**Final report**

# ADDpower

**Next Generation Power Supply**

**EUDP 2014-II**

**Project identification 64014-0525**

AALBORG UNIVERSITET

Serenergy
The Power of Simplicity

## 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 |

# Content


1. Project details ... 1
2. Short description of project objective and results ... 1
   2.1. In English ... 1
   2.2. In Danish ... 1
3. Executive summary ... 2
   3.1. In English ... 2
   3.2. In Danish ... 2
4. Project objectives ... 4
5. Project results and dissemination of results ... 5
   5.1. System Design ... 5
   5.2. Control design ... 6
   5.3. Stack test ... 7
   5.4. Reformer test ... 14
   5.5. System test ... 15
   5.6. Cost of key components ... 16
      5.6.1. Bipolar plates ... 16
      5.6.2. Membrane Electrode Assembly – MEA ... 16
      5.6.3. System excluding burner and reformer ... 17
      5.6.4. Reformer and Burner ... 17
      5.6.5. RMFC Module ... 18
   5.7. 1st Integration in an urban bus in China ... 19
      5.7.1. Conclusion of 1st integration ... 22
   5.8. 2nd Integration in an urban bus in China ... 23
      5.8.1. Conclusion 2nd integration ... 26
   5.9. Dissemination ... 27
6. Market and Oppotunities ... 28
      6.1.1. Backup Supplemental Power Generators (SPG) ... 29
      6.1.2. Auxiliary Power Units ... 29
      6.1.3. Material handling auxiliary vehicles ... 29
      6.1.4. Automotive-Range extender ... 29
7. Utilization of project results ... 31

8. Project conclusion and perspective ........................................ 32

# 1. Project details

| | |
|---|---|
| Project title | ADDpower – Next Generation Power Supply |
| Project identification (program abbrev. and file) | 2014-II, Project ID 64014-0525 |
| Name of the programme which has funded the project | Energiteknologisk Udviklings-og Demonstrations Program (EUDP). Brint og brændselsceller. |
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| Project partners | Serenergy A/S<br>Aalborg Universitet |
| CVR (central business register) | DK 39170418 |
| Date for submission | August 2014 |

# 2. Short description of project objective and results

## 2.1. In English

The project will develop and test a 20kW generator platform based on High temperature PEM fuel cells combined with a methanol reformer. The project will focus on replacement of diesel generators in larger material handling vehicles where the more than double efficiency and low fuel price will make the generator competitive.

## 2.2. In Danish

Projektet har til formål at udvikle og teste en 20 kW generator platform baseret på Høj temperatur PEM brændselsceller kombineret med en Metanol reformer. Der er fokus på erstatning af diesel generatorer i større arbejdskørertøjer hvor den mere end dobbelt så høje effektivitet og lave brændstofs pris gør generatoren konkurrencedygtig.

# 3. Executive summary

## 3.1. In English

The purpose of the ADDpower project is to develop and test a 20kW generator platform based on High temperature PEM fuel cells combined with a methanol reformer and thereby enable use in larger material handling vehicle segments.

The project will develop a complete new generator platform based on core technology developed in related projects for other applications and power sizes. The project is based on a decade of research into HT PEM and RMFC technology from both academia and industrial sectors.

Today the Reformed Methanol fuel cell technology is used for small sub 5 kW generator replacement for stationary applications such as backup power and supplemental power. The products can be combined for larger power outputs however the economy beyond 2-3 units are not feasible even considering economies of scale. A dedicated platform is needed to ensure a competitive equipment cost compared to a diesel generator.

The ADDpower project will be based on a strong demand from the South African mining and transport industry and key players are involved in the projects as external partners to ensure alignment of technical features and commercial feasibility. The market potential however is scalable worldwide and the platform will be designed with sufficient flexibility.

For larger material handling vehicles, the main cost driver in a lifetime perspective is fuel. In south Africa the diesel price is 1,4 USD/L and 0,2 USD/L for water/methanol mix. Including the conversion efficiency of combustion engines and fuel cells the per energy unit fuel cost is reduced with up to 8 times. In a total cost of ownership calculation including service and equipment investments, the overall TCO reduction will be up to 50% by implementing the platform.

The developed HT PEM and RMFC technology is unique and patented with a strong potion from SerEnergy as the leading manufacturer in this segment and a sustainable operation growing steadily year by year.

At project completion, a fully functioning prototype will have been tested in a context relevant to customers with a demand. The commercial compliance and system design will have been finalized and by 2018-2020 significant volumes of the platform is projected to be in the field.

## 3.2. In Danish

Formålet med ADDpower projektet er at udvikle og teste en 20kW generator platform baseret på Høj Temperatur PEM brændselsceller kombineret med en metanol reformer og derved sikre anvendelighed i større arbejdskøretøjer.

# ADDpower

Projektet vil udvikle en komplet ny generator platform baseret på kerne teknologi udviklet i relaterede projekter målrette imod andre applikation og størrelser. Projektet er baseret på et årtis forskning inden for HT PEM og RMFC området fra både universiteter og industri.

I dag bruges Reformeret metanol brændselsceller til mindre 5 kW generator erstatnings i stationære applikationer såsom nødstrømsanlæg og supplerende energi-Produktet kan kombineres og få større effekt men ud over 2-3 sammenkoblede anlæg er det ikke økonomisk bæredygtigt, ej heller med det øgede volumen i betragtning.   En dedikeret platform er nødvendig for at kunne sikre en konkurrencedygtig udstyrspris sammenlignet med en diesel generator.

ADDpower projektet er skabt på baggrund af et stærkt behov fra den sydafrikanske mine og transport industri og nøglespillere er involveret i projektet som eksterne partnere for at sikre tilpasning af tekniske funktionaliteten og kommercial bæredygtighed. Markedspotentialet er trods det valgte fokus verdensomspændende og platformen vil blive designet med passende fleksibilitet.

For større arbejdskøretøjer er hovedomkostningen set I et livscyklus perspektiv brændstofs omkostninger. I Sydafrika koster en liter diesel 1,4 USD/L og Metanol/vand blanding 0,2 USD/L. Hvis man kombinere brændstofs prisen med konverteringseffektiviteten kan brændstofs omkostningen per energienhed blive reduceret med op til 8 gange.I en total omkostnings model hvor service og investerings omkostninger er inkluderet viser det en overordnet reduktion på 50% ved at implementere platformen.

Den udviklede HT PEM og RMFC teknologi er unik og patenteret med en stærk position via SerEnergy der er den ledende producent i dette segment med en bæredygtig drift og stabil vækst år efter år.  Ved projektets afsluttelse vil en komplet fungerede prototype have være teste i en relevant kontekst med kunder der har et direkte behov. Hertil kommer at kommercielle og tekniske parametre vil have være tilpasset hvilket vil resultere i signifikante antal af systemer vil være i marken ved 2018-2020.

# 4. Project objectives

The goal of project is to build a 20kW HT PEM Reformed Methanol Fuel cell platform. The goal is to build a 20 kW RMFC platform that can be competitive in a higher power segment than the current 5 kW platform. The feasibility for higher power requirements in Material handling and large machinery APU requires a cost effective, compact and efficient solution.

**The goals of the 20kW platform are:**

Reduce Bipolar plate cycle time with 80%
Reduce Reformer milling time with more than 50%
Reduce MEA cycle time with 50%
Reduce stack Assembly time with 50%
Reduce the BOP cost per kW with 50-75% Commercial & Demonstration Goals
Demonstrate a prototype in a target application
Demonstrate commercial feasibility
Plan further commercial roll out.

