Final report

1.1 Project details

Project title	FC2Scale
Project identification (program abbrev. and file)	EUDP j. nr: 64012-0014
Name of the programme which has funded the project	EUDP
Project managing company/institution (name and address)	Ballard Power Systems Europe Majsmarken 1 9500 Hobro
Project partners	Stofa, Ektos DK, Ektos UA, Desitek
CVR (central business register)	30804996
Date for submission	31-12-2016

1.2 Short description of project objective and results

English: The main goals of the project were to investigate the cost benefits in scaling the fuel cell systems main components. The main component and the most expensive component in the fuel cell system is the fuel cell stack. The project scope was therefore to scale the fuel cell stack in order to uncover the cost benefits and the technical performance by fuel cell system with smaller stacks.
The second goal in the project was to develop a remote SNMP communication interface. The SNMP protocol is well known and used for remote monitoring by the typical backup customer. The remote monitoring is an essential tool for the customer to insure stable operation of the backup systems.
The last goal in the project was to improve the fuel cell backup system's reliability by improving the self-diagnostic and self-maintenance functionalities. Self-maintenance (self-test) functions are essential for the fuel cell system to insure the readiness when there is need for backup from the fuel cell system. Self-diagnostics functionalities are important for the system's reliability and robustness against degradation and shut down because of non-critical errors internal in the fuel cell system.

Dansk: Hovedformålet med dette projekt var at undersøge de økonomiske fordele ved at skalere brændselscelle systemets hovedkomponenter. Hovedkomponenten og det dyreste komponent i brændselscellesystemet er brændselscellestakken. Formålet var derfor at skalere brændselscellestakken for at synliggøre den økonomiske gevinst og den tekniske formåen for et brændselscellesystem med en mindre brændselscellestak. Det andet mål i projektet var at udvikle en fjern SNMP kommunikationsinterface. SNMP protokollen er kendt og meget brugt til fjernovervågning af den typiske backup kunde.
Remote overvågning er et essentielt værktøj for kunden til at sikre sig en stabil drift af backup systemerne.
Det sidste mål med projektet var at forbedre brændselscellesystemets pålidelighed ved at forbedre selvdiagnostik og selvvedligeholdelses funktioner. Selvvedligeholdelses (selvtest) funktionen er essentiel for brændselscellesystemets parathed når der er brug for backup fra brændselscellesystemet. Selvdiagnostik funktionaliteten er vigtig for systemets pålidelighed og robusthed mod degradering og mod nedbrud på grund af ikke kritiske fejl internt i brændselscellesystemet.

1.3 Executive summary

The FC2Scale project managed successfully to develop scalable systems, improving the system control reliability and remote monitoring via SNMP according to the project plan. Through market research and technical investigations, we ended up in choosing 5 system sizes based on 4 different stack sizes 66, 56, 46 and 34 cell. 66 and 56 cell stack sizes were used before in standard systems, but the 46 and 34 cell were built with the standard stack sizes as basis.

The test system with scalable stack was built with system components which were scaled according to the smaller stack size. We found out that the cost reduction only makes sense with scaling the number of DCDC converters and ultra-capacitor bank (bridge power). Other existing components were kept as they were. The mechanical components and cabinet were unchanged from the existing 5kW product with two main arguments: 1. The customers didn't ask for smaller mechanical size and 2. Keeping the existing mechanical design made it possible to upgrade the scalable system from i.e. 3,2kW to 5kW.

The analysis of the cost reductions showed a proportional decrease in price for the three costliest components: stack, DCDC's and ultra-caps. This meant that the system cost reduction was significantly but not proportional, because mechanical and many BoP components were unchanged in the scalable systems.

The development and field test of the scalable system showed that the concept works from a technical point of view. However, the feedback from the project partner Stofa indicated that there is no need for scalable sizes below 5kW.

The remote monitoring through SNMP was met by development of SNMP box that are intended to be used together with all scalable sizes based on the 5kW system and the 1,7kW system.

The field test of the SNMP box on the 4 test sites provided by Stofa showed a very stable and robust communication interface that was tested in integration with existing Stofa Network Operation Center (NOC).

The SNMP box gives great potential for remote monitoring not only for the customers NOC but also as an interface for the fuel cell systems service department to optimize service simply by having the possibility to get a better picture of the fuel cell system condition and error type in case of shut down.

1.4 Project objectives

The project objectives were following 3 activity tracks:

- Develop and investigate the technical and economic advantages of scalable system sizes with main focus on fuel cell stack size scalability.
- Develop communication interface with SNMP. To support remote monitoring in order to improve reliable operation of the fuel cell system.
- Improve fuel cell system self-diagnostics and self-maintenance functionalities in order to improve the system reliability and robustness.

1.5 Project results and dissemination of results

WP1 - Specifications and requirements for a scalable fuel cell solution

The list below summarizes the WP task content and the status.

