Final report

1.1 Project details

Project title	US DAN
Project identification (program abbrev. and file)	64011-0025
Name of the programme which has funded the project	EUDP
Project managing company/institution (name and address)	Ballard Power Systems A/S
Project partners	Aalborg university
CVR (central business register)	30804996
Date for submission	31/05/2018

1.2 Short description of project objective and results

Development of the next generations of 1 to 2 kWe low temperature proton exchange fuel cell based on micro combined heat and power unit (µCHP) and supplemental power unit. The focus is on the cost optimization of a multi-fuel low-cost fuel processor. 2 generations have been developed and more than 40000 hours of field trial have been demonstrated on the 5 G generation.

Udviklingen af de næste generationer af 1 til 2 kWe lav temperatur proton exchange brændselscelle systemer baseret på mikro kraftvarme (µCHP) og supplerende power enhed. Fokus er på omkostningsoptimering af reformeren. 2 generationer er blevet udviklet. seneste generation 5 G har akkumuleret totalt mere end 40.000 driftstimer.

1.3 Executive summary

A multi fuel power conversion has been developed. The platform is capable of converting commercial hydrocarbon feedstock such as NG or LPG into high quality hydrogen. The conversion process inside the reformer is based on a 3-stage reactor: reforming, shift and gas clean-up. The primary stage is essential to ensure a high efficiency and a long-life time of the reformer. An extensive steam reforming catalyst screening been performed at Aalborg University and 2 materials have been identified as potential candidates. The characterisation has been performed on both NG and LPG. The catalyst has been integrated into the design of the 5G system.

Two generations of systems platforms have been developed, one generating 1 kW referred as "4G" or "4th generation" and second one producing 2.0 kW referred as "3G" or "3rd

generation"). All system integration has been done in Denmark. The second system generation is designed on a different reformer platform due to closure of the activity of the Ballard USA facility. Nevertheless, the 5G platform has been operated for more than 40000 hours (over 5000 hours/machine). The material and labour cost has been reduced by 50% in yearly quantity 50 and over 30% in projected yearly quantity 3000.

1.4   Project objectives

The objectives of the USDAN project is to develop a new micro CHP/supplemental power unit based on a novel reformer platform. This includes two system design iterations, one based on the nitrogen tolerant reformer CE6 from Tokyo gas (4G) and a second iteration based on new developed reformer from Ballard Maryland.

The project has been affected by two major changes, a power output increase from 1 kW to 2 kW as well as the closure of the Ballard Maryland facility. The first change was motivated due to the adoption by all major European boiler manufacturers of Japanese technology fuel cell technology rated to 700W. Keeping a 1 kW platform will have placed BPSE in a very competitive market situation due to the significant advancement of the Japanese technology. 2 kWe output on the other hand allows to address larger residential, small commercial. It is also well aligned with telecom power output demand which could offer potential economy of scale with the growing telecom market. The abandon of the reformer development by Ballard Maryland has been a serious threat to the project but the activity was consolidated between Aalborg University and Ballard Europe. It has led to the screening of various reformer manufacturers and a German supplier named WS reformer GmbH was chosen for the 5G system.

1.5   Project results and dissemination of results

1.5.1   WP1 - Evaluation of reforming catalyst for LPG and Natural Gas fuel

The performance (activity, selectivity and short-term stability) of commercial catalysts for the process of steam methane (or propane) reforming in small-scale steam reformer for micro combined heat and power (μ-CHP) system is presented in this WP1.

Catalyst samples and test conditions

Six pelletized catalysts have been tested including both the nickel based catalyst and precious metal catalyst as shown in Table 1. Early tests also include two fanfold catalysts which were not further considered due to the high cost.

Catalyst	A	B	C	D	E	F
Active metal	Ru	Nickel	Pt/Rh	Ce/Rh	Rh	Ce, Zr, Rh
Form	Pellets	Pellets	Pellets	Pellets	Pellets	Pellets
Bulk density (g/ml) measurement in test cell	0.973	1.044	1.148	0.610	1.180	0.680
Composition	2%w Ru/α-Al_2O_3	15-20%w Ni Support Al_2O_3	0.4%w (Pt, Rh) Support Al_2O_3	8%w Ce Support Al_2O_3	0.2%wt Rh 0.2%wt Pt	<1% w Rh 3-5% w Ce - Zr

Table 1. Catalyst samples

A small stainless-steel reactor (shown in Fig. 1(a)) was used in most of the catalyst performance test, while a quartz tube reactor (shown in Fig. 1(b)) was also used for preliminary bench-scale investigation. Electrical heaters with a collective heating capacity of 1000 W and 3000 W were used to obtain the required temperature range for the two reactors respectively. A positive displacement Iwaki pump (0-20 mL per minute) was used to meter the water flow while gas flows were regulated by mass flow controllers. Siemens gas analyzer was used for flow composition measurement. The operating conditions for the tests are presented in Table 2.
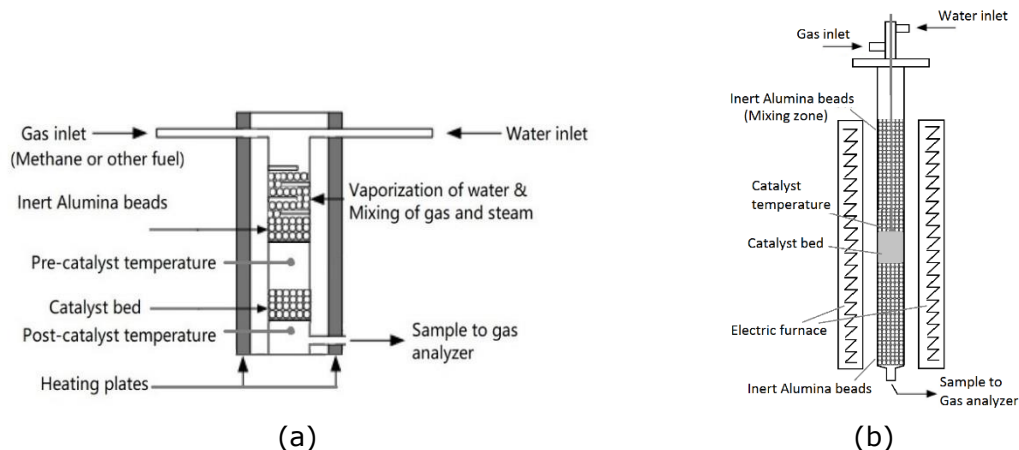

(a)   (b)

Figure. 1. (a) Stainless steel reactor; (b) quartz tube reactor.