**Milestones**
M1 -Component design
M2 -System design
M3 -System test
M4 -System implementation

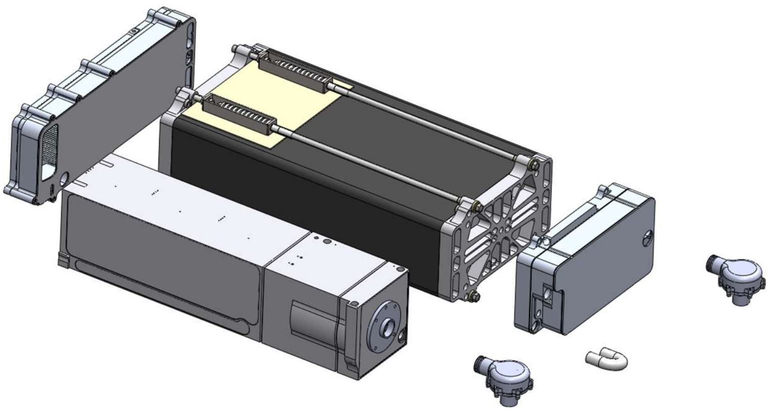
**Commercial milestones**
CM1 -Commercial compliance
CM2 -Commercial OEM contracting

**Work packages**
WP1 -Project management
WP2 -Module Specification
WP3 -Stack development
WP4 -Reformer Development
WP5 -System development
WP6 -Control design
WP7 -Stack test
WP8 -Reformer test
WP9 -System test
WP10 -Prodcut demonstration
WP11 -System implementation
WP12 -Dissemination and communication

# 5. Project results and dissemination of results

The main activities of the ADDpower project consisted in control design of a complete RMFC system, which was supported by stack and reformer characterization tests. This was followed by complete system test for reliability and start-up tests in extreme weather conditions and under different reformate compositions. To prolong lifetime and increase system reliability, fault identification and isolation algorithms were also developed based on HT-PEMFC stack characterization tests. Even though, fault identification and isolation alone is not able to improve system reliability, it is a foundational work for an on-line predictive control of RMFC system. Therefore, the work done under the ADDpower project on control design and fault identification and isolation algorithms can be combined for the design of a more robust RMFC system that is continuously monitored for faults and optimized via predictive control system for a longer lifetime.

## 5.1. System Design



Figur 1 : 3rd Generation alucore with S165L HTPEM 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.

## 5.2. Control design

A control system was developed with the main goal to stabilize the system and increase efficiency without causing degradation. This control is based on a cascade control system, which controls the temperature of the burner and reformer. The temperatures are controlled directly with the use of fans in the burner and thereby also the reformer temperature. The schematic of the control strategy is shown in Figure 1.

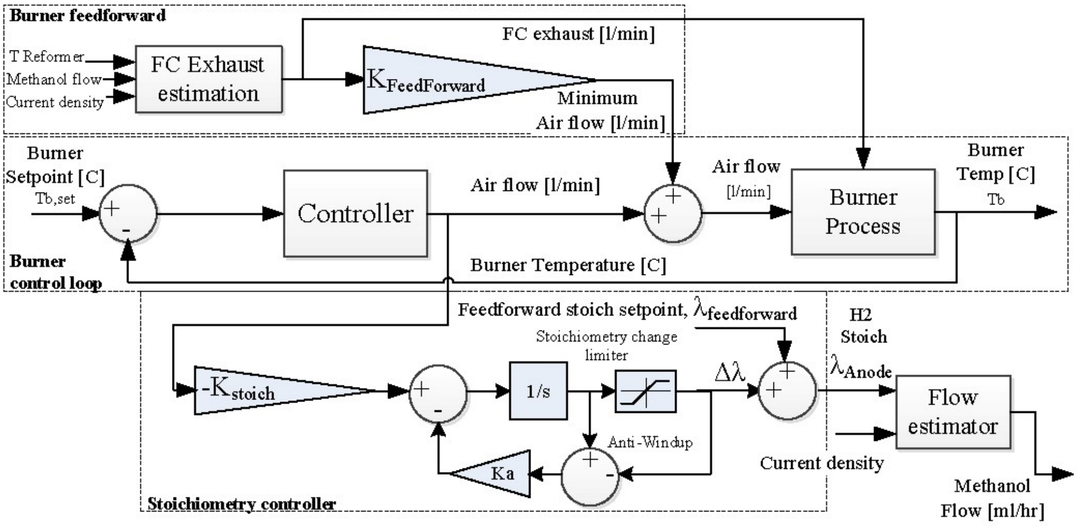



Figure 1 System control based on reformer and fuel cell stack tests at AAU

If the temperature of the burner is higher, compared to the burner set-point, the Burner control loop will regulate the fan to cool the burner immediately. Additionally, the Burner feedforward control will set the minimum flow for the fan to the minimum airflow required for the burner to operate safely. The fan airflow is estimated with an observer design that calculates the flow coming out of the fuel cell. This is calculated using the temperature of the reformer, the methanol flow and the fuel cell current.

The stoichiometry controller takes the air flow as input and multiplies it with a small gain. This signal is integrated, which summarizes the work done by the burner air fan, therefore, a stoichiometry change is introduced and added to the initial stoichiometry set-point. The stoichiometry is intended to be a slow reacting controller, which can make small adjustments to the system stoichiometry.

The initial purpose of this controller is to decrease excessive use of the air fan for the burner. Using a slow regulating stoichiometry controller also has the benefit of increasing the total system efficiency as this is mainly linked to the stoichiometry. By utilizing a controller, it is possible to increase the system efficiency by 1% at 0.24 A/cm2 and 2% at 0.47 A/cm2. The increase in the efficiency confirms the usability of the controller, however, because the efficiency is linked directly to the stoichiometry, it corresponds mainly to the lowest possible stoichiometry allowed by the HT-PEMFC. Therefore, a careful study of the HT-PEM fuel cell stack is necessary before implementing this controller in a system, in order to avoid starvation and other negative effects of lowering the stoichiometric ratios.

## 5.3. Stack test

To optimize stack operating conditions for improved efficiency and extend lifetime, a parametric study is necessary, including the effects of the composition of the anode feed. Therefore, to understand the effects of the methanol reformate impurities, EIS characterization was done on a Serenergy short stack. From 0.25% to 1.5 % by volume CO and up to 0.5% by volume of unconverted methanol on the feed were tested, and the results as shown in Figure 2 and Figure 3 confirm the degradation mechanisms of the impurities, which were also previously observed on single cells. However, the effects are more pronounced at stack level. Understanding these degradation mechanisms and quantifying them is crucial both for the control strategy and for diagnostics algorithms.

