Final report

COmmercial Breakthrough of Advanced Fuel Cells

COBRA II

Energy Efficiency

EUDP 2013-I

Project identification 64012-0257

Abbreviations and acronyms

MEA	Membrane Electrode Assembly
CO	Carbon Monoxide
Pt	Platinum
PBI	Poly Benz Imidazole
HT PEM	High Temperature Polymer Electrolyte Membrane
RMFC	Reformed Methanol Fuel Cell
BOP	Balance Of Plant
TRL	Technology Readiness Level
RMFC	Reformed Methanol Fuel Cell
LPG	Liquefied Petroleum Gas
LT PEM	Low Temperature Polymer Electrolyte Membrane
SOFC	Solid Oxide Fuel Cell
USD	United States Dollar
DC	Direct Current
CAPEX	Capital Expenditure
OPEX	Operational Expenditure
TCO	Total Cost of Ownership
kW	Kilo Watt
kWh	Kilo Watt Hour
APU	Auxiliary Power Unit
OEM	Original Equipment Manufacturer
HAZOP	Hazardous Operations

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1.1. Project details

Project title	COmercial Breakthrough of Advanced Fuel Cells – COBRA II
Project identification (program abbrev. and file)	2013-I, Project ID 64012-0257
Name of the programme which has funded the project	EUDP
Project managing company/institution (name and address)	Serenergy A/S Lyngvej 8 9000 Aalborg
Project partners	Serenergy A/S Danish Power Systems A/S Aalborg University - AAU Danish Technological Institute - DTU
CVR (central business register)	DK 39170418
Date for submission	31-05-2017

1.2. Short description of project objective and results

English

The main objective of COBRA II is to take the results and advancements from COBRA I and apply them to the next stage of the COBRA development stages – this includes, among other:

- an increased focus on an integrated system with balance of plant components
- fundamental core technology
    - MEA
    - Stack
    - Reformer.

In addition to the above the objective is to realize the parameters on the COBRA technology Roadmap. The roadmap entails the results from COBRA I, the objectives from COBRA II and the targets corresponding with the official HT PEM roadmap.

Dansk:

Hovedformålet med COBRA II er at tage resultaterne og fremskridtene fra COBRA I og anvende dem til næste fase af COBRA-udviklingsfasen - dette inkluderer blandt andet:

- øget fokus på et integreret system med balance af plantekomponenter
- grundlæggende kerneteknologi
    - MEA

- Stack
- Reformator.

Udover det ovennævnte er målet at realisere parametrene på COBRA teknologi køreplan. Køreplanen medfører resultaterne fra COBRA I, målene fra COBRA II og de mål, der svarer til den officielle HT PEM køreplan.

1.3. Executive summary

A three-stage plan was formulated In COBRA I – the following material is an outline for the COBRA II project application.

Stage 1 (COBRA I)

The previous projects have created the foundation for the present status today and COBRA is the next important step. As mentioned the purpose of COBRA is to demonstrate a 5 kW. air cooled high-power fuel cell module using methanol as fuel. We have named this stage 1.

Stage 2 (COBRA II)

The next stage that should be started in about two years concerns production and product maturation on MEA"s, stacks and systems. It includes further innovation and optimization of all processes. Certification (CE-marking) of the systems should be achieved. The final production setup must be defined. The financing of stage two will be a combination of funding from development bodies, the involved companies and investors.

The prime application and product behind the COBRA program is a Reformed Methanol Fuel cell (RMFC) module capable of providing conditioned DC power from a Methanol water mix directly to a battery pack.

The product offer advantages in form of lower operation expenses (OPEX) and thereby total cost of ownership (TCO) and a number of peripheral advantages that leads to cost savings and efficiency. In prime application, the capital expenditure (CAPEX) will be competitive and in others the Return on investment (ROI) will be from 1 to 3 years.

On a ten year scale the platform will form basis for several hundreds of jobs up to a quarter of a million DKK turnover per year.

The target customers are divided into four areas representing sequential and parallel markets that will gain traction based on the progress in cost and performance.

1. Backup-supplemental power generators
2. Auxiliary power units
3. Material handling-Auxiliary vehicles
4. Automotive-Range extender

The target customers are OEM's or professional integrators into their solutions. The primary aim is Telecom operators and telecom solution providers. The secondary aim is vehicle OEM's and vehicle integrators.

Perspectives

An application for COBRA III will be submitted within the legal timeframe specified by EUDP. At this stage, some of the objectives can be outlined since they are carried over from project to project, leading to incremental changes in processes, both in R&D, as well as regarding commercial applications according with EUDP directives of research outcome, alongside the particular applications defined by the different stakeholders envolved on the project. The third stage (COBRA III) includes construction of the first production lines in production scales of 5-10 kW/year. This contains ramp-up strategy, trimming of production, automation and other innovation development processes concerning the production technology. Outsourcing of non-core processes will be pursued and LEAN management principles will be applied to achieve full integration. Benchmarking towards similar industries will be evaluated to acess competitivity of the technology, visibility and optimize product placement in the global markets.

1.4. Project objectives

- The primary project objective is to optimize an integrated fuel cell module from COBRA I.
- The module and key components should be optimized and increase performance within key parameters according to technology roadmap.
- In addition to technology optimization and development focus will be on Balance of Plant (BoP) and system components other that MEA, stack and reformer.
- Cost optimization and production setup will be in focus to follow the commercialization track from MEA to niche applications to mass markets.
- 3-5 modules should be taken to field demonstration and OEM customer test
- Further commercial analysis and activities.

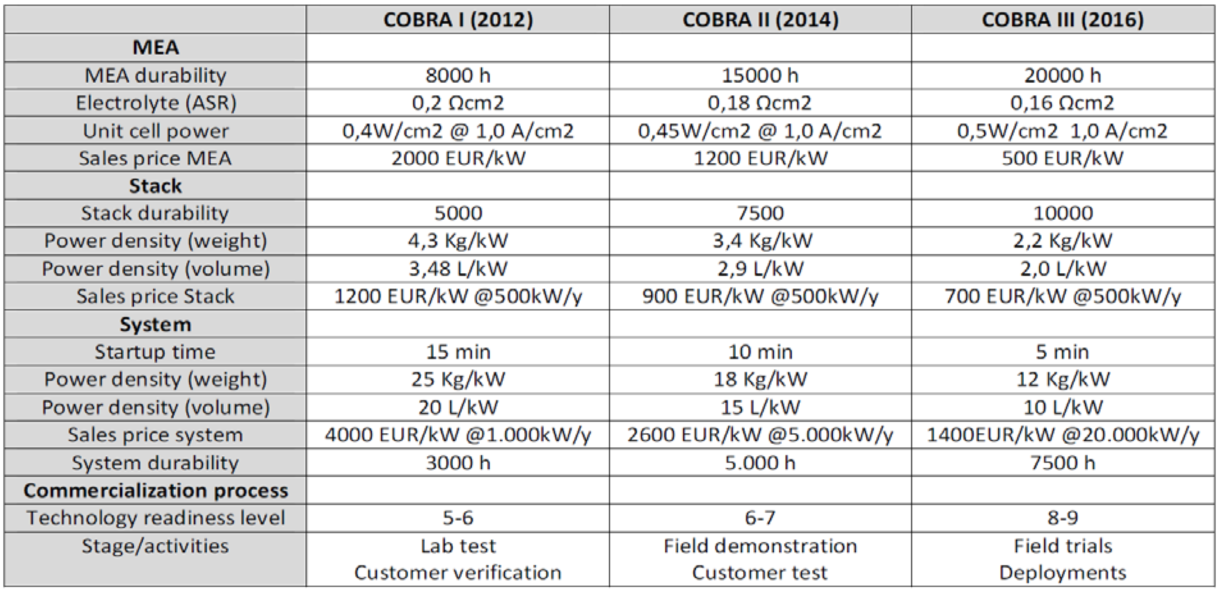
Production

The optimization of production processes related to core components is a vital step towards commercial viable products and a will be in focus in COBRA II. The objective is to enable a larger batch production and semi-automated processes enabling high quality and a somewhat cost effective and rational production. The intention is to align the expected mid-scale volume with the level of automation and investments in production.

Product maturing

An increased focus area in COBRA II is the product platform and the underlying elements. This focus entails balance of plant, ancillary systems and overall system design. As a platform project, COBRA will look at several generic applications and ensure the key components are optimized to meet the relevant markets with a timing that fits a commercial viable business case. The commercial ramp will be defined in detail and executed with OEM interaction through module and systems test.

COBRA Key Roadmap



	COBRA I (2012)	COBRA II (2014)	COBRA III (2016)
MEA			
MEA durability	8000 h	15000 h	20000 h
Electrolyte (ASR)	0,2 Ωcm2	0,18 Ωcm2	0,16 Ωcm2
Unit cell power	0,4W/cm2 @ 1,0 A/cm2	0,45W/cm2 @ 1,0 A/cm2	0,5W/cm2 1,0 A/cm2
Sales price MEA	2000 EUR/kW	1200 EUR/kW	500 EUR/kW
Stack			
Stack durability	5000	7500	10000
Power density (weight)	4,3 Kg/kW	3,4 Kg/kW	2,2 Kg/kW
Power density (volume)	3,48 L/kW	2,9 L/kW	2,0 L/kW
Sales price Stack	1200 EUR/kW @500kW/y	900 EUR/kW @500kW/y	700 EUR/kW @500kW/y
System			
Startup time	15 min	10 min	5 min
Power density (weight)	25 Kg/kW	18 Kg/kW	12 Kg/kW
Power density (volume)	20 L/kW	15 L/kW	10 L/kW
Sales price system	4000 EUR/kW @1.000kW/y	2600 EUR/kW @5.000kW/y	1400EUR/kW @20.000kW/y
System durability	3000 h	5.000 h	7500 h
Commercialization process			
Technology readiness level	5-6	6-7	8-9
Stage/activities	Lab test Customer verification	Field demonstration Customer test	Field trials Deployments

Goal fulfilment

Following the COBRA Key road map (above) and the objectives stated on point 4.2 of this document, some considetations can be done at this stage about the fulfilment of the aimed goals and the work on progress to reach them and go beyond, since COBRA III goals were also used to push the bounderies of Research and Development beyond COBRA II, using that factor as leverage to improve the overall systems intergration to optimize the final product as a whole, buying precious time at the final stages to make adjustments if needed.

- The startup time heating goal was missed due to further research needed to make the module more compact and heat resistant materials application. On the field trils, the clients were comprehensive and adjusted the runtime to compensate a slightly bigger time, having the system performed so far in line with client's expectations.
- The final price is still significant but not a hurdle on itself since the clients are willing to pay the price, since other savings, comparing with legacy systems, are achieved and helped mitigate the difference. The clients also consider an advantage to be early adpoters of the HT-PEM technology since serviceman on the field will be ready at a later stage to deal with cutting-edge technology that so far exceeds the reliability goals fixed by both parties.
- Following the previous point, the commercial roadmap for early roll-out and field testing of the technology was met and input from clients lead to other advances in research to optimize performance in all-weather conditions, from the Tropics to the Poles.
- Regarding Core lifetime, we exceeded the initial established goals and a solution for recore planning for clients is being studied to simplify deployment and management on the field of the units, alongside refueling and routine/preventive systems check.
- On overall system level, the achieved performance was not so good, mainly due to time constraints and constant input from partners and field users of the technology. As previously stated, using the goals for COBRA III as an incentive, some systems were developed in an intermediate form, to know

where to optimize and reach greater integration, making the roll-out for field test process significantly harder for project members, but at the same time, it simplified the learning curb.

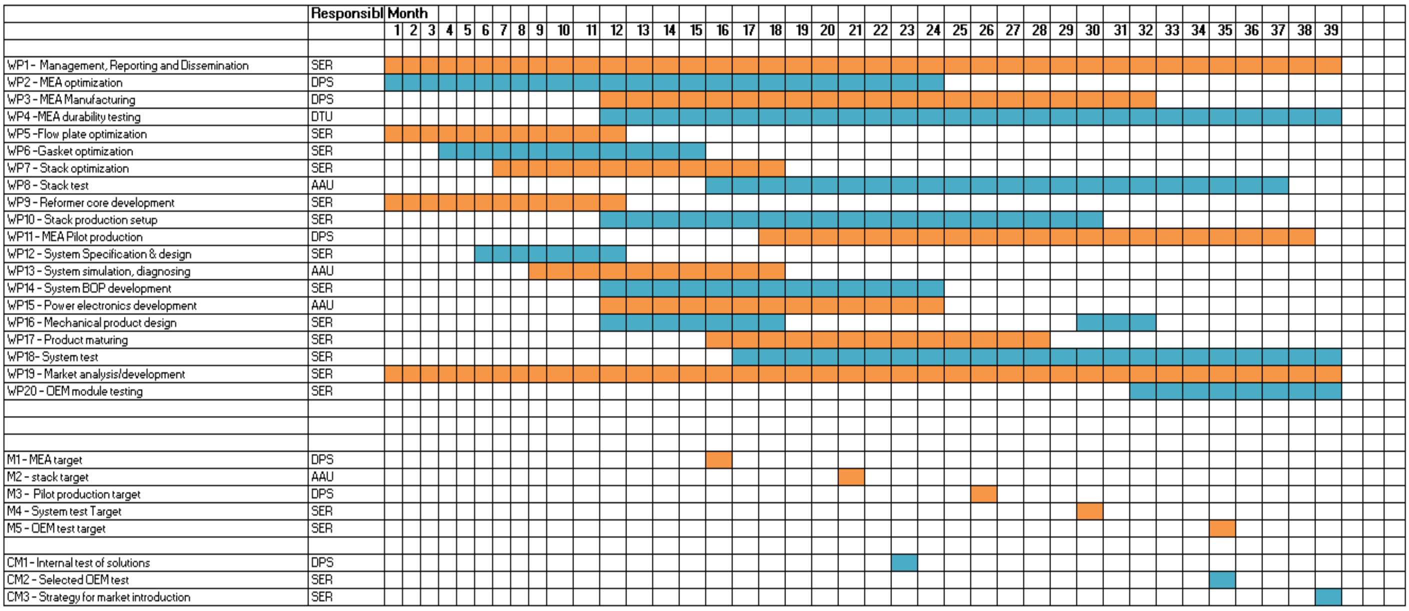
- At the time of submission of this report, COBRA III application will be already submitted. The goals for system level are now in line with the transition forecasts for COBRA III, overcoming COBRA II with considerable success. The new components allow a greater level of predictability regarding performance, having the efforts devoted to the supply chain management helped on costs and quality of the developed solution.

Prospects

The optimization of production processes related to core components is a vital step towards commercial viable products and a will be in focus in COBRA II. The objective is to enable a larger batch production, semi-automated processes enabling high quality, a cost effective and rational production model. The intention is to align the expected mid-scale volume with the level of automation and investments in production. This focus entails balance of plant, auxilliary systems and overall system design. As a platform project, COBRA II will look at several generic applications and ensure the key components are optimized to meet the relevant markets with a timing that fits a commercial viable business case. The commercial ramp will be defined in detail and executed with OEM interaction through module and systems test.

Timeplan

Projecttitel: COBRA II
Starting Date: 01.08.2013



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WP1 - Management, Reporting and Dissemination	SER	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧			
WP2 - MEA optimization	DPS	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦																		
WP3 - MEA Manufacturing	DPS												🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧										
WP4 -MEA durability testing	DTU												🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦			
WP5 -Flow plate optimization	SER	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧																														
WP6 -Gasket optimization	SER				🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦																											
WP7 - Stack optimization	SER							🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧																								
WP8 - Stack test	AAU																🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦					
WP9 - Reformer core development	SER	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧																														
WP10 - Stack production setup	SER												🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦												
WP11 - MEA Pilot production	DPS																		🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧				
WP12 - System Specification & design	SER						🟦	🟦	🟦	🟦	🟦	🟦	🟦																														
WP13 - System simulation, diagnosing	AAU									🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧																								
WP14 - System BOP development	SER												🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦																		
WP15 - Power electronics development	AAU												🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧																		
WP16 - Mechanical product design	SER												🟦	🟦	🟦	🟦	🟦	🟦	🟦														🟦	🟦	🟦										
WP17 - Product maturing	SER																🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧														
WP18- System test	SER																	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦			
WP19 - Market analysis/development	SER	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧			
WP20 - OEM module testing	SER																																🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦			
M1 - MEA target	DPS																🟧																										
M2 - stack target	AAU																					🟧																					
M3 - Pilot production target	DPS																										🟧																
M4 - System test Target	SER																														🟧												
M5 - OEM test target	SER																																			🟧							
CM1 - Internal test of solutions	DPS																							🟦																			
CM2 - Selected OEM test	SER																																			🟦							
CM3 - Strategy for market introduction	SER																																							🟦			

1.5. Project results and dissemination of results

Milestones

M1 – MEA target	
Lead: DPS	
Start/End	M16
Description	Reaching the roadmap parameters in terms of single cell power and electrolyte area specific resistance.
Link	WP2 – WP3 – WP4 – WP11

M2 – Stack target	
Lead: AAU	
Start/End	M21
Description	Reaching the roadmap parameters in terms of density and durability.
Link	WP7 – WP8

M3 – Pilot production target	
Lead: DPS	
Start/End	M26
Description	Enabling a production setup that can sustain production techniques that offers mid volume and quality targets in form of product variance.
Link	WP16

M4 – System test target	
Lead: AAU	
Start/End	M30
Description	Reaching the roadmap parameters in terms of single cell power and electrolyte area specific resistance.
Link	WP12 – WP13 – WP14 – WP18

M5 – OEM test target	
Lead: SERENERGY	
Start/End	M35
Description	Reaching the roadmap parameters in terms of single cell power and electrolyte area specific resistance.
Link	WP20

Commercial Milestones

CM1 – Internal test of solutions	
Lead: DPS / SERENERGY	
Start/End	M23
Description	Completing an internal benchmark test of solutions or adapted solutions against OEM and application metrics.
Link	WP20

CM2 – Selected OEM test	
Lead: SERENERGY	
Start/End	M35
Description	Completing an external test of systems and/or solutions at selected OEM’s within relevant applications
Link	WP20

CM3 – Strategy for market introduction	
Lead: SERENERGY	
Start/End	M35
Description	Completing a detail strategy and execution plan for next steps towards mass market introduction, including volume deployments in niche markets and early mass markets.
Link	WP19
Objects	• Business Plan

1.5.1. Work packages

WP1 – Management	
Lead: SERENERGY	
Start **End**	M1 M39
Description	Project management including coordination of steering committee meetings and summaries, the half yearly reporting to ENS and that the project is in general proceeding according to plan and budget. Dissemination of the project results and general awareness creating on the technology and stakeholders will be increased to reflect the increased progress and maturity.
Link	All WP
Objects	• Weekly/biweekly meetings • Quarterly statements • Progress reporting • Dissemination • End reporting

WP2 – MEA optimization	
Lead: DPS	
Start **End**	M1 M24
Description	The objective is to optimize the MEA in order to obtain higher performance and longer durability compared to the present MEAs. The work will be focused on the following: Membrane reinforcement Alloy catalyst in order to gain a voltage decrease and a price reduction Electrode structure (ink formulation) Membrane/electrode interface The improved MEAs will be tested in different configurations and under different testing conditions.
Link	WP3 – WP4
Objects	• MEA to single cell test at DTU, AAU and Serenergy • Milestone 1

In this work, the individual components of single membrane electrodes assemblies have been optimized in order to achieve the required power density of 450 mW/cm^2.

Thermally treated membrane on Dapozol® standard MEA

In one hand, the implementation of new thermally cured PBI membranes have been successfully long term tested. During the experiment, constant stoichiometry was chosen for all fuel cell tests: 1.3 for pure hydrogen and 2.0 for air. This test has resulted in more than 15,000 hours or continuous operation at 0.3 A/cm^2 with a degradation rate of 4.5 µV/h over the first 14,000 hours which is shown in Figure 1.

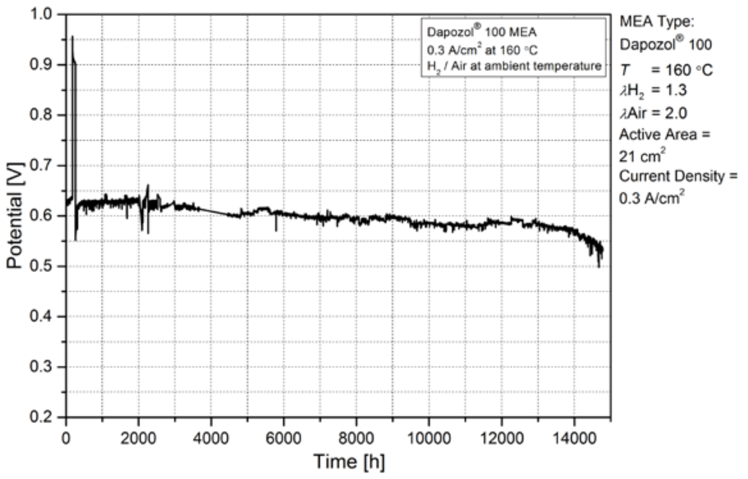


Figure 1. 15.000 hours durability test of thermally treated MEAs. T=160 °C, 0.3 A/cm^2, ⍰$_{H2}$/ ⍰$_{Air}$=1.5/2, p=ambient pressure, serpentine flow field, 21 cm^2 MEA active area.

Development of new cathode architecture (Pt alloy) with reduced catalyst loading using tape casting technique.

Pt alloy catalyst are promising alternatives due to their high activity on the oxygen reduction reaction (ORR). The ink recipe has been optimized to obtain a slurry to enable electrode coating processes that increases the manufacturing capacity and thus, MEA price reduction.

Therefore, a PtCo catalyst (Tanaka) containing Pt 46.4 % and Co 5.8 %, PTFE and non- ionic surfactant Titron X-100 have been coated on the gas diffusion layer using tape casting technique. The obtained catalyst loading lays on the range 0.8 - 0.97 mgPtCo/cm^2 on the cathode side. As the phosphoric acid uptake of the catalyst layers are determined by their hydrophobicity and the use of the non-ionic surfactant improves ink homogeneity, PTFE and Titron X-100 content on the catalyst layer have been modified from 5 to 10 wt% and from 5 to 15 wt%, respectively.

Sprayed pure platinum catalyst Pt/C has been kept constant on the anode side with an approximately loading of 1.5 mgPt/cm^2. In Figure 1, it can be seen different polarization curves for different amount of PtCo/C catalyst, PTFE and Titron X-100 as explained above.