Work packages	Milestones, Deliverables	Status
WP1 - Specifications and requirements for a scalable fuel cell solution	M1 - Specifications for the modular fuel cell solution established and PRD prepared, D1-Product requirement document (PRD) KM1 - Marketing strategy report, D2-Marketing strategy report	Done
WP2 - Development of a flexible and scalable fuel cell core module	M2 – Core elements design and operation parameters established D3 – Report on the operating and design parameters of core fuel cell elements (internal, confidential report) M3 – Fuel cell module prototype constructed D4 – Prototype fuel cell module that can fit into an overall solution architecture adaptable to any installation KM2 – Evaluation of cost target €/kW	Done
WP3 - Development of scalable power conditioning/management system	M4 – Power management system designed for production D5 – Design for a high efficiency cost-effective scalable power management system	Done
WP4 - Development of communication interface	M5 – Communications interface designed and ready for implementation D6 – Fully functional communications interface	Done
WP5 - Technology integration, testing and prototyping	M6 – Prototype power backup systems lab tested and ready for field trials D7 – Complete mechanical design of the integrated fuel cell-based power backup system D8 – Report on laboratory testing and verification of test results D9 – Prototype power backup systems to be tested in field trials	Done
WP6 - Field trials	M7 – Field trials concluded and documented D6 – Report on the results of the field trials	Done
WP7 - Project Management and Dissemination	M8 – Mid-term assessment M9 – Final deliverables and reports D10 – Management periodic status reports (every 6 months) D11 – Dissemination plan D12 – Management final report	Done

1.5.1 WP1 description

The product is specified in detail based on the market knowledge gained over the past generations of fuel cell power backup systems, combined with customer requirements and the known limitations of the technology. The work is done in close cooperation with the involved parties and includes a comprehensive analysis of the overall and specific characteristics of the solutions needed to meet demands and performance targets of partners and operators in general.

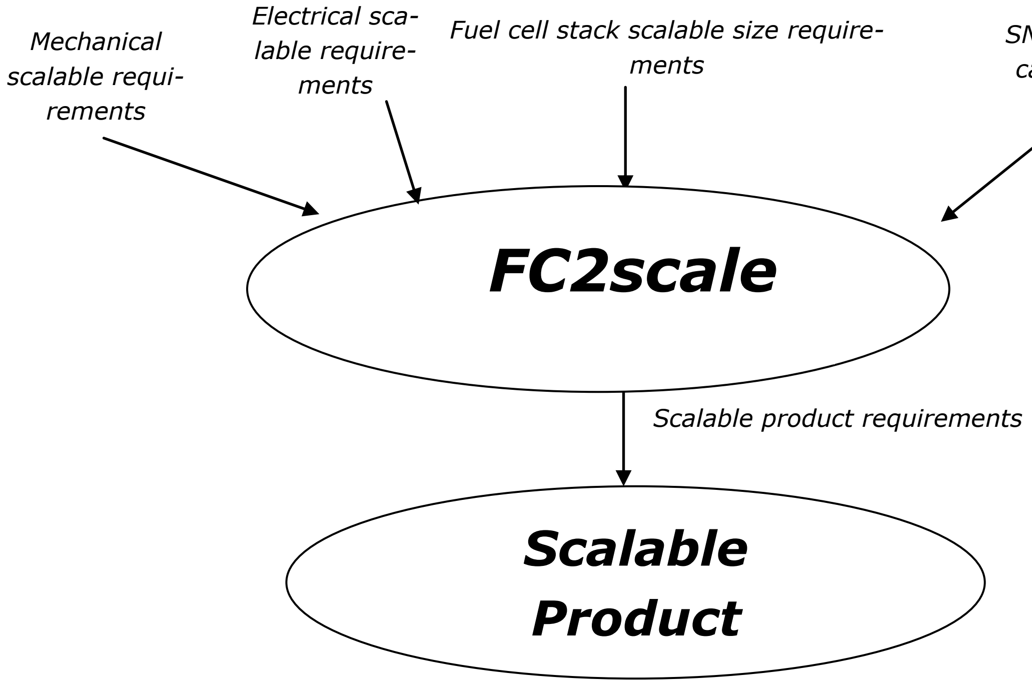
The outcome is a clear understanding of demands and background, technical and commercial, to ensure the best basis on which to develop the *FC2Scale* concept.

1.5.2 WP1.1.2 - Product requirements from KM1

The primarily project goal that the EUDP originally approved was, in short terms, to make cheaper systems based on scaling the fuel cell unit to the actual customer requirement. If customer requires a FC system with output power of 3kW or 1kW, then the existing 5kW or 1,7kW system is too expensive because of the fuel cell stack is oversized. Scaling existing power electronics and improving control and communication interface to be more reliable was also in the scope of the project.

Scope for Marketing strategy report
Based on the market knowledge and the competitive advantages of the product, a specific market exploitation strategy was defined during the course of the project.
This exploitation has been carried out and can be divided into four categories:

- Mechanical scalable sizes investigations for customer requirements WP1
- Fuel cell stack scalable sizes investigations for customer requirements WP1 and WP2
- Electrical scalable customer requirements WP3
- SNMP communication customer requirements WP1 and WP4



Scalable components in system

Figure 1 Exploded view of complete 5kW fuel cell system are the 3 most expensive components that all are possible to scale together with the fuel cell stack.