Reforming flows	Steam methane reforming	Steam propane reforming	Steam-to-carbon ratio (S/C)	2.0-4.0
Methane, Nl/min	0.62, 1.24*	–	Operating temperature, ℃	650-700
Propane, Nl/min	–	0.2	Weight hourly space velocity (WHSV), hr^{-1}	116-117, 47*
Water, mL/min	1.5, 3.0*	1.45	Gas hourly space velocity (GHSV), hr^{-1}	81000-175000
Nitrogen, mL/min	2.0*	–	Test time, hr	24, 2.0*

Table 2. Test conditions (* Operating conditions for bench-scale catalyst test)

Results and discussions

Small-scale reactor (stainless steel reactor, 1gram of catalyst)

The test was aimed at measuring the activity, selectivity (of CO_2) and stability (short-term) of the pelletized catalyst candidates at the operating temperature range of 650-700℃ at high WHSV of 116-117 hr^{-1} and GHSV of 90000-180000 hr^{-1}. 1 gram of the pelletized catalyst sample was packed in the catalyst bed volume (3.6 mL) of the test cell, and each test lasted 24 hours. As shown in Table 2, certain flow rates of methane (99.9995%), propane (99.95%) and ultra-pure water (18.2 MΩ.cm resistivity) were used in the test for steam reforming of methane and propane.

Steam methane reforming (SMR)

Early test showed obvious deactivation of the precious metal catalyst samples within several hours due to the contamination of sulfur compound in the pipe for water supply, which indicates that desulfurization is needed if there is sulfur compound in the water supply system. This problem has been fixed by changing new pipes (PTFE). The catalyst was

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reduced before starting performance measurements by pure H_2 at 500°C (2 hours for precious metal catalyst and 4 hours for nickel based catalyst).

Activity

The average conversion of methane and corresponding catalytic activity (reaction rate of CH_4) of the catalyst samples A-F at a typical steam-to-carbon ratio of 3 and temperatures (650°C and 700°C) are shown in Fig. 2. At the operating GHSV, conversions of 12.4−40.8% (650°C) and 16.6−52.2% (700°C) were achieved by the test cell with 1g of the catalyst samples (see Fig. 1(a)). As shown in Fig. 1(b), the catalyst activities at 700°C are 1.2−1.3 times of those at 650°C, the activity of the precious metal catalysts (A, C−F) are 1.1-2.3 times higher than that of the low-cost nickel based catalyst (sample B), the activity of sample A, C and F are close, while that of sample E is lower. Sample D showed the highest activity, however, the extrudate structure of sample D showed low mechanical intensity during the test, which is not recommended for long-term use. By considering the activity per volume instead of the activity per weight (shown in Fig. 1(c)), sample F showed relative lower activity than other precious metal catalyst due to its low bulk density (see Table 1), in other words, more volume is needed for packing sample F to achieve the same catalytic activity for a steam reformer.
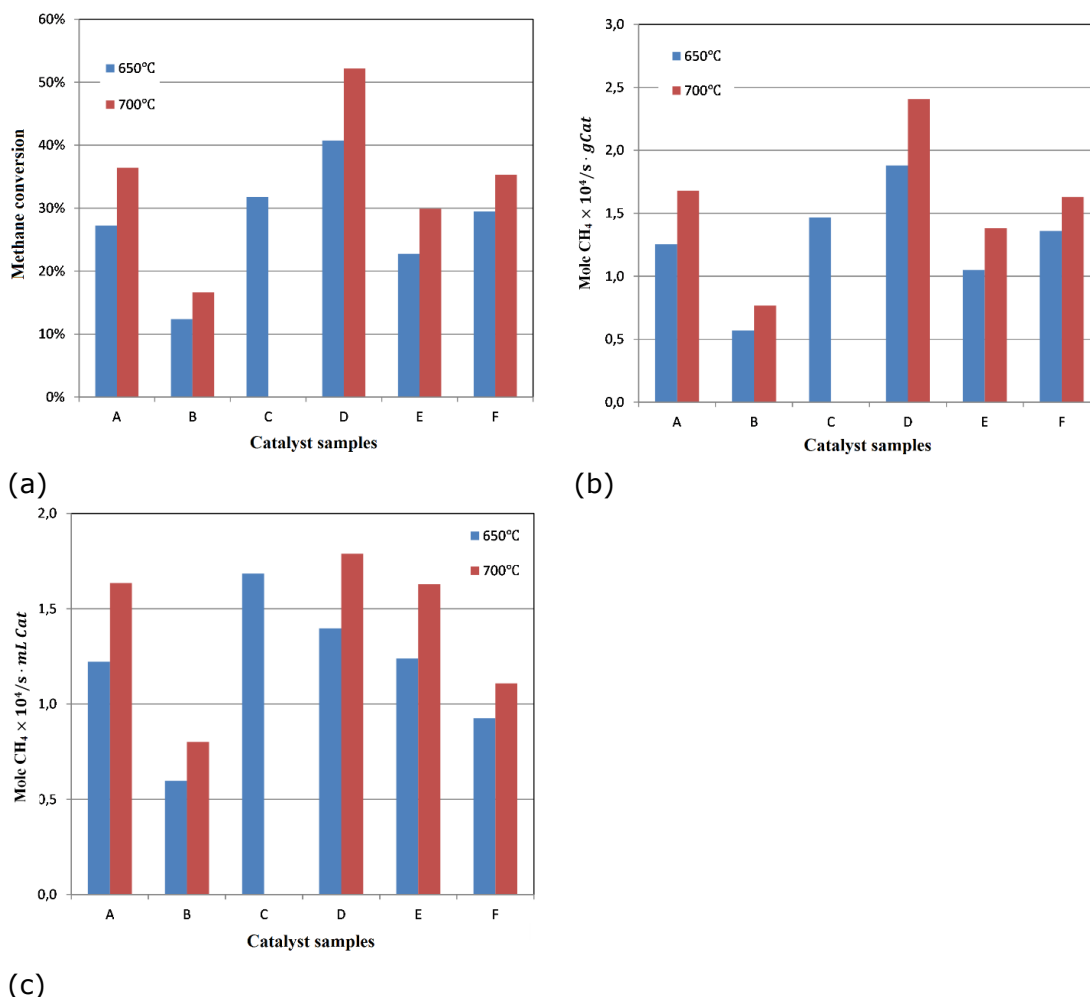

(a)

(b)

(c)

Fig. 2. (a) Conversion of methane, (b) reaction rate of methane (per weight) and (c) reaction rate of methane (per volume) of catalyst samples.