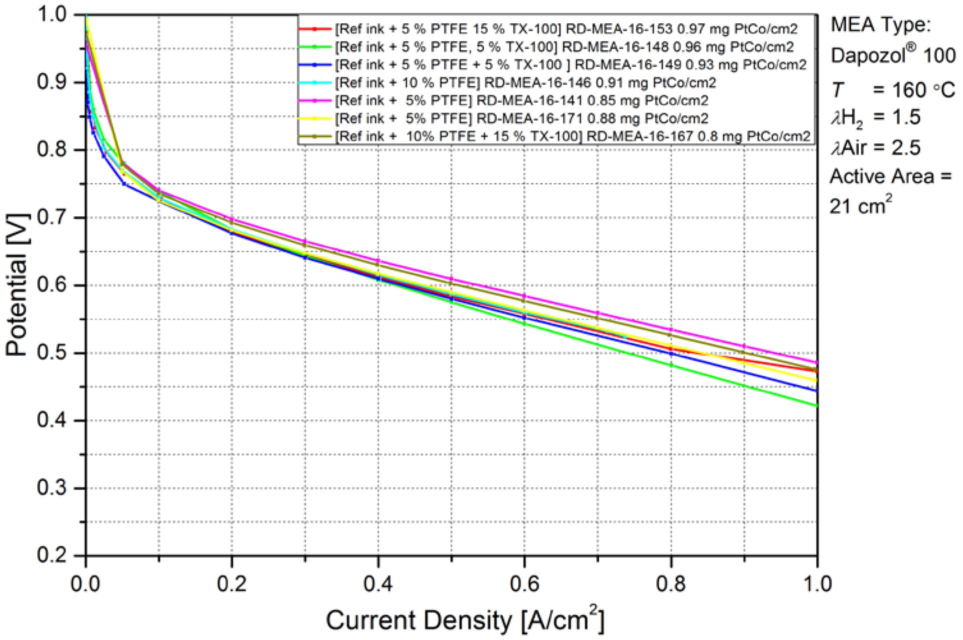


Figure 2. *Polarization curves data after activation period. T=160 °C, λ_{H2}/ λ_{Air}=1.5/2.5, p=ambient pressure, serpentine flow field, 21 cm^2 MEA active area.*

The data point at 0.2 and 0.4 A/cm^2 has been mainly correlated with the PtCo loading for each of those MEAs, (See Table 1)

Table 1. Performance data-points correlated with PtCo/C catalyst loading casted on the cathode side.

	Polarization curves data- points obtained at t > 144 h		
	0.2 A/cm2	**0.4 A/cm2**	**PtCo (mgcm^{-2})**
MEA-RD-16-141	0.704	0.636	0.85
MEA-RD-16-167	0.699	0.630	0.80
MEA-RD-16-153	0.686	0.613	0.97
MEA-RD-16-171	0.683 [48 h]	0.618 [48 h]	0.88
MEA-RD-16-146	0.683 [90 h]	0.616 [90 h]	0.91
MEA-RD-16-149	0.677	0.610	0.93
MEA-RD-16-148	0.683	0.608	0.96

The polarization data reveals that all MEAs performance are clearly over 0.6 V at 0.4 A/cm^2 under hydrogen/air conditions. The catalyst loading has been reduced to approximately 47% with respect to the current loading using on standard Dapozol ® MEAs (1.5 mgPt/cm^2). Also, there seems to be an indication that better performance is obtained for those MEAs with PtCo/C loadings on the range of 0.8 rather than catalyst loading of approximately 0.9 mgPtCo/cm^2.

The tape coater use for electrode manufacturing is shown in Figure 3.a. Post-mortem analysis done on a used MEA (Figure 3.b) confirm that significant improvement of the uniformity of the catalyst layer have been achieved using tape casting as coating technique as compared to the spray technique.

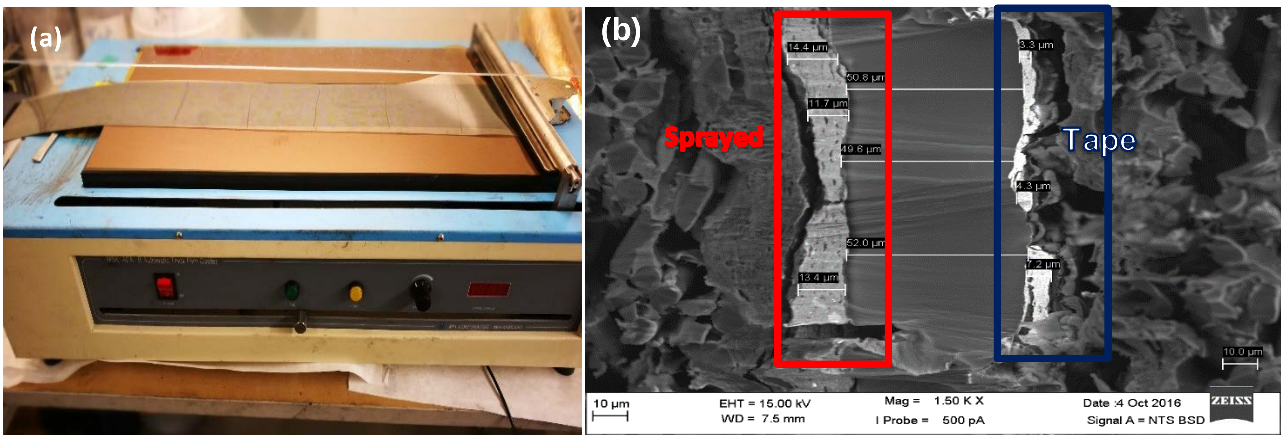


Figure 2.a. Tape casting machine MTI.corp (U.S.A). b) SEM on an MEA after 235 h at 0.2 A/cm^2 of continuous testing. (Left side)

Figure 3.b. Ultrasonic Spray method ~ 12 µm Pt/C catalyst layer on anode side, (right side) tape casted ~7 µm PtCo catalyst layer on cathode side Reduced PtCo catalyst loading on anode and cathode side. Symmetric MEAs with Thermally treated versus standard membrane

Further work has been made to further decrease the total amount of catalyst on the anode and cathode (symmetric MEA with a loading of approximately 0.8 mgPtCo loading on either electrode). As indicated above in Figure 1, the thermally cured membrane lead to a significant decrease of the degradation rate. For this reason, the direct comparison between standard versus thermally cured membrane have been made.

The results are shown in Figure 4.

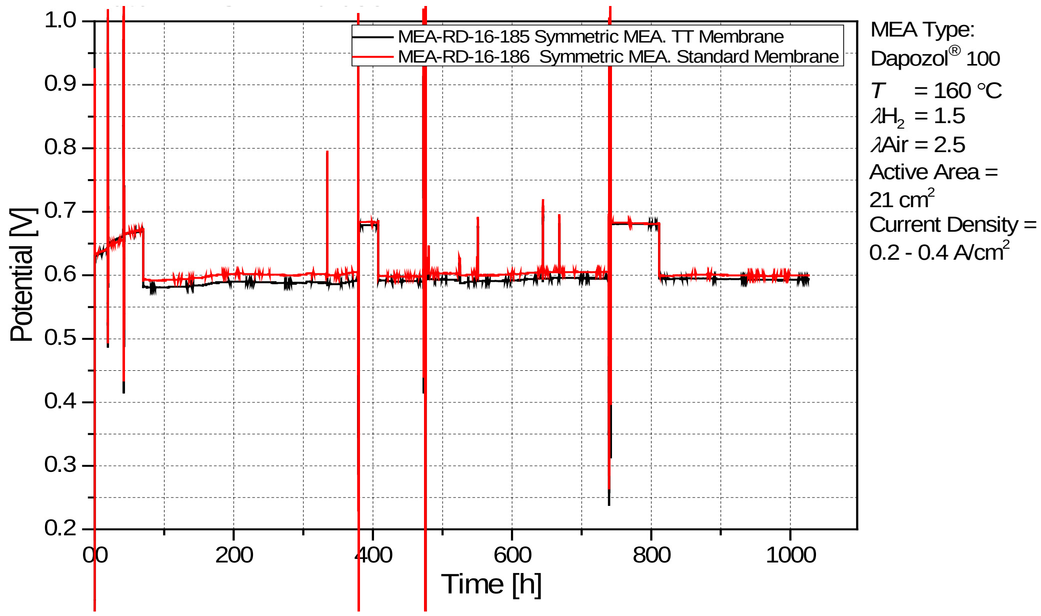


***Figure 3**. Durability test of tape-cast MEAs with PtCo catalyst. MEA-RD-16-185: thermally treated membrane with cathode/anode = 0.89/0.62 mg PtCo/cm^2. MEA-RD-16-186: standard membrane with cathode/anode 0.73/0.68 mg PtCo/cm^2. Increased current density of 0.4 A/cm^2 after 90 hours of activation period, λ_{H2}/ λ_{Air}=1.5/2.5, p=ambient pressure, serpentine flow field, 21 cm^2 MEA active area.*

It can be seen in Figure 4, that the performance is increasing on both symmetric MEA with thermally cured membrane and symmetric MEA with standard membrane, respectively). However, the MEA-RD-16-185 (thermally treated membrane) has lower performance as compared to the MEA-RD-16-186 (standard membrane). This is further studied by performing oxygen gain analysis and EIS measurements after 740 h of long term test at 0.4 A/cm^2 (See Figure 4.a and 4.b).

The Specific Area Resistance from both type of membranes (SAR) can be obtained from EIS measurements (Figure 4.b). This analysis shows a low specific resistance of 0.16Ωcm^2 and 0.18 Ωcm^2 for standard and thermally cured membrane respectively, which explains that the performance on MEA-RD-16-185 has approximately 20 mV lower performance at 0.4 A/cm^2. The thermally cured membrane has double the resistance of the standard membrane, corresponding to approx. 20 mV lower performance at 400 mA/cm^2. The long-term test will continue to verify whether there is a significant difference on the degradation due to the implementation of either membrane on the MEA.

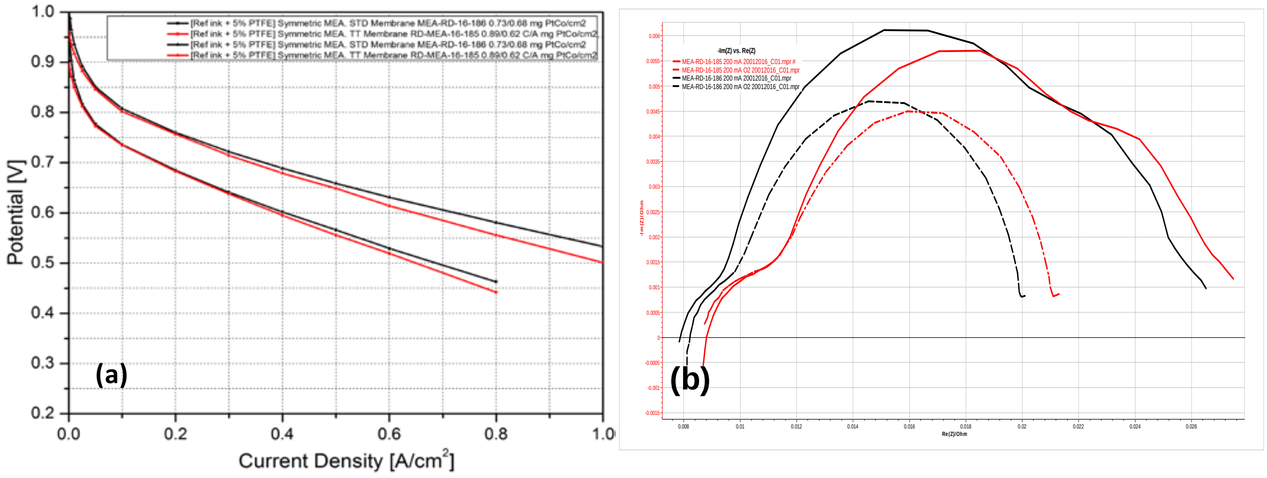


Figure 4. ***(a)*** *Polarization curves data after 740 h long term test at 0.4 A/cm^2 with H2/Air and O$_2$/Air. MEA-RD-16-185: thermally treated membrane with cathode/anode = 0.89/0.62 mg PtCo/cm^2.* ***(b)*** *EIS Measurement performed at 0.2 A/cm^2 after 740 h long term test at 0.4 A/cm^2. MEA-RD-16-186: standard membrane with cathode/anode 0.73/0.68 mg PtCo/cm2, T=160 °C, λ_{H2}/ λ_{Air}=1.5/2.5, p=ambient pressure, serpentine flow field, 21 cm^2 MEA active area.*

Conclusion:

- Standard Dapozol® Johnson Matthey in combination with thermally cured membranes have demonstrated good performance and excellent surability (approx. 635 mV at 0.3 A/cm^2) and 14.000 hours with a degradation rate of -4.5 µV/h (test still on-going) using H_2 and Air.
- The tape casting techniques allows MEA mass production enabling further reduction on MEA price.
- New development has been made on the electrode architecture whereby the introduction of PtCo alloy (Tanaka catalyst) has successfully accomplished the required target of 0.45 W/cm^2 at 1.0 A/cm^2. The durability tests at different current densities of 0.4 – 0.55 and 0.6 A/cm^2 shows still a positive trend and therefore MEA degradation have yet not being observed (>1.200 h test on going).
- Development of symmetric MEAs with increased performance and 50 % less catalyst as compared with the Dapozol® MEA combined with thermally cured membrane have been successfully long term tested (tests still on-going).

WP3 – MEA Manufacturing	
Lead: DPS	
Start **End**	M12 M32
Description	The main objective is to reduce the batch to batch variation in the MEA manufacturing. This requires detailed control of the individual manufacturing steps including membrane production, catalyst preparation and electrode manufacture, assembly and conditioning technology. Further, process development towards project targets (edge reinforcement, MEA sixe flexibility, manufacturing capacity and process time) will be in focus.
Link	WP2 – WP4 – WP11
Objects	• Roadmap/study – Production scaleup + cost analysis • Analysis of processes and quality control of manufacturing processes • Proven Batch verification max 5% deviation

The final quality control is being conducted at singles MEAs. These MEAs follows an activation procedure at 0. 2A/cm^2 for the first 120 h of operation. However, polarization data is obtained at 5 h, 24 h and 48 h. Next figure shows the average polarization data obtained during 2016 for two different commercial MEA type from DPS (see Figure 6). Those are.

a) Dapozol® 100: Standard developed product, this MEA is designed to fulfill the customer requirements under H_2/air
b) Dapozol® 101: Product with Extra-hydrophobic treatment of the gas diffusion layers designed to withstand wet fuel gasses commonly obtained from methanol reforming.

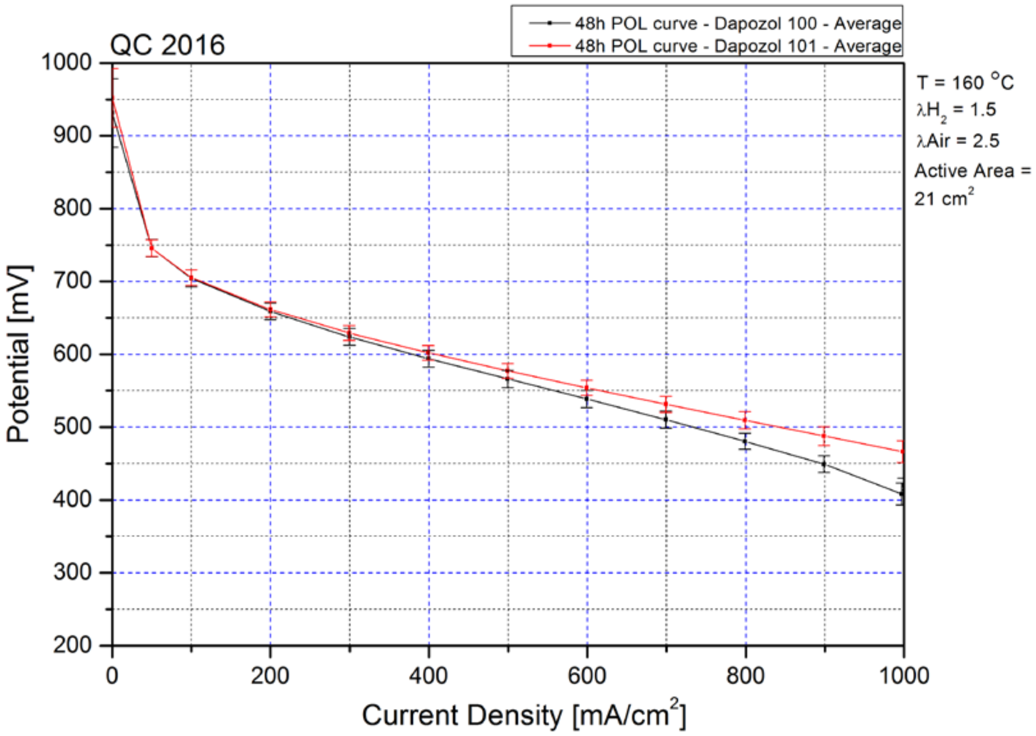


Figure 5. *Quality control test (QC) conducted on two different MEA type. (Red dotted line), average polarization curve obtained in 2016 on Dapozol® 100 at time = 48 h. (Black dotted line), average polarization curve obtained in 2016 on Dapozol® 101.*

The statistics on MEA variation for both types of MEA product based on Figure 6 can be seen in Table 1.

Table 1. *Statistics on MEA polarization data obtained at 48 h of continuous operation for Dapozol 100 & 101 product*

	Polarization data time (h)	*Number of batches*	*Average performance at 0.2 A/cm^2 (mV)*	*Standard Deviation on average performance at 0.2A/cm^2 (mV)*	*Relative Standard Variation (%)*
Dapozol 101	48	24	656.2	11.1	**1.7**
Dapozol 100	48	36	661.3	10.4	**1.6**

Conclusion:

- The Relative Standard Variation (STD) obtained for a total number of 24 batches has been 1.7 % on Dapozol® 101 MEAs
- The Relative Standard Variation (STD) obtained for a total number of 24 batches has been 1.6 % on Dapozol® 100 MEAs

Both types of MEA product have clearly overcome the target of a verified variation of less than 5 %. Furthermore, the low variation of less than 2 % has been clearly shown for a large number of different batches. The number of tested batches have been 24 and 36 for Dapozol® 100 and Dapozol® 101, respectively.

WP4 – MEA durability testing	
Lead: DTU	
Start **End**	M12 M39
Description	The main objective is to clarify the degradation mechanisms by performing Single Cell durability studies using hydrogen as the fuel. As a next step Single Cell durability studies using reformate will be performed. SerEnergy will deliver input from the reformer development (i.e. reformate composition). The effects of variations in fuel composition on performance – including water content and unreacted methanol will be studied. The outcome of these investigations will be performance and degradation data needed for the MEA optimization (WP2) and manufacture (WP3). An analysis of the electrochemical sensitivity of changes in fuel gas composition will be performed. Benchmarking with MEAs from competitors will also be performed.
Link	WP2 – WP3 – WP8
Objects	• Durability projections towards targets on reformate gas, including start stop cycles and storage/standby functionality

Focus in the work package has been on testing MEAs developed in the prvious work packages as well as clarify degradation mechanisms.

Long term durability test of the developed thermally threated membrane has been performed and compared to standard Dapozol MEAs. A number of different samples were run to compare how the degration meachanism changes over time.

The results were published in Journal of Power Sources, Volume 342, 28 February 2017, Pages 570-578, and summarised below.

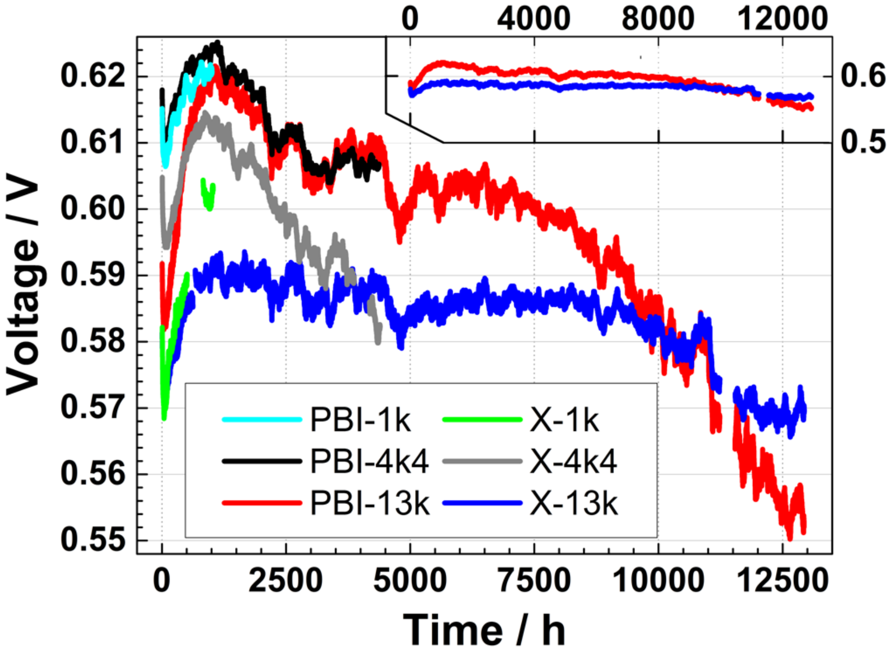


***Figure 7**. Steady state lifetime curves for MEAs operated at 160 °C, 200 mA cm^{-2}, λ_{air} = 4, and λ_{H2} = 2; cf. sample names with PBI, satandard PBI and X thermally threated PBI. The insert presents an overview of the two MEA samples that have been tested the longest.*

The cross linked PBI experiences a significantly reduced degradation rate under steady state conditions, and is projected a significantly longer service life. Summary of degration data for the 2 logest lived samples are given in the table below

Characteristics summary of MEAs operated for 13,000 h at 160 °C, 200 mA cm^{-2}, $\lambda_{air} = 4$, and $\lambda_{H2} = 2$.

	PBI-13k	*X-13k*
Time until 10 % degradation / h	12200	19400[a]
Time until 20 % degradation[a] / h	18100	31200
Degradation (V_{max} vs. V_{min})[b] / %	-11.5	-4.7
Average degradation rate until EoT[c] / $\mu V\ h^{-1}$	4.6	1.4
Average degradation rate until 10 % degradation[d] / $\mu V\ h^{-1}$	4.1	3.2
EIS series resistance[e] / %	173	22.4
Acid loss[e] / %	64.8	24.9
Membrane thinning[e] / %	55.3	32.8
Cathode ECSA[e] / %	-80.1	-68.7

Effort has also been made to understand the mayor degration meachnism involved during fuel cell operation. It is well known that a mayor degration mechanism is the lost of phosphoric acid over time.

In order to map the effect of different operating parameters on the acid loss a number of different dapozol MEAs (older generation in order to keep consistency) has been run, and the acid loss has been systematically mapped.

As summary of the results at an operating temperature of 180°C, is given below.

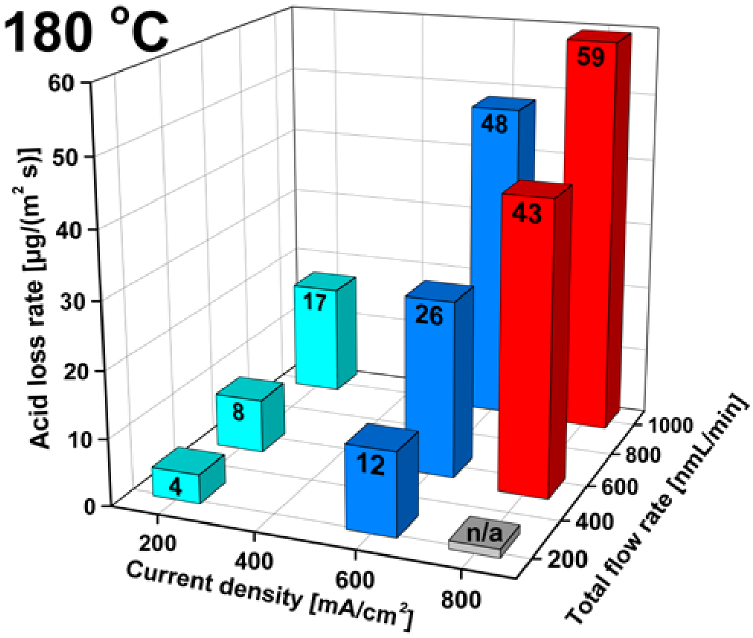


Figure 8 *Average acid loss rate from BoL and until EoT as a function of current density and total exhaust flow rate for cells operated at steady state at 180 °C.*

The results have also been repeated at 160°C showing the same trends but with a lower acid loss rate. As can be seen from the data there is a direct correlation between acid loss rate and flow rate thorugh the system, but also with increase in current density.