- Fuel cell unit
- Controller unit
- Bridge power unit

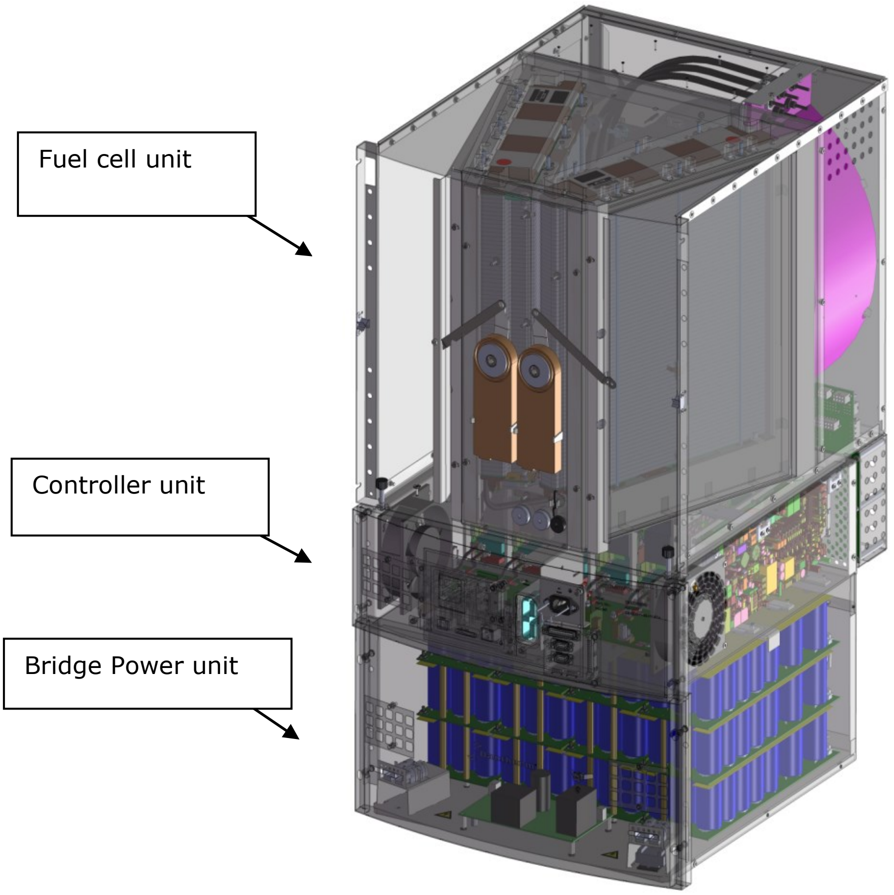


Figure 1 Exploded view of complete 5kW fuel cell system. The three most expensive components.

Mechanical scalable sizes investigations WP1

Mechanical scalability Scope
Feedback from key customer and project participant SydEnergi (Stofa).
There is no requirement from the market to reduce mechanical dimensions of the product even if it's a 1KW system. SydEnergi has typical 19 inch. rack space for backup purpose and this space is enough for two 5kW systems, which is the maximum power demand seen from fiber net distribution sites. So it brings no value to reduce mechanical outline dimensions. Besides that, keeping the same mechanical platform on all scalable products will reduce stock expenses and make it easier for customers to upgrade the product. It can be cut down to the following requirement input based on market feedback:

- FC2Scale products are based on the same mechanical platform as the DIBDBX5000.
- Upgrade possibilities must be implemented
    - Replacing of existing FC stack with new larger FC stack
    - Or upgrading with new small FC stack so system have two small FC stacks.

Fuel cell stack scalable sizes investigations WP2
Stack scalability Scope

This is the key requirement from project scope, due to reducing the price, if customer doesn't need 5kW, but for instance only 3kW. The customer feedback indicates the possibility to upgrade, for instance, a 3kW system to an 5kW system. The choice of scalable sizes is a key point of the work. The investigations of actual load demand from customer sites give input to the choice of the reasonable stack sizes. The table below shows a typical actual load from 48VDC backup in Fibernet distribution shelter from Danish customer NRGI.

Load demand from typical backup customer NRGI see Figure 2

Name	Location		Load demand required	Actual load demand	H2 bottles
MES-A	Thorsagervej 13a	Ryomgård	10 kW	10 kW	8+1
HOR-A	Emilies Plads	Horsens	10 kW	9 kW	7+1
HED-A	Gesagervej / Mosegade	Hedensted	5 kW	4 kW	3+1
ARC0110	Brendstrupgårdsvej 5	Århus N	5 kW	2,5 kW	2+1
HOR0907	Hattingvej 1	Horsens	5 kW	4 kW	3+1
HOR0801	Ane Staunings Vej	Horsens	1,7 kW	1,7 kW	2+1
ELE-A	Høvej 33	Lystrup	5 kW	3 kW	3+1

Figure 2 List of field sites that represent different load requirements

The number of systems and power capability of the systems that can be realized, based on the DIBDBX5000 platform, are determined by the fact that the DCDC converters can deliver 1kW output power each, down to a voltage input limit of 30VDC. Also, the systems parasitic power must be drawn from the DCDC converter's output, which reduces the net power output capability of a system. The power capability of the DCDC converter is illustrated on the figure below see Figure 3.

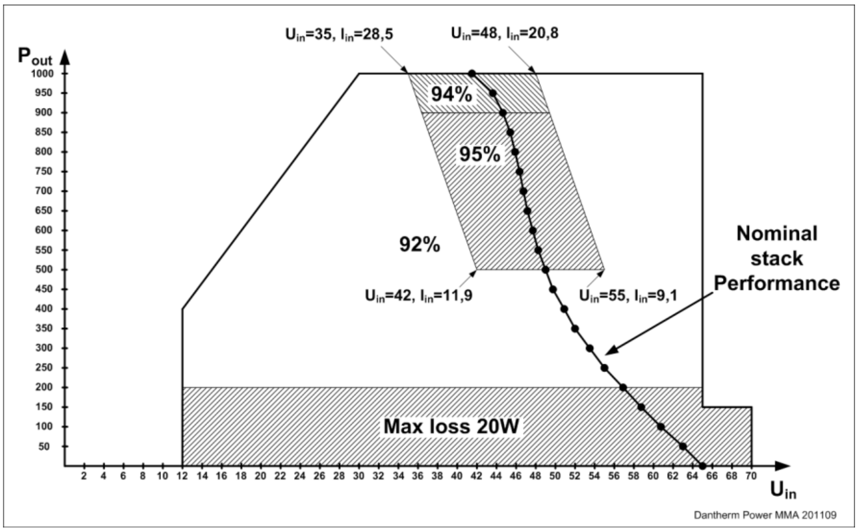


Figure 3 DCDC load curve

Scalable system cost comparison

The scalable system cost has been analyzed in order to visualize the cost benefits for different scalable system sizes (see Figure 4). Based on the analysis, the cost increases very little going from 2,5kW to 3,6kW system size, which must be seen as the optimal scalable size looking at the cost/power.