Selectivity and stability

As CO from the product gas of the SMR process can poison the catalyst of the downstream PEM fuel cell in a μ-CHP system, the water gas shift (WGS) process is usually needed after SMR to convert CO to CO_2. A high content of CO in the product of SMR may increase the

load and cost of the downstream WGS process. Therefore, a catalyst that can achieve a high selectivity of CO_2 (i.e., low selectivity of CO) in SMR is recommended. The selectivity of CO_2 (see equation (1)) of the catalyst samples for the SMR process (S/C = 3) are shown in Fig. 3(a). At 650℃, high selectivities have been achieved by sample A, B, E and F (79%−84%), while sample D showed a lower value (73%), and sample C gave the lowest selectivity value of 56% which is not recommended. The selectivity decreased with the increase of temperature, at a higher temperature of 700 ℃, the selectivities were 72%−74% for sample A, B, E and F, and 63% for sample D.

$$Selectivity\ of\ CO_2 = \frac{mole\ flow\ rate\ of\ CO_2}{mole\ flow\ rate\ of\ CO + mole\ flow\ rate\ of\ CO_2} \times 100\% \qquad (1)$$
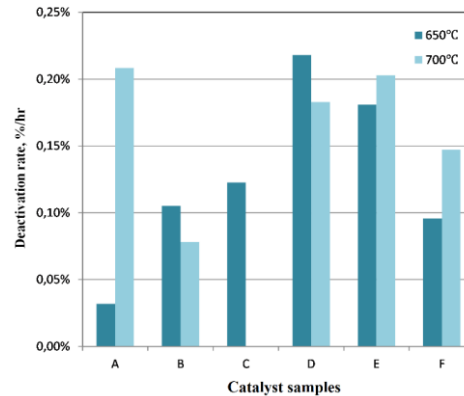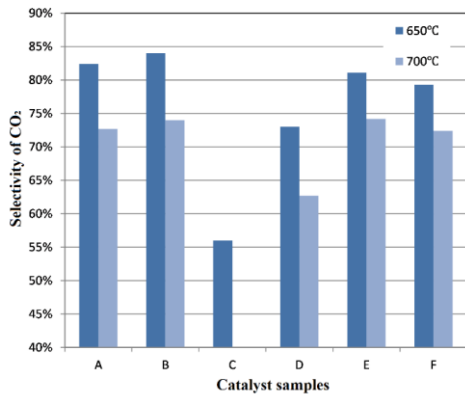
(a)   (b)

Fig. 3. (a) Selectivity of CO_2; (b) Deactivation rate of catalyst samples.

$$Deactivation\ rate = \frac{Decrease\ of\ catalyst\ activity\ per\ hour}{average\ catalyst\ activity} \qquad (2)$$

The stability of the catalyst samples in SMR is presented by the deactivation rate (see equation (2)) as shown in Fig. 3(b). The deactivation of the catalyst samples could be caused by carbon formation on catalysts, sintering problem at high temperatures and catalyst poisoning by the contaminations in the system. Sample A showed the lowest deactivation rate at 650℃, this good catalytic stability agrees with the result from Tokyo Gas. At 700℃ the tested deactivation rate is not accurate for sample A. Sample B, C and F provided similar deactivation rate, while higher deactivation rates were found for sample D and E. As the deactivation rates mentioned above is according to the 24-hour tests, long-term test is still needed for further investigation of the selected catalyst sample.
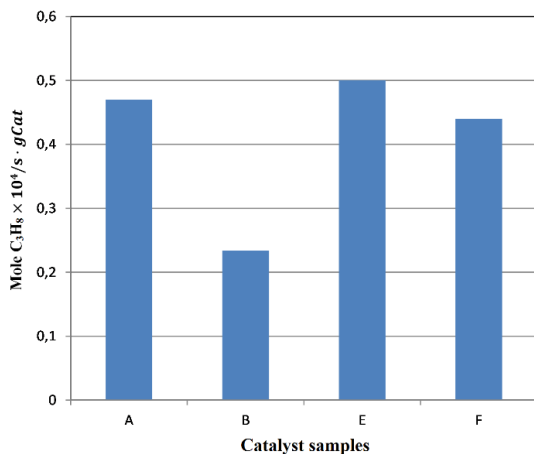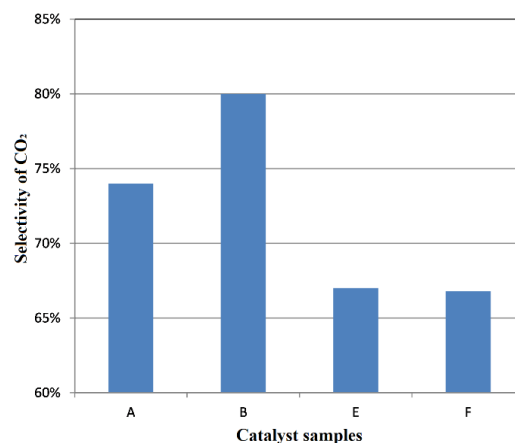
(a)   (b)
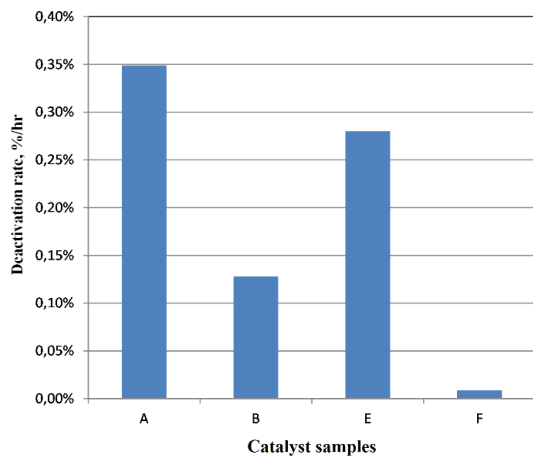
(c)

Fig. 4. (a) Reaction rate of propane per weight of catalyst, (b) selectivity of CO_2 and (c) deactivation rate of sample B.

Steam propane reforming (SPR)

The catalyst performance under the process of steam propane reforming was also investigated for sample A, B, E and F. Fig. 4 presents the activity, selectivity and stability of the catalyst samples at 650℃ and S/C = 3. Compared with the results in SMR (see Fig. 2 and 3), lower reaction rate of the heavier propane (completely converted to CO and CO_2) was achieved for the SPR process. Similar trend of activity was found, where the activity of sample A, E and F are close, and the nickel based catalyst (sample B) showed lower activity. Compared with the results of SMR, the selectivity of CO_2 in the product of SPR decreased, which is obvious for sample E and F. For the short-term stability, sample B showed close stability to that in SMR, while the stability of sample A and E decreased. Sample F kept stable for the SPR process and showed very low deactivation rate.

Bench-scale reactor (quartz tube reactor, 5 gram of catalyst)

A bench-scale SMR test with 5 gram of the nickel based catalyst (sample B) was also conducted in the quartz tube reactor (with an inner diameter of 25 mm) to investigate the performance of the catalyst in a larger reactor at 650℃ and 700℃, S/C = 3 and GHSV = 81000 hr^{-1}. Compared with the reaction rate in the small-scale reactor (see Fig. 2(b)), lower catalyst activity was found in the bench-scale test. The reaction rates of CH_4 were 2.8×10^{-5} mole/(s·gcat) at 650℃ and 3.7×10^{-5} mole/(s·gcat) at 700℃, while those of the small-scale SMR test (GHSV = 144000 hr^{-1}) were 5.7×10^{-5} mole/(s·gcat) at 650℃ and 7.6×10^{-5} mole/(s·gcat) at 700℃, respectively. The lower catalyst activity for the bench-scale test could be attributed to the higher heat resistance of the larger catalyst bed which resulted in lower center temperature and catalyst activity. In additions, the lower GHSV in the bench-scale test can also influence the mass transfer in the catalyst bed. Therefore, for a bench-scale or a larger steam reformer, the catalyst activity could be lower than that of the small-scale test.

