_x (ppm, dry basis)	<2	<2
CO (ppm, dry basis)	<3	<4
UHC***) (ppm, dry basis)	40	10-180

Beta system test data from DGC

Production of 20 systems have been executed under the Dankísh mCHP project in parallel with this Accelerated Deployment project. Production is seen on the following picture.

Production of Beta systems for DKmCHP project

WP7: Cost calculation and verification. Cost breakdown and BoM with suppliers

Beta system Cost Breakdown

The Cost breakdown for the Beta BW Rev B (Beta system) system clearly identifies the major cost carriers and identifies where further effort can be made to reduce cost. We see a clear positive trend from the Alpha BW system in the total cost, although there have been some components that we haven't been able to cost reduce as we are dependent of a few specialized vendors that need to see high volume production to go into even minor design changes.

The bill of material for the Alpha BW system and the Beta BW System in categories in US$ is seen below.

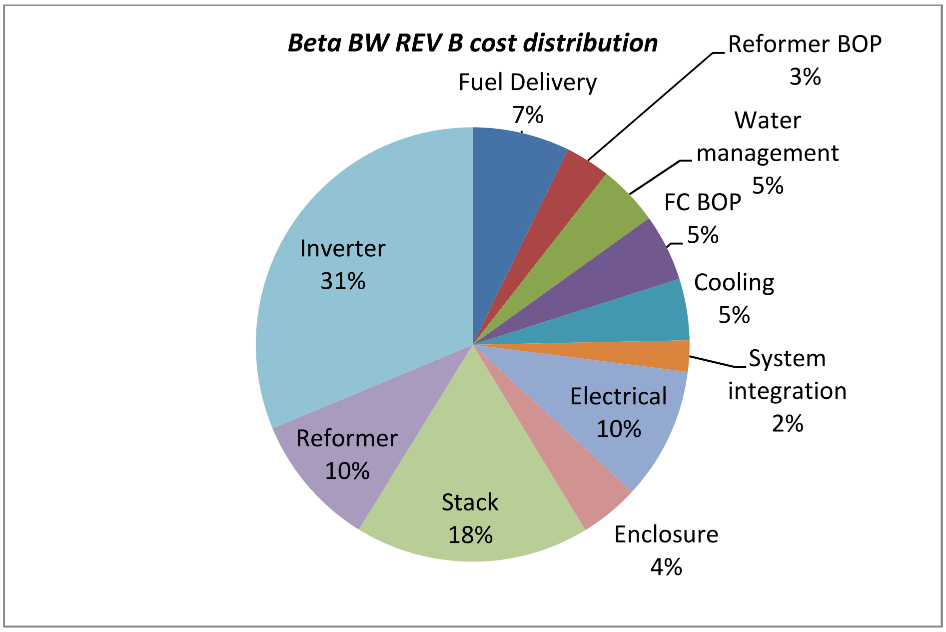
	Alpha BW	Beta BW REVB
Fuel Delivery	$847	$621
Reformer BOP	$489	$287
Water management	$646	$390
FC BOP	$907	$427
Cooling	$302	$394
System integration	$170	$200
Electrical	$844	$844
Enclosure	$381	$381
Stack	$1.500	$1.500
Reformer	$850	$850
Inverter	$2.687	$2.687
Total	**$9.623**	**$8.581**

Alpha and Beta system material costs (3000 systems per year)

These prices are based on a yearly demand of 3000 pc.

The complete bill of material can be presented on request. We are unfortunately not able to share a complete supplier list, as we have protected the intellectual property of both Dantherm Power A/S and the supplier, and signed mutual non-disclosure agreements with all key suppliers. An example of the BoM list is shown in WP 4.

The cost distribution for the component categories:



Beta system material cost break down

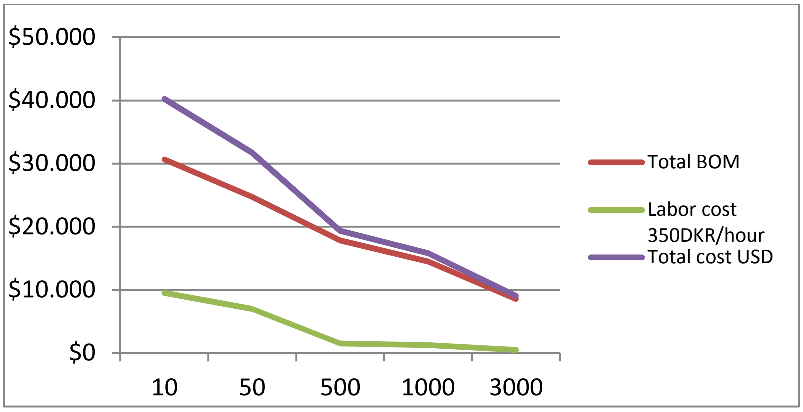
Yearly Demand Effect on the System Cost

The yearly demand has a major impact on the price structure, and the system cost is very sensitive to the market development.

	Qty				
#/Year	***10***	***50***	***500***	***1000***	***3000***
Total BOM	$30.680	$24.715	$17.828	$14.516	$8.581
Labor cost 350DKR/hour	$9.550	$7.003	$1.528	$1.273	$509
Total cost USD	**$40.230**	**$31.718**	**$19.356**	**$15.790**	**$9.090**

Yearly demand/production volume impact on system cost

The labor cost has been added to visualize the further cost reduction at higher numbers



Production cost in volume production

Potential cost optimization areas identified:

Inverter:

The inverter cost is the largest contributor to the complete cost and also a component that has a large potential for cost reduction when the yearly demand increase. When looking at small numbers we are forced to work with standard solutions and we have special demands for the input window and the control of the inverter based on the input and not the output alone. This has forced us to customize very expensive solutions and be dependent of a very few high-end vendors. The experience is that with minor changes to window for the input current and changes to the control strategy within the inverter we are able to reduce size and numbers of the inverters needed. To get the commitment from vendors to make these changes we need to commit to the higher yearly numbers.