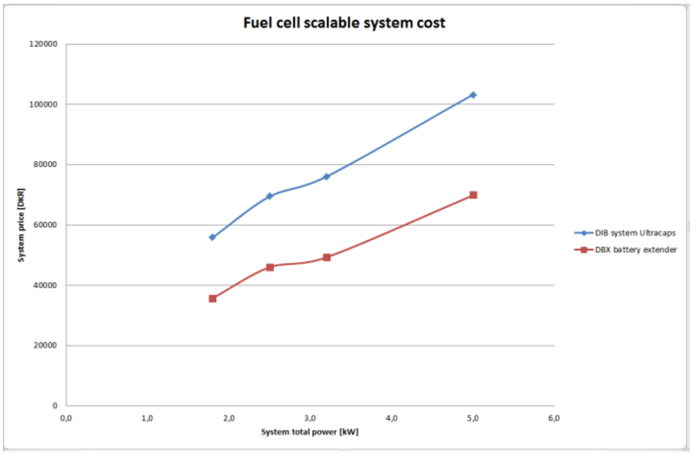


Figure 4 Scalable system cost for different system load sizes. Its seen that going from 2,5kW to 3,2kW are related to the smallest cost increase.

Preliminary suggestions for stack sizes based on market knowledge from WP1

Following stack sizes were chosen to build for prototyping and later field test.

1.1 5kW system NOT BUILD BECAUSE IT IS A DEFAULT SYSTEM

In the 5kW configuration two 66 cell stacks are being used along with 2 times three DCDC converters.

Main power data from the system:

- Maximum gross power from stacks at 40 DegC: 5500W
- Maximum power from stacks at BoL (Beginning Of Life): 5800W
- Maximum DCDC input current capability per stack : 70A (limited by SW)

1.2 3.2kW system BUILD AS PROTOTYPE

In the 3.2kW system two 46 cell stacks are used in combination with two times two DCDC converters

Main power data from the system:

- Maximum gross power from stacks at 40 DegC: 3900W
- Maximum power from stacks at BoL: 4000W
- Maximum DCDC input current capability per stack: 70A (limited by HW)

1.3 2.5kW kW system BUILD AS PROTOTYPE

In the 2.5kW system one 66 cell stack is used in combination with three DCDC converters.

Main power data from the system:

- Maximum gross power from stacks at 40 DegC: 2900W
- Maximum power from stacks at BoL: 2800W
- Maximum DCDC input current capability per stack: 70A (limited by SW)

1.4 1.6kW system BUILD AS PROTOTYPE

In the 1.6 kW system one 46 cell stack is used in combination with two DCDC converters.

Main power data from the system:

- Maximum gross power from stacks at 40 DegC: 1700W
- Maximum power from stacks at BoL: 2000W
- Maximum DCDC input current capability per stack: 70A (limited by SW)

1.5 1kW system NOT BUILD AS PROTOTYPE STACK SIZE IS EXPECTED TO BE SMALL.

In the 1kW system one 34 cell stack is used in combination with two DCDC converters.

Electrical scalable requirements WP3

Electrical scalability Scope

In the same way as scalable stack requirements argument, to scale electronics is to reduce cost on end product. Based on experience from the service department with system errors, there is a need for using scalable possibilities also for making redundancy and hereby more robust systems.
Based on feedback from SydEnergi there are also requirements for building AC backup solution. This requires investigations for an add on solution containing AC inverter and AC distribution components. The conclusion based on customer feedback can be cut down to the following requirements:

- Scalable electronics by reducing number of DCDC converters and Bridge Power modules to fit actual power demand.
- Improved robustness by using possible redundancy of components hence DCDC converters and Bridge Power ultra-cap building blocks.
- AC backup requirements.

SNMP communication investigations WP4

SNMP communication Scope

To an end-user, the communication interface is a core attribute of a power backup system as reliability and knowledge of system status is the highest priority. The fuel cell module must be possible to implement in an overall operation structure at any given operator.
The interface must live up to the demands for type on protocol and call out strategy. The novel communications protocols for network integration must be identified and incorporated into the modular design. The communication interface will be developed on the basis of the new communications protocols for network integration identified in the PRD (SNMP expected from WP1). The outcome is a complete variety of communication options either as standard or as an option with slight modifications. It is imperative that all demands can be met by configuring or adapting the standard solution. Both integrated solutions and external add-on solutions must be explored.

1.5.1 WP2 - Development of a flexible and scalable fuel cell core module

WP2 Summary

The first task within WP2 comprised R&D in key attributes of the core technology, thereby enabling the development of a solution that entails the features specified in WP1. The activities were related to:
- temperature capabilities;
- start-up times of the fuel cell stack;
- cell loading trade-offs;
- cell and stack design for scalability.

The membrane humidification and hydrogen distribution on the cells under real life conditions are the main challenge for optimization but also the cooling/temperature conditioning under these conditions is of great importance. The in-depth investigations of these parameters under impact of real life conditions resulted in a choice of fuel cell stack operating parameters that can be considered the optimal choice with the present knowledge.