The main conclusion from the work is that under steady state conditions the loss of acid is varyfied as the mayor degradation mechanism and that there is a increase in acid loss with increase in current density as well as flow rate. Serenergy identified a potential problem with air pollutance in some of their key markets. Tests have been performed to see how sulphur pollutance might affect the performance of MEAs. It is known from low tmerperatur system that even small amount of sulphur will kill the cells.

A summary of the results is given below.

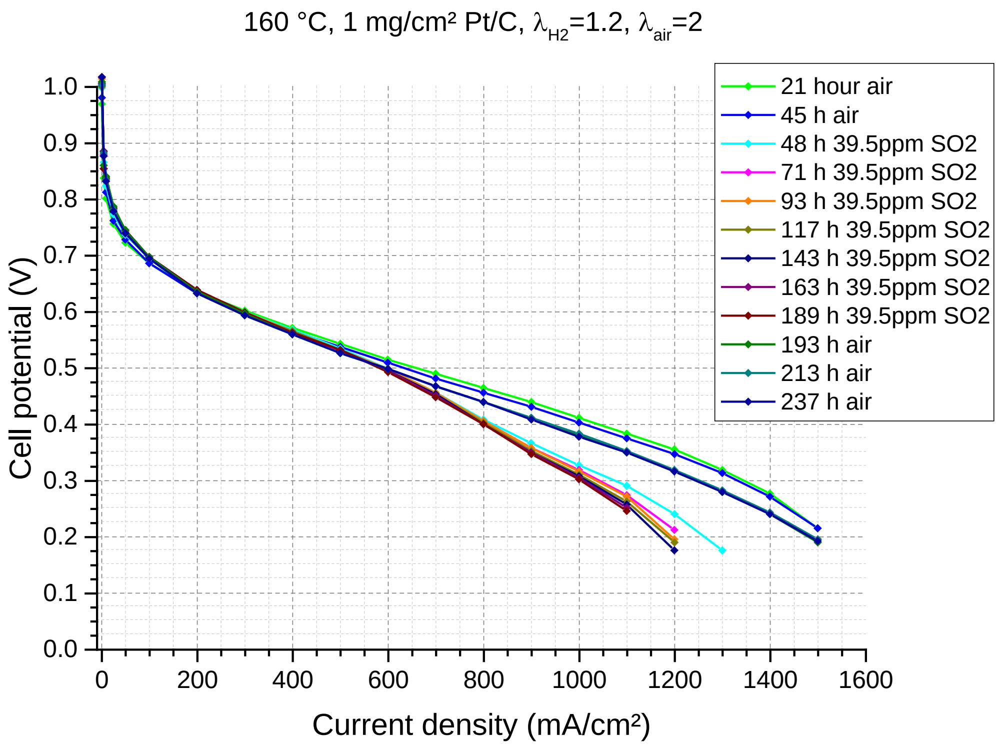


Figure 6*. Polarisation curves showing tolerance towards SO_2 contamination on the cathode side using binderless electrodes and conventional H_3PO_4-PBI electrolyte kindly provided by Danish Power Systems.*

An MEA was tested with 39.5 ppm SO_2 on the cathode side. This concentration is beyond the permissible exposure limit, and is improbable to encounter through air pollution. The polarisation curves can be seen on Figure 9. The behaviour was very similar to the one observed with 50 ppm H_2S on the anode side, with the voltage barely affected in the practical operational current range. The recovery at high currents was also rapid and of similar magnitude upon change to clean air feed.

The conducted experiments show a clear improved tolerance towards sulphur species contamination in both anode and cathode compartments, as compared to the conventional LT-PEMFC technology.

Some of the durability work has been done in collaboration with the ForskEl project DuraPEM, since data are continuous for a number of years.

Conclusions

A better understanding of degradation mechanism has been obtained and the developed thermally treated MEAs show a significant improvement towards the key durability parameters. It has also been shown that the MEAs are capable of tolerating higher limits that those assumed on the empiric models.

WP5 – Flow plate optimization	
Lead: SERENERGY	
Start **End**	M1 M12
Description	The goal is to optimize the current flow plate design to allow a higher performance in terms of power density, elevated temperature and higher compression. Furthermore focus is on enabling a simpler and more cost effective design en terms of production by removing hard stop and lowering tolerances In addition to the above efforts will be made to explore alternative materials and concepts to improve thermal properties affecting temperature distribution and flow though the plate and single cell. Through analysis and simulations a number of designs will be tested and the optimum will be prototyped and tested in a benchmark setup with only the flow plate as a change.
Link	WP2- WP6-WP7-WP10
Objects	• Optimized flow plate design • Prototypes production • Test of flow plate in benchmark setup

Results:

The optimized flow plate should fulfill the following conditions:

- Thin Bi-Polar Plate (BPP) thickness
- A gas flow, evenly distributed over the flow field.
- A stable BPP, that do not brake
- Easy and cheap to produce

Several flow plate designs have been considered in the optimization of the flow plate. Figure ??? show the current design. This is an open-end design, where the flowing gas in principal can travel through the flow area without encountering the MEA. In the design shown in figure ???+1 the gas channels are closed, in this case the gas is forced through the MEA which in principle should increase the utilization of gas. The latter design, however, would increase the pressure drop across the BPP. Simulation of the gas velocity is shown in the figure 10-2.

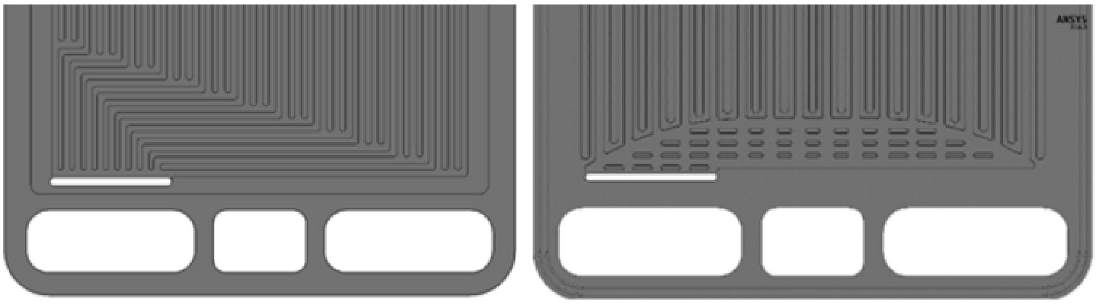


Figure 10 - 1

Prototypes of the flow plate in figure 10-1 was developed and tested in a small stack with 29 cells. The stack was tested with pure hydrogen and simulated reformer gas. Polarizations curves and hydrogen and air utilizations data have been recorded. In an air utilization test, some of the prototyped flow plates showed low performance, see figure 10-2.

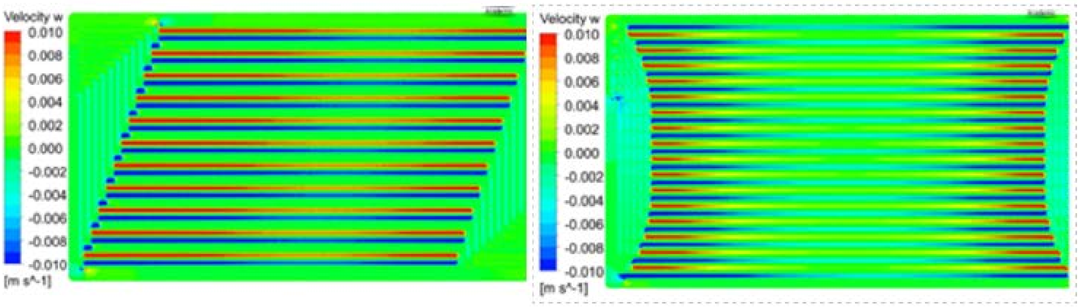


Figure 10 - 2

When the stack was dissembled after the test, liquid was found on the flow plates. The liquid was trapped in the flow channel that was blocked. In order for the liquid to escape it needed to pass through the MEA.

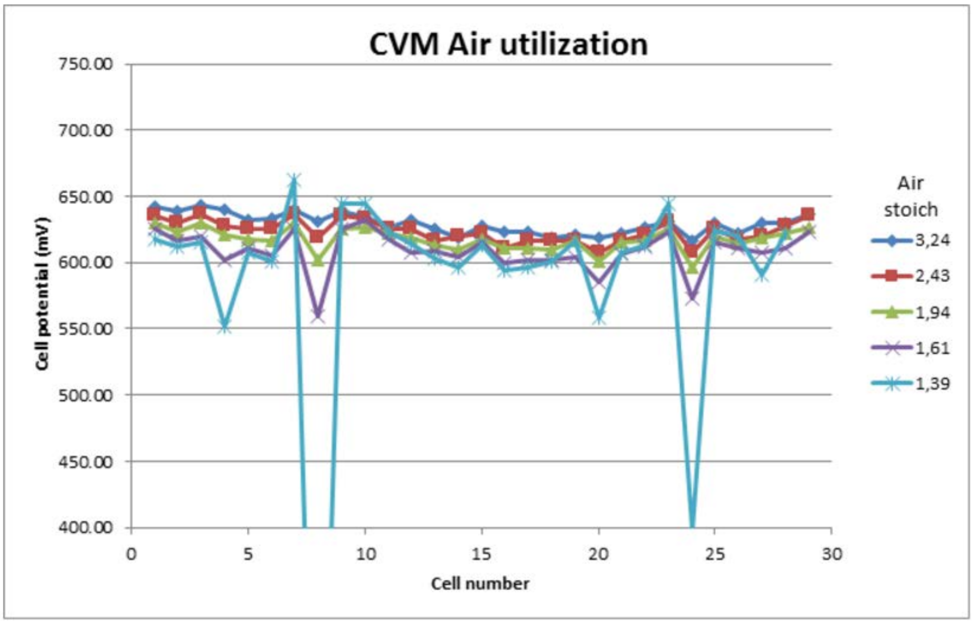


Figure 10 – 3

Conclusion:
A flow plate has been designed to achieved better stack performance and a more compact stack. With the designed flow plates, the BPP thickness was reduced from 2,7 mm to 2 mm, which will make the stack much more compact. The plate has been examined via simulation. The simulation showed good gas distribution, however, the prototype test showed that liquid management in MEAs are necessary in order to utilize the plate design.
The above flow plate was produced in a milling process. In order to get a cheaper flow plate, it is necessary to create a plate design can be moulded.

WP6 – Gasket optimization	
Lead: SERENERGY	
Start **End**	M4 M15
Description	The goal is to optimize the gasket between flow plates and MEA to ensure a lower leak rate, simple assembly and cost effective materials. Furthermore, the material composition must be compatible with the durability targets of the overall system design. Especially in focus is the stability of the gasket and the compatibility with the no-hardstop design of flow plates. The focus is to design a simple gasket with low tolerances that can be manufactured with ease by several external suppliers or internally. Manual and automated assembly of stacks requires a stable yet rigid gasket design than offers a low scrap rate of the gasket and assemble tests. Through analysis and material tests a design will be selected and tested in a benchmark setup.
Link	WP2- WP5 - WP7 - WP10
Objects	• Optimized gasket design • Prototype • Test of gasket in benchmark setup

Results:
Several stack was built with the Teflon gasket as a substitute for the standard FKM gasket, see figure 12.

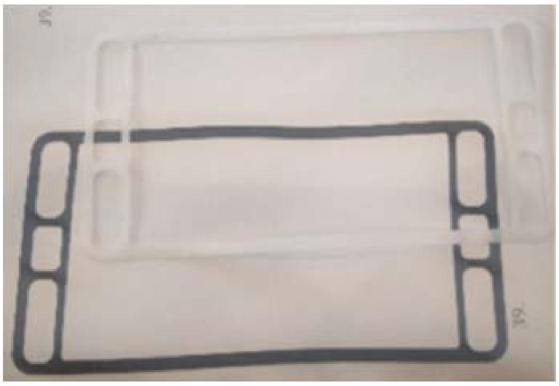


Fig. 12 Teflon gasket (white) and FKM gasket (black).

The key characteristics are listed in table 1. The Teflon gasket is harder to get leak tight when is built and have a higher likelihood to leak during stack operation. To try to avoid stack leaking, several tests were performed in which the Teflon gasket was pre-pressed to get a non-flat packing surface. The non-flat gasket did not prevent leaking in stack test. After 5000 hours of stack operation the imprint in the gasket have vanished.

In another test, the Teflon gasket was glued on to the BPP and MEA. In this test, the stack managed to run for almost two yours. Toward the end of the test the coolant in the stack started to crystalize, which then cased the stack to get hot resulting increased cell performance, see fig.8

Gasket comparison:	Teflon:	FKM gasket:
Difficult to get stack leak tight	Medium	Easy
Difficult placing the gasket during stack assembly	Easy	Medium
Product cost	Cheap	Expensive
Likelihood of stack leak during operation	Medium	Low
Gasket quality after 2 years' operation	No damage	Gasket breaking
Chemical against coolant at elevated temperature	Stable	Poor

Table 2: Comparison of key characteristic

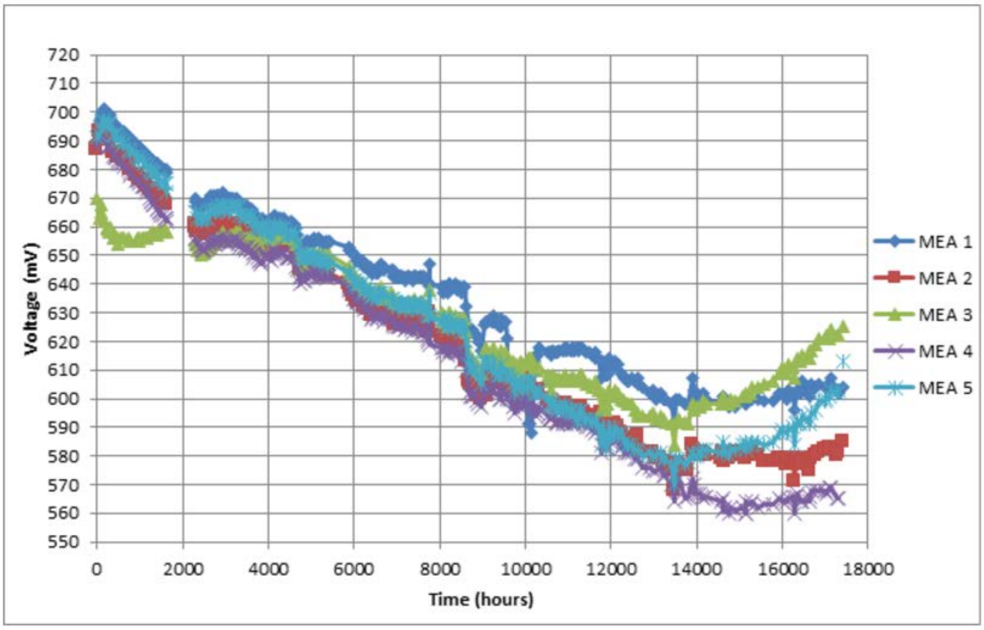


Fig 13: Cell performance of stack with Teflon gasket glued to the BPP and MEA. The stack in running with a current density at 0,16A/cm2

Conclusion:

The Teflon gasket is superior to the FKM gasket on many key parameters, see table 2. The only drawback the Teflon gasket has is the ability to be leak tight. This can, however, be solved by glued the gasket to the BPPs. By gluing the leaking problem is solved, but the stack is much harder to assemble.

The Teflon gasket is much more durable to the stack environment compared to the FKM gasket. The FKM is braking after two hours of stack operation whereas the Teflon gasket is still intact. Hence the Teflon gasket will be able to extend the stack operation time to more than two hours, at which point the FKM gasket would most likely fail.

Further test, where the BPP is shaped with a grove or nudge to hold the Teflon gasket, will be performed to achieve greater leak tight stack.

WP7 – Stack optimization	
Lead: SERENERGY	
Start	M7
End	M18
Description	The Goal is to optimize the stack assembly with focus on end End plates, fixing, compression method, Assembly and general performance related to the components. The components not covered directly in separate work packages such as; current collectors, cathode and anode connections, cooling connections. The focus is primarily on enabling high compression with a stable and easy to assemble design, this includes optimizing the stack assembly to interconnect with the reformer core and to be implemented in a product. This includes; simple and cost-effective connection methods resistant to heat and materials and optimization for insulation needed to prevent heat loss. Main methods include CAD models and concept deigns related to product work packages. The optimized components from WP2 WP5, WP6 will be included in a working prototype to be tested and subject to a design review.
Link	P8-WP10
Objects	• Optimized stack design • Prototype • Initial stack test • Design review

The focus of WP7 has been to process optimize the fuel cell stack suspension system, length varians handling, and higher compression to the less compreaable electrodes of the DPS MEA.

As can be seen in Figur 14, the spring housing has been attahed to the positive charge end of the stack, facing toward the layers at the back. The spring housing is fixed, such that is can not rotate during assembly or vibrations conditions in the products.

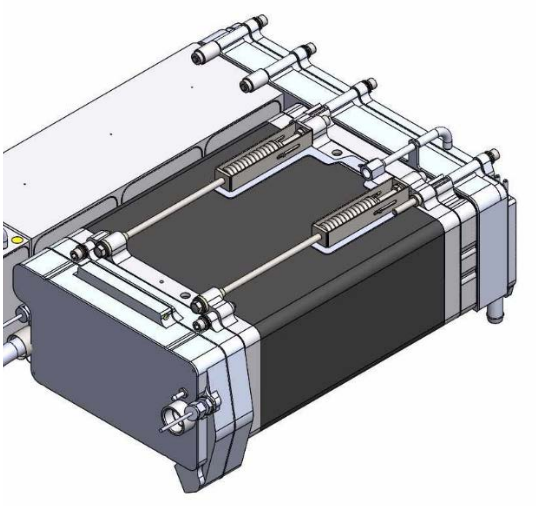


Fig 14: SerEnergy S165L stack with new suspension system, and build in stack extension system.

Between the stack and the layers, a spacer can be seen. The purpose of the spacer is to support systems with various stack length – supporting from 40-120 cells per module. Also, it can used to level out the varians of long staks with different lengths. The acceptable stack length diviation on the nominal length is plus/minus 25mm. This is not supported by the module, and therefore a spacer is needed for “short” stacks.

The new design has been assembled in 3 prototype systems, has been performance a durability tested. The results are the it has no impact of the product lifetime.

WP8 – Stack test	
Lead: AAU	
Start **End**	M16 M37
Description	The main goal is to test the complete stack as a main component in the system and attain knowledge on operating parameters. The focus is to follow benchmark testing procedures with other known deigns to compare results. A series of stack test will be initiated with a short stack design enabling several tests running parallel. Included general test metrics for performance it is alos sought to get a better understanding of the following: Reformat composition and the individual cells behavior Reaction to varians in wet or dry reformat Water balance in the cell and varians from benchmark results. Acid distribution in the cell and cell components The test will include metrics corresponding to the COBRA technology roadmap and input relating to specific applications such as start/stop cycles, storage cycles and performance predictions.
Link	WP7-WP12
Objects	• Test specification • Test execution • Test report

- **Results**

At AAU, a series of electrochemical impedance spectroscopy (EIS) measurements were performed to map the performance of HT-PEMFC stacks for varying fuel compositions. As shown in Fig. 2, one of the experiments was conducted for CO contents between 0% and 1.5% by volume at a step of 0.25 and methanol compositions of 0%, 0.25% and 0.5%, at 21 different current set points. Three EIS measurements were recorded for each test point, for a total of 1323 EIS measurements. CO_2 was also included in all test points, and was slightly varied as the contents of the other constituents of the anode feed varied, as can be seen in Fig. 16. The ten-cell short stack used in these tests was installed in a GreenLight Innovation test stand at AAU as shown in Fig. 15.

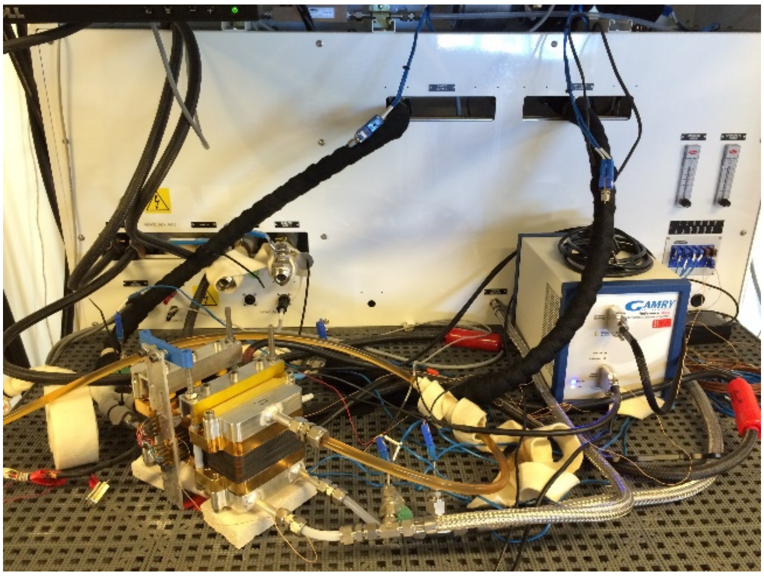


Figure 15 An example of a 10 cell short-stacks characterized at AAU

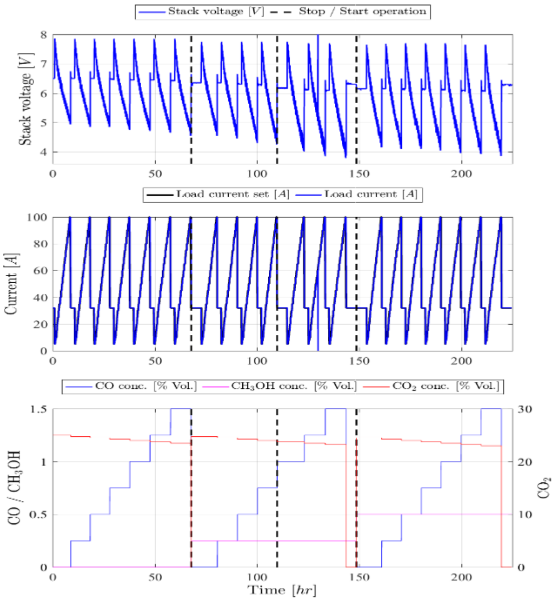


Figure 16 The total characterization experiments. 21 different gas composition set points all at 21 different currents

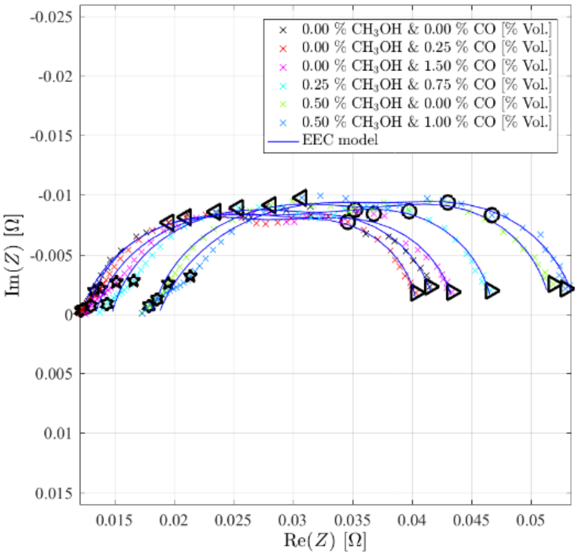


Figure 17 stack nyquist plots at with different fuel compositions

The work showed that when adding CO and methanol vapor to the anode gas the whole frequency range of the measure impedance spectra is affects. This indicates that the two to three arcs in the spectra are a combination of phenomena and cannot be ascribed to one reaction, an effect, or a part of the fuel cell stack. These comparisons are shown in Fig. 17.