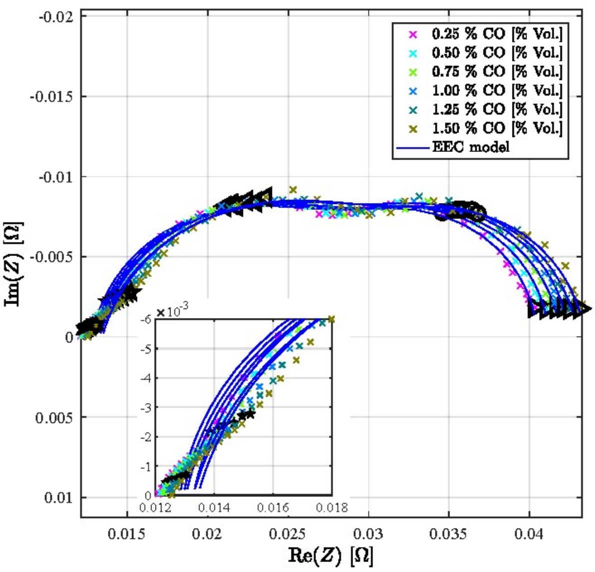



Figure 2 CO poisoning on a stack

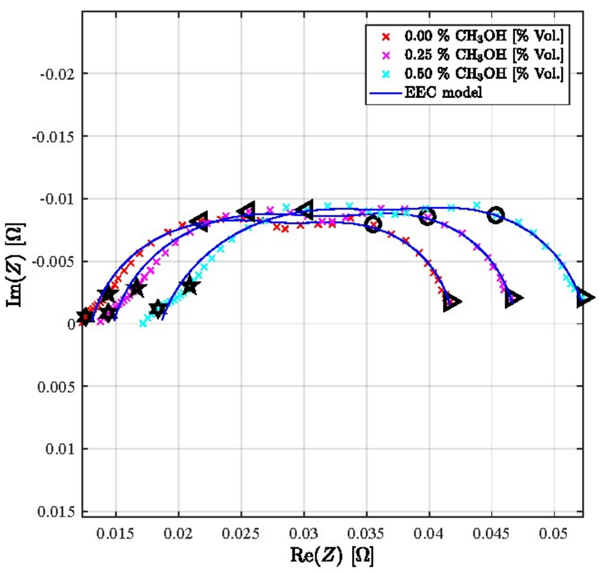



Figure 3 Methanol slip on a stack

Another way of ensuring a prolonged lifetime of an HT-PEMFC stack is using diagnostic tools to identify faults and isolate them when they happen, so that an intervention can be done to correct or minimize their effects on the stack. A data-driven impedance-based methodology (shown in **Error! Reference source not found.**) was used for fault detection and isolation (FDI) of different typical faults for high temperature PEM fuel cell stack.

The fault detection and isolation is divided into 4 steps (see Figure 4); acquiring of EIS measurement, pre-processing of data, feature extraction and artificial neural network classification of fault class. The pre-processing of the impedance spectrum is conducted by a zero phase Butterworth filter, which is used to remove outliers. The extracted features used in this work are the DC component of the fuel cell current, and two angles between the impedance at 100 Hz and 1 kHz and between 0.1 Hz and 1 Hz ($f_2$ and $f_3$ in Figure 4).

The faults considered in the algorithm and their realistic causes are listed below:

$\varphi_1$ - decrease in cathode stoichiometry. This could be due to a faulty fan/compressor or that the deployed systems is at high altitude.

$\varphi_2$ - An increase in cathode stoichiometry. This could be due to a change in fan/compressor characteristics or a software error. The anode gas content of carbon monoxide increases from the normal level. This could be due to a change in the temperature profile of the reformer, or a fault on the reformer catalyst.

$\varphi_3$ - The anode gas content of carbon monoxide increases from the normal level. This could be due to a change in the temperature profile of the reformer, or a fault on the reformer catalyst.

$\varphi_4$ - Methanol vapour content in the anode gas appears, which could be due to a change in the temperature profile of the reformer, or a fault on the reformer catalyst. Alternatively, it could be due to more methanol delivered by the methanol pump than expected or a fault on the methanol evaporation system.

$\varphi_5$ - A decrease in the anode stoichiometry. This could be due to a decrease in methanol delivered by the methanol pump or due to a fault on the reformer catalyst.

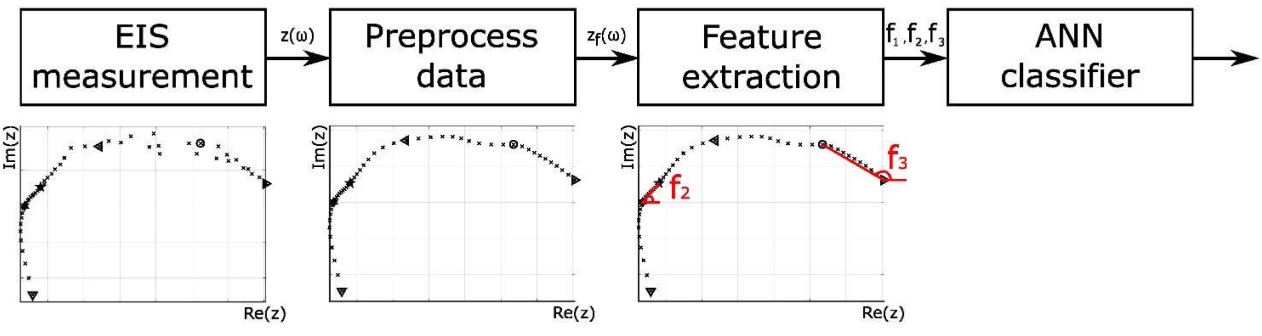



Figure 4 . Flow chart of the proposed artificial neural network fault detection and isolation methodology

The results of the ANN when tested on experimental data on short stack and its strength on detecting the different faults is shown Table 1. The Overall global accuracy on the test data is 94.6%, which is considered a good result, and it can be concluded that the artificial neural network together with the suggested features, is feasible for fault detection and isolation. The achieved accuracy for faults related to CO pollution, anode- and cathode stoichiometry is 100% success rate. However, it can be concluded that the proposed algorithm has difficulties distinguishing between the high methanol vapor concentration in the anode gas fault and normal operational data.

| | | Target class | | | | | |
|---|---|---|---|---|---|---|---|
| | | $\varphi_0$ | $\varphi_1$ | $\varphi_2$ | $\varphi_3$ | $\varphi_4$ | $\varphi_5$ |
| ANN output class | $\varphi_0$ | 98 | 0 | 0 | 0 | 70 | 0 |
| | $\varphi_1$ | 0 | 100 | 0 | 0 | 0 | 0 |
| | $\varphi_2$ | 0 | 0 | 100 | 0 | 0 | 0 |
| | $\varphi_3$ | 0 | 0 | 0 | 100 | 0 | 0 |
| | $\varphi_4$ | 2 | 0 | 0 | 0 | 30 | 0 |
| | $\varphi_5$ | 0 | 0 | 0 | 0 | 0 | 100 |

The shaded values are, the accuracy of each estimated fault given the correct fault class.

**Table 1 The result of the test data, listed in a confusion matrix. The results are listed in %.**

The work builds on a data driven method, and there is no knowledge of how the methodology would perform if utilized on a different stack from another production batch. Therefore, for deploying this methodology in the field, a larger database with impedance data from different production batches is needed, since there is no information of the impedance variance from stack to stack in the literature.

Other tests that could enhance the operation strategies of a HT-PEMFC stacks have also been carried out on single cell setups with the intent of extending the tests to stack level. Three different tests were carried out to investigate the break-in of a reformed methanol HT-PEMFC. The objective was to reduce the complexity involved in the break-in process of HT-PEMFC. The first two tests focused on reducing the break-in time to intermediate times and/or to completely do away with the break-in process. The first and second tests were same with the only exception being the break-in time was 30 hours and 50 hours, respectively for the two tests. The third test involved the break-in using simulated reformed methanol fuel on the anode.