The second task in WP2 was to determine the load profile and match this to the fuel cell stack size based on operating parameters defined in task 2.1.
This was used to develop the fuel cell module and incorporate the stack into a complete system. The main priority was on the development of a simple solution that entailed all technical aspects of task 2.1 and ensured an optimized solution in accordance with WP1. Primary focus was paid to a modular and flexible solution that enabled an easy scalability without compromising the competitive sustainability of the solution.

1.5.2 Design of prototypes

In the following chapter scalable mechanical system design will be discussed based on the selected load sizes chosen in previous chapter.

3.2kW system

In the 3.2kW system two 46 cell stacks are used in combination with two times two DCDC converters see Figure 5 and Figure 6

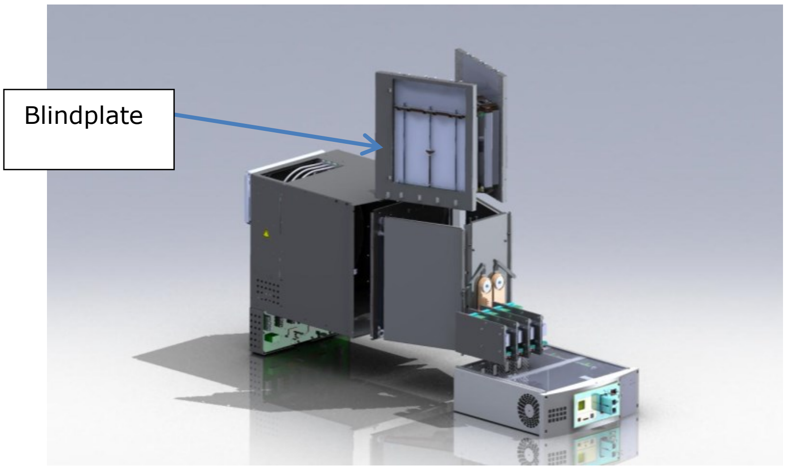


Figure 5 3,2kW scalable system mechanical design.

Figure 6 3,2kW scalable syste hanical components are unchanged compared with 5kW system. Blind plates are added on l stack to reach the height of a 66 cell stack.

2.5kW kW system

In the 2.5kW system one 66 cell stack is used in combination with three DCDC converters see Figure 7

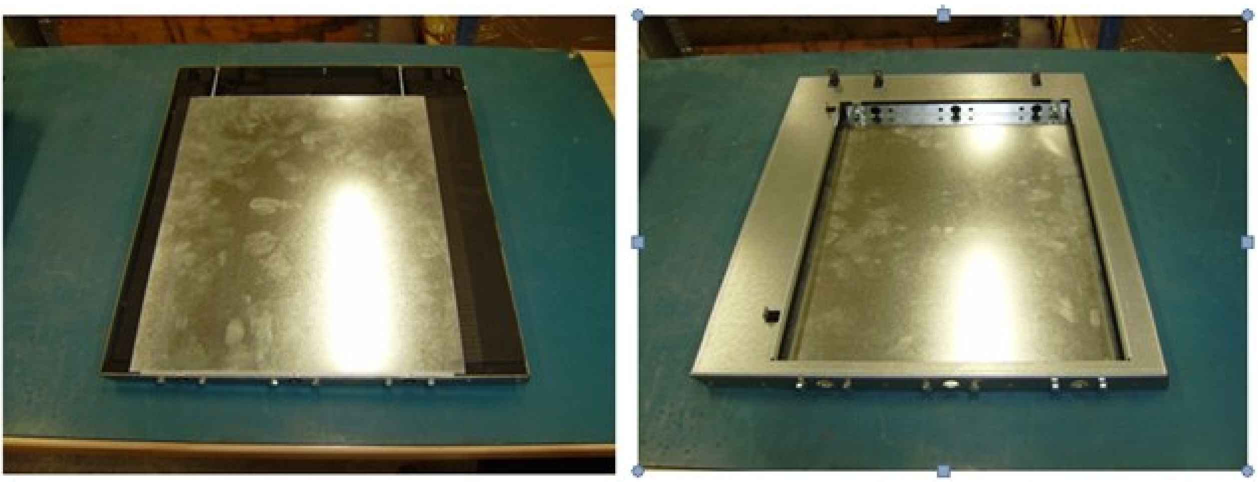


Figure 8.

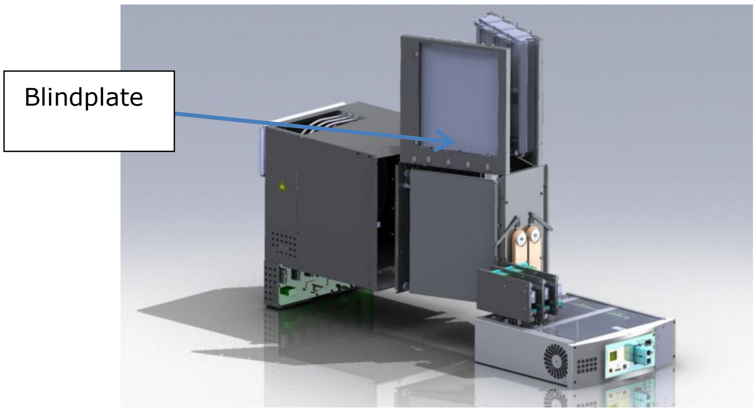


Figure 7 2,5kW scalable system consists of one 66cell stack compared with 2 stacks in an 5kW system. Blind plate is mounted Instead of the missing stack in order to keep airflow intact.