Conclusion

Catalyst screening of six commercial catalyst samples has been conducted for the SMR and SPR processes in small-scale and bench-scale reactors with the following conclusions:

SMR

- Sample A (Ru) showed good performance (including the long-term test in Tokyo Gas), and is a good catalyst candidate except the condition with nitrogen in the feed gas.

- Sample B (Ni) has good selectivity, short-term stability and sulfur tolerance but needs a larger amount of catalyst and a larger reactor due to its low activity. Long-term stability test is also needed to check the risk of carbon formation for this nickel based catalyst.
- Sample C and D are not recommended due to the low CO_2 selectivity and poor mechanical intensity, respectively.
- Sample E and F also have good activity and selectivity. However, long-term stability test is still needed for the two samples.
- The results of the bench-scale test indicate that the heat or mass resistance of a larger reactor may result in lower catalytic activity than that in the small-scale test. Relevant parameters i.e., pellet size of catalyst, material and geometry of reactor should be considered.

SPR

- Lower values of activity and selectivity were found for the SPR process than those for the SMR process. Sample A and B still provide high selectivity, while sample E and F showed lower values. Good short-term stability was found for sample F, which indicates its good carbon resistance for propane reforming.

1.5.2 WP2 – Development of the 4th generation

The 4th generation has been developed to be tolerant to nitrogen gas present in commercial NG in Europe. The composition is defined according to the EN 437. The 3rd generation could tolerate a maximum of 2%. As shown below H gas could contain up to 7.5% of nitrogen and L gas up 18%, so new reformer referred as CE6 was implemented into the systems.

Group H	Reference gas	G 20	$CH_4 = 100$	45,67	34,02	50,72	37,78	0,555
	Incomplete combustion and sooting limit gas	G 21	$CH_4 = 87$ $C_3H_8 = 13$	49,60	41,01	54,76	45,28	0,684
	Light back limit gas	G 222	$CH_4 = 77$ $H_2 = 23$	42,87	28,53	47,87	31,86	0,443
	Flame lift limit gas	G 23	$CH_4 = 92,5$ $N_2 = 7,5$	41,11	31,46	45,66	34,95	0,586
Group L	Reference gas and light back limit gas	G 25	$CH_4 = 86$ $N_2 = 14$	37,38	29,25	41,52	32,49	0,612
	Incomplete combustion and sooting limit gas	G 26	$CH_4 = 80$ $C_3H_8 = 7$ $N_2 = 13$	40,52	33,36	44,83	36,91	0,678
	Flame lift limit gas	G 27	$CH_4 = 82$ $N_2 = 18$	35,17	27,89	39,06	30,98	0,629

A desulphurizer was designed, based on the learning from the Simba project and implemented into the system. The units were designed to operate on NG as well as LPG gas. The fuel line was modified to accommodate operation with LPG. An adaptive control was designed to ensure proper reactant control to ensure a proper steam to carbon ratio. After some preliminary test at BPSE's facility, 2 units were constructed and shipped to the UMD and Aalborg universities.

The new design incorporates the following key changes:
o Nitrogen tolerant Steam Methane Reforming catalyst and compatible with LPG operation (CE6 from Tokyo gas).
o SMA inverter supplemented with an electrical transformer has been added to comply with the US grid requirements.
o Ballard stack 1030 V3 liquid cooled – reformate tolerant.

Nominal gas input (LHV)	2,7[kW] (commercial LPG)
Nominal electric power net Pel	0,92[kW_AC]
Nominal heating power Pth	1,5 [kW]
Electric power consumption, nominal operation	0,1[kW]
Hot water temperature	63[°C]
Max water pressure	2,5[bar(g)]
Max temperature, Hot water circuit (safety)	90[°C]
Electric efficiency BOL	33 %LHV
Thermal efficiency BOL	54 %LHV
Air intake	68[NLPM]
Exhaust	74[NLPM]
Condensate drain	0,33[NLPH], pH value is 5 to 7
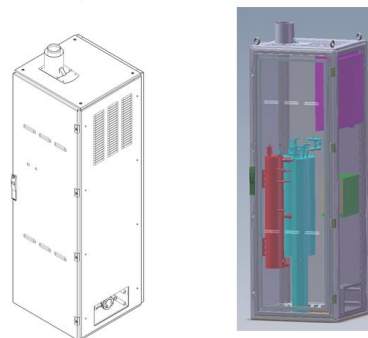
Figure 1 Illustration of the mikroCHP Systems outer connections and main components

■	Reformer
■	Fuel Cell stack
■	DC/AC Inverter
■	Heat integration

Table 2: Color codes of the mCHP main components

A detailed cost study showed a significant opportunity for cost reduction with volume. In small quantity the material cost is around USD 45k/kW for material and USD 25 k/kW for the labour. The labour price can be reduced in quantity 50 by implementing addition design for manufacturing features. In annual produced quantities of 3000, it is assumed that the product is either produce in fully automatized production line or low labour rate country. The cost break-down of the material has been done and core technology (Fuel cell, Re-former, Inverter) covers 51% of the bill of material. The inverter itself is still very high and cover 26% of the total material cost.
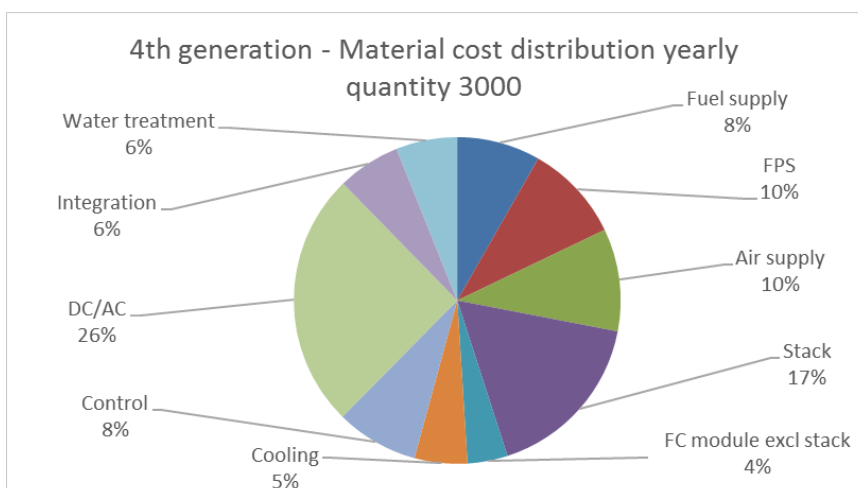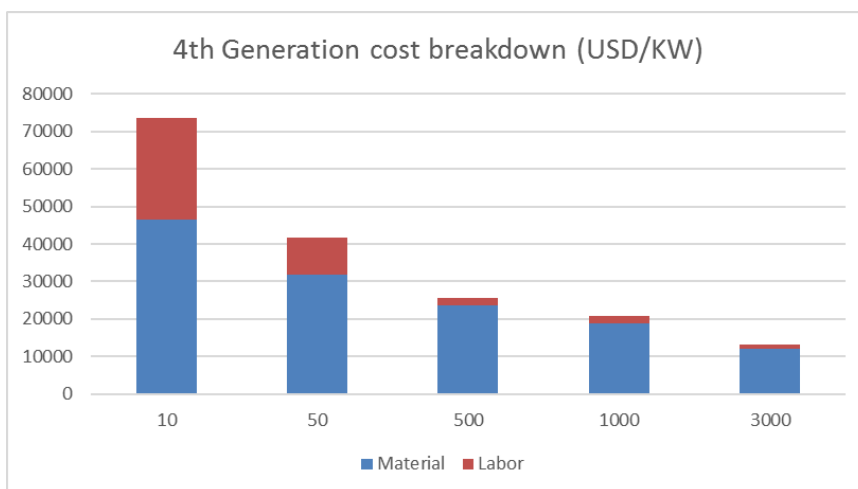
1.5.3 WP 2 - LPG reformer design verification