Adding CO affected more the higher frequency end of the spectrum, confirming its poisoning mechanism through adsorption on Pt catalyst surface. Methanol on the other hand, caused a more pronounced increase on the ohmic resistance than can be found in literature, while also affecting the high frequency arc, implying that CO intermediates maybe formed on the Pt surface.

Such parametric mapping with different reformate compositions and at different currents can be used to design and control an integrated system of methanol reformer and HT-PEMFC, where no additional gas purification systems is required. There is also potential for using such data to develop a diagnostic tool for the system. However, the changes due to CO and methanol are too similar to be isolated from one another, making the development of fault detection and isolation tools more difficult.

Other stack characterization tests at AAU investigated the effects of different parameters, such as temperature, anode and cathode stoichiometric ratios and compared simulated steam reforming gases and auto-thermal reforming gases. The characterization was done to study the effects of the different parameters and to find the relevant thresholds and trends for CO poisoning and stoichiometric ratio values to help develop a robust control system for an integrated reformer-FC system.

The results showed that temperature increase at a step of 5 ^{0}C, brings about only slight increase in performance, both for dry hydrogen and reformate operation. Stoichiometry on the other hand has a significant effect on the fuel cell stack performance. A hydrogen stoichiometric ratio of 1.25 and 1.3, during dry H_2 and reformate gas operation modes, respectively show a 45-degree diffusion limitation line on the Nyquist plot, as can be seen in Figures 5 and 6. These are however, easily corrected in both cases by increasing the anode stoichiometric ratio by 0.5 in both cases.

Decrease in cathode stoichiometric ratios also causes mass transport limitation, both under dry H_2 and reformate gas feeds. The work showed that it is important to guarantee sufficient mass transport in the cells by setting appropriate stoichiometric ratios. However, once sufficient mass transport is achieved, further increase of either anode or cathode stoichiometric ratio does not enhance the stack performance appreciably. In this work, sufficient mass transport is achieved at $\lambda_{anode} = 1.3$ for dry hydrogen, $\lambda_{anode} = 1.6$ for reformate operation and $\lambda_{cathode} = 4$ in both cases. The effects of anode and cathode stoichiometric ratios both under dry hydrogen and reformate operations are given in Figures 18-21.

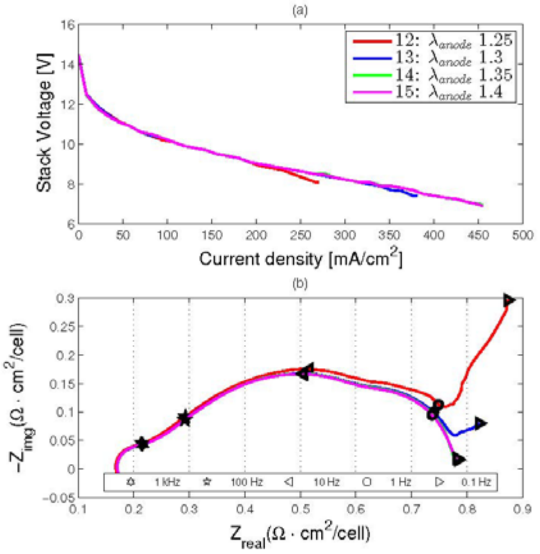


Figure 18 Effects of anode stoichiometry under dry hydrogen operation

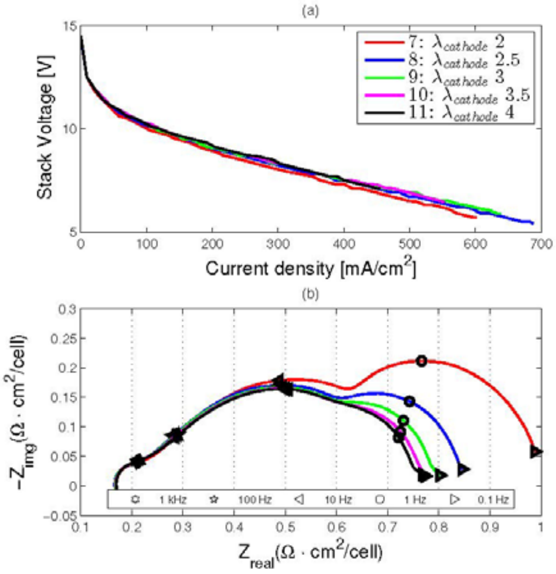


Figure 19 Effects of cathode stoichiometry under dry hydrogen operation

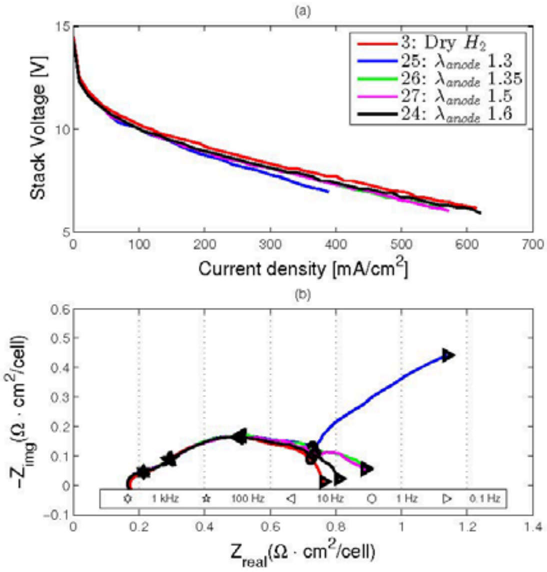


Figure 20 Effects of anode stoichiometry under stream reformate operation

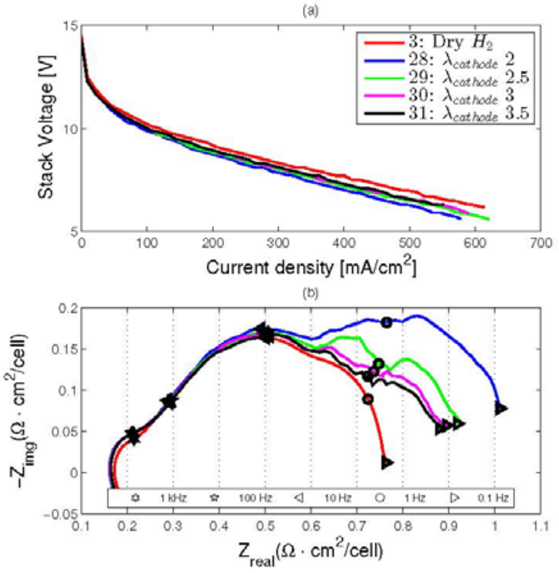


Figure 21 Effects of cathode stoichiometry under steam reformate operation

Serenergy also performed several tests that were aimed at testing different MEA developments and the effects of different operating conditions, including start/stop cycles and constant load long term durability tests. Their facilities are equipped with setups that can reform methanol into hydrogen gas mixture and the ability to monitor individual cell voltages within a fuel cell stack.

In Fig. 22 the acid content of different MEA technologies are compared. It can be seen that the DPS and BASF MEAs have similar overall trends, implying similar acid loss rates. The acid content measurements were performed by means of titration when the stacks stopped for different reasons, such as coolant oil leak, bad cell performance and unplanned sudden stops. Because of this, tests are done at room temperature, far from the operating temperatures of a stack, and since both the stop and test conditions were different from each other, certain degree of uncertainty is expected in the test results.

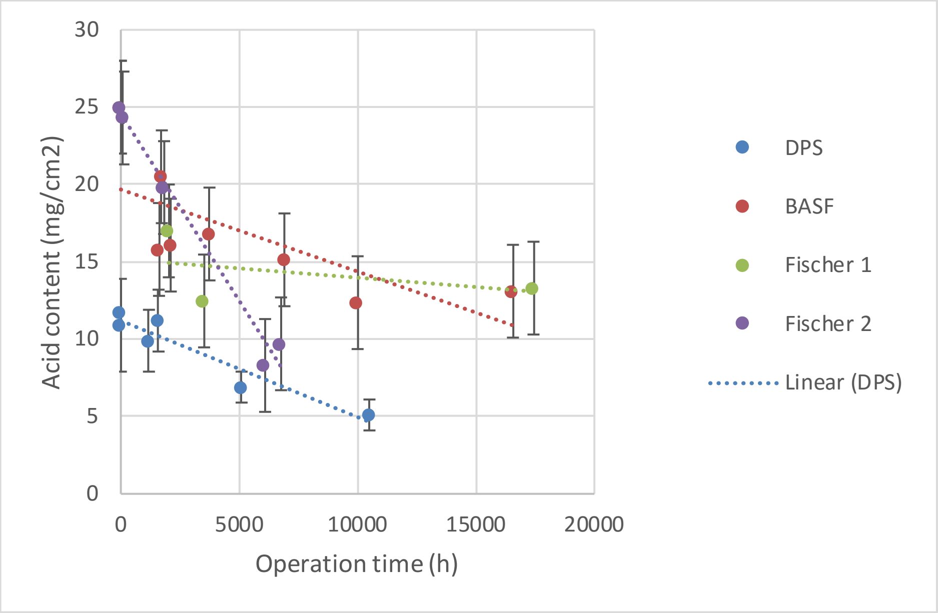


Figure 22 MEA titration tests at different instances to estimate the acid contents

Danish Power Systems has developed different MEAs during the period of the project, where attempts were made to reduce the acid loss, while also lowering the Pt catalyst loading. Some of these membranes were thermally treated and their degradation was investigated both at single cell and stack level at Serenergy. Initial test at single cell level with thermally treated DPS MEAs show low degradation rates. At stack level, the degradation rates have been more difficult to determine, as non-MEAs related errors occurred during the test, resulting in MEA performance change, as can be seen from the non-uniform and dispersed cell voltages in Fig. 23. However, the MEAs appears to regain lost performance after the errors.

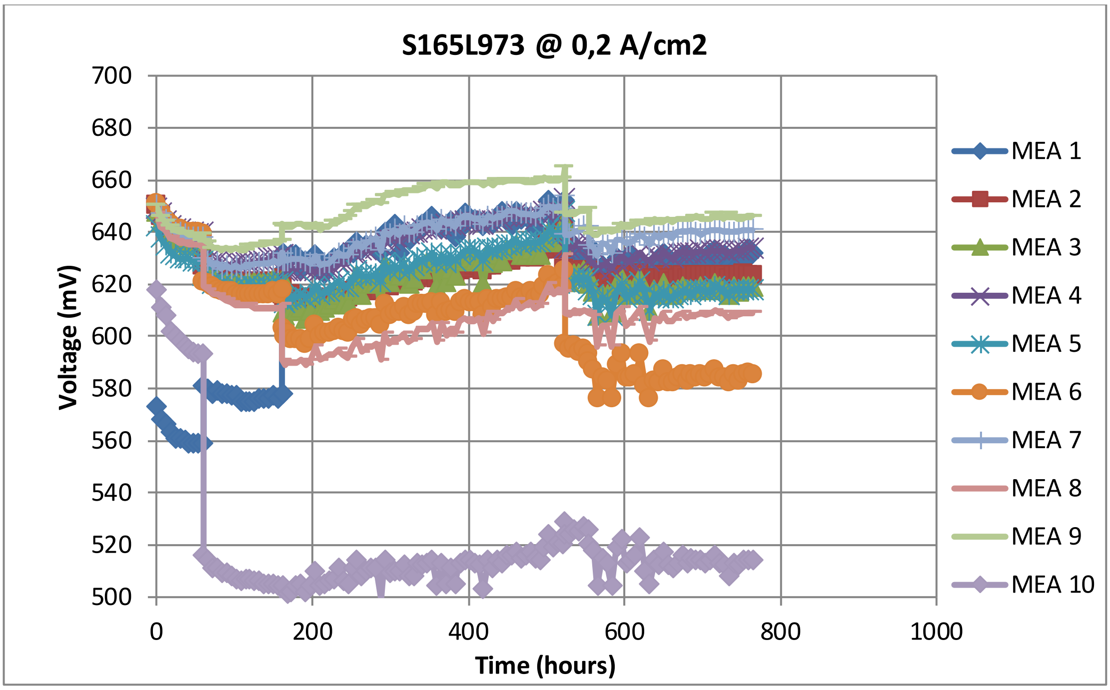


Figure 23 Single cell voltages of a short-stack made up of thermally treated MEAs

WP9 – Reformer core development	
Lead: SERENERGY	
Start **End**	M1 M12
Description	The main goal is to optimize the reformer core development related to burner, evaporator and reactor. This is primarily to optimize stability, durability and conversion efficiency. Additionally, the focus is on enabling a compact and integrated design that allows an efficient heat and reactant transfer to and from the fuel cell stack assemble and that offers quick and simple assembly. The main areas of interest is to ensure a low heat loss from the reformer and a rapid catalytic startup of the reformer that in turn will enable a rapid system startup. Furthermore, the focus is on a low methanol slip and high durability. Lastly a design that enables a recore or overhaul function that allows for change of catalyst. The methods will primarily focus CAD models and CFD modeling of steady state/dynamic models, including characterization of said models and a prototype build based on the optimized model.
Link	WP7 - WP13
Objects	• Optimized reformer core • Optimized burner design • Optimized Evaporator • Prototype build • In situ test of prototype

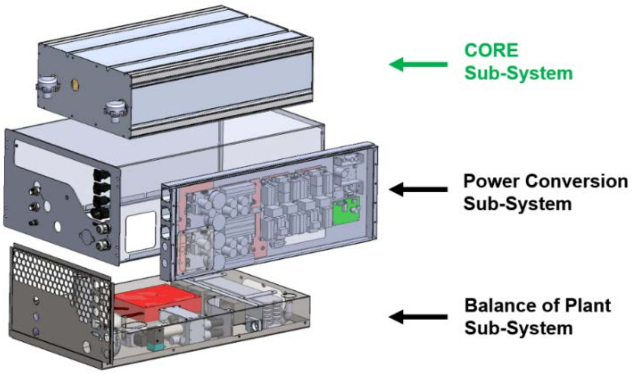


Fig 24 – H3-5000 HT-PEM Sub-Systems

Results:

A new generation of the alucore has been specified, designed, developed and tested. The test has been conducted as stand-alone test and in-system tests.

The focus in the design has been on

- Manuafaction assembly and quality.
- Cost including assembly and test.
- Higher reliability in operation.
- Better performance.

To achieve the design goal is was clear that new production methods had to be introduced.

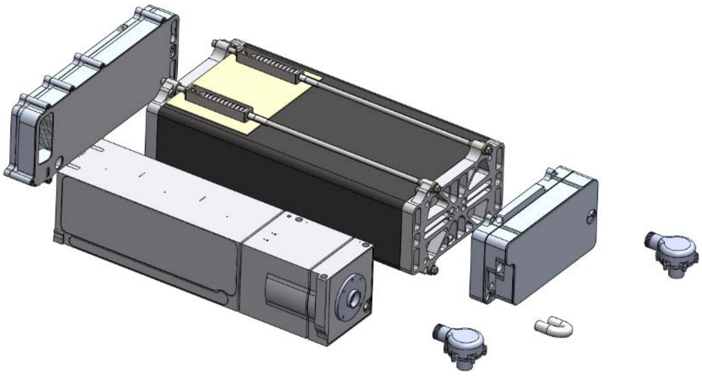


Fig 25 – 3rd generation alucore with S16L HT-PEM stack

For the 3rd generation of alucore the preheater, burner, reformer, layers has been redesigned. In the exploded view in Figur 1 the 3rd generation of the alucore can be seen.

Conclusion:

Preheater and layers increased the durability from 500 thermal cycles to more than 5.000, with increased heattransfter of more than 20%. The overall cost is maintained.

The burner and reformer has a reduced cost of 40%. Durability is more than 300 thermal cycles, and 2.000 hours of operation, and is still ongoing.

For qualification, validation and performance test, more than 30 alucores has been assembled and tested, without any major failures.

WP10 – Stack production setup	
Lead: SERENERGY	
Start **End**	M12 M30
Description	The main goal is to optimize a mid-volume production stage enabling a series production of stacks with high quality and low variation. The focus is on equipment optimization, method and quality processes. In this process knowledge from other stack design will be adapted to the new liquid cooled design. Assembly methods will be developed enabling a simple component verification and low variance in the placement of components such as gaskets and MEA's. In addition to this an assembly station will be designed and optimized to accommodate the optimized design of the flow plates, gaskets and MEA's In addition to the assembly station a semi-automated test bench will be designed and build to enable a set of distinct quality metrics and verify stacks.
Link	WP7
Objects	• Assembly flow analysis • Assembly station design • Test station design • Assembly station build • Test station build

Results:

A stack assembly setup has been developed. The setup is shown in fig. 26. The stack is manually build in the setup. The stack builder, places the stack components from the bottom up. The endplate, gasket, BPP, gasket, MEA, BPP, and so on. The setup has a piston than can be used to compress the stack at any point during the assembly.

When a stack is finished, the piston is compressing the stack. In the bottom of the setup, inlet and outlet valves are fitted, such gas can be let into the stack's individual manifolds: Anode, cathode and coolant. The valves are used to analyse if the stack is leaking are if the stack have cross flow between manifold.

When a stack is build, approved in a leak test, the rods and springs are fitted onto the stack endplates. The piston can then be pulled back and the stack can be removed from the setup as a single unit.

Fig. 26 (left) and fig 27 (right)

A stack tester has been developed, see fig. 27. The finished stack can be placed in the stack tester and clamped down. In the setup, the stack is tested with an automated program. When the program is started, the stack is heated with heated oil. When the stack has reached its initial operation temperature the anode and cathode gasses are let into the stack. The current is drawn through the stack. At the wanted temperature, the stack tester can perform automated measuring schemes. Such as:

- Polarization test with hydrogen
- Polarization test with simulated reformer gas
- Stoich test with air
- Stoich test with simulated reformer gas

The setup is fitted with a Cell Voltage Measurement (CVM) bar, which measure voltage on all cells in the stack during the whole test procedure.

Conclusion

The stack builder setup has been completed, enabling mid-volume production. However, stack components, such as BPPs and MEAs have to be improved to get more leak tight stacks. The stack tester setup has been completed, enabling an easy test on stack. The setup can detect error in stack such as faulty single MEAs. The detection of error MEAs, will enable easy repair of the stacks since the root of the problem can now be pinpointed.

WP11 – MEA Pilot production	
Lead: DPS	
Start **End**	M18 M38
Description	The objective is to produce a sufficient number of MEAs for verification at SER (i.e. test in modules and stacks). A generic pilot production line for MEAs is currently being developed and constructed within the HT-FUMA project. The pilot setup will support the present project. However, this WP includes the necessary changes and adjustments to facilitate MEA sizes and performance dedicated to the present project.
Link	WP2- WP3
Objects	• Batch of 200 MEA to stack test and verification at SER

Results:

More than 500 large commercial size MEAs have been manufactured at DPS for stack testing purposes. At this point DPS has been able to manufacture the necessary MEAs demanded within the project.

An overview of the different DPS products are included on Table 3, 4 and 5 covering the period from 2014 to 2016

Table 3. Overview of large size MEAs manufactured at DPS in 2016

Batch no	Amount	Product type
G1018-16-012	51	Dapozol 101 TT
G1018-16-013	57	Dapozol 101 TT
G1018-16-014	54	Dapozol 101 TT
G1018-16-015	55	Dapozol 101 TT
G1018-16-005	56	Dapozol 101
G1018-16-003	10	Dapozol 101
G1018-16-002	67	Dapozol 101
SUM	**350**	

Table 4. Overview of large size MEAs manufactured at DPS in 2015

Batch no	Amount	Product type
G1018-15-007	5	Dapozol 101
G1018-15-014	25	Dapozol 101
SUM	**30**	

Table 5. Overview of large size MEAs manufactured at DPS in 2015

Batch no	Amount	Product type
G1018-14-009	2	Dapozol 200
G1018-15-008	15	Dapozol 101
G1018-15-012	95	Dapozol 101
G1018-15-013	13	Dapozol 200
SUM	**125**	

The MEA targets in the COBRA2 road map:

	COBRA I (2012)	COBRA II (2014)	COBRA III (2016)
MEA			
MEA durability	8000 h	15000 h	20000 h
Electrolyte (ASR)	0,2 Ωcm2	0,18 Ωcm2	0,16 Ωcm2
Unit cell power	0,4W/cm2 @ 1,0 A/cm2	0,45W/cm2 @ 1,0 A/cm2	0,5W/cm2 @ 1,0 A/cm2
Sales price MEA	2000 EUR/kW	1200 EUR/kW	500 EUR/kW

The MEA sales price in the COBRA ll (and COBRA lll) are based on 0.45 W/cm^2 (and 0.5 W/cm^2), meaning that the MEA/stack should be operated at 1 A/cm^2. A 165 cm^2 MEA have a sales price of 85 € (as of 1/1-2017), corresponding to 1190 €/kW. This is at low MEA production volume (<10000 MEAs/year).

Currently the maximum current density is 0.6 A/cm^2 (corresponding to 0.33 W/cm^2) due to limitations on efficiency and cooling of the stack. This mean that approx. 35% more MEAs are needed for 1 kW power. A detailed process and cost analysis have been performed in order to estimate the cost at high production volumes (>200,000 MEAs/year). The cost analysis is based on quotations and negotiations with all component and material suppliers.

Results of the MEA cost analysis for 200,000 MEAs:

MEA price	**Total EUR**	**Total EUR / p**	**Pt**	**Without Pt**
Personel	478.667	2,39		2,39
Materials	3.533.505	17,67	12,05	5,98
Total		**21,00**		**8,37**

This results in a MEA cost corresponding to 356 €/kW including Pt. However, there is a number of assumptions related to this MEA cost:

- 200,000 MEAs/year (all obtained quotes are based on this volume)
- It includes only direct cost of materials (incl. waste) and personnel
- No overhead or revenue is included
- Development of continuous processes for electrodes and membranes as it is required that electrodes and membranes are manufactured on roll

Conclusion:

Objectives for WP11 and cost target in the roadmap have been successfully completed.