The results showed that break-in could be useful to make sure the cells operate with reproducible performance over time. It is also seen that when operating under load cycling profile the break-in procedure could be avoided as the maximum performance could be drawn immediately. However, break-in with hydrogen is important to ensure a longer durability of HT-PEMFC when operating with reformed methanol as can be seen in **Error!**

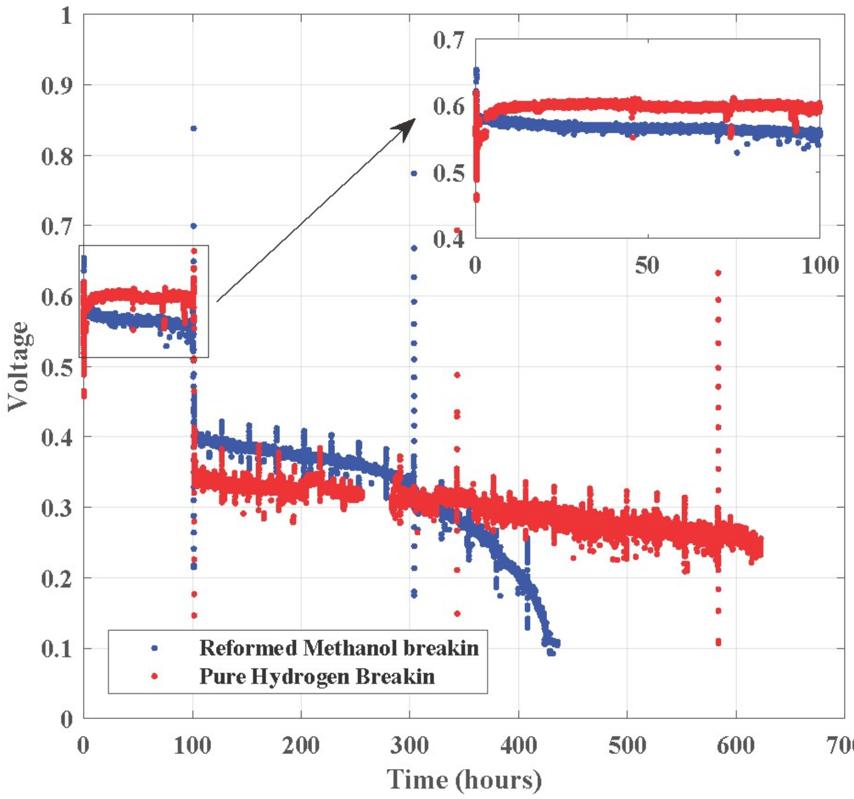



Figure 5 Break-in tests on single cell

**Reference source not found.**Figure 5.

In other tests the effect of humidification was tested. Although, the operation of HT-PEM fuel cell does not rely on liquid water, water vapor can be seen in the HT-PEM fuel cell when it is fed with syngas, which is produced by a stream methanol reforming. Therefore, the effect of anode humidification on the performance of a single HT-PEM fuel cell was thoroughly studied, as shown in Figure 6. It was observed that under different operating temperatures, the highest performance was achieved under different anode dew point temperatures. Under lower operating temperature, the low anode dew point temperature resulted in better cell performance. While under higher operating temperature, the better cell performance was achieved under high anode dew point temperature.

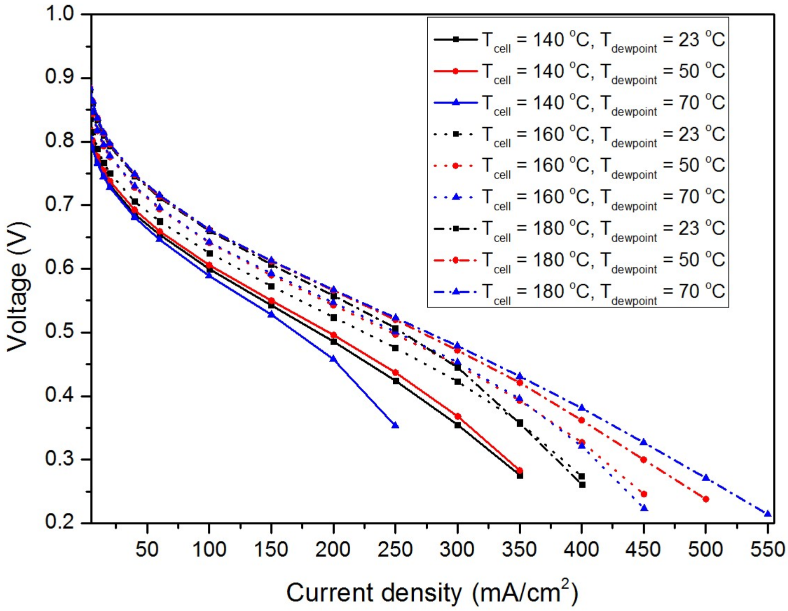



**Figure 6 Characterization of single cell under different operating temperatures and different gas dew point temperature**

The findings of this study were successively extended to stack level for optimizing control strategies and the operating condition of the HT-PEM fuel cell system integrated with a methanol reformer. The tests on stack level were performed on a 2.5 kW, 65 cells Serenergy A/S HT-PEMFC stack with Phosphoric acid doped PBI membrane and an active area of 165 cm$^2$. The operating conditions for the stack characterization were, operating temperature of 160 $^o$C and dry reformate (68.3% H2, 0.9% CO, 21.3% CO2 and 9.5% N2) and wet reformate (68.3% H2, 0.9% CO, 21.3% CO2 and 9.5% H2O) feeds on the anode to study the effects of humidification at varying stoichiometric ratios both on the anode and cathode side.

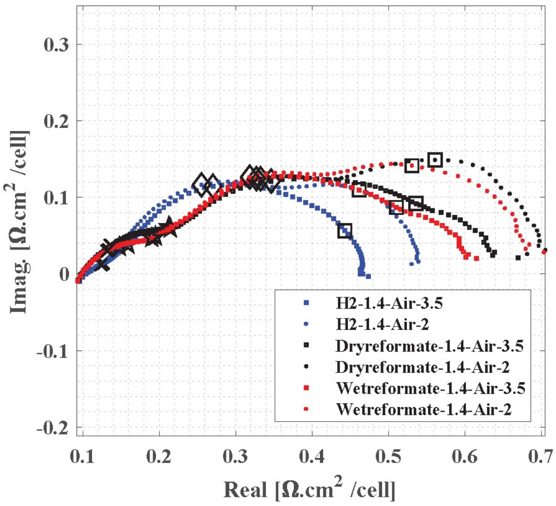



Figure 7 EIS of the cathode side stoichiometric ratios at dry and wet reformate anode feeds

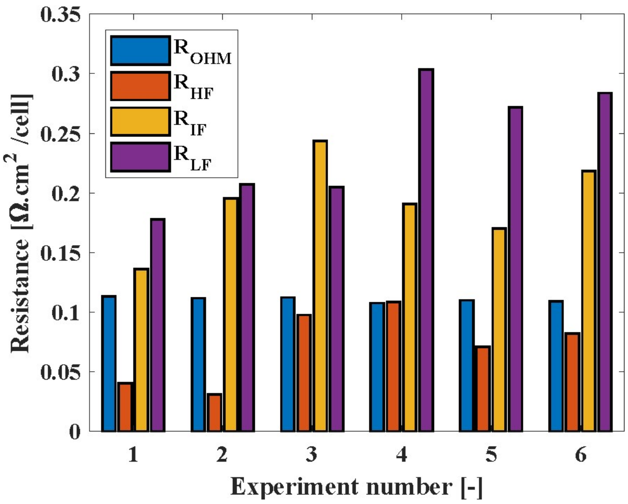



Figure 8 fitted equivalent circuit resistances of cathode EIS measurements

The results show that the low frequency resistance, which is normally dominated by mass transport losses is most affected by changes in stoichiometric ratios as can be expected. It can be seen from Figure 7 the low frequency region shrinks with the introduction of water, which may be attributed to enhanced reactants transport under humidified conditions. From the equivalent circuit fits in Figure 8, where the conditions for the experiment numbers on the x-axis are numbered according to their order of appearance on the legend in Figure 7, it can be seen that the ohmic resistance shows no changes and the high frequency resistance decreases for wet reformate fuel compared to dry reformate. Moreover, a slight benefit of increased humidification is seen on the intermediate frequency resistance at higher air stoichiometric ratio.