The test with LPG on system 22 aims at investigating first CE6 reformer performance on LPG as well as clarifying necessary adjustment of system control parameters for system to run autonomously, this will include changing fuel parameters and fixed fuel flow settings.

<u>Test set-up:</u>

- System #22 4G, modified for reformate sampling from stack anode and burner AWG (shared stream with startup reformate
- Thermal load
- Gas analyzer rack set to sample flow 1 Nlpm dry air equivalent
- LPG 10kg cylinder
- MFM5 replaced with 2NLPM propane version.
- Dräger tube for THT and hand-pump
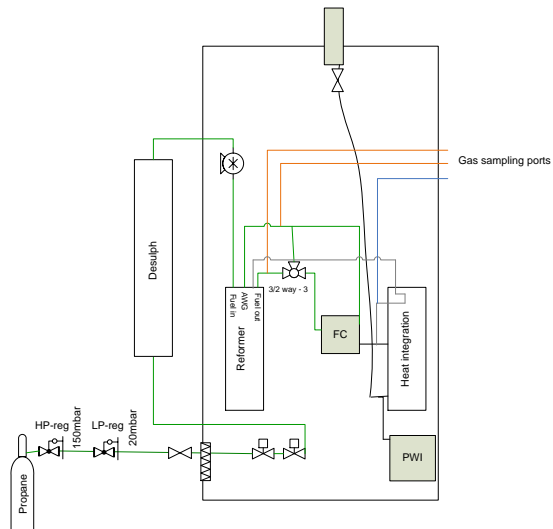
<u>Main results:</u>

- LPG flow is fluctuating on start-up which require a high lambda to ensure a proper conversion and modification of the fuel supply.
- CO content in the exhaust flue gas peaked at 1500 ppm for less than 10 seconds during ignition.
- Unconverted hydrocarbon above 4000ppm during burner ignition.
- Within 60 seconds, all emissions requirements are fulfilled.
- Reformer efficiency around 92%.
- System efficiency around 35%.
- Low propane slip.
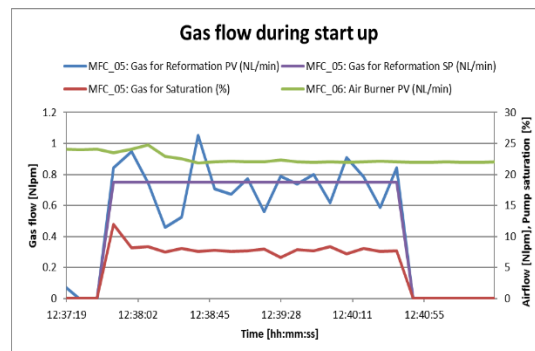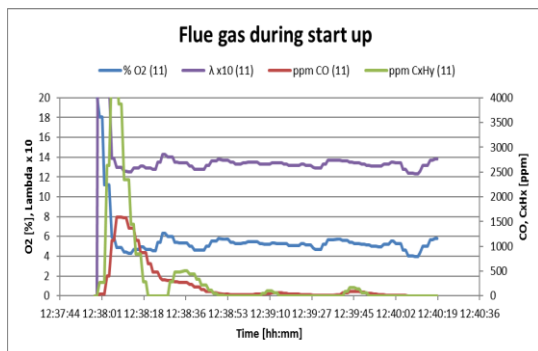
1.5.4 WP 3 - External test of the 4th generation of micro CHP

The objective of this test campaign is to evaluate the 4G platform at the academic project partners in order to provide a training platform prior to integrate the 5G. Each system should operate for a minimum of 1000 hours at 3 various locations.

	Location	Hours	Gas Consumption (Nm³)
System 2	AAU lab test	1101	113.9
System 1	UMD lab test	1125	110
System 0	BPSE	1987	192

The results:

- The systems were operated on commercial LPG from 2 regions (US and Denmark).
- All systems passed the 1000 hours durability test.
- University of Maryland (UMD), the unit operate successfully over 1100 hours on commercial LPG, at three different power outputs. Flue gas emissions was measured once a week.
- University of Aalborg (AAU), the unit was operated for 1100 hours. Test were also done on different test gasses including simulated biofuel= simulated biogas CO_2+CH_4.

Performance target	Target	Demonstrated
Reformer efficiency on various fuels	>65%LHV	>73%LHV at rated power on methane, propane, butane and commercial LPG-DK
System electrical efficiency	>32%LHV	>33%LHV at rated power on methane, propane, butane and commercial LPG-DK
Stack Degradation over 1000h	<2%	0,9% on AAU system = 6,48[µV/(h*cell)] 1,6 % on UMD system = 11,28[µV/(h*cell)]
CO – Flue gases	<1000	<300 ppm CO - UMD

1.5.5   WP 4 - Development of the 5th generation of mCHP

The power output in the 5G platform is designed to deliver 2.5 kW to fit the telecom prime power as well as large residential and commercial buildings applicable for the micro CHP market. The unit can be either fueled by NG or LPG. The control algorithms have been designed to be independent from the electrical interface configuration. The controller solely relies on fuel quality inputs as well as stack current. The unit can be configured with inverter interface or with a DC/DC converter and operate as a battery charger.

The screening of the reformer suppliers has been performed to identify suitable replacement candidate (WP5) since the development of the PRNG2500 reformer was stopped at Ballard Maryland in 2015. A reformer screening led to the identification of 5 candidates. The C3 reformer from WS Gmbh is the only commercial option available. This reformer platform uses a different clean-up stage based on selective methanation reaction which eliminate all BOP related to preferential oxidation process and offer an additional cost reduction of 300 USD.