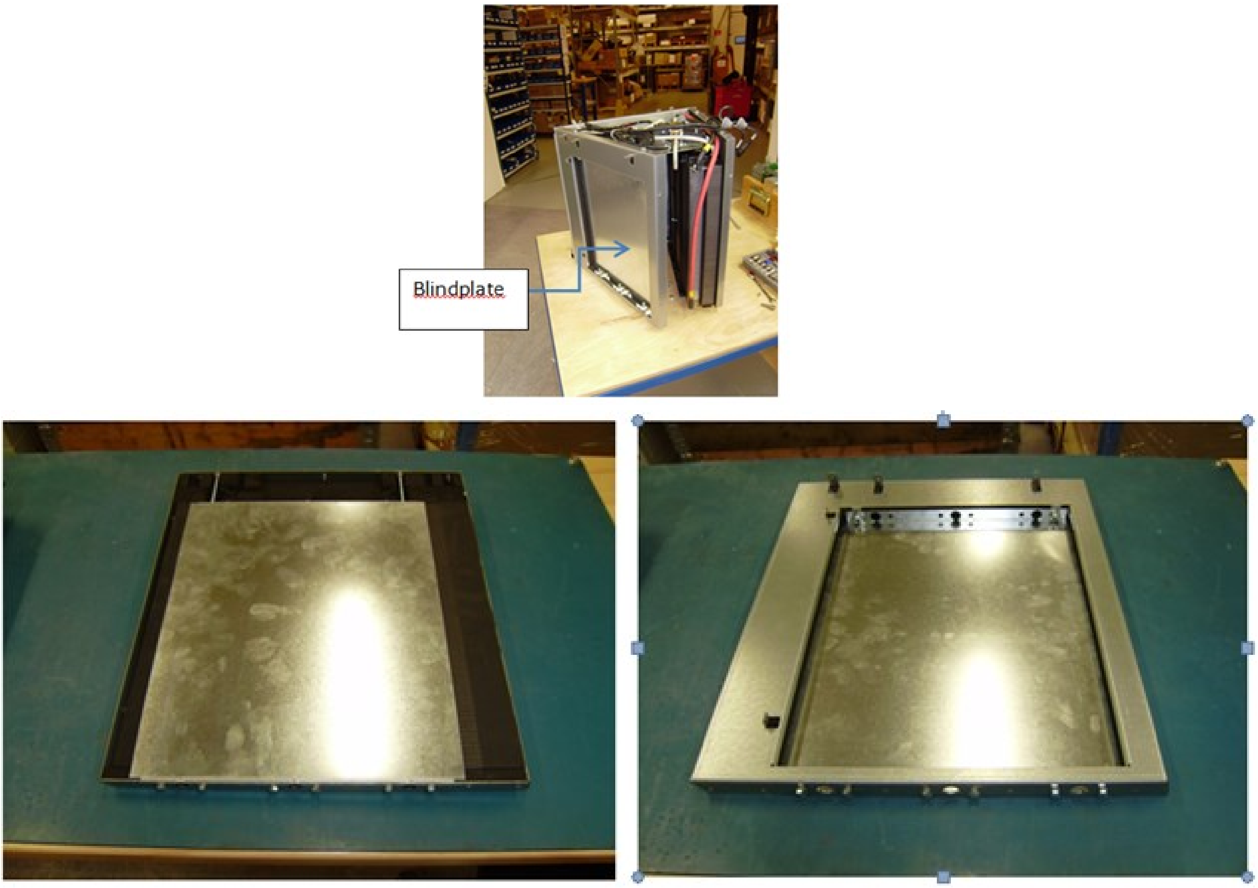


Figure 8 2,5kW scalable system in real. Blind plate that replace on 66cell stack is needed to be tight in order to keep airflow intact for the remaining 66cell stack

1.6kW system

In the 1.6 kW system one 46 cell stack is used in combination with two DCDC converters see Figure 9.

Figure 9 1,6kW scalable system with one 46cell stack. Blind plates are mounted in both sides to keep stack room air tight.

1.5.3 WP3 - Development of scalable power conditioning/management system

WP3 description

A scalable fuel cell system solution requires a corresponding scalable power management architecture. Similarly, the efficiency of the power management system is of great importance as electrical losses add to the size requirements of the fuel cell stack and also the hydrogen consumption. The power management system has to accommodate requirements from the PRD (WP1) regarding output voltage and possibly both DC and AC output power. An aspect of a flexible and scalable solution is ensuring the correct type of electrical power and architecture. The subject is both in relation to internal power management and auxiliary power management.

The internal power hardware of the fuel cell module was developed to meet explicit demands from standards and regulations but also to ensure an architecture that fits the overall concept e.g. redundancy or easy scalability, where applicable external components

Fuel Cell Controller (FCC) SW improvements

1.5.3.1 Software improvement. ‘Adaptive self-test’

Requirement: Because the self-test was found not working on old fuel cell stacks with degraded stack performance, an improved adaptive self-test was added. It was required that self-test should adapt to the individual stack performance so even an old stack could pass self-test with the possibility to downgrade it were needed. In this way, the Fuel cell system is more robust because it helps the stack get up running at its maximum load and hereby prevent system error which was the case before this functionality was added. See Figure 10 for adaptive self-test flowchart.