Control Platform:

The current technology used is based on a Beckhoff IO modules platform and a mini PC. This not the most cost effective choice of components but allows us to make adjustments to control parameters quickly and in an cost effective way based on the knowledge gained during test in the laboratory and during field test. This controls hardware platform is also chosen because it is relatively uncomplicated to transfer to an embedded platform, when the volume and maturity is there and is expected to reduce the cost with 50%. A further cost reduction will be obtained when the demand from the market increases and we can move the production of controls to BRIC countries for another 40-50% cost reduction. These numbers are based on experiences made in other fuel cell systems developed and currently commercially available on the market.

Stack:

The current Beta system uses the Ballard 1030V3 fuel cell stack. Ballard is launching a new fuel cell stack series; the Ballard 1330 stack that is more robust and more cost effective. The Ballard 1330 fuel cell stack is targeting a price that is half the price of the 1030V3. This has been challenged due to the development in the Platinum prices, and we will see a stack price that to some degree will follow this trend.

Platinum price fluctuations

Fuel Processor:

The CE4 fuel processor from Tokyo Gas is used in the Beta V2 system. In the future the Ballard fuel processing system developed at the Ballard Fuel Processing Center of Excellence will be available and a competitive solution for the next generation of systems. This will give further cost reduction to the system.

BOP components:

There are several validated cost optimization possibilities, when we are targeting the higher volume.

Today we have more than 200 fittings for hoses in the system. By looking at the same hot formed hosing system used in the automobile business, we are able to reduce this number to around 40. This is not only reducing the component cost but reduces also assembly time and the risk for leaks in the system.

Summary and conclusion

This project has been focusing on developing a mCHP system based on leading reformer and stack technology. The development has been successful though development of test systems and Alpha and Beta prototypes resulting in a system design that has been demonstrated in both Danish mCHP project and with real end customers in Japan and South Africa.

The mCHP product has achieved an electrical efficiency of 35% and total efficiency of 95% which ex-ceeds the objectives of the project.

The product has been demonstrated in the Danish mCHP project and the 20 systems have accumulated more than 125.000 hours over a heating season with good performance and positive feedback from house owners. Single systems have passed 15.000 hours of operation but due to time limitations accumulating more hours has net been possible. All systems are still performing well after the demon-stration period.

The average CO2 emission savings from a mCHP system in Denmark have been calculated to be around 1.500 kg CO2/year based on average CO2 content of 498 g/kWh in the Dansih electricity grid.

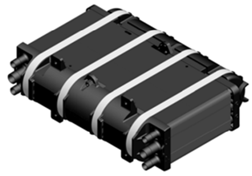
Based on the results and learning's in this project the project team is continuing the efforts on especially two fronts to meet the goals. First the further cost reductions by using a next generation reformer and a next generation stack and by simplifying the system. Secondly the robustness to fuel quality variations and to enable also using bio gas and LPG.

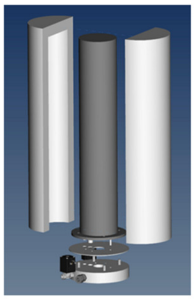
The next generation stack and reformer used in the follow on project USDan are in progress, and the concepts are illustrated in the figure below.

Next Generation

Dantherm Power

- Ease for manufacturing (ie fiiting reduction)
- Less BOP or smaller BOP ie humidfier
- Next gen stack
- Next gen reformer / burner

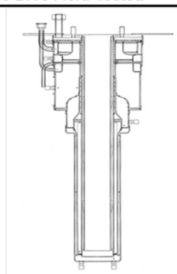
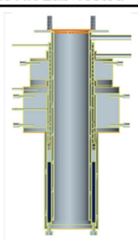
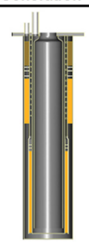




Next generation fuel cell stack and reformer

Further FPS Optimization and Cost Reduction

Dantherm Power

1.0 kWe Fuel Processor Design & Cost Evolution						
	2005-2008 Field Tested		State of the Art Lab Tested		Next Generation	
Length (in)	21.7		18.7		18.7	
Major Dia (in)	6.4		5.6		3.4	
Volume (Liters)	6.0		4.1		2.9	
Structure Weight (lbs)	28.0		15.2		11.6	
SR Catalyst Bed (lbs)	1.0		0.4		0.4	
WGS Catalyst Bed (lbs)	5.2		2.9		0.7	
PrOx Bed (lbs)	1.2		1.0		0.4	
Total Weight (lbs)	35.4		19.4		13.0	
Parts Count	~ 80		47.0		<30	
Welded or Brazed Joints	~ 80		42.0		<20	
Cost at 10,000 Units/Year 5.0kW Units ($/kWe)	$3,200		$800-$1000		$200-$250	

- Next generation FPS uses advanced structured catalyst beds to dramatically reduce weight, volume and cost.
- Designed for high-volume manufacturing to meet US DOE goal of $220/kW
- Cellular manufacturing concept with very low capital cost
- Develop & test initial units June 2011 – Dec 2012. DOE funding requested.
- Would like to collaborate with Tokyo Gas

Next generation reformer concept