In Figure 9 and Figure 10 the effects of anode side stoichiometric ratios on dry and wet reformate conditions are shown. It can be seen that there is no significant effect in changing anode stoichiometric ratio between 1.15 and 1.5 under pure $H_2$ operation. However, the effects of anode stoichiometry on the mass transport dominated low frequency resistance is clear when operating with reformate, at both wet and dry conditions. Even though, similar spectra are seen for dry and wet reformate conditions, it can be said that reformate operation in general exacerbates starvation effects at lower anode stoichiometric ratios.

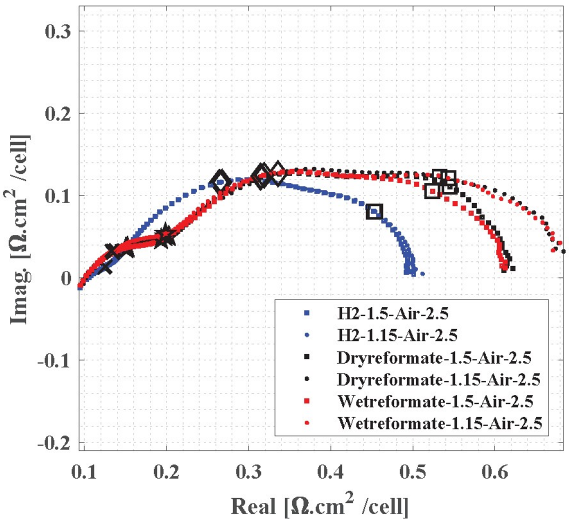



Figure 9 EIS of the anode side stoichiometric ratios at dry and wet reformate anode feeds

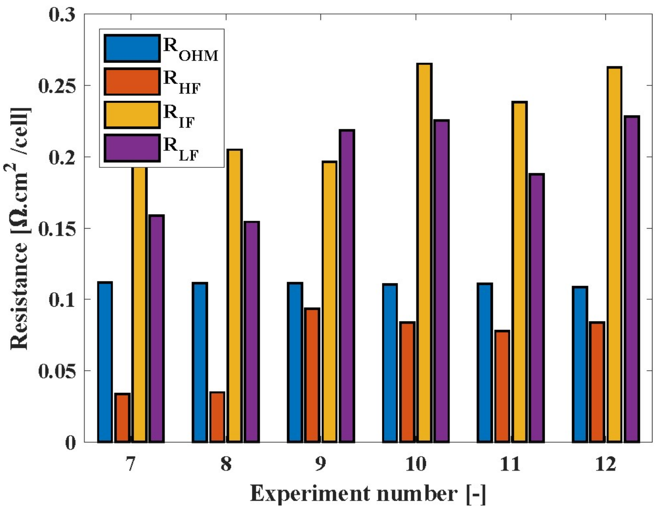



Figure 10 fitted equivalent circuit resistances of anode EIS measurements

## 5.4. Reformer test

Mapping the reformate gas composition is an important test in HT-PEM fuel cell stack development. This is because many design and control parameters of the reformer and fuel cell stack depend on the how much undesired CO and methanol is present in the reformate gas mixture that is fed into the fuel cell. Therefore, reformate gas composition mapping tests focused on CO and unconverted methanol were previously done on an older version of the reformer, which was heated by oil. The results can be seen in Figure 12 and Figure 11. Results showed that the reformer observer is a critical part of the system control, and therefore, these mappings of the reformate output are critical for robust control an

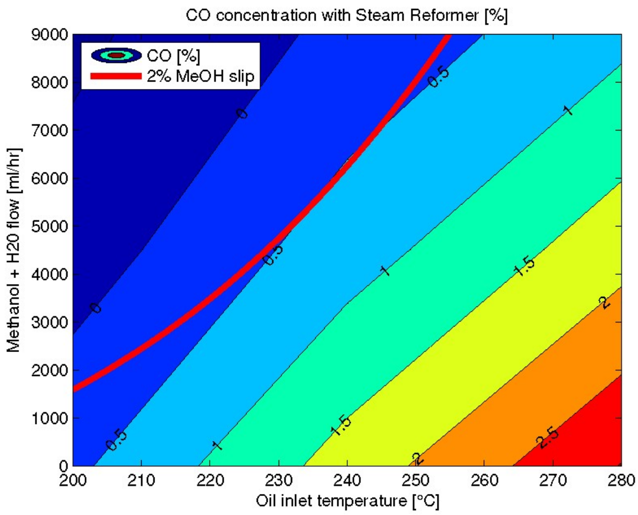



Figure 12 CO concentration mapping of a reformer at varying temperatures

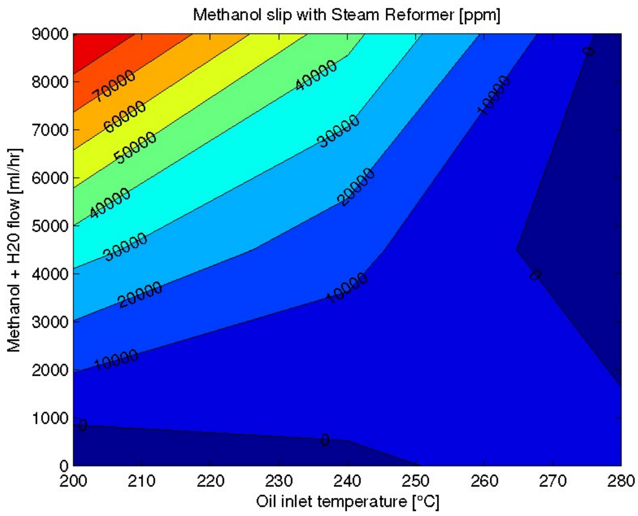



Figure 11 Methanol slip mapping of a reformer at varying temperatures

## 5.5. System test

A series of tests during startup were performed to investigate the startup time and gas composition. The goal was to identify how the different parts in the system affect the startup time. Other tests were also performed during a low temperature (below -10°C) and it was found that the oil pump for the cooling system had the biggest influence on the startup time at these subzero temperatures. Based on the results, several changes to the system software were proposed and implemented and the startup temperature was significantly reduced.

An additional test was done on at ambient temperature (about 20°C) and a control of the system exhaust gasses was performed. No significant issues were found with the startup process, however, a focus on the heat-up of the fuel cell stack is found to be the main cause of slow startup. Some of these results are shown in Figure 13.