	PBS MD	WS reformer	Kaori	Powercell	ZBT
Model	PRNG2500	C3-LT	RNFG 006		FP_075_1_xx_02
Clean – up stage	Preferential oxydation	Selective methanation	Preferencial oxydation	Preferential oxydation	Preferential oxidation or Selective methanation
Development stage	Prototype	Pre-commercial	Prototype	Prototype	Technology platform
Price (USD)	7760 (qty 10)	15605 (qty 10)	TBD	TBD	TBD
Availability	2.5 kW	1, 3, 5 and 10 kW	Only 1 kW	No	1 kW
Fuel	NG/LPG/MeOH	NG/LPG/MeOH	NG/LPG/MeOH	Ethanol. DME, Biodiesel, Diesel, Gasoline	NG/LPG/MeOH

A complete design study has been performed on Hysys process. The study lead to the identification of the critical parameters affecting the efficiency (reformer heat loss, steam to carbon, burner lambda). The test data were implemented in the model to optimize the design. We found, during the initial test, some lack of performance of the system mainly related to air flow limitation on the cathode side of the fuel cell. It was decided to downgrade the power down to 2kW. This power loss could be regained since a new blower developed with BoP-op associated to a new stack will be able to increase the output power of the fuel cell stack. Efficiency was determined to be around 38% BOL and 34% EOL.

Once the modelling study completed, all components requirements were delivered and components were identified, tested in an open test bench for several hundreds of hours (stack, humidifier, pumps, compressors, BOP, power electronics). A design for manufacturing study has been performed by consolidating all learnings from the two-adjacent funded project (SIMBA and BOP-OP). This led to several design proofs of concepts shown in the 3D drawing below. Different configuration of the humidifier, DI cartridges, Water knock out, expansion tank has been incorporated into different designed options. This led to the selection of vertical, counter flow humidifier arrangement.
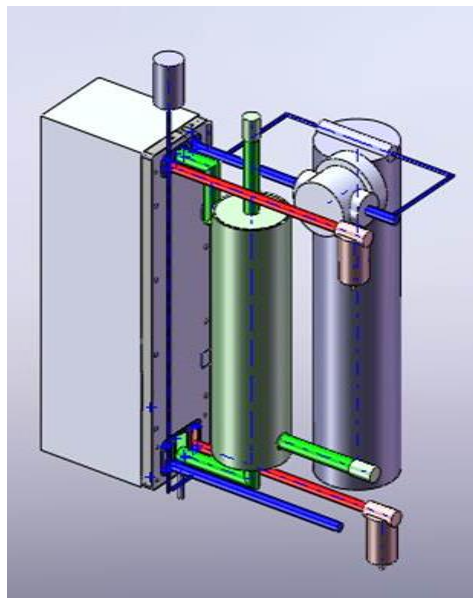
The new design is based on the following key changes:

o Low cost Nickel based Steam Methane Reforming and compatible with LPG operation.
o Reformate purification stage change from preferential oxidation to selective methanation and elimination of Prox air BOP.
o New inverter platform – Elimination of the power supply and DC/DC converter (6G – Simba implementation).
o Low cost Ballard 1310 stack modified for reformate MEA.
o Implementation of polymeric tubing
o Aluminum heat interface.
o Easy access to serviceable item (Desulphuriser, air filter, ions exchange resins).
o Certified burner controller (flame detection and operation).
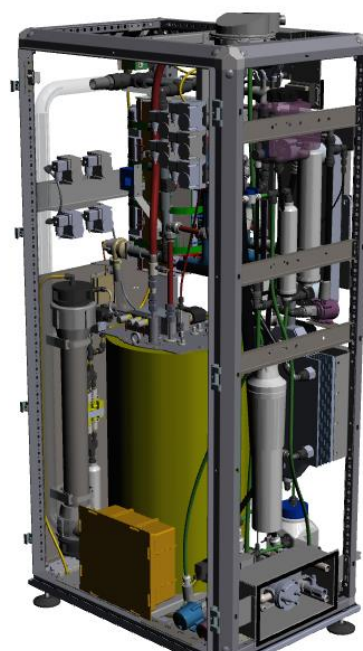
The 5G specification are shown in the table below. The achieved efficiency of 26.5% was much lower than numbers from the model and the MRD target.

|	
Nominal gas input (LHV)	7.4kW - G20
Nominal electric power net P_{el}	2.00[kW_AC]
Nominal heating power P_{th}	4.397 [kW]
Hot temperature water to central heating	67[°C]
Max water pressure	2.5[bar(g)]
Max temperature water to central heating circuit(safety)	90[°C]
Desired return temperature from the central heating	Less than 45°C
Max return temperature from central heating	55 °C
Electric efficiency BOL	26,5 [%L_{HV}]
Thermal efficiency BOL	64 [%L_{HV}]
Air intake	171[Nlpm]
Exhaust temperature	45[°C]
Exhaust	160[Nlpm]
Condensate drain	0,133[kg/h], pH value is 5 to 7
NOx	<2.5 [ppm, mol dry basis]
NOx Class	5
SOx	<4[ppm, mol dry basis]
UHC (Unburned hydrocarbons)	10-180 [ppm, mol dry basis]

A proved field trial level of electric efficiency of 25 % is not satisfactory and misaligned with the initial prospect of the project. The reason for the low efficiency has been identified and will be corrected in the next revision of the machine:

- Steam to carbon: The water to gas ratio injected into the reformation process is above the levels in the industry, and needs to be revisited and tested to gain confidence in close corporation with the reformer manufacturer. The first steps and experiences have been made, and suggest that the water can be reduced by 25 %, and thereby reducing the energy needed for evaporation, and thus raising the electric efficiency more than 2.6 % points.

- Electric power conversion: Despite much effort, a one-step conversion from the fuel cell to the grid was not implemented in the units deployed in the field trial. In the industry, a 95 % efficiency has been obtained of power conversion from e.g. solar panels to grid. This is quite far from the 85 % realized in the current platform. This leads to a net gain in efficiency of 4.9%.

- Efforts are needed in the Balance of plant components or architecture. The system has a self-consumption of more than 10 % of the produced energy. This is not satisfactory. A reduction of 15% of the BOP can be achieved which leads to an increase in electrical efficiency of 0.7%.

- The current lambda (air / fuel ratio) on the burner air is set to 1.8. This could be reduced to 1.1 by implementing some of the controls implemented on the previous platform resulting in a gain of electrical efficiency of 0.7%. This is also allowing to increase the water return temperature from 45°C to 50°C and still comply with the process water neutrality.

- Stack performance. The adopted stack platform contains 38 cells. With an increase of 8 cells, 1.7 % of efficiency is gained.

- The heat radiation of the components has been minimized by insulation. Since one of heat exchanger is operating as a condensing boiler, harvesting the latent heat in the exhaust is critical to achieve a total efficiency nearer 100 % but will be constraints by the heating water return temperature.