WP12 – System Specification & Design	
Lead: SERENERGY	
Start **End**	M6 M12
Description	The main goal is to incorporate the core technology components into a product perspective and elevate the work from COBRA I to a customized and specific product target in terms of features, specs and functionality. This will allow the direct BOP development of key critical components and selection of existing components. The product level offers a number of increasingly intricate demands and needs that will opt for a detailed specification according to target market. The deep specification directed at specific applications identified in COBRA I: • Backup power generators • Auxiliary power unit • Automotive/mobility range extender Based on already executed work the application is generic in the core technology, but different in application on a set of key metrics including but not limited to: • Startup time • Load jump capable • Temperature resistant • Weight optimized • Configurable/autonomous The primary method will be a iterative process with relevant OEMS and data analysis from WP19.
Link	WP19 – WP 13
Objects	• System specification Backup power generators • System specification Auxiliary power unit • System specification Mobility range extender • Generic adaptable/configurable design

Results:

Overall product specification has been completed for the three market segments: Backup Power generators, Auxiliary power and mobility. In the mobility market segment, flat integration is important. Most electrical vehicles have battery compartment under the seats and cargo room, to keep the weight low and centralized in the vehicle.

The Auxiliary and backup market segment requires a rack mountable solution in 19” rails. The system is stationary, but must be easy to handle, install, maintain, and repair. Also, it must be possible to perform fleet service, both preventive maintainanse, scheduled service and urgent replace or repair in case of failures.

Duing the specification phase, multible telecom customers and car manuafcators has been involved, and the development has been focused mainly on:

- Reliable system operation and start-up
- Modular design to support various packing types of well defined sub-systems (flat layout, 19” rack layout, common fuel supply support etc.)

- Robust to vibrations, both duing transport and operation.
- Low emissions.
- Low start-up time.
- High power density.

WP13 – System simulation & diagnostics	
Lead: AAU	
Start **End**	M9 M18
Description	The main goal is to simulate the systems specified in WP12 to direct purposes and operations patters and to optimize and develop new control concepts. The effort is both in steady state, thermal optimization, and dynamic operation, control and regulation. The focus is furthermore on improving dynamic abilities in startup and load jump situations and ensuring high efficiency in all situations. This includes the fuel cell and reformer, but also the overall balance of plant including heat integration and exchange. Additionally, a diagnosing functionality will be developed enabling a online measurement of system health and time to service or end of life.
Link	WP12 – WP14
Objects	• Simulation models • System optimization • System design • Diagnostics - algorithms

Simulations

System level simulation models were developed to study the steady state and dynamic performance of the system. The model includes all major system components, such as the fuel cell stack, the reformer, heat exchangers and blowers. The model predictions were compared with measurements from the laboratory.

A dynamic fuel cell model based on a single HT-PEM fuel cell was prepared with the scope of validating the response of the reformer fuel cell system to parametric changes, in order to develop an appropriate control strategy. The model was validated both for steady state performance on a polarization curve and for dynamic operation by comparing it to a load current step experiment at varying reactant stoichiometric ratios.

The reformer gas output composition was measured with focus on the methanol slip and the CO content for model validation, and the results can be seen in fig. 28, where opposite trends were observed for methanol slip and CO concentration in the reformate gas.

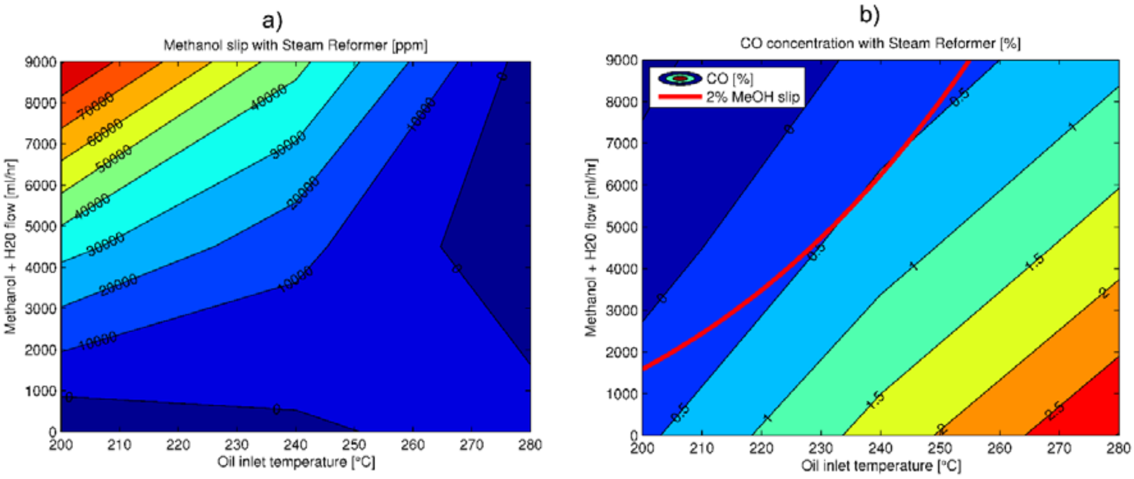


Figure 28 Composition of impurities in the reformate. a) Methanol slip from reformer compared to input oil temperature and fuel flow rate b) CO gas concentration from reformer compared to input oil temperature and flow, with the red line indicating a 2% methanol slip.

Combining the methanol slip and CO content gives the possibility to ensure a tolerable methanol slip with a low CO content. For example, methanol slip of 2%, which has been previously tested and reported to have negligible effect on the performance of an HT-PEMFC, corresponds to a CO content of below 0.5% with a small overall effect on the fuel cell performance.

An open loop system simulation was done, where no temperature controller is not used on either the reformer or the burner. Based on an iterative training process a constant hydrogen stoichiometry of 1.4 was found, where the reformer and the fuel cell temperature are within working range. It can be concluded that a system based on the open loop design is capable of operating without any temperature controller on the reformer, however, the temperatures of the components are not in any ideal range, and a controller may improve the system.

System design and optimization

The system design and optimization in this work is mainly focused on the optimization of the control system based on the modelling and validation results obtained. A schematic of the reformed methanol fuel cell systems used in this project, with oil as a heat transfer fluid is shown in fig. 29.

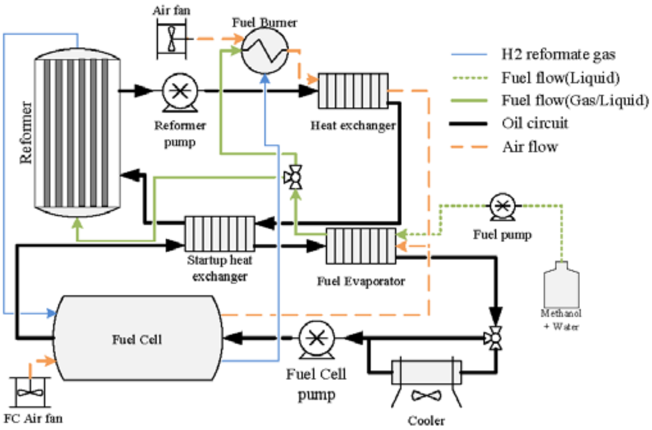


Figure 29 Schematic of reformed methanol fuel cell system

The controller used in this work is shown in fig. 30. Since the burner dynamics is significantly faster compared to the reformer, a cascade controller is used to control reformer temperature. The input oil reformer temperature is used as the input for the controller and is shown as $T_{r,set}$ in fig. 3.

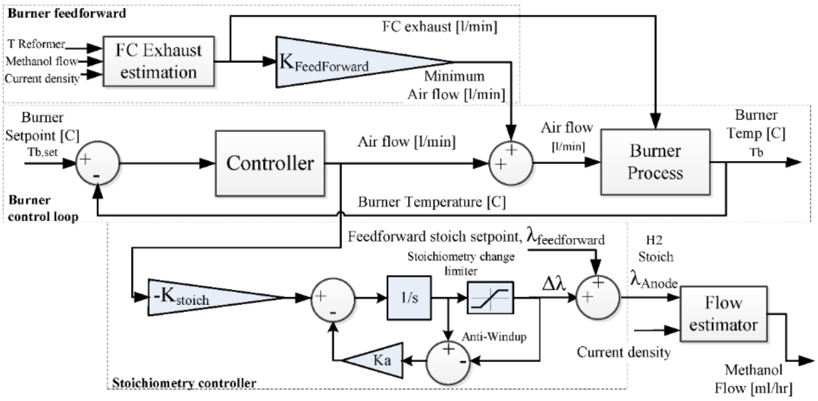


Figure 30 Burner temperature controller

Moreover, a simulation of the running cost for the system can be seen in fig. 31. The price used is without VAT or taxes and it includes distribution costs, which can vary depending on the amount and application.

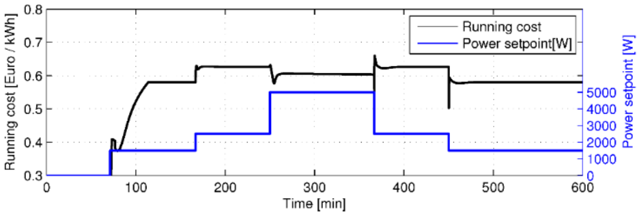


Figure 31 Running cost based on the methanol price of 0.59 €/l based on the electric power set-point

To enable a better gas composition during different loads a varying temperature on the reformer is needed. Therefore, a reformer with controlled and varying temperature was simulated and compared to the fixed temperature reformer, open loop system design. The variable reformer temperature control based on the gas composition experiments show that utilizing the knowledge of the reformate slip and CO can significantly improve the resulting gas composition, thereby increasing the possibility to prolong the lifetime of the HT-PEMFC, as degrading impurities can be avoided.

Diagnostics

For fuel cells to become ready for large scale commercialization, prices need to come down and the durability needs to be improved. One method to improve durability and availability is by designing fault detection and isolation (FDI) algorithms, which can commence mitigation strategies for preventing down time and to ensure smooth fuel cell operation with minimal degradation.

An FDI algorithm based on an artificial neural network (AAN) classifier was developed for the diagnostics of an HT-PEMFC stack. The flow chart of the ANN algorithm along with the obtained results is shown in fig. 32.

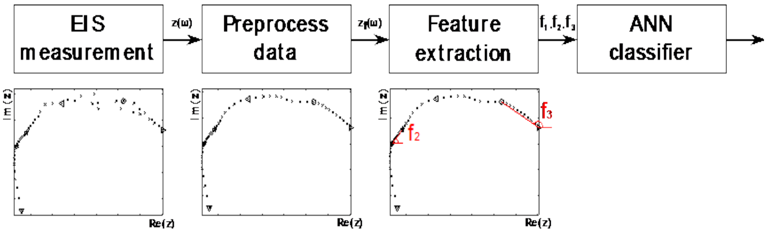
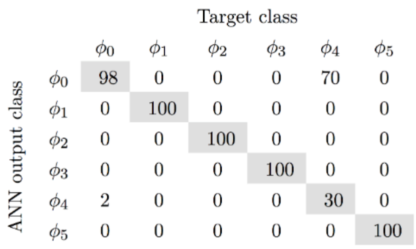


Figure 32 Flow chart of the artificial neural network fault detection and isolation methodology

The FDI algorithm was tested for detecting five common faults in high temperature proton exchange membrane fuel cells and demonstrated a global accuracy of 94.6%, with a good detectability for four of the five faults investigated, with the exception of methanol vapor contamination (φ_4) in the anode gas, see fig 33



Target class

ANN output class	ϕ_0	ϕ_1	ϕ_2	ϕ_3	ϕ_4	ϕ_5
ϕ_0	98	0	0	0	70	0
ϕ_1	0	100	0	0	0	0
ϕ_2	0	0	100	0	0	0
ϕ_3	0	0	0	100	0	0
ϕ_4	2	0	0	0	30	0
ϕ_5	0	0	0	0	0	100

Fig. 33 The result of the test data, listed in a confusion matrix

Conclusion

Based on a parametric study, dynamic model and experimental validation a new control concept was developed for a reformed methanol fuel cell system. The control concept resulted in a few percentage point improvements of system efficiency and also improved the ability of the system to follow the load under dynamic operating conditions. Furthermore, a fault detection and isolation (FDI) algorithm based on an artificial neural network (AAN) classifier was developed for the system. The algorithm was demonstrated and showed a global accuracy of 94.6%, with a good detectability for four of the five faults investigated, i.e., carbon monoxide contamination on the anode, methanol vapor contamination on the anode, hydrogen starvation, air starvation and too high air flow.

WP14 – System BOP development	
Lead: SERENERGY	
Start **End**	M12 M24
Description	The main goal is to specify, design or adapt components to the specific system design both in regards to applications but also to temperature and material capability where HT PEM offers challenges not normally seen in similar systems. Additionally, the BOP overall deigns and components must fit with targets within cost, weight and form factor to accommodate an acceptable system design. The components primarily in focus is: • High temperature liquid circulation pump • Cathode air blower • Integrated fluid heat exchanger • Control and regulation platform • Heat rejection radiator • Fuel Feed pump A component verification and durability insitu test will be carried out to ensure full functionality in system level and focus on core technology in module tests. A cost analysis will be carried out to ensure alignment with volume cost targets.
Link	WP12 – WP13
Objects	• BOP Specification • Single component CFD • BOP component scan • BOP component adaption • BOP component insitu test • Component Cost analysis

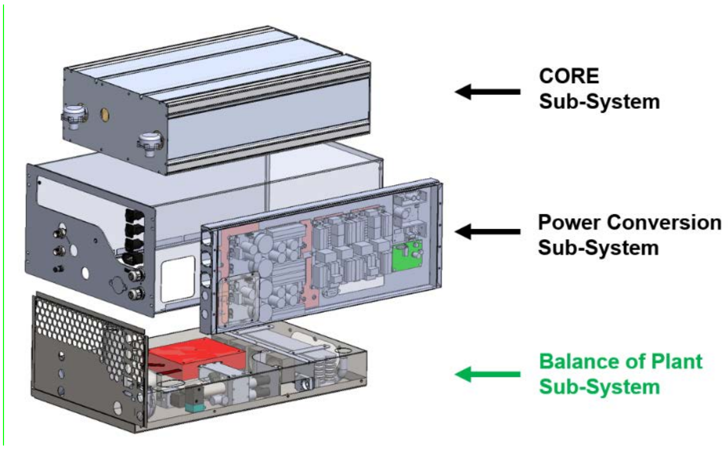


Fig 34 – 3rd generation alucore with S16L HT-PEM stack

Results:

As a result of the work in WP14, several important components have been specified and developed. Some based on exsisting design, but modified to meet the H3-5000 product requirements.

The main coolant circulation pump has been improved to handle media temperatures up tp 180°C and viscosities up to 100cSt, and still being applicable for load cost solutions.

Fig 35 – air cooling pump

The cooling of the H3-5000 system, can be devided into two scenarios: liquid cooling, and air cooling. For the air cooling, a liquid or air heatexchanger has been designed to meet the extended requirements for the H3-5000 product. The heatexchanger is exposed to high coolant temperature and large temperature gradients during operation. Also, the compactness and high efficientcy design has been improved to acommandate the requirements.

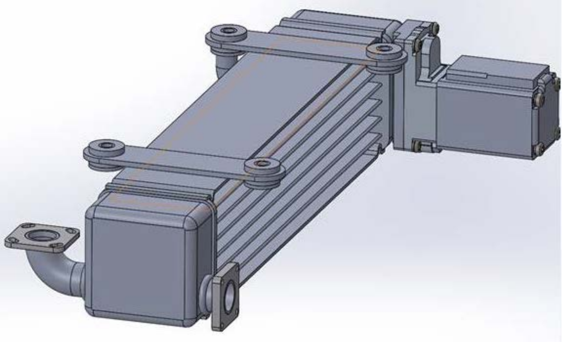


Fig 36 – air cooling pump

The H3-5000 has multible heatexchangers which has all been special desgined to improve performance, compactness, and reliability. Below is a picture of the external liquid to liquid heat exchanger, which can be used if applicable in the overall system integration. The product can provide 5 kW of electrical power, and 3 kW of high quality thermal power at a temperature above 120°C.

Fig 37 – air cooling pump

The fuel system for the H3-5000 module, has been designed to improve reliability and performance of the system, but also to acommandate higher level of functional safety in the product. The fuel system developed, is a low preassure injector based system.

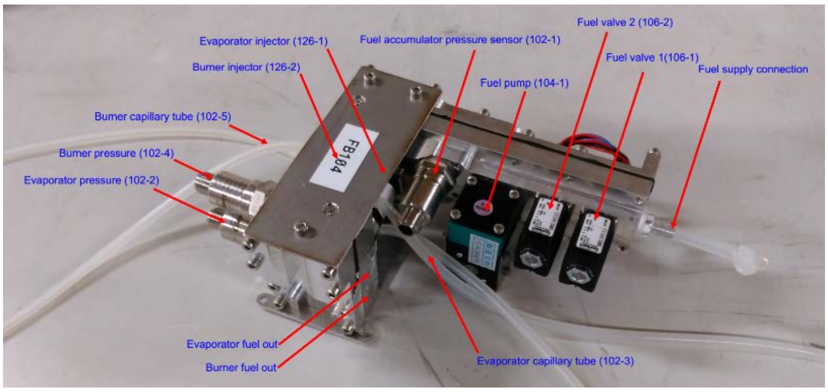


Fig 38 – air cooling pump

A test bech for qualification and performance validation of the reformer has been developed. The mixing, heat transfer, pressure drop, emissions etc. are all important parameters that must be proper measure and evaluated, to improved the overall system performance.

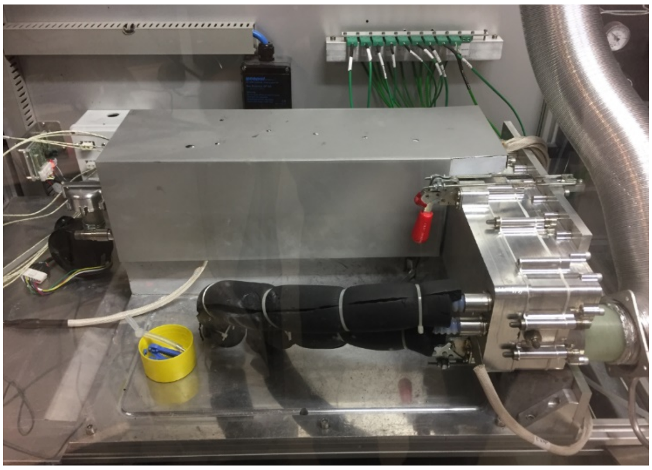


Fig 39 – air cooling pump

WP15 – Power electronics development	
Lead: AAU	
Start **End**	M12 M24
Description	A key component in any fuel cell system is power conversion enabling a power transfer from system to application. In all relevant applications, the interface will be to a battery bank of varying voltage and type, e.g. lead acid or lithium ion. The goal is to specify and adapt a modular approach enabling existing power converter sub components to fit the power conversion design of the relevant applications. The adoption of existing sub components will be an excellent mid-range solution offering flexibility and focus on demonstration and the main challenges in the fuel cell and reformer technologies. Furthermore, the focus is to develop suitable hybridization strategies and the control and regulation strategies to fit said strategies. This will to some extent be done I collaboration with to be identified specifications and OEM's
Link	WP12 - WP14- WP 16
Objects	• Specification of DC/DC conversion step • Development of adapted DC/DC platform • Test of adapted DC/DC platform

The topic of the work was to analyze and redesign the current solution with a two-stage power converter of the 5-kW power HT PEM fuel cell system. The goal was a high efficient, cost effective solution with reduced number of passive components, that is relevant for a number of specific applications.

Constraints

The analysis is focusing on non-isolated solutions for telecommunication applications, considering following design constraints:

Table II Design constraints

Fuel cell	V_{in_max} [V]	V_{in_nom}[V]	I_{in_nom} [A]	V_{o_min} [V]	V_{o_max} [V]
Big stack	120	60	100	40	60
Small stack	60	30	100	40	60

V_{in_max} represents the maximum input voltage to the converter from the fuel cell, V_{in_nom} is the nominal input voltage, I_{in_nom} is the nominal, controlled input voltage while V_{o_min} and V_{o_max} are the minimum and maximum output voltage, depending on the load charge status. As presented above the buck (big stack) and the boost (small stack) operation mode has also to be covered with using the power converter.

Possible converter topology

Different topologies are used for power management of fuel cell power. Depending on the output voltage requirements many solutions have been discussed in the literature. After analyzing the relevant literature and the system requirements, one promising non-isolated solution for the described wide input and output voltage application could be a so-called **H-bridge buck-boost** converter topology, used also for PV applications:

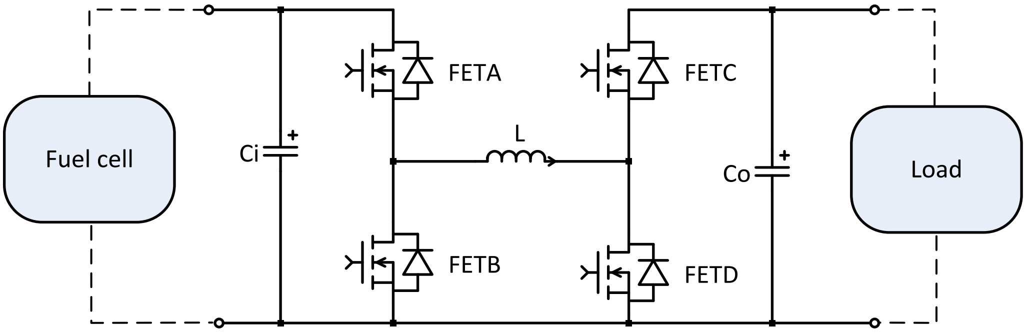


Figure 40 H-bridge buck and boost converter

The topology can be used in two different structures: either in a single converter structure or in modular structure. The advantage of the modular solution is that depending on the number of converter modules is decided based on the power demands. Disadvantage is that it has also an increased number of switches and the number of magnetic components is equal to the number of modules. The modular solution was deeper analysed and a prototype built by the Serenergy A/S power electronics development team.

Results based on modular converter structure using the chosen H-bridge buck-boost converter (Serenergy A/S)

A modular non-isolated H bridge buck-boost converter was designed, built and tested. The key features of the developed prototype, using traditional silicone switches, are the followings (one module):

Boundary Conduction Mode (BCM), Variable frequency control for BCM, Peak current control in boost mod, Valley current control in buck mode, Zero Voltage Switching (ZVS) at turn off, Zero Current Switching (ZCS) at turn on. The experimental tests were done with different input voltages between Vin=28 V and 64 V. The results with controlled output voltage (50 V) and input current (50.5 A) show a peak efficiency of 99% at

Vin=48 V and with controlled output voltage (50 V) and input current (100 A) show a peak efficiency of 98.5% at Vin=50 V.

Experiments and analysis of GaN devices for fuel cell DC-DC converters (AAU-ET):

Combining the advantages of the of the above topology with wide band gap switches could show good perspectives for a non-isolated solution of the fuel cell connected power supply to telecommunication system. In comparison to the presented prototype with soft switching and boundary conduction mode operation (BCM), the scope of the analysis of the wide bandgap material based switches is to operate the converter in the classical continuous conduction mode (CCM) with hard switching, using the good performance of such switches. Low voltage applications below 1 kV is the target for the Gallium Nitride **(GaN)** based wide band gap technology. The characteristics of the GaN switches can be summarized as follows:

- High operating temperature and high current density
- High breakdown voltage
- Low gate charge and output capacitance -> High frequency switching
- No reverse recovery charge and on resistance
- Higher conduction and switching efficiency compared to Si
- Ultra-high-power density – surface mounted components

Different variations of these wide bandgap switches exist already on the market. From packaging point of view, we can distinguish through hole and surface mounted solutions. Few of the main manufacturers are Transform (through-hole components), EPC and Gan Systems (surface mounted switches). From packaging point of view GaN Systems products seemed easier to handle and more accessible for fast prototyping and measurements. A GS66508T EVBHB 650V GaN E-HEMT Half Bridge Evaluation Board was purchased, consisting of a half-bridge with 650V 30A 55mΩ GaN transistors in order to perform fast measurements with these switches.