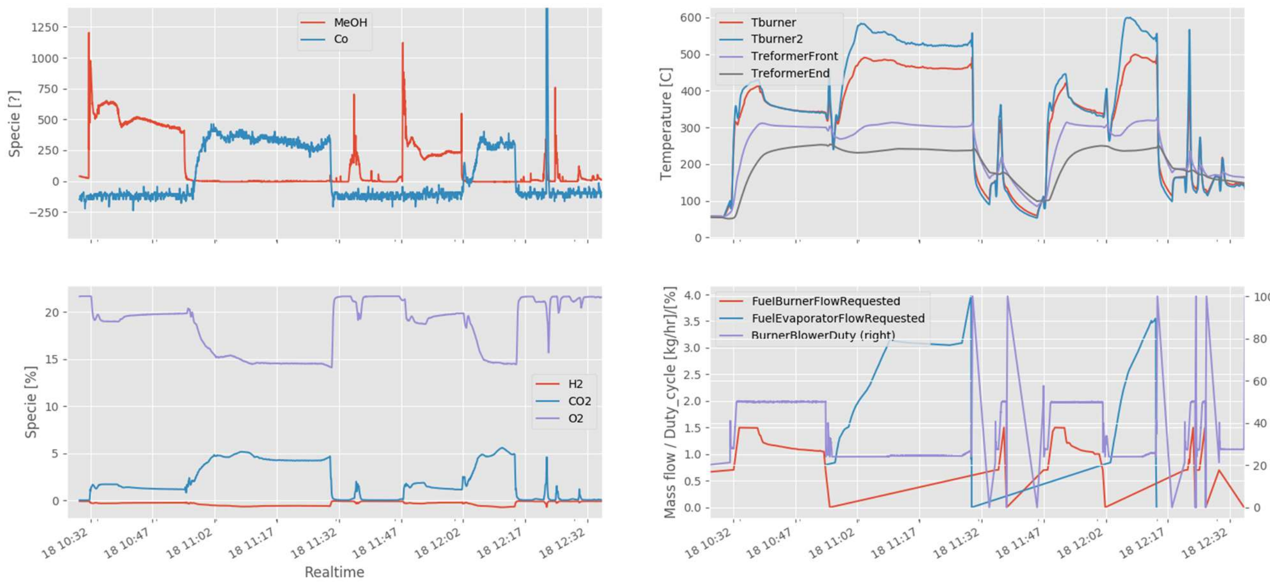



**Figure 13 Exhaust gas analysis during system startup**

## 5.6. Cost of key components

### 5.6.1. Bipolar plates

The project has focused on introduction of new production methods, for improving yield and especially deducing the cycle time of the membrane electrode assembly production. The cycle time has been reduced from 12min to 3 minutes in semiautomated operation. The is a reduction of 75% (target was 80%).

Overall the direct cost of the bipolar plates has been reduced from index 100 to index 55, hence a reduction of 45%. Especially the direct process cost has been dramatically reduced. The process cost includes machine cost, yield loss, and cleaning cost, and highly depend on the cycle time of the machine.

| | **Current Production** | | **ADDpower demonstration** | | **2022 Introduction, low volume** | |
|---|---|---|---|---|---|---|
| | Cost Index | Cost Share | Cost Index | Cost Share | Cost Index | Cost Share |
| Direct Material Cost | 100% | 28% | 100% | 51% | 90% | 74% |
| Direct Process Cost | 100% | 39% | 21% | 15% | 15% | 17% |
| Direct Labour Cost | 100% | 33% | 58% | 34% | 9% | 9% |
| **Total** | **100%** | | **55%** | | **34%** | |

### 5.6.2. Membrane Electrode Assembly – MEA

The project has focused on introduction of new production methods, for improving yield and especially deducing the cycle time of the BPP production. The cycle time has been reduced from 2min 30seconds to 60 seconds in an manual operation. The is a reduction of 60% (target was 50%).

Overall the direct cost of the MEA has been reduced from index 100 to index 80, hence a reduction of 20%. Especially the direct process cost has been dramatically reduced. The process cost includes machine cost, yield loss, and cleaning cost, and highly depend on the cycle time of the machine.

| | **Current Production** | | **ADDpower demonstration** | | **2022 Introduction, low volume** | |
|---|---|---|---|---|---|---|
| | Cost Index | Cost Share | Cost Index | Cost Share | Cost Index | Cost Share |
| Direct Material Cost | 100% | 60% | 92% | 69% | 83% | 80% |
| Direct Process Cost | 100% | 35% | 33% | 14% | 23% | 13% |
| Direct Labour Cost | 100% | 6% | 238% | 17% | 78% | 7% |
| **Total** | **100%** | | **80%** | | **62%** | |

### 5.6.3. System excluding burner and reformer

The project has been focused on reducing the overall balance of plant (BOP) cost. A design has been made introducing new coolant circulation pumps, blowers and reducing the overall component count.

Unscaled, the project as indicated a cost reduction of 45% from todays production cost.

| | Current Production | | ADDpower demonstration | | 2022 Introduction, low volume | |
|---|---|---|---|---|---|---|
| | Cost Index | Cost Share | Cost Index | Cost Share | Cost Index | Cost Share |
| Direct Material Cost | 100% | 28% | 100% | 51% | 90% | 74% |
| Direct Process Cost | 100% | 39% | 21% | 15% | 15% | 17% |
| Direct Labour Cost | 100% | 33% | 58% | 34% | 9% | 9% |
| **Total** | **100%** | | **55%** | | **34%** | |

### 5.6.4. Reformer and Burner

The project has focused on introduction of a larger and more efficeint reformer bed. The production method was build on less machining time and more extrued material. This combination would reduce the process time significantly. However results has shown, that heat distribution and leakthightness has been more challaging than expected. 2 reformer bed, and 3 burner desigs has been design, manufacted, and tested, unfortunately resulting in too high methanol slip, and too high CO values. Conclusion is, that more iterations are needed to succed with the extruted reformer type.

The extruted design has, however, proven a cost saving potential of 43% in total (no only milling). For this reason this work will be continiued, and will need even more focus in the futres.

| | Current Production | | ADDpower demonstration - FAILED | | 2022 Introduction, low volume | |
|---|---|---|---|---|---|---|
| | Cost Index | Cost Share | Cost Index | Cost Share | Cost Index | Cost Share |
| Direct Material Cost | 100% | 57% | 87% | 87% | 174% | 89% |
| Direct Process Cost | 100% | 37% | 15% | 10% | 10% | 3% |
| Direct Labour Cost | 100% | 6% | 29% | 3% | 139% | 8% |
| **Total** | **100%** | | **57%** | | **112%** | |

### 5.6.5. RMFC Module

During the project, the overall module cost has been reduced from index 100 to index 80 – that is 20%. This does not include the effect of scaling the production from todays 500 modules per year. It is important to notice that any scaling would require process and quality optimization, and first step has been taken in ADDpower project. The new production methods are suitable for increasing also cell area, but this has been exclueded from the project on module level to reduce risk of total failure. All methods has to be demonstrated before scaling the geometri, and so far we still see challenges with the new productions methods. The MEA and BPP production is only prototype level, and the methods has to be improved quality vice, before changing the production, and before changing the geometry for larger cell areas.

| | **Current Production** | | **ADDpower demonstration** | | **2022 Introduction, low volume** | |
|---|---|---|---|---|---|---|
| | Cost Index | Cost Share | Cost Index | Cost Share | Cost Index | Cost Share |
| Direct Material Cost | 100% | 67% | 87% | 72% | 52% | 81% |
| Direct Process Cost | 100% | 24% | 68% | 20% | 21% | 11% |
| Direct Labour Cost | 100% | 9% | 70% | 8% | 34% | 7% |
| **Total** | **100%** | | **81%** | | **43%** | |

## 5.7. 1st Integration in an urban bus in China

Installation Location: Bus roof top
Installed power: 20kW (25kW demonstrated)
Energy capasity in tank: 400kWh
Estimated drive time (Urban): 15-20h
Configuration: fuel cell, ultracaps hybrid.
Power: SerEnergy reformed methanol fuel cell modules (RMFC)

The motivation for the 1st integration has been to get operational experience as fast and low risk as possible, while educating the bus company engineers in the fuel cell technology. The 1st integration was intended only for first experience, and to ensure a 2nd design would fulfill the needs for bus operation with passengers.