The functionality was implemented to flow charts and specification specified in sw. specification

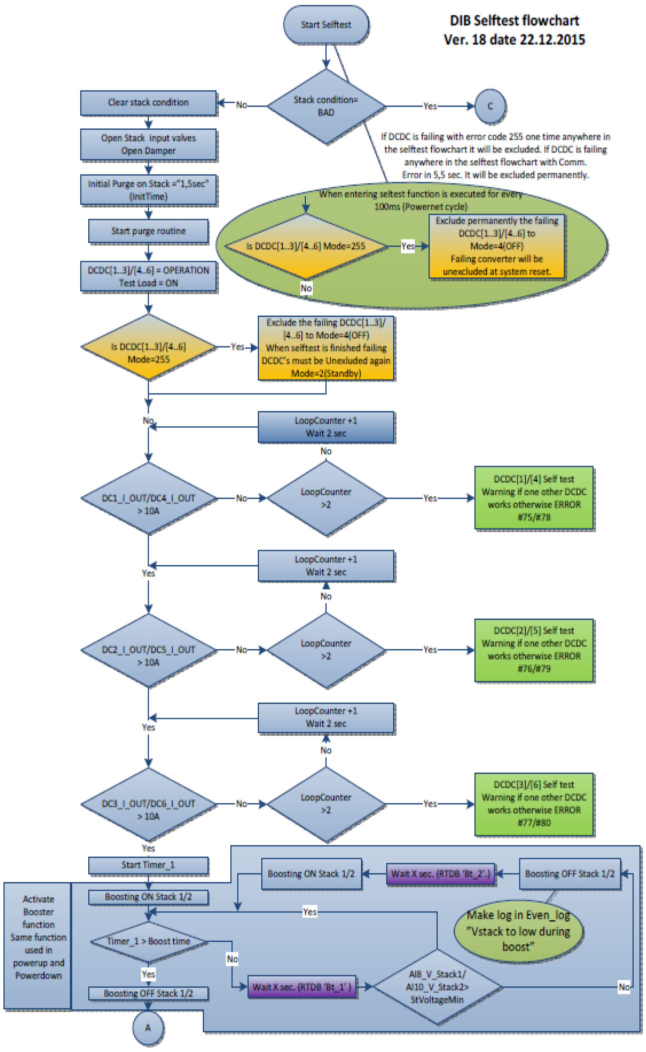


Figure 10 flowchart showing the sw. functionality 'adaptive self-test' added under Fc2scale project. The functionality adapts to the fuel cell stack performance and 'helps' it get up a running instead of pushing the system to system error.

1.5.3.2 Stack sensor disregard functionality. Sw. Improvement.

Requirements:
The sensor error results in that the temperature measurement drifts up (resistance of sensor drifts down). Therefore, the software must be able to disregard a stack sensor that drifts upwards in temperature measurement. The following software change were made s(ee also **Fejl! Henvisningskilde ikke fundet.**):
Delta T Stack 1 = |Tstack 1,1 - Tstack 1,2|
Delta T stack 2 = |Tstack 2,1 - Tstack 2,2|

If Delta T for stack 1 or stack 2 rises above 10 deg C (set point must be configurable in RTDB), the system must do the following:

1: The highest temperature must be disregarded in all system functionality (e.g. safety, control loops, etc.)

2: The sensor value must still be logged

3: This shall be done in all system states

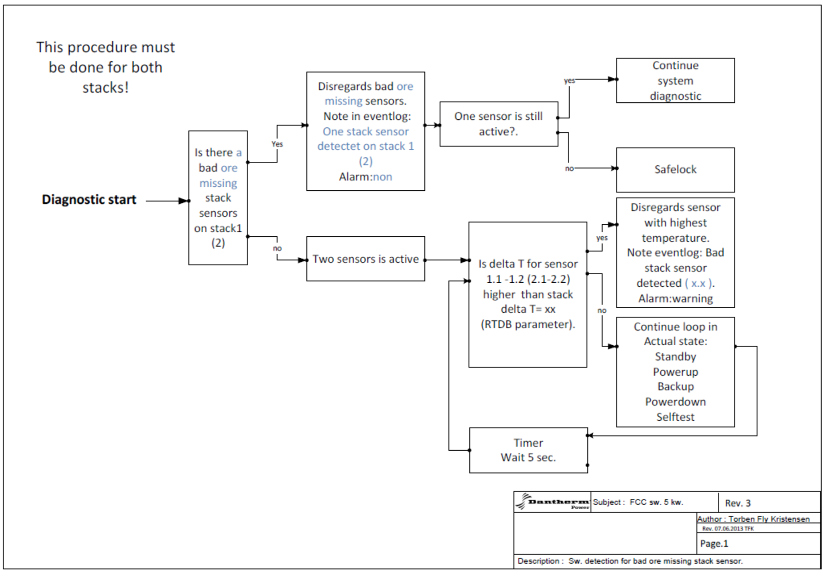


Figure 11 Functionality diagram for sw. functionality 'bad stack sensor disregard'. the function disregards a stack sensor if it fails, in this way the system can stay operational instead of going to system error.

1.5.3.3 Sw. improved robustness during improved DCDC converter error handling.

SCOPE: The system can operate with down to 1 working DCDC converter out 6, if the load requirement allow it see Figure 12. This functionality gives much more robust system since system stay operating if up to 5 DCDC converters fails and the load demand allow it. This functionality is developed and added in the Fc2scale project and tested with success in Stofa field test systems.