Firstly, **pulse tests** were done with the specific demo board to analyse the switching behaviour of the switches at different current levels. Measurements were done at 20°C laboratory temperature. A 160 µH low capacitance toroid inductor was connected in parallel with the low-side switch of the half bridge. **Secondly**, to test the switches in operation, a **synchronous buck converter** was built from the half bridge demo module, using a 120 µH inductor (different than the first one, to meet the load current density) and operated up to ~ 1.5 kW.

In order to analyze the switching characteristic and behavior of the GaN FETs, a loss model was created for the switches, with data requested and obtained from the manufacturer. The loss models were included in the simulation model to estimate the thermal behaviour of the synchronous buck converter. Simulation results show that with 100kHz switching, at 1.5 kW power, with Vin=400V and Vo=200V the conduction losses are identical, but there is a bigger stress on the low side switch, Q2 due to turn on at a higher current. The overall estimated switching losses are 13.8W which represents 0.9% of the nominal power. To measure these parameters a more complex hardware would be needed as it is almost impossible to measure the drain or source current of the surface mounted switches without changing the layout. As layout is a key element of the converter design, these changes would lead to further oscillations and losses.

Conclusions

Based on the results presented by the Serenergy A/S power electronic team, the modular solution using H-Bridge buck-boost converter is a suitable solution for a non-isolated next generation power conditioning unit for HTPEM fuel cells using soft switching technology or boundary conduction mode (BCM). By analysing wide bandgap switches, they show new perspectives for the future in hard switching (continuous conduction mode - CCM) operation. The advantages of using GaN transistors like low switching loss characteristics at high frequency operation will lead to smaller cooling and magnetic components and higher power density and make them suitable in the future for building new high efficiency DC-DC power converters for fuel cells. The price of such devices also makes them promising candidates if we look at the possible improvements and resulting efficiency.

WP16 – Mechanical product design	
Lead: SERENERGY	
Start **End**	M12 M32
Description	The goal is to insure an alignment of product specifications and mechanical product design to fit requirements covering several applications. This includes especially physical and technical interface specifications found to be critical. An optimized system packaging is key to ensure customer adoption and compatibility in regards to materials, size, weight and interconnectivity with the end user applications such as a vehicle or a telecom based station. Furthermore, the focus will be on a tight integration of the module to ensure high power density and optimal functionality and thermal integration. This includes integration of new insulation materials. Although not a primary goal attention will be paid to easy of assembly and to some extent service in form of initial demonstration and deployment and a recore of stack/reformer replacement to enhance cost effectiveness in specific applications.
Link	WP12 – WP13
Objects	• Product design of relevant models • Prototype development • Integration test

To fulfill the 3 market segment requirements, the system has been devided three sub-system:

- The core system, wich covers the fuel cell stack and reformer unit
- The Ballance Of Plant system which includes pumps, blower and control electronics
- The power conversion box, for handling input and output power conversion.

By rearranging the boxes, the total system can fit into different packing requirements, and still share the development platform. The outcome is the SerEnergy H3-5000 product.

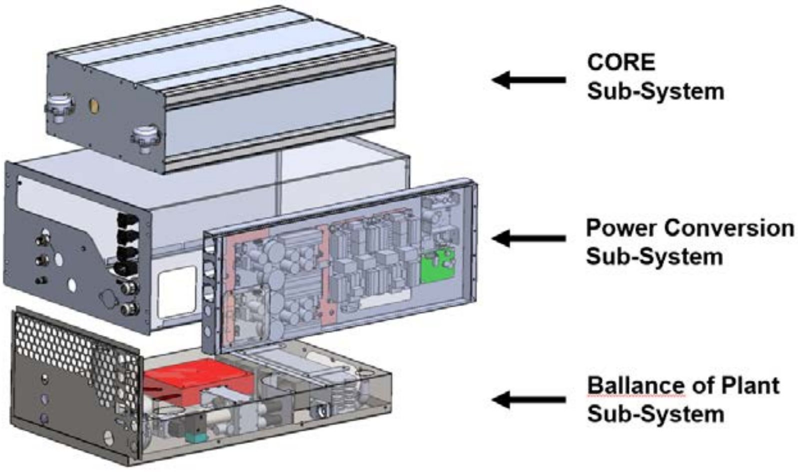


Fig 41 – air cooling pump

The first prototype of the H3-5000 product, demonstrated the performance and concepts of the design and production methods. The test was successful, but is was clear that packing had to be improved.

Fig 42 – air cooling pump

In the figure below, you can see the H3-5000 19” rack design in the beta product stage. The module has air intake in the front, and all liquids in the left side of the front, electrical connections in the right side of the pront, and venting and process air exhaust in the rear of the module. 6 pcs of the beta modules were assembled and tested, before the pilot product stage was reached early 2016.

Fig 43 – air cooling pump

WP17 – Product maturing	
Lead: SERENERGY	
Start **End**	M16 M28
Description	The goal of is to mature the product and take the concept through a review with focus on certification and direct integration into complete systems. This entails external application systems such as tank, park control and other application relevant features. The certification process will be done t a level where it is possible to demonstrate and test modules in a controlled environment and gain the basis of concepts that can be taken through a final certification. This will be done in cooperation with external certification bodies relevant to the application and through a HAZOP process. The main focus is sequently also the actual build process of the module for system test in WP18.
Link	WP12 – WP16 – WP14 – WP15 – WP18
Objects	• Design review • HAZOP process + final report • External certification process • OEM validation

General description

The fuel cell power system has been redesigned from the version 2 to the version 3 in order to improve the production speed and cost, compared to the version 2. The most notable improvements are the following:

- The fuel buffer tank was replaced by an injector controlled system
- The external heat exchanger was switched to a commercially available radiator solution.
- The ventilation through the module has been improved.
- The power line routing has been changed from wires to a bus bar.

The module has been examined for the most common risks, during a hazards and operability study or HAZOP and the outcome of the study was used for the design of the internal safety system. This was performed in the form of an Design Failure Mode and Effect Analysis (DFMEA), as recommended by chapter 4.1 of the standard for Safety in Stationary Fuel Cell Power Systems. During the analysis the components of the system were analysed, and the failure effects were defined for the components. This has led to a set of design requirements, i.e. sensor redundancy in some cases, which improves the safety of the system.

In the scope of 2017 the company is going to be ISO 9001 certified and in that regard a model for the development has been defined and followed. This model embraces the product from cradle to grave, to ensure that the correct documentation has been delivered at the different stages of the product lifetime. One of the outcomes has been a risk register, which ensures that the product risks are tracked in an orderly fashion.

For stationary applications

The Fuel Cell Power System must be certified according to the following standards:

- DS/EN 62282-3-100:2012 "Fuel cell technologies - Part 3-100: Stationary fuel cell power systems - Safety"
- DS/EN 62282-2:2012 "Fuel cell technologies - Part 2: Fuel cell modules"
- DS/EN 62282-3-201:2012 "Fuel cell technologies - Part 3-201: Stationary fuel cell power systems - Performance test methods for small fuel cell power systems"
- DS/EN 61000-6-2:2005 "Electromagnetic compatibility (EMC) - Part 6-2: Generic standards - Immunity for industrial environments"
- DS/EN 61000-6-4:2007 "Electromagnetic compatibility (EMC) - Part 6-4: Generic standards - Emission standard for industrial environments"
- DS/EN 50581:2012 "Technical documentation for the assessment of electrical and electronic products with respect to the restriction of hazardous substances"
- DS/EN ISO 13849-1 "Safety of machinery - Safety-related parts of control systems - Part 1: General principles for design"
- DS/EN ISO 13849-2 "Safety of machinery - Safety-related parts of control systems - Part 2: Validation"
- DS/EN 60079-10-1:2015 "Explosive atmospheres - Part 10-1: Classification of areas - Explosive gas atmospheres"
- DS/EN 60204-1:2006 "Safety of machinery - Electrical equipment of machines - Part 1: General requirements"

- DS/EN 60950-1:2006 "Information technology equipment – Safety – Part 1: General requirements"

The product will be certified according to the overall standard of the DS/EN 62282-3-100 and the remaining standards are for supporting the main standard where needed. The product will be tested according to the described tests presented in the given standards.

For automotive applications

There are some differences, when looking at the certification of the fuel cell system for mobility and automotive, compared to the stationary applications. This is more of a grey area where the fuel cell can be approved with the final installation in an electric vehicle. This was the approach chosen for MECC. Approval of the fuel cell unit it self can be done, if the fuel cell is approved as a spare part to be installed in any electric car. The difference is that the fuel cell standards mentioned above are superseded by the UN regulations and European adoptions of these rules.

- R10 - Electromagnetic compatibility
- R100 - Electric power trained vehicles
- European regulation 79/2009 Hydrogen driven vehicles
- European regulation 406/2010 Type approval of fuel cell driven vehicles

Conclusion

There are additional considerations but the proposed standards and regulations are for the most common parts of integrations within the two fields presented. The final documentation of the module will result in a technical construction file with the technical documentation needed for the proof of the compliance with the standards and automotive regulations. Additionally, the risk register based on the FMEA will be produced during 2017, and most of the preparation has been done for this.

WP18– System test	
Lead: SERENERGY	
Start **End**	M17 M39
Description	The main goal is to initiate a rigorous and focused test session enabling a setup for the variants targeted at application with specific e.g. drive cycles and operational conditions e.g. temperature, load jumps and startup times. Furthermore, the test package will contain a dedicated focus on testing against main metrics of the technology roadmap. This is both internally at SER and at AAU to get a comparable set of results.
Link	WP17 – WP20
Objects	• Test setup specification • Test report

To validate the system design, performance and durability, multible test stations has been build:

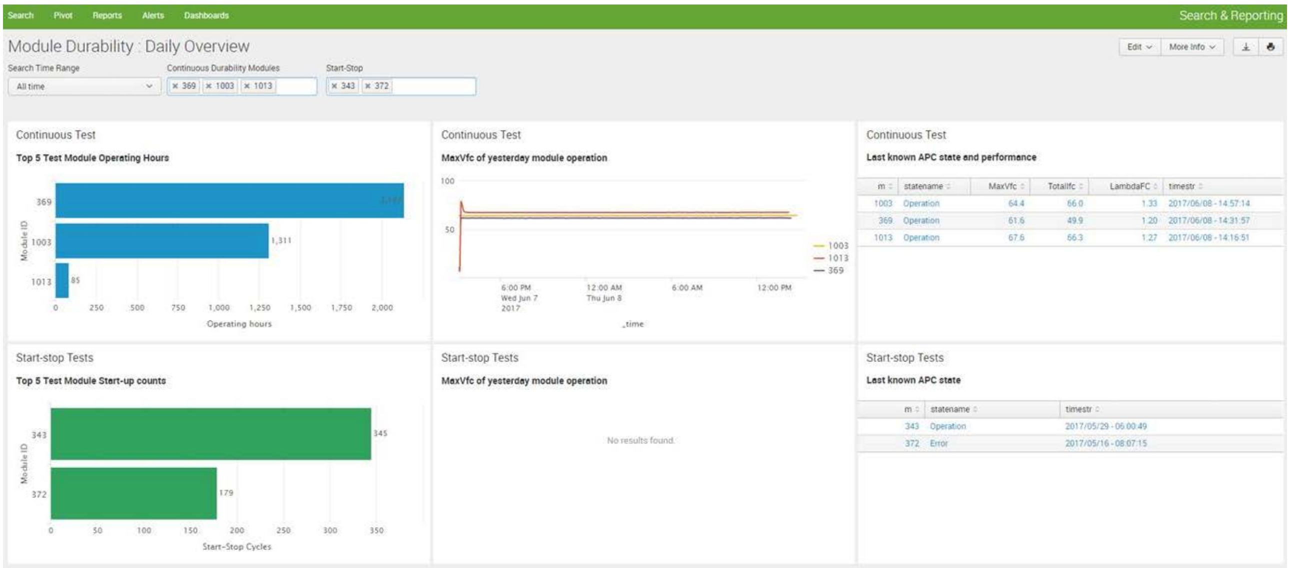
- Indoor start-stop cycle test, capacity: 2 modules
- Indoor performance test, 8 modules
- Outdoor performance and durability test: 4 modules
- Outdoor climate testing: 1 modules

The modules have demonstrated more than 3000 hours of operation, and on components and sub-system level, lifetime equivivalent to more than 20.000 operation hours has been reached on many components. The overall target for the COBRA project was 3000 hours of operation and 250 start-stop cycles. Both were reached.

Fig 44 – air cooling pump

Fig 45 – air cooling pump

To keep the overview of test activities, a big-data system has been set up to store and display large amount of data. Below a dashboard of some of the outdoor durability test can be seen



Module Durability : Daily Overview

Search Time Range: All time

Continuous Durability Modules: × 369 × 1003 × 1013

Start-Stop: × 343 × 372

Continuous Test

Top 5 Test Module Operating Hours

Continuous Test

MaxVfc of yesterday module operation

Continuous Test

Last known APC state and performance

m	statename	MaxVfc	TotalIfc	LambdaFC	timestr
1003	Operation	64.4	66.0	1.33	2017/06/08 - 14:57:14
369	Operation	61.6	49.9	1.20	2017/06/08 - 14:31:57
1013	Operation	67.6	66.3	1.27	2017/06/08 - 14:16:51

Start-stop Tests

Top 5 Test Module Start-up counts

Start-stop Tests

MaxVfc of yesterday module operation

No results found.

Start-stop Tests

Last known APC state

m	statename	timestr
343	Operation	2017/05/29 - 06:00:49
372	Error	2017/05/16 - 08:07:15

Fig 46 – air cooling pump

WP19 – Market analysis/development	
Lead: SERENERGY	
Start **End**	M1 M39
Description	To ensure a strong focus and interaction with the end customer and reach target market demands the market analysis and development process will be conducted parallel with the development process of especially the product section of COBRA II. A main goal is to ensure a commercial track and a contact to key OEM customers with the option to engage in the OEM test of modules. Furthermore, supplemental technology tracks will be explored on a component level to follow a commercial pattern with test and engagement on a technology level.
Link	WP12 – WP17 – WP20
Objects	• Enhanced Market analysis • Market development – OEM identification • GoTo market strategy on commercial markets

The market analysis for the Methanol Fuel Cell technology was develop following several considerations, due to the substantial range of applications.

Most of the analysis over markets and segments are stated on the business plan designed and delivered alongside this report (Point 8).

For the E-mobility solutions, a 3 key-point strategy was design to ensure that the usage of the vehicle is cost effective and the technology has a maximum positive effect over the utilization and environmental outcome:

- The vehicle must have a daily usage period of over 8 hours
- It must have a low power usage to allow the range extender to fill the gap and provide the extra needed power.
- Heavy duty vehicle, to accommodate the batteries and methanol fuel cell. As in a last mile service provider, the vehicle will reduce emissions on city centers, the extra cargo space will make it cost effective and the reduced service required adds to the competitive ROI. This same operational paradigm was used for the China Bus project due to the overall size of the vehicle and the complementary roles that each vehicle on its own can perform on the city-centers and metropolitan areas.

OEM manufacturers and partnerships are being developed in order to ensure a greater level of components integration, sizeable economies of scale, continuous integration of new technology and research outcome to be the key drivers towards price reduction and increase the sales volume to reach the forecasted goals stated on the commercial roadmap regarding GoTo market strategy. A OEM analysis was also conducted mainly over the supply chain management for the build of the fuel cell, since some specific components were developed by our project key partners.

E-Mobility applications take the OEM identification and integration to a new level, since it requires further developments beyond the fuel cell development. For the last mile applications, which includes small/medium vans, several automotive OEM have been approached in order to guarantee a strategic partnership for joint-development over a vehicle platform, to ensure a normal look vehicle, integrating the components alongside the construction of the same, making impossible to distinguish it from a conventional vehicle currently available on the market. This platform and size of vehicles have another set of applications, mainly taxis, due to the zero emissions and the predominant usage of the vehicle in city centers and greater metropolitan belts. The development of the Serenus concept car, allowed Serenergy to initiate contacts towards this outcome since enough data has been generated and processed to make the proof of technology and concept a reality and economically feasible at the present/near future.

This process follows the 3 stated principles early stated and meet as well the surveyed client pretentions regarding the adoption and transition towards new and more efficient mobility solutions.

On the Telco's segment, a number of subsidiaries can be deployed across the global markets where the field trials are being conducted, on a first stage, to ensure a more effective market penetration, making the transition from trials to client with a sizeable first order expected, implementation of the technology, training and proper scheduled servicing of the fuel cells to comply with the contracts and services that are delivered by both parties, with the use of the methanol fuel cells in on/off grid applications.

WP20 – OEM module testing	
Lead: SERENERGY	
Start **End**	M32 M39
Description	The objective is to test and validate the technology directly at the OEM's relevant for the commercial roadmap. The focus is to take technology out of the labs as early as possible to close the gap between the development and application. The demonstration and verification will be made in a controlled environment with a clear understanding of scope and demonstration objectives. The result of the test will determine the next steps for the commercial progress toward commercial launch effectively ensuring focus is paid to the correct market and the correct OEM's.
Link	WP18 – WP19
Objects	• Test specifications • Test report

The test specifications were designed according to the highest international standards of safety (DS/EN) regarding its specific application, both on a stationary basis and regarding the E-Mobility projects.

Internal testing:

- IEC 62282-2-100 (2012) – stationary fuel cell electric testing requirements (chapter 5)
- IEC 62282-3-201 (2013) - testing of electrical/thermal performance (chapter 14) to test and certify the specific power output (Kw) of the fuel cell for the specification sheet.
- IEC 60950-1 (2015) – IT safety - general requirements (part 1) for telecommunication applications
    - Chapter 5 – electrical requirements and simulated abnormal conditions
    - Chapter 6 – connection to telecommunication tests
    - Chapter 7 – connection to cable distribution systems

An additional set of requirements was formulated in order to test on the field the fuel cell performance and all its components on different applications, and the list of practical outcomes to be performed and measured, in order to fulfill all the previous official requirements stated above.

HT-PEM METHANOL FUEL CELL	
Stationary FC testing	Serenus vehicle FC testing
● hot/cold environment start-up & components performance ● refueling operation ● components integration ● total off-grid operation ● integration with battery power banks ● transportation & integration issues ● on-site safety homologation testing	● hot/cold environment start-up & components performance ● refueling operation components integration ● integration with battery power banks ● CHP testing ● autonomy measurement ● components performance on a moving platform for issue tracking ● fuel behavior on board and fuel test – methanol mix ● controlling state of charge

Telecom segment (stationary power):

The field trials scope was wide and had a global range to test, develop and prove the technology on the field and, through Data analysis, identify and improve key components towards reliability and overall efficiency, to ensure that the final commercial application of the technology will present high levels of operation, regardless of the deployment envionrement.

Partnerships were made with:

- OEM of Telecom equipment, to try joint systems integration on the field and better understand next to them, the full potential and future aplications of the technologyin other projects.
- Telecom companies to deploy the equipment and run the tests, proof of reliability and overall stability of the system as a whole.

COUNTRY	HT PEM MODULES (KW)	UNITS	WEATHER/LOCATION	TEST SPECIFICATIONS/ RUNNING MODE	TEST SPECIFICATIONS/ LOCATION
Philipines	5	5	Tropical - Hot	PRIME POWER	OFF GRID
India	2.5 + 5	4	Sub-Tropical & Altitude - Cold	PRIME POWER + BACKUP	OFF GRID + GRID CONNECTED
China	2.5 + 5	2	Altitude - Cold	PRIME POWER + BACKUP	OFF GRID + GRID CONNECTED
Finland	5	1	Extreme Cold	PRIME POWER	OFF GRID
Norway	2.5	1	Altitude - Cold	PRIME POWER	OFF GRID
South Africa	5	2	Altitude - Hot	PRIME POWER + BACKUP	OFF GRID

Prime power applications run in a setup 24/7/365(6), providing power to the telecom towers in off-grid locations. Different sites, different loads running over the HT-PEM generators, to acess multiple parameters and prove reliability and scalability of both equipment and generators setup to match the demand of clients.

Backup power configurations on the field vary according to client and Serenergy request to acess different paramenters, namely, start-stop operation and number of supported cycles, peak power generated, total system integration and testing of different fuel tanks and configurations to improve OPEX due to off-grid location.

- Configuration 1 - System setup with Solar Photovoltaic panels and batteries. HT-PEM provides backup for the batteries if needed, working over night in summer time and between 6 to 10 hrs in the winter to compensate the lack of sun.
- Configuration 2 - System setup to provide both backup or prime power in areas where, although the system is connected to the grid, the latter one is highly unreliable and dependent of weather factors and quality of the connection itself.

Stationary tests results:

- hot/cold environment start-up & components performance – test conducted in cold environment in Denmark. Hot testing in KIWA, Netherlands at 50C and 95% humidity for preliminary benchmarking, to compare with future tests and data gathered from the current field tests.
- Refueling operation – the pre-mixed fuel is 60% methanol + 40% de-ionized water (V/V). 200 liters' tank as a standard. No major issues to report over the process, although some occurred due to contamination of the fuel during transportation (residues on the transport tanks) that distorted some results. Action measures were taken in collaboration with the suppliers to eliminate this issue in the future.
- Components integration – test of all components in hot and cold environment. Some improvements were performed over the electronics to optimize their stability and performance on both conditions.

- Total off-grid operation – the system proves to be reliable and due to the high output of the system (5Kw), additional Telco equipment instalment didn't affect the performance of the fuel cell.
- Integration with batteries power banks – initial issues due to different batteries models used by different operators. During pre-start of the module, some high in-rush current occurred, but quickly solved with some setup configurations.
- Transport & Integration issues – Some transport companies consider the fuel cell as a "dangerous good", although others just require some preliminary safety procedures. Substantial efforts have been dedicated to solve this matter to streamline shipping of fuel cells in the near future when mass production starts. Serenergy staff was dispatched on the initial field trials to provide guidance and training to the field operations telco customers, including issue tracking and components replacement (cables, connectors, etc.) on site.

Figure 47 – Philippines field test site

- On-site safety homologation testing – depending on location and local/regional/national fire regulations concerning noise & vibrations, methanol spill and potential effects. Local partners collaborate to expedite the process before the installation of the module.

The data analysis conducted during the tests, allowed to pinpoint some components inconsistencies, as well as some start-stop differences in timing due to the multitude of climates and latitudes, loads of equipment and required up-running time.

The current deployed units have hardware and software updates that have uniformized the operations standards and extended the overall lifetime of the fuel cell. These updates now allow a greater predictability on the models offered to the customers, for performance and reliability of operations.