	Actual	Potential	Gain in electrical efficiency
S/C (unitless)	3	4	+2.6%
Electric Power conversion (%)	85%	95 %	+4.9 %
BOP reduction (W)	250	208	+0.7%
Burner Lambda (unitless)	1.8	1.1	+0.7% /gain in return temperature of 5°C
Cell count (unitless)	38	46	+1.7%
Total	27.2%	37.8%	+10.6%

The cost study shows a significant cost reduction of 40% in comparison with the 4G and more than 50% in small volume. In small quantity the material cost is around USD 23k/kW for material and USD 3 k for the labour. In yearly produced volume of 3000, the cost can be reduced to 8k USD/kW which comply with the market requirement. The cost break-down of the material has been done and core technology (Fuel cell, Reformer, Inverter) covers 41% of the bill of material. The power conversion is optimized and reduced by 7 points compared with its predecessors.
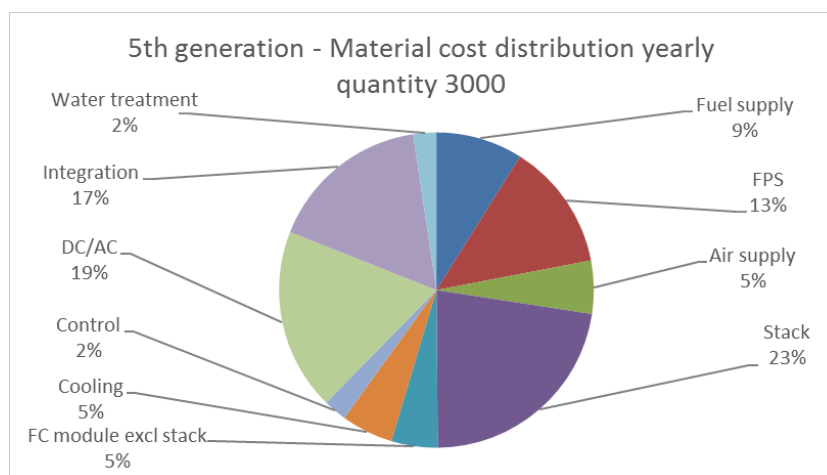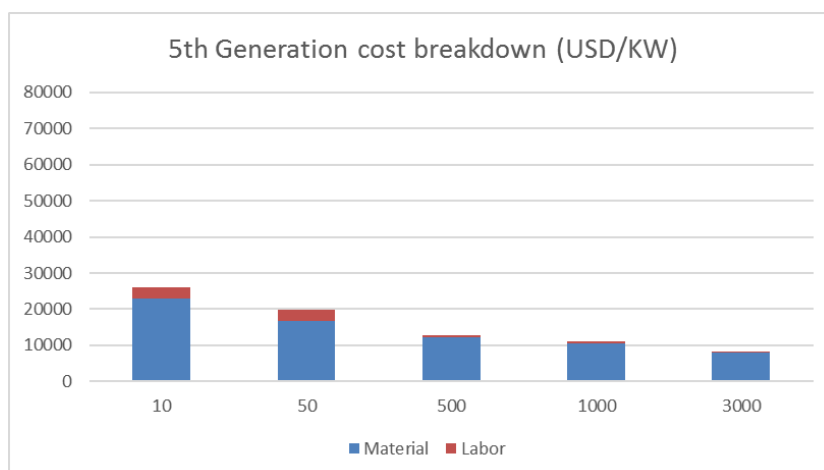
As part WP 4.9, reformers units from the field are screened for methane slip and CO to evaluate BOL- MOL potential performance lost. Methane slip provides an indication of the deactivation of the steam methane reforming and CO slip of the state of health of the selective methanation catalyst.

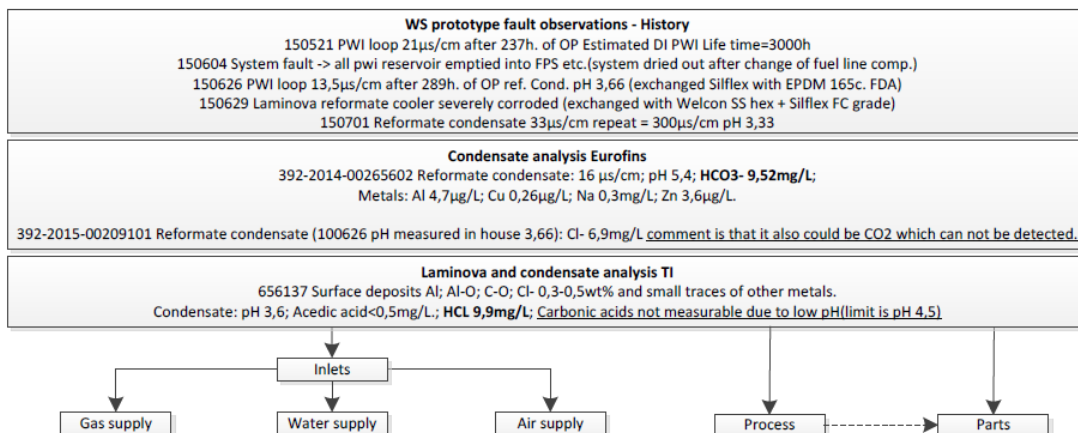| hours	0	4669
Methane Slip (%CH4)	0.8%	1.23%
Reformate quality (ppm)	13.0	5,6

	In-situ (WP1)	Ex-situ-4669
Deactivation rate	0.1%	0.01%
GHSV	81000	4500

We observed a slight increase of the methane slip. Assuming that the methane slips were measured in similar operating regimes (reactor temperature, steam to carbon ratio, load) and the deactivation rate can be determined. Based on the EOL methane slip criteria of 4%, the reformer will last 44000 hours assuming a linear degradation of the Steam reforming bed. Regarding the CO content in the reformate gas, the performance is still good and is improving. Further monitoring is required to identify the degradation rate of the selective methanation catalyst bed.

A critical issue was discovered during the field trial related to the corrosion of the heat exchanger for on the reformate cooling. The reformate cooler was evaluated in the 4G and a controlled corrosion was observed. Once installed in the 5G, it was observed that there was a steep deactivation of the ion exchange resin. The reformate cooler was inspected and major corrosion was observed.

A complete failure mode analysis has been performed to identify the source of the corrosion. Condensate were 100 time more acidic than usual. This led to the acid identification of hydrogen chloride as the contaminants. Different potential sources were analysed and the reformer was the contributor. It appears that chloride is used a dopant in one of the catalyst bed. WS reformer and the catalyst supplier acknowledge the limitation of the catalyst. The development of Chloride free catalyst was initiated and implemented in the very last field trial. Significant reduction of the acid content was observed but still some remaining Chloride.