- If DCDC goes to error, then FCC tries to start it up again.
- If the DCDC sends error message more than 5 sec. Before its excluded from operation

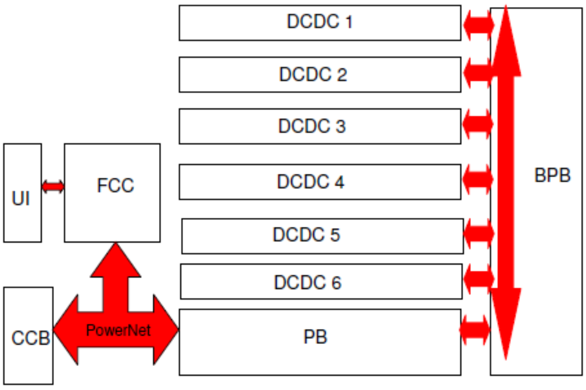


Figure 12 functionality diagram for electronics boards inside the fuel cell controller. With sw. functionality 'DCDC error handling' added the 6 DCDC converters gives more robust system since system doesn't go to system error mode if up to 5 DCDC converters fail.

1.5.3.4 Description of the problem

We have an inrush circuit on the DCDC converter that works when the DCDC converter is not powered up. To make the DCDC converter more useful in different system setups, we wanted to implement a solution where the inrush protection is also working if the DCDC converter is already powered on. An example of this kind of system could be a system where ultra-capacitors are connected to the input of the DCDC converter to insure fast startup. If a system like this charges, ultra-capacitors can keep the DCDC converter powered on even if the fuel cell system is disconnected from the 48V line. If the fuel cell system, then is connected to the line before the ultra-capacitors are discharges the inrush protection is not active and we risk a site breakdown.

The fuel cell backup system needs to be able to be connected to a running site without any interfering to the line to avoid that the site breaks down. For that purpose, an inrush circuit is implemented on the output of the DC/DC converter. The inrush circuit prevents that the output capacitors on the DCDC converter is charges directly from the line because this would draw a big current from the line and this might result in that the line/site would breaks down.

Charging the output capacitors is done though a resistor and when the same voltages is present on the output capacitors as on the output a switch will shorten the resistor so the DCDC can deliver its full power without significant extra losses. See Figure 13.

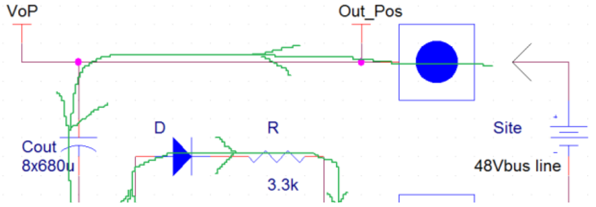


Figure 13 showing electrical circuit for output stage on DCDC converter with the output switch turned off.

However, if the DCDC converter is already powered on before the site is connected 0V is present both on the output capacitors and the output terminals after the inrush protection. In this situation we also have a state of equal voltages across the inrush protection circuit and the switch will also close. When the fuel system afterwards is connected to the site the switch will still be closed and the output capacitors will charge through the switch instead of through the resistor resolving in that a big current is drawn from the line and a possible site break down to follow.
See Figure 14

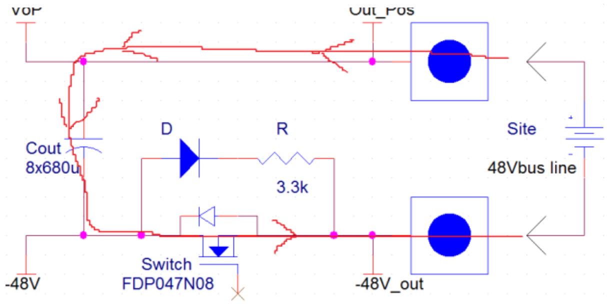


Figure 14 showing electrical circuit for output stage on DCDC converter with output switch turned on.

1.5.3.5 Solution and verifications

To solve this problem a software solution was implemented, that active holds the switch off until the fuel cell system is connected to the site and the voltages is present on the output of the DCDC converter. Then the output capacitors on the DCDC converter will charge and first when they are charged, the switch will close.
To verify the solution, a small test setup was built. A small 1A laboratories power supply and a 10.000uf capacitor are simulating the 48V telecom bus line. A single DCDC converter is used to verify the solution and after it's connected to the powered 48V bus. See Figure 15

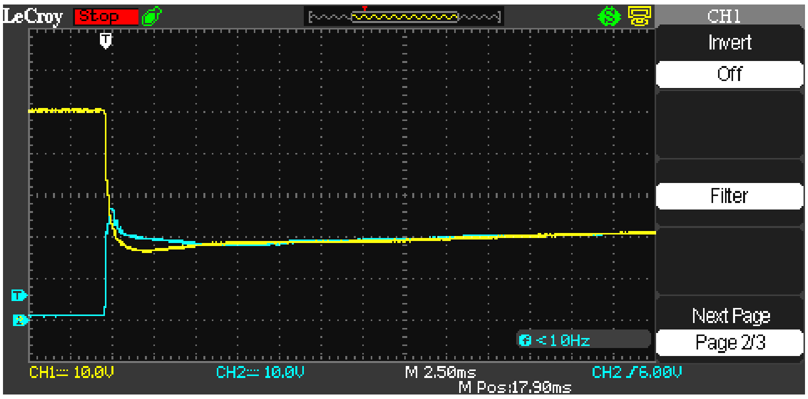


Figure 15 [Yellow is the simulated +48V telecom bus line and Blue is the voltages measured on the DCDC converters output terminals.]

The measurement above is where the new software solution is not implemented.
We have a situation where the 48V bus voltage is dropping when the DCDC converter is connected to the bus. The settling level is the relationship between the capacitance of the bus line and the output of the DCDC converter