Mobility application:

The Serenus vehicle was developed with the intend of delivering a feasible concept and practical application of the HT-PEM as a range-extender for a market available Nissan EV-200 vehicle. This project fits within the parameters set for the mobility projects on which a fuel cell application has its full power and potential maximized. The vehicle is currently the service vehicle of Serenergy in Aalborg for corporate use.

Fig. 48 Serenus Vehicle exhibited in the H2FC 2017 at the Hannover Messe

Serenus vehicle FC testing results:

The use of the Methanol fuel cell in the Serenus demonstration vehicle proved to be successful but without its hiccups and continuous learning curb. The adaptation of the technology led as well to substantial improvements over components and overall stability, creating the basis for a platform that can now be deployed in scale, going towards the E-Mobility projects goals stated as well on the commercial roadmap.

- Starting time similar to the stationary version, despite the methanol tank location under the vehicle. The initial integration was full of bugs, on second trial, movement and vibrations caused additional issues that were expected.
- The refuel operation occurred naturally, not presenting significant challenges, just the use of the methanol mix.
- Integration with batteries – a connection with the original vehicle high-voltage system was made to make possible to charge batteries. The module was design to fit the voltage range of the system.
- CHP testing – the external cooling system of the fuel cell passed through a custom radiator, mounted on the HVAC system of the vehicle. Currently working on an improved version.
- Autonomy measurement – still work in progress to connect the different parts of the system, to give a more reliable figure, just like a conventional vehicle.
- Fitting the methanol fuel cell in a moving platform presented some unique challenges. From the tank positioning, to the wiring and the placement of the remaining components, the final process was lengthy and laborious. When testing the vehicle, the asphalt vibration on different surfaces caused some wires to break or simply disconnect. The connectors itself had to be better fastened to prevent this fault to recur again.
- Loss of cooling pressure was an issue in the initial installation. It was developed a new external expansion tank for the cooling liquid. Using the v3 version, a more permanent solution is on working.
- Controlling state of charging - the system works, and estimated state of charge is done by measuring the voltage of the battery pack (standard).

- Test fuel – methanol mix – The fuel specifications are the same as the stationary version. Refueling test were performed in Serenergy facilities and OK petrol station in Aalborg.

This project was followed closely by the manufacturer in order to get full compliance and relationship building towards future joint-projects.

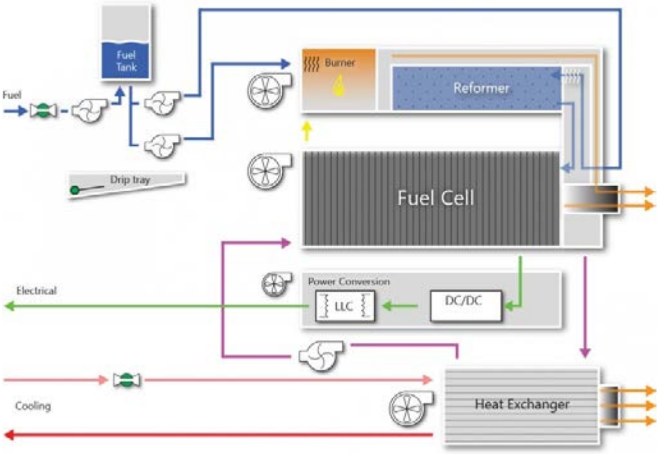
Another project currently on work is a long-term partnership with a Chinese OEM manufacturer for the development of a bus, primarily moved by the HT-PEM for city-center and metropolitan areas. This project results as an outcome of the Serenus vehicle project, taking the concept to a larger platform, market orienteded towards largre fleet deployment.

Technical Insights

Reformed Methanol System

Methanol and water can be converted into a hydrogen rich gas by the use of a reformer. A reformer is a device that contains a catalyst and heat-exchanging surfaces for process heat transfer.

Methanol reforming typically takes place at 220-300 deg. C and is an endothermic process, having therefore the need to add thermal energy to drive the process.



Due to the relative low reforming temperature of methanol, it is especially advantageous to use a methanol reformer in combination with a HT-PEM fuel cell. For Methanol reforming, there is no need for any additional gas clean up and can take the reformate gas as it is directly from the reformer. The final outcome of this process and technology is a simple, compact and cheap system.

The prime application and product behind the COBRA II project is a RMFC module capable of providing conditioned DC power from a Methanol water mix directly to a battery pack.

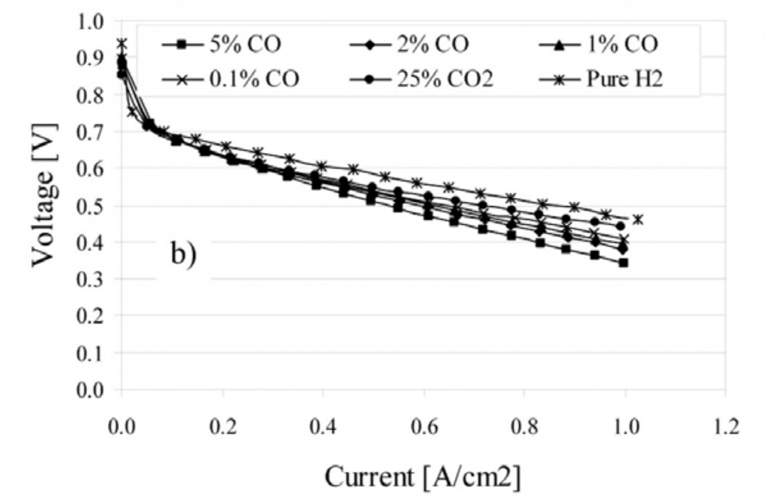
There are two levels of integration in this terminology: module or integrated

- The module is limited in functionality providing only the basic module and no auxiliary's, battery, fuel system, heat integration or interfaces.
- The integrated solution is where all is included in the application. This application is then again forwarded to an integrator, but on a higher level.

HT PEM Technology

The HTPEM (High Temperature Polymer Electrolyte Membrane) fuel cell system developed by Serenergy operates at 150-180 degrees C. This gives some key benefits and advantages over other types of fuel cell systems. Mainly CO tolerance (High fuel flexibility), ease of cooling and no need for humidification.

HTPEM fuel cells are highly tolerant to CO. CO is a known fuel cell poison and is a result of using reformed liquid fuels. The high CO content in gases from fuel reformers most often necessitates fuel clean up, which in turn then gives larger more complex and more costly systems.



Due to the elevated operation temperature of the HTPEM fuel cell, hydrogen with a higher CO concentration can be used without the same negative impact on performance, and without the same need for gas cleanup. This makes it possible to use hydrogen reformate originating from cheap, and easy to handle energy-carriers such as methanol, ethanol, diesel etc.

The HTPEM fuel cell can tolerate up to 3% (30,000ppm) CO and up to 20ppm of sulphur without permanent degradation. In comparison, LTPEM fuel cell normally can tolerate less than 30ppm CO and less than 1 ppm of Sulphur. This is a factor of 1,000 difference in CO tolerance. Because of the high operating temperature, a PrOx reactor after the reformer is normally not necessary. PrOx reactors are expensive, bulky and significantly lower the system efficiency. The result is that very simple, lightweight and inexpensive reformers can be used to produce hydrogen from a broad range of energy-carriers including the choices listed above.

As a result of not needing the humidifiers, air compressor and oversized radiator as in the LTPEM systems, the HTPEM system architecture seems very simple. The Serenergy fuel cell system uses less than 4% of fuel cell power output for balance of plant components -making this the system type with one of the lowest parasitic power consumption. Partly due to the low parasitic losses, the fuel cell system reached efficiencies of up to 57%. Most other fuel cell systems have an energy waste of approximately 10-20% of the fuel cell output, just to achieve operational status.

Current development stage

- Manufacturing some units at some TRL extend
- Comproved field experience from the Trials

- Core technology is performing beyond the initial stated expected results
- Underperforming on the module due to the reduced number of hours and planning at the same time to achieve a level of economies of scale to improve the overall feasibility of the product with more cost-effective components (cables, etc.)
- Initial production started to evaluate how to design and deploy

Dissemination of results

The project progress will be presented at the frequent meetings in "The stationary/ PEM Strategy Group" within the Danish Partnership for Hydrogen and Fuel Cells.

Scientific results from the project will be published in peer review journals and presented at international conferences, alongside with relevant Danish technical magazines, such as Ingeniøren, Electronic Supply and so will Fuel Cell Bulletin, Fuel Cell Today, Electric and Hybrid and Hzwei.

Participation in the Fuel cell seminar & Exhibition (USA), Hannover Messe (DE) and H2 Fair (Japan).

- http://www.h2fc-fair.com/hm17/exhibitors/serenergy.html
- The link above contains as well the videos regarding both Public and Technical Forums on which the whole Serenergy approach and strategy was outlined and the technology was showcased, encompassing the three key areas of operation: Stationary, Mobility and Maritime.

Conference "Green Mobility: The Future of Transportation in Denmark and in the EU", promoted and organized by the Nordic Folkcenter for Renewable Energy (Hurup Thy, DK). Nordic Folkcenter is an NGO which, since 1983, is active in the promotion of the renewable energy technologies on a national and international scale. It was held in Nordic Folkcenter in the period 28-30 April 2017. The event is meant to be of international relevance, with speakers coming from different countries, with focus on a different technology every day: Biofuels (28 April), **Hydrogen and Fuel cells (29**) and Electric and Hybrids (30).

Serenergy was invited as a keynote speaker on the 29th, and Mikkel Præstholm Ehmsen was the representative of the company in the event.

Fig 49 Conference "Green Mobility: The Future of Transportation in Denmark and in the EU"

In supplement to the above events will be held targeting the supplemental telco community such as on the Intelec fair and seeking greater cooperation with TowerXchange group and other market key players.

From DTU, the results of the long-term durability test of the developed thermally threated membrane were published in Journal of Power Sources, Volume 342, 28 February 2017, Pages 570-578. Those results are related with the content published in WP4 on this report.

1.6. Utilization of project results

Following the Commercial Roadmap setup for this project, both COBRA I and COBRA II have on itself, delivered a substantial range of knowledge over the technology developments and feedback from the initial trials, TELCOS and field engineers, plus the E-Mobility projects on which Serenergy is currently envolved.

From TELCOS, the initial field trials allowed Serenergy to set an early foot into the very competitive market of supplemental power generation. Understanding the demands from the sector and the constraints presented by competing technologies, allowed the development of more cost-effective systems and increase the range of applications, not only for powering of equipment, but also to supply in situ, a more reliable electricity source for other complementary uses, as well to serve the local population if needed. The 5 Kw module proved itself during the demanding trials across the globe and the use of Methanol as a fuel, carries on itself several advantages much appreciated by the end-users since it diminishes the impact on environment regarding noise and emissions, plus reducing the risk of pilferage, increasing therefore reliability and on-time usage.

The E-Mobility applications of the Methanol Fuel Cell is another key area of focus. The automotive range extender concept has passed from concept to reality with the Nissan Serenus vehicle. Several trials were conducted with project partners and a substantial number of OEM's have already expressed interest over the technology, providing feedback and exchanging experiences that allowed the streamlining of processes and better understanding of the results/learning curb associated with new disruptive technology such as this one. The potential for market application of the technology is immense, being the last mile delivery services a viable option that fulfills all current requirements towards a transition to a more sustainable mobility solution and environmental regulations.

The China Bus project is another development of E-Mobility. Following the 3 key principles stated for the use of the fuel cell in mobility projects (WP19), it shaped from the beginning the requirements for the development and deployment of this application towards efficiency, cost effectiveness and overall integration of components. The zero emissions factor, growing regulations over city-centers circulation plus the attractive usage costs, including the reduce operational costs were key factors for the development of this initiative. Initial field trials will start soon to build a test platform, data gathering and benchmarks to compare it against similar systems, assess total Capex and Opex in order to capitalize over acquired knowledge and deliver a final product that can compete head-to-head with existing legacy systems (diesel) and upcoming technologies (LNG & Hydrogen) on global markets.

Market Applications

Backup Supplemental Power Generators (SPG)

The platform will replace combustion engine generators and large battery packs as a maintenance free and highly reliable solution. Fuel distribution costs and storage density enables a low operational cost and a small footprint saving siting and rental fees for the operator.

The backup market is a well-established market with thousands of fuel cell systems deployed over the last 5 years. The addressable market potential is significant. The wireless telecom sector opportunities amount to 2 billion USD spend on DC backup systems and 300,000 base station additions yearly with an immediate fuel cell opportunity of 25,000 or 8%.

The market can be divided in two:

- the stable markets where the system is not in operation very often and the cost per kW or CAPEX is key
- the unstable markets where cost per kWh is key.

The competitive advantage of a methanol system is where the stabile market needs high energy density/runtime onsite with limited space available. In unstable markets, it is where the yearly runtime is higher than 300 hours and fuel/refuel/service cost is a total cost driver.

Auxiliary Power Units

The platform ensures off grid power supply to e.g. large vehicles/vessels thereby removing the need to start up the main engine, a secondary engine or an extended battery pack. This saves primary fuel, enables silent operation and saves the battery capacity ensuring startup capability of the main engine.

The total market for Auxiliary power units is diverse and enormous. Focus is on vehicles and marine applications with a total market potential of 3-6 Billion EUR. The technology will be able to compete at a 1-2.000 EUR/kW price with an addressable market for the solution of 1-2.000 units per year in 2018

Material handling auxiliary vehicles

The RMFC platform removes the need for large infrastructure installations in form of battery charging/swap stations or hydrogen refilling stations effectively supplying cost-effective, silent and efficient operation of forklifts and auxiliary vehicles.

Automotive-Range extender

The Range extender concept that enables the Battery electric vehicle (BEV) is one of the biggest potential for the RMFC technology. The main concept is to enable the BEV to move from a niche product to full market adoption by ensuring range, instant refueling in established well know infrastructure, competitive fuel cost and secondary features such as free heating and cooling. The Range extender enables the battery electric vehicle by reducing battery size, enabling fast refilling, providing heat in cold conditions and ensuring storage of an automotive fuel.

The electric vehicle is the absolute most energy efficient machine however the down side is energy density translated into range. This is where methanol has a huge advantage offering a factor of 5-10 better energy densities.

With 80 mio road vehicles sold per year with 10-30 mio classifies as city vehicles the market is substantial. The technology is enabled in 2017-2018 and competitive in 2020 however on a smaller scale. The scale hugely dependent on OEM adoption to vehicle concepts.

Niche road transportation

The Niche road transportation market entails many different segments; working vehicles like, postal, service, municipalities and urban vehicles. The main differentiator is that is somehow different in demands and characteristics from the main market. Serenergy has been looking into this for some time and demonstrated feasibility.

Among other OEM's Serenergy has just started an application project with ECOmove a Danish BEV manufacturer. Here the focus is to tailor make a specific concept around their Qbeak vehicle offering a completely modular energy carrier concept (MECc. The reuse from COBRA is core components which are not entailed in the MECc project. Furthermore, to ensure commercial viability the HT PEM roadmap will need to be followed, these more fundamental efforts handled in the COBRA program. The estimated city vehicle market is 10-30 million.

The purpose is to deliver a mass-production solution combining electric vehicle technology with a range extender based on fuel cells driven by methanol, with an estimated reduction of CO2 emissions by 75 % compared to an internal combustion engine (ICE) vehicle. The final result is a range extended electrical vehicle (R.E.E.V).

A 3 key-point strategy was design to ensure that the usage of the vehicle is cost effective and the technology has a maximum positive effect over the utilization and environmental outcome:

- The vehicle must have a daily usage period of over 8 hours
- It must have a low power usage to allow the range extender to fill the gap and provide the extra needed power.
- Heavy duty vehicle, to accommodate the batteries and methanol fuel cell. As in a last mile service provider, the vehicle will reduce emissions on city centers, the extra cargo space will make it cost effective and the reduced service required adds to the competitive ROI. This same operational paradigm was used for the China Bus project due to the overall size of the vehicle and the complementary roles that each vehicle on its own can perform on the city-centers and metropolitan areas.

Mass vehicle market

The mass market within road transportation of 80 million is a significant potential and challenge. Serenergy has for some time had interactions in form of product sale and test cycles with among others PSA handling the Peugeot and Citroen brands – the 2nd largest EYU manufacturer.

A joint technology and demonstration project AMREX was granted under EUDP, but reduced significantly from the original scope resulting in the delay of this opportunity. Work is ongoing to manage the objectives separately.

This market segment is not aligned with the aforementioned 3 key-point strategy and OEM partnerships need to be considered to pursue further developments.

Business Plan & Marketing

Competitors

Due to the large scope of applications of the technology, the competitive environment is very comprehensive.

Therefore, a 3 level-segmentation was considered upon dividing the market:

- competing technologies (market available and on use)
- competing fuel cell technologies
- HT PEM & systems level;

Competing technologies (market available and on use)

There are two main competing technologies and that is on the one side *long lasting small diesel generators* and on the other side lead-acid batteries (and Li-ion batteries).
When it comes to diesel generators the HTPEM technology has advantages when it comes to noise, emissions, efficiency, CO_2/kWh, vibrations, heat-utilization, pack-ability etc.
In order to compete against long lasting small diesel generators, the end customer has to appreciate and be willing to pay a premium price for one or more of the advantages associated with HTPEM.
Another possibility are markets where customers are forced to make changes by regulation (trucks are e.g. not allowed to have the engine running in idle mode during stops at rest areas along motorways etc.)

Competing Fuel Cell technologies

There are a number of different fuel cell technologies. The three most important are however:

- DMFC - Direct Methanol Fuel Cells
- LTPEM - Low Temperature Polymer Fuel Cells
- SOFC - Solid Oxide Fuel Cell

HT PEM and system level competitors

For the assembly of the final system, and taking into Account the specifics of the different components, the analysis of competition is divided into three levels:

MEA

The main competitors in the HT-PEM MEA area are as follows;

- BASF(DE)
- Elcomax (DE)
- Advent(GR/US)
- Samsung (KR)
- Johnson Matthey (UK)

BASF is by far the industry leader in terms of size and capability. The other competitors are working towards specific markets/niche applications in terms of size and performance.

Stack

Looking isolated at HT PEM stacks there are only manufacturers that makes stacks for their own dedicated system/application, they are as follows;

- Clearedge (US) – 5 kW micro CHP systems
- Elcore (DE) - small micro supplemental CHP systems
- Truma (DE) - Recreational power products
- Enymotion (DE) – Rekreationen power products
- Enerfuel (US) – APU and micro CHP systems
- Trenergi (US) – Recidental power generation
- GEI (US) – technology/APU offerings
- Samsung (KR)- Micro CHP systems

There is a large spread in concepts and features of the various stacks in the market and the manufacturers are looking at options for consolidation.

System

On a system level, the main competition is the combustion engine, however the hydrogen fed PEM fuel cell system should be included looking at generic systems.

Backup-supplemental power generators

The direct competition is Hydrogen backup systems, the main advantage is the density of complete system including fuel and the corresponding size of runtime/autonomy.

Main competitors within the backup power are is fuel cell related:

- Idatech (US)
- Altergy (US)
- Relion (US)
- Ballard/Dantherm Power (CA/DK)
- Future E (DE)
- Electro power systems (IT)

Auxiliary power units

The competition is Lithium battery packs or combustion engines. Main advantages are silent climate independent operation with high fuel/energy density that can be refueled furthermore service and reliability of small combustion engines is problematic compared to the platform.

Material handling-Auxiliary vehicles

Competition is hydrogen batteries and new low emission combustion engines. The main advantage is a low TCO due to simple infrastructure, low cost fuel and high reliability while maintaining the features of a battery/hydrogen variant.

Automotive-Range extender

The main competitor is battery hybrid vehicle with combustion engine. The key advantage of the platform concept is silent operation with few moving components offering very low maintenance. Furthermore, the engine energy conversion efficiency is double with the methanol fuel cell platform.

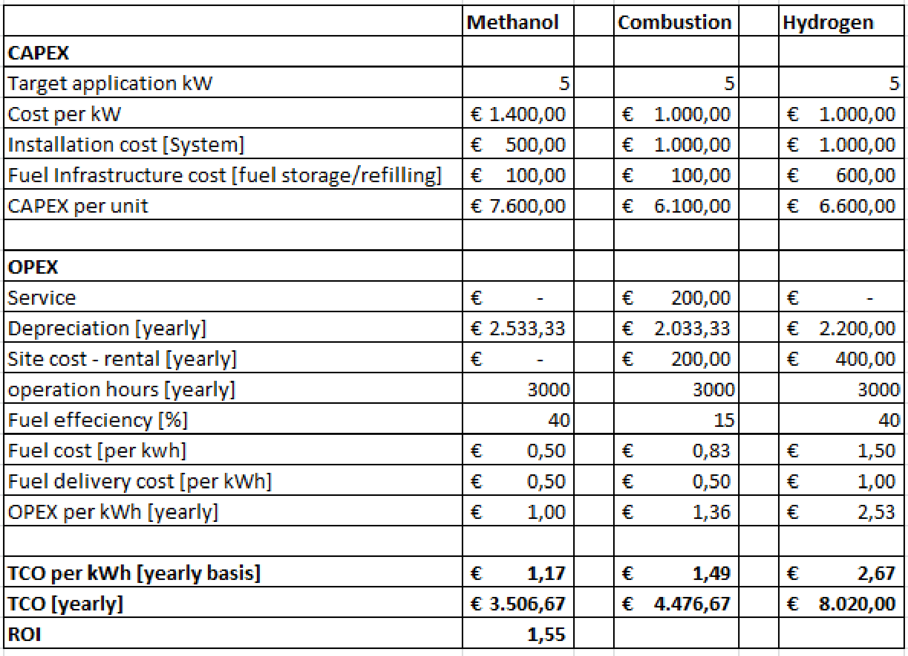
Economic analysis

The economic analysis will outline some typical user cases within specific applications:

Backup-supplemental power generators

The backup power case in focus on a medium usage supplemental power system – this will often be located in a decentralized location or in a difficult to reach central location e.g. a rooftop site.

What is demonstrated is that the advantages of a small footprint/weight, cheap fuel and no preventive maintenance makes up for a premium price based on the 2016 price predictions. It is demonstrated the ROI is 1,5 years within the scope of decision makers in the telecom sector.