WS prototype fault observations - History
150521 PWI loop 21µs/cm after 237h. of OP Estimated DI PWI Life time=3000h
150604 System fault -> all pwi reservoir emptied into FPS etc.(system dried out after change of fuel line comp.)
150626 PWI loop 13,5µs/cm after 289h. of OP ref. Cond. pH 3,66 (exchanged Silflex with EPDM 165c. FDA)
150629 Laminova reformate cooler severely corroded (exchanged with Welcon SS hex + Silflex FC grade)
150701 Reformate condensate 33µs/cm repeat = 300µs/cm pH 3,33

Condensate analysis Eurofins
392-2014-00265602 Reformate condensate: 16 µs/cm; pH 5,4; HCO3- 9,52mg/L;
Metals: Al 4,7µg/L; Cu 0,26µg/L; Na 0,3mg/L; Zn 3,6µg/L.

392-2015-00209101 Reformate condensate (100626 pH measured in house 3,66): Cl- 6,9mg/L comment is that it also could be CO2 which can not be detected.

Laminova and condensate analysis TI
656137 Surface deposits Al; Al-O; C-O; Cl- 0,3-0,5wt% and small traces of other metals.
Condensate: pH 3,6; Acedic acid<0,5mg/L.; HCL 9,9mg/L; Carbonic acids not measurable due to low pH(limit is pH 4,5)

Inlets

Gas supply — Water supply — Air supply — Process ---------> Parts

1.5.6 WP 5 - Test of the FPS candidates:

As mention in WP4, 5 potentials candidates have been evaluated. Only one was tested and compared with the initial performance of the PRNG2500. The C3 reformer from WS reformer has been tested based on a specific DOE. Different operating parameters were evaluated to understand the thermal behaviour of the reformer during transient condition. 8 potential test conditions have been identified and validated in steady state operation. In the table below, 3 tests are shown performed under different conditions. In all cases, the conversion rate, CO level in reformate is above requirement.

Index	WS reformer	PRNG2500	Temperature 600	Temperature 700	S/C 3	S/C4	Methane	Propane
1	x		x		x		x	
2	x		x		x			x
3	x		x			x	x	
4	x		x			x		x
5	x			x	x		x	
6	x			x	x			x
7	x			x		x	x	
8	x			x		x		x

Test ID		1	3	2
Date/time		150226	150309	150310
Reformer		WS C3	WS C3	WS C3
Stack		1310 - modified	1310 - modified	1310 - modified
Fuel		G20	G20	G20
Water		Wall	Wall	Wall
Water	µS/cm	0.06	0.06	0.06
CH4 slip Gas analyser	% CH4	0.75%	1.83%	1.95%
CO analyser ADC 0-200ppm ZRH 200-1100ppm	ppm CO	13	na	1
% CH4 corrected dry	%mol	0.76%	1.85%	1.97%
K conversion rate based on %CH4 slip calc method	%	**96.3%**	91.4%	90.9%
Fuel input (LHV)	W	3940	7283	7104
H2 Output (LHV) using k	W	4575	8023	7781
H2 Output (LHV consumed)	W	2824	5349	5558
Reformer Efficiency (H2 consumed by stack)/Fuel input	**% (LHV)**	**71.7%**	**73.4%**	**78.2%**
CO emission				
Lambda display Bosh		1.10	1.10	1.12
Lambda testo		1.30	1.30	1.32
O2 excess Bosh calc		1.9%	1.9%	2.2%
O2 excess testo display		4.8%	4.8%	5.1%
O2 excess testo calc	%	4.9%	4.9%	5.0%
CO flue gases	ppm	5	9	9
CO corrected at zero O2 using lambda testo	ppm	6.5	11.7	11.88
CO corrected at zero using O2 testo	ppm	5	9	9
CO corrected at zero O2 using bosh lambda	ppm	6	10	10
CO corrected at zero using bosh O2 calc	ppm	5	10	10

The PRNG 2500 reformer from Ballard Maryland offers good BOL performances but poor stability due to insufficient mechanical strength of the catalyst. Post-mortem catalyst analysis is well aligned with the catalyst study performed in WP1. Pricing on PRNG 2500 was 50% cheaper but catalyst poor mechanical strength as well as poor burner emission resulted to the abandon of the development of the reformer.

BEFORE   AFTER
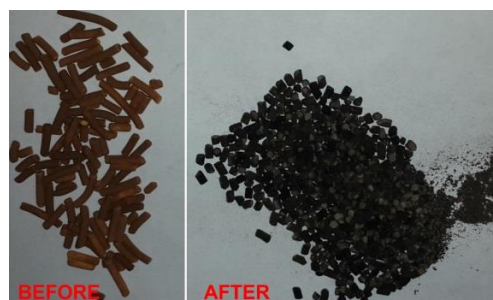
The table below represents a comparison of the two platforms benchmarked against the component design requirement. The C3 reformer has long start-up time due to his larger size. The high steam to carbon as well as the insufficient level of insulation leads to a lower efficiency and also contributes to the low start-up time. Both CO and conversion rate are within the requirements. Burner emission complies with the requirements from the low voltage directives.

	Requirement	BPSS MD	WS reformer
Model	NA	 PRNG2500	 C3-LT
Clean – up stage	Selective methanation preferred	Preferential oxydation	Selective methanation
Development stage	NA	Prototype	Pre-commercial
Price (USD)	<15000	7760 (qty 10)	15605 (qty 10)
Availability	NA	2.5 kW	1, 3, 5 and 10 kW
Fuel	NG/ LPG	NG/LPG/MeOH	NG/LPG/MeOH
CO Level Reformate	<10 ppm	<3 ppm	<10 ppm
Conversion rate – 650°C	>90% (2% CH4% slip BOL)	86% (verified)	90% (Mesured)
Efficiency	>80 %	>80%	72%-78% (measured)
Start-up – time (min)	<60	<120 min	120 min -180min
CO Burner		<300 ppm (5min)	11-13ppm
Life time		>10000	>10000

1.6 Utilization of project results

The results of the project are used by Business Development to promote the technology platform. Several meetings occurred with energy providers such as OK amba, Kosan Gas, Engie etc… On the micro CHP, the technology has been well accepted during the trial but the price of electricity remains too high even in Denmark or Germany to reach a good return of investment (less than 10 years). Natural gas price has a minimum impact especially if the end-user is using a gas boiler.

The prime power market is much more attractive but require a water neutral system as well as freeze protection kit. This market required a very high robustness to be successful and the platform require a couple of more iteration to reach such requirements.

While continuing searching for investors for the next round of development, all learnings will be transferred to other fuel cell markets such as Back-up, motive and adjacent markets. All learnings on material durability, control, stack integration, liquid cooled stack integration, system monitoring will be implemented in the next product development projects related to BPSE activity plan.

1.7 Project conclusion and perspective

The project led to the identification of major failure mode on the reformer. Very promising catalyst has been identified and could be integrated in the next generation of reformer. The new catalyst is claimed to be sulfur tolerant which could offer new concept of reformer integration and reduced catalyst cost combined with adsorbent by a factor of 10. The modification of the WS reformer with Chloride free catalyst will significantly reduce cost and improve life time. The commercial effort to seek partners for the next phase of industrialization and technology solution transfer is possibility but need to be focus towards high added value market i.e. generator for pipeline corrosion protection.