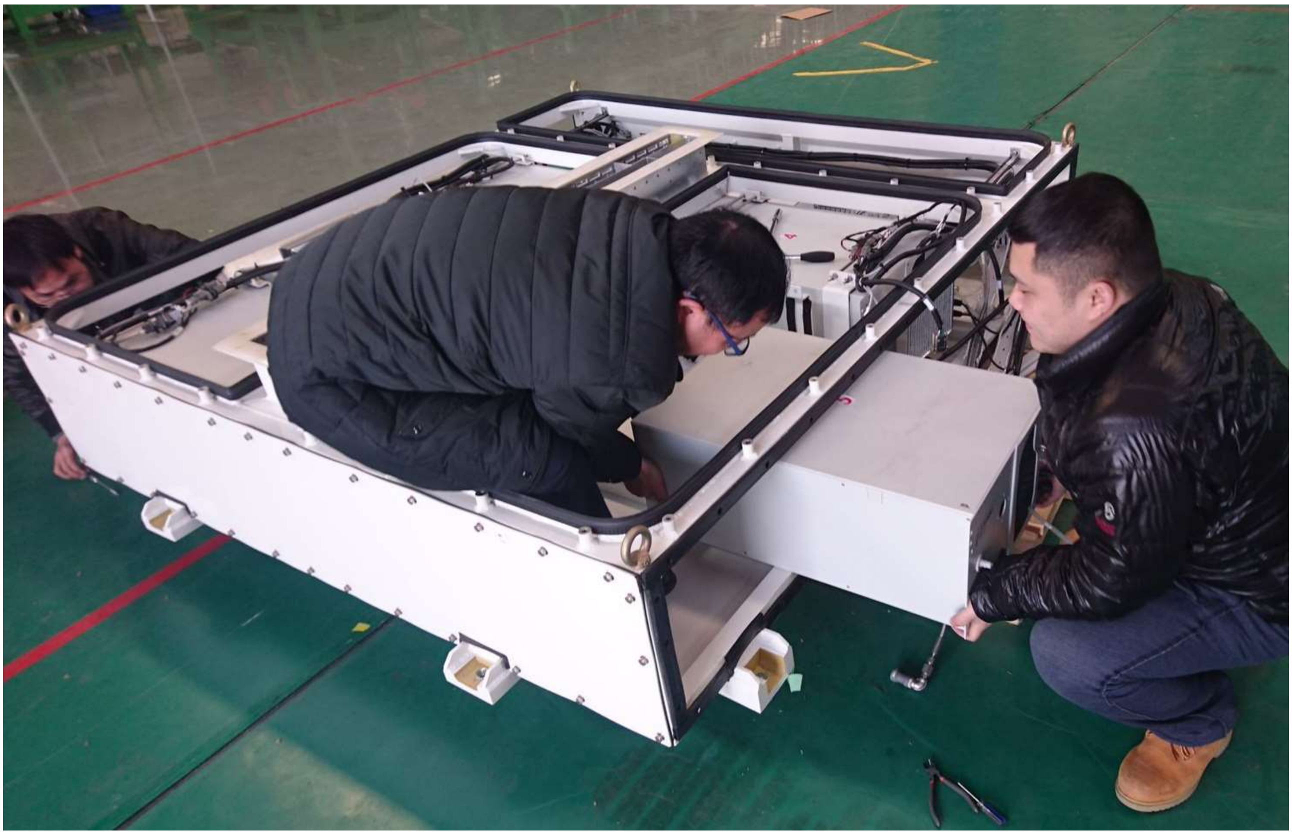


Figure 14: Mounting of SerEnergy fuel cell modules in the roof top box at bus manuafactor.

Figure 15: Fully assembled roof top box, ready for mounting on the electrical bus.


Figure 16: Fuel cell roof top box mountied on bus top.


Figure 17: Fuel cell roof top box mountied on bus top.


Figure 18: Fuel cells in operation. The display for the user is provided by the bus manufactor.

### 5.7.1. Conclusion of 1st integration

A 20kW roof top fuel cell system was successful installed and operated internally at the bus manufactor company. The integration showed a well dimensioned system able to provide the needed power for a urban drivecycle. The hybrid configuration with ultracaps for power shaping, was working well.
The system was tested for safety and performance, and only minor issues was identified, and corrective measures could be taken for the 2nd integration.

## 5.8. 2nd Integration in an urban bus in China

Installation Location: Bus roof top
Installed power: 20kW (25kW demonstrated)
Energy capasity in tank: 600kWh
Estimated drive time (Urban): +24h
Power: SerEnergy reformed methanol fuel cell modules (RMFC)

The motivation for the 2nd integration was a fully operational bus tested in Denmark. The bus would not be allowed for commercial operation, as the electrical bus did not have EU approval at the end of the project. The fuel cells has been mounted in an updated roof top box, with would from a fuel cell integration point of view, be ready for commercial operation.

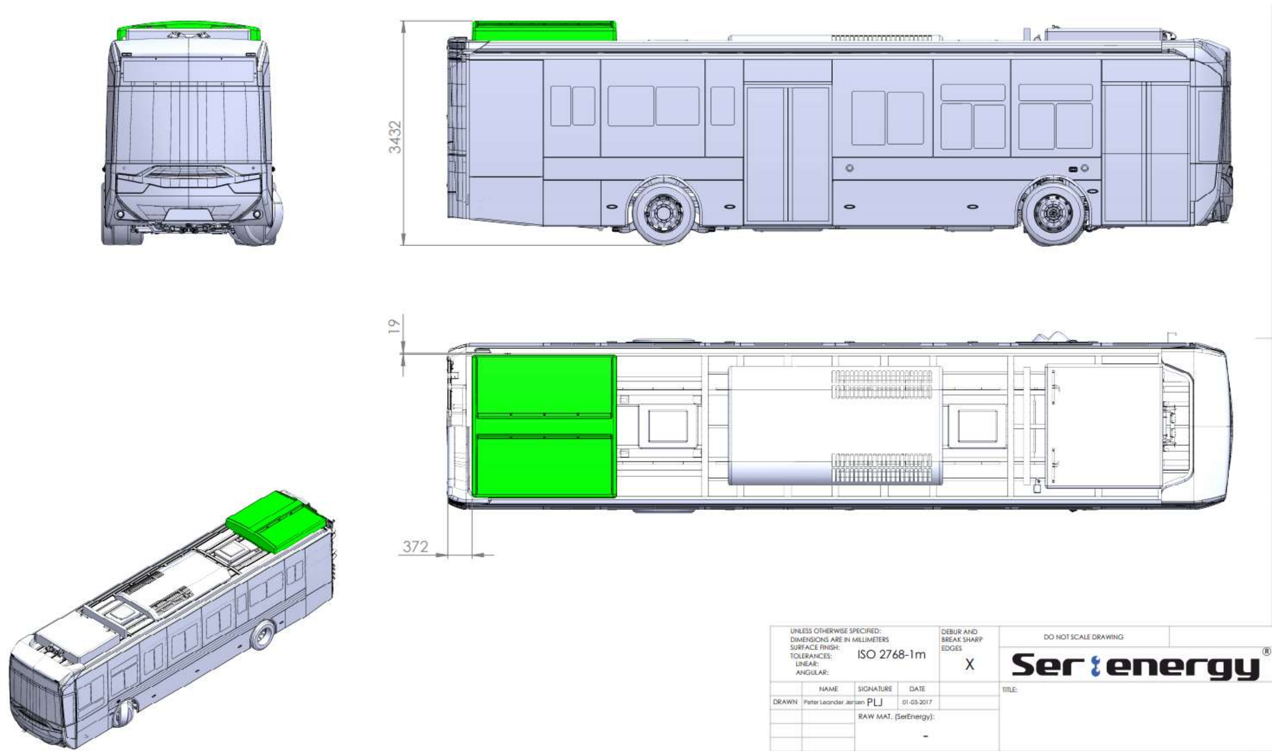



Figure 19: Principal design of 2nd integration.