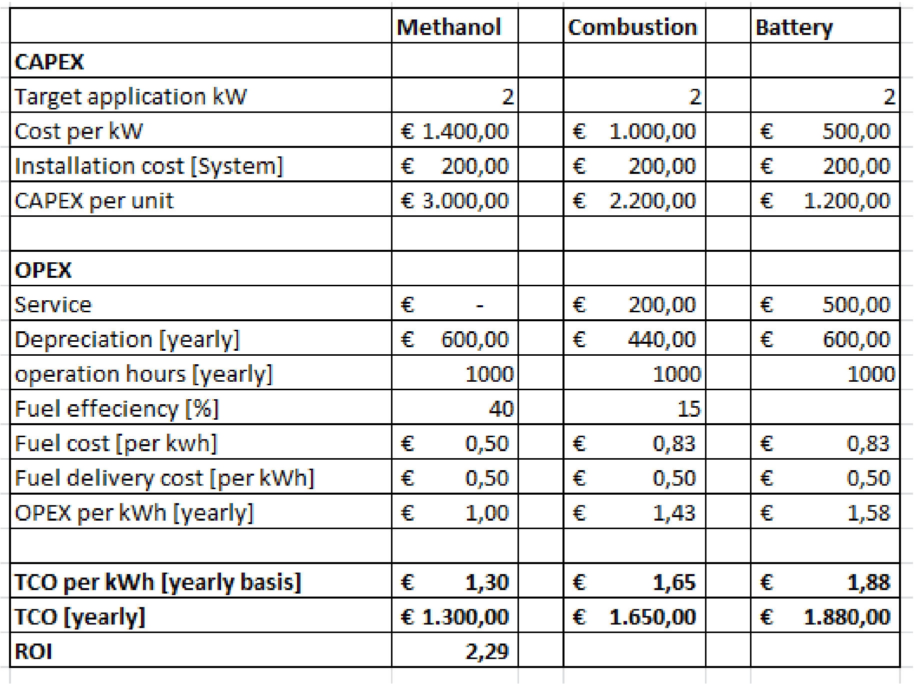
	Methanol		Combustion		Hydrogen
CAPEX					
Target application kW	5		5		5
Cost per kW	€ 1.400,00		€ 1.000,00		€ 1.000,00
Installation cost [System]	€ 500,00		€ 1.000,00		€ 1.000,00
Fuel Infrastructure cost [fuel storage/refilling]	€ 100,00		€ 100,00		€ 600,00
CAPEX per unit	€ 7.600,00		€ 6.100,00		€ 6.600,00
OPEX					
Service	€ -		€ 200,00		€ -
Depreciation [yearly]	€ 2.533,33		€ 2.033,33		€ 2.200,00
Site cost - rental [yearly]	€ -		€ 200,00		€ 400,00
operation hours [yearly]	3000		3000		3000
Fuel effeciency [%]	40		15		40
Fuel cost [per kwh]	€ 0,50		€ 0,83		€ 1,50
Fuel delivery cost [per kWh]	€ 0,50		€ 0,50		€ 1,00
OPEX per kWh [yearly]	€ 1,00		€ 1,36		€ 2,53
TCO per kWh [yearly basis]	**€ 1,17**		**€ 1,49**		**€ 2,67**
TCO [yearly]	**€ 3.506,67**		**€ 4.476,67**		**€ 8.020,00**
ROI	**1,55**				

Economic case analysis – Supplemental power

Auxiliary power units

The case for auxiliary power units is based on an actual customer case in a high-performance application with extreme positive temperature conditions making battery system difficult to manage. Furthermore, a note here is that the battery system requires a regular charge from the main engine, breaking silence and offering low charge efficiency.

The calculation shows that there is a break even after two years of operations and the added benefits of no preventive maintenance, no noise and complete autonomy is to be included as soft parameters.



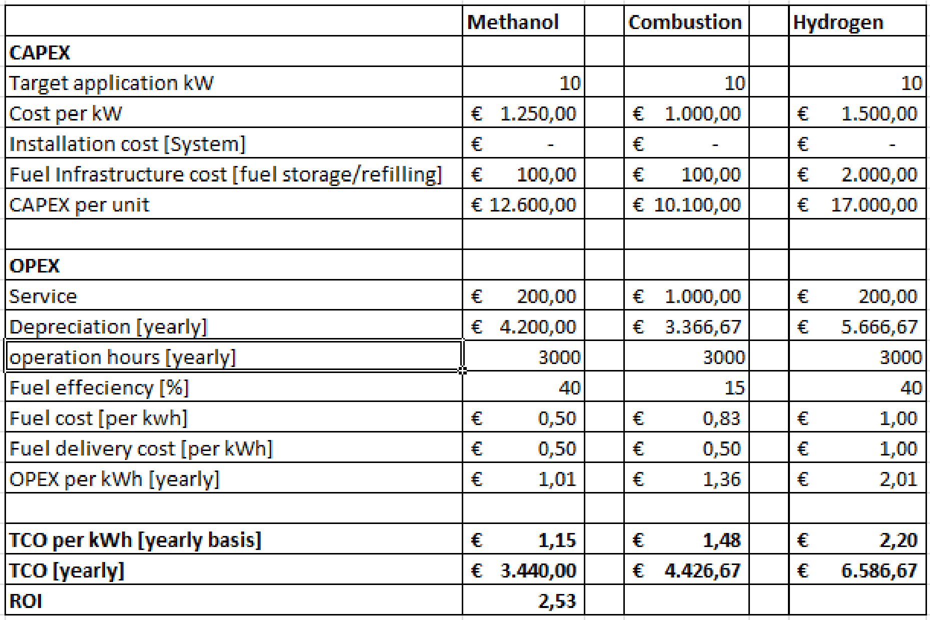
	Methanol		**Combustion**		**Battery**
CAPEX					
Target application kW	2		2		2
Cost per kW	€ 1.400,00		€ 1.000,00		€ 500,00
Installation cost [System]	€ 200,00		€ 200,00		€ 200,00
CAPEX per unit	€ 3.000,00		€ 2.200,00		€ 1.200,00
OPEX					
Service	€ -		€ 200,00		€ 500,00
Depreciation [yearly]	€ 600,00		€ 440,00		€ 600,00
operation hours [yearly]	1000		1000		1000
Fuel effeciency [%]	40		15		
Fuel cost [per kwh]	€ 0,50		€ 0,83		€ 0,83
Fuel delivery cost [per kWh]	€ 0,50		€ 0,50		€ 0,50
OPEX per kWh [yearly]	€ 1,00		€ 1,43		€ 1,58
TCO per kWh [yearly basis]	**€ 1,30**		**€ 1,65**		**€ 1,88**
TCO [yearly]	**€ 1.300,00**		**€ 1.650,00**		**€ 1.880,00**
ROI	**2,29**				

Economic case analysis – Auxiliary Power Unit

Material Handling-Auxiliary vehicles

The below case is based on a material handling forklift with a medium usage pattern. The main focus is on the Fuel infrastructure cost where an investment in a fuel delivery system is distributed among several systems.

The calculation shows that even at a relatively high fleet count, approximating 2000 EUR/vehicle establishment cost excluding maintenance of the refueling system, the Methanol platform is superior. With a lifetime target of 10.000 hours the RMFC is comparable for recore/overhaul with a combustion engine. The ROI is two and a half years which offer options for leasing and other models favorable of CAPEX heavy solutions.



	Methanol		Combustion		Hydrogen
CAPEX					
Target application kW	10		10		10
Cost per kW	€ 1.250,00		€ 1.000,00		€ 1.500,00
Installation cost [System]	€ -		€ -		€ -
Fuel Infrastructure cost [fuel storage/refilling]	€ 100,00		€ 100,00		€ 2.000,00
CAPEX per unit	€ 12.600,00		€ 10.100,00		€ 17.000,00
OPEX					
Service	€ 200,00		€ 1.000,00		€ 200,00
Depreciation [yearly]	€ 4.200,00		€ 3.366,67		€ 5.666,67
operation hours [yearly]	3000		3000		3000
Fuel effeciency [%]	40		15		40
Fuel cost [per kwh]	€ 0,50		€ 0,83		€ 1,00
Fuel delivery cost [per kWh]	€ 0,50		€ 0,50		€ 1,00
OPEX per kWh [yearly]	€ 1,01		€ 1,36		€ 2,01
TCO per kWh [yearly basis]	**€ 1,15**		**€ 1,48**		**€ 2,20**
TCO [yearly]	**€ 3.440,00**		**€ 4.426,67**		**€ 6.586,67**
ROI	**2,53**				

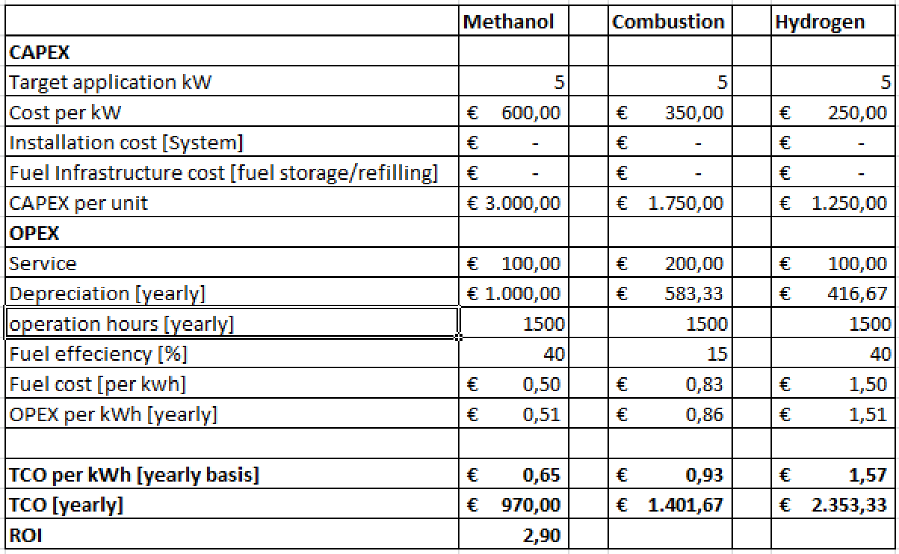
Economic case analysis – Material handling

Automotive-Range extender

The Automotive range extender case is based on data from “Alternative drivetrains 2012” and updated targets from the COBRA technology roadmap. It shows that a range extender platform with a high operation pattern is comparable

The cost per kW is beyond the 2020 target and is based on a separate automotive track with collaboration of several OEM’s. The main focus is the total cost in relation the e.g. glider and battery pack where the offset will be diminished further. What can be seen in the calculation is that the concept will be competitive based on a clean calculation in less than three years a typical leasing period.

Soft facts such as noise, emissions and total vehicle efficiency are not included nor are the large aspects of infrastructure which will be significant in the case of hydrogen.

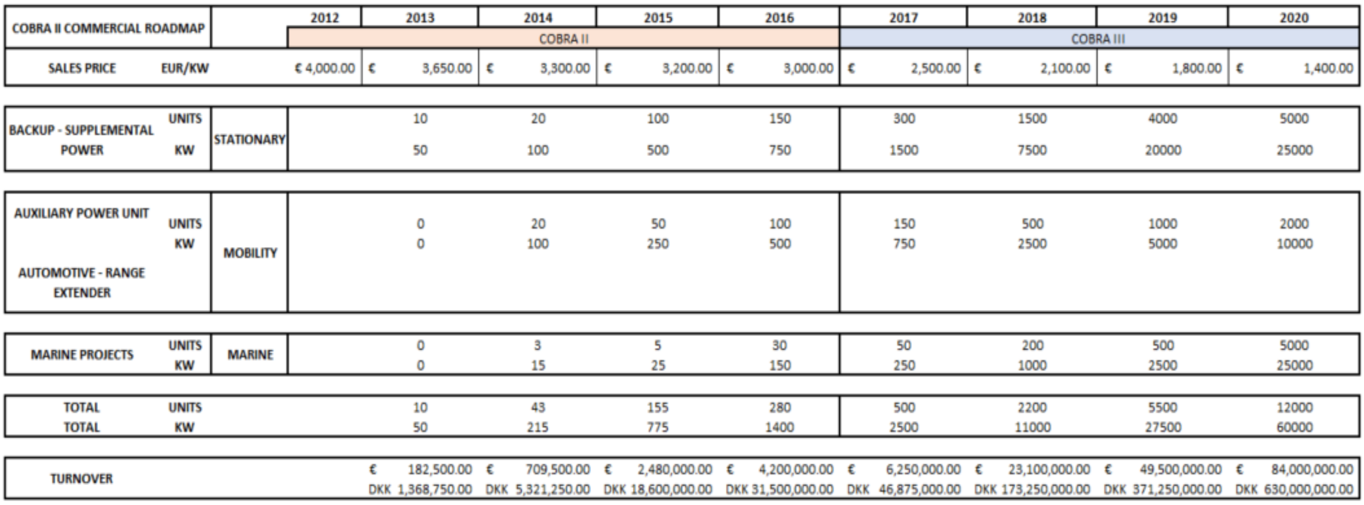


	Methanol		Combustion		Hydrogen
CAPEX					
Target application kW	5		5		5
Cost per kW	€ 600,00		€ 350,00		€ 250,00
Installation cost [System]	€ -		€ -		€ -
Fuel Infrastructure cost [fuel storage/refilling]	€ -		€ -		€ -
CAPEX per unit	€ 3.000,00		€ 1.750,00		€ 1.250,00
OPEX					
Service	€ 100,00		€ 200,00		€ 100,00
Depreciation [yearly]	€ 1.000,00		€ 583,33		€ 416,67
operation hours [yearly]	1500		1500		1500
Fuel effeciency [%]	40		15		40
Fuel cost [per kwh]	€ 0,50		€ 0,83		€ 1,50
OPEX per kWh [yearly]	€ 0,51		€ 0,86		€ 1,51
TCO per kWh [yearly basis]	**€ 0,65**		**€ 0,93**		**€ 1,57**
TCO [yearly]	**€ 970,00**		**€ 1.401,67**		**€ 2.353,33**
ROI	**2,90**				

Economic case analysis – Automotive range extender

Commercial Roadmap

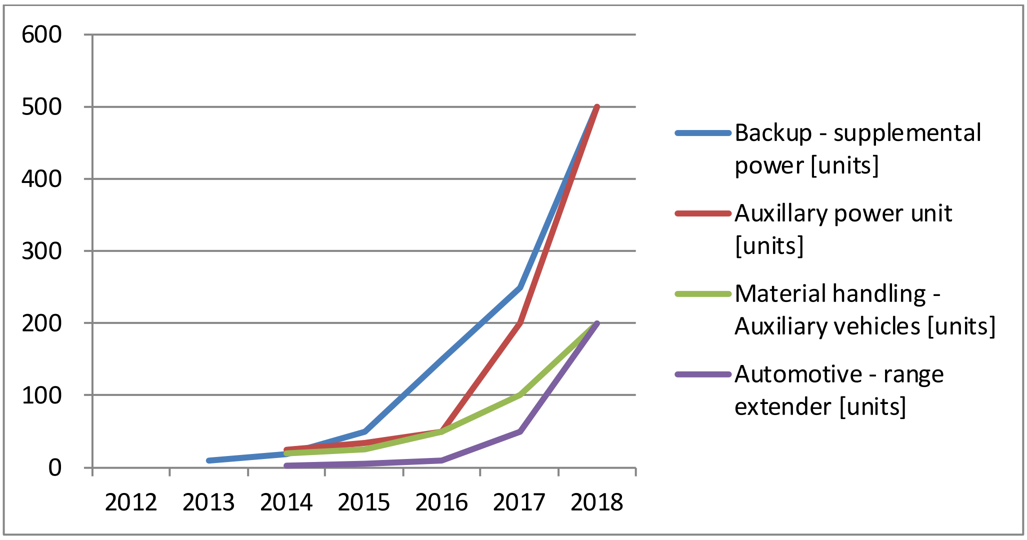
The below commercial roadmap incorporates sales prices derived from the technical roadmap and the corresponding sales volumes including a pre-commercial deployment for accumulated test systems. The chart was reviewed to incorporate the forecasts for COBRA III, giving sequence to the work being developed up to this point.



COBRA II COMMERCIAL ROADMAP			2012	2013	2014	2015	2016	2017	2018	2019	2020
			COBRA II					COBRA III			
SALES PRICE	EUR/KW		€ 4,000.00	€ 3,650.00	€ 3,300.00	€ 3,200.00	€ 3,000.00	€ 2,500.00	€ 2,100.00	€ 1,800.00	€ 1,400.00
BACKUP - SUPPLEMENTAL POWER	UNITS	STATIONARY		10	20	100	150	300	1500	4000	5000
	KW			50	100	500	750	1500	7500	20000	25000
AUXILIARY POWER UNIT AUTOMOTIVE - RANGE EXTENDER	UNITS	MOBILITY		0	20	50	100	150	500	1000	2000
	KW			0	100	250	500	750	2500	5000	10000
MARINE PROJECTS	UNITS	MARINE		0	3	5	30	50	200	500	5000
	KW			0	15	25	150	250	1000	2500	25000
TOTAL	UNITS			10	43	155	280	500	2200	5500	12000
TOTAL	KW			50	215	775	1400	2500	11000	27500	60000
TURNOVER				€ 182,500.00 DKK 1,368,750.00	€ 709,500.00 DKK 5,321,250.00	€ 2,480,000.00 DKK 18,600,000.00	€ 4,200,000.00 DKK 31,500,000.00	€ 6,250,000.00 DKK 46,875,000.00	€ 23,100,000.00 DKK 173,250,000.00	€ 49,500,000.00 DKK 371,250,000.00	€ 84,000,000.00 DKK 630,000,000.00

HT-PEM Commercial Roadmap

The below graph shows the unit deployment projections towards 2018 in the various segments – the early deployments will be based on project deliveries and early demonstration at selected partners.



Unit deployment projections

Project Partnership & Research

The research conducted over the project, obeyed to the principles stated on WP1, being shared and applied to the final product as the R&D effords unfold over time. The impact of the redesign components was accessed by all partners to avoid any malfunction of additional pressure top the overall system that could lead to downgraded performance. The MEA's performance reached the stipulated requirements on the roadmap and the new BOP components added extra performance and reliability to the system.

Danish Energy Policy

The project partners represent a strong and dedicated effort in bringing Danish research, development and demonstration within the area of fuel cell technology, as well as integrating solutions and technologies in a working environment.

The project supports the strategy for liquid biofuels especially the main focus on:

- Ensuring a cost effective long term energy supply
- Ensuring growth potential for Danish companies
- Ensuring the fulfillment of Danish goals in sustainable fuel development
- Maintaining and develop the Danish research platform

Furthermore, the project to some extent support the effort within wind and gasification and the related strategies – this is due to the potential production methods for methanol via biomass gasification and hydrogen/carbon synthesis.

Energinet.dk – the entity in charge of the Danish gas and electricity grid has outlined in their new strategy that Methanol and DME is central in the "power to gas to fuel" chain enabling an interaction between power and gas infrastructure.

The project is aligned with pt 7.3 of the Danish fuel cell and hydrogen strategy related to strategy and goals for the PEM area. Where support is given to production of cells, stacks and systems and enabling the deployment of said systems. The project is related to and supporting the updated 2012 Danish RD&D strategy and Road Map for HTPEM Fuel Cells and Transport under the Partnership for Hydrogen & Fuel Cells.

Future Context for Research & Development

Serenergy

The efforts conducted over COBRA II project, were deployed in the development of parallel projects, pushing further the timelines to incorporate always the newest and most recent innovations to cement the technological platform and having a focus on continuous incremental outcome towards a new platform, with stability, reliability and practical production feasibility possible.

Supplemental Power Supply (SPG) was one of the projects also supported by EUDP on which this methodology was followed and constitutes one of the pillars of the commercial strategy being carried out by Serenergy. The focus of this project is the stationary telecom power supply market, mainly off-grid applications for continuous or backup power.

Both COBRA II and SPG lead to the release of the v3.0 of the Serenergy HT-PEM fuel cell, currently on final trials and early deployments.

Future COBRA III focus is to reach a final, multi-modular platform on which all these improvements can occur and be retrofitted to v3.0 and beyond, as well as ramp-up production with global markets as primary target.

Patents

Since the scope of the COBRA II project is the development of core technology, Serenergy is considering to take out patents on some of the mechanical designs obtained during the optimization of the system and the reformer design and components.

Results transfer to other institutions

The results of the research conducted are used solely by the parties involved on the project and shared between them. In Serenergy, those results are translated into further research and development towards optimization of components and achieving greater economies of scale to enable greater commercial success across the different stated markets.

For AAU and DTU the work conducted on this area, reinforce the leading position of the institution on the area of Fuel Cell research. The renewed commitment s by both parties over continuous projects (COBRA III application) is fulcral to carry on works and keep attracting the best and brightest minds to this field.

Ph.D. s participation

For this project, no Ph. D students were involved on the work developed, although the outcome of the project can be used by future PhD students to pursue deeper knowledge levels over the core technology and new materials applications.

1.7. Project conclusion

The primary objective of the COBRA II, the optimization of an integrated fuel cell module was reached within the timeframe of the project. Several changes were incorporated in the designs that also lead to other major improvements and changes over the system architecture to achieve a Balance of Plant (BoP) on which the remaining system components were integrated in a more logical and convenient way.

COBRA II required a greater level of cooperation and interaction between the partners since the module and key components developments for greater performance demanded an overall review of existing designs and a reformulation on developing strategy to meet the tight deadlines stipulated on the agreed timeplan.

The cost optimization was achieved by having a higher level of components integrations and increased standardization in the electric/electronic side, allowing larger production of units and enhanced quality control procedures, to reduce the number of potential bottlenecks and recall of unperforming units before leaving the facility. The stack production is still the most expensive part of the system due to the specifics of the employed technology, but work is being carried on to optimize as well other key parts, being the reformer design a focus point.

In the Philipines, India, China and South Africa, 2.5 & 5kW modules are currently in final test and being rolled-out/upgraded for use by local telcos. The same in Finland and Norway, but withstanding negative temperature for a full multi-purpose global deployment strategy.

The data analysis conducted during the tests, allowed to pinpoint some components inconsistencies, as well as some start-stop differences in timing due to the multitude of climates and latitudes, loads of equipment and required up-running time. The current deployed units have hardware and software updates that have uniformized the operations standards and extended the overall lifetime of the fuel cell.

The data gathered across all mentioned sites has been invaluable to the current R&D efforts and reinforce the commercial analysis of markets and applications. The disparities between envioronements and configurations, presented on itself a considerable number of challenges. From the Philipines and Norway, Serenergy has already received commercial orders for sale and deployment of the HT PEM in the near future, with additional orders from the different markets being expected in the mid-term.

Perspectives

By the time this report is delivered, the COBRA III application has been already submitted to continue the developing efforts carried on from COBRA I & II. The application proves and renew the commitment amongst all envolved parties towards the pursue of more innovative approaches to evolve the current technological platform, to reach the final stages of commercial applications and conquer a relevant position on the global markets.

Both the technological and the commercial road maps were updated to meet the new challenges, since the field tests and deployment of units worldwide has largely exceeded the initial forecasts. The continuous improvement over materials and software, allows to adjust both products, in 2.5 and 5 kW variants, to reach greater performance and meet the reliability goals established on the roadmap and agreed with the clients for future adoption and continuous use of the technology.

The key applications of the technology follow the EUDP directives for independence of fossil fuels, development of technology with added value for the Danish industry, as well as growth and employment projections to reflect the economic effects generated within the given 1 to 5-year period end in terms of sales, exports and jobs creation.

The COBRA projects and derivative practice indentations will drive the expansion of the production facility to accommodate up to 3 shifts, with as many as 50 workers per shift to respond to the increased demand, both of the methanol fuel cell on itself, as well as on dedicated assembly of existent vehicles and build up from zero of a E-mobility solution. This will also enable the company to reach the desired goal of 75.000 DKK per unit (fuel cell), with an estimated production and delivery of 5000 units, totaling 375.000.000 DKK within the 5-year timeframe stipulated on the project application.

A major restructure over the corporate structure of the company occurred during 2017, to meet the demand of the market and enable a greater level of growth over the three key segments target by the company for commercial applications of the HT-PEM fuel cell technology: Stationary, Mobility and Maritime.

By other hand, this move had a significant impact over the development and production departments, allowing a greater focus on LEAN and AGILE methodologies, to adapt the production to the growing demand and orders placement as the company transits from field testing to delivery of the first units on the Telecom segment and expanding the cooperation and joint projects in the mobility and maritime segments of the market.