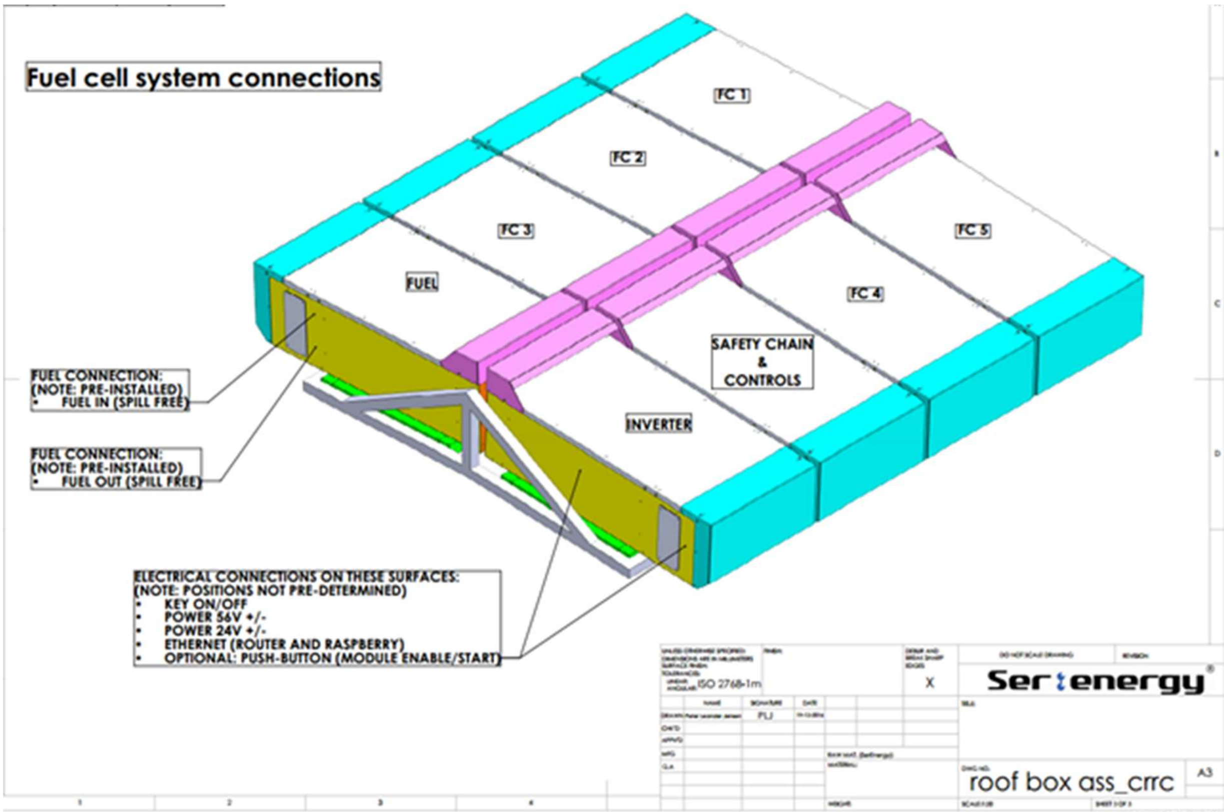


Figure 20: Roof top box for 2nd integration.

Figure 21: Assembled roof top box, excluding fuel cell modules and fuel feed system.


Figure 22: Integration of 2nd roof top box at SerEnergy in Denmark.

### 5.8.1. Conclusion 2nd integration

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.

## 5.9. Dissemination

The project results in several scientific publications which were partly or fully funded by the ADDpower project. Some of the publications are listed below.

Investigation of the Effect of Humidity Level of H2 on Cell Performance of a HT-PEM Fuel Cell. F Zhou, D Singdeo, SK Kær - Fuel Cells, 2019

Hydrogen mass transport resistance changes in a high temperature polymer membrane fuel cell as a function of current density and acid doping. S Thomas, SS Araya, SH Frensch, T Steenberg, SK Kær - Electrochimica Acta, 2019.

Investigating different break-in procedures for reformed methanol high temperature proton exchange membrane fuel cells. S Thomas, SS Araya, JR Vang, SK Kær- International Journal of Hydrogen Energy 43 (31), 14691-14700, 2018.

New load cycling strategy for enhanced durability of high temperature proton exchange membrane fuel cell. S Thomas, C Jeppesen, T Steenberg, SS Araya, JR Vang, SK Kær - International Journal of Hydrogen Energy 42 (44), 27230-27240, 2017.

Impedance characterization of high temperature proton exchange membrane fuel cell stack under the influence of carbon monoxide and methanol vapor. C Jeppesen, P Polverino, SJ Andreasen, SS Araya, SL Sahlin, C Pianese, ...- International Journal of Hydrogen Energy 42 (34), 21901-21912, 2017.

Fault detection and isolation of high temperature proton exchange membrane fuel cell stack under the influence of degradation. C Jeppesen, SS Araya, SL Sahlin, S Thomas, SJ Andreasen, SK Kær - Journal of Power Sources 359, 37-47, 2017.

An EIS alternative for impedance measurement of a high temperature PEM fuel cell stack based on current pulse injection. C Jeppesen, SS Araya, SL Sahlin, SJ Andreasen, SK Kær - International Journal of Hydrogen Energy 42 (24), 15851-15860, 2017.

Experimental study to distinguish the effects of methanol slip and water vapour on a high temperature PEM fuel cell at different operating conditions. S Thomas, JR Vang, SS Araya, SK Kær - Applied energy 192, 422-436, 2017.

Electrochemical impedance spectroscopy (EIS) characterization of reformate-operated high temperature PEM fuel cell stack. SL Sahlin, SS Araya, SJ Andreasen, SK Kær- International Journal of Power and Energy Research 1 (1), 20-40, 2017.

# 6. Market and Oppotunities

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.

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.

### 6.1.1. 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 amounts to 2 billion USD spend on DC backup systems and a 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.

### 6.1.2. 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

### 6.1.3. 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.

### 6.1.4. 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.

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.

## 7. Utilization of project results

Following the Commercial Roadmap setup for this project, 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 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 China Bus project is development of E-Mobility. Following the 3 key principles stated for the use of the fuel cell in mobility projects, 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.

## 8. Project conclusion and perspective

The primary objective of the ADDpower, has been to increase the overall power output, and decrease the kW cost to provide a suitable product for semi high power integration in e.g. heavy duty applications. The design and test of the integrated 20kW fuel cell system was reached within the extended 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.

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, 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 enviorenments 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.

The ADDpower projects and derivative practice indentations will drive the increased demand of a high power, high quality product, at a acceptable cost. 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 3000 units, totaling 225.000.000 DKK within the 3-year timeframe stipulated on the project application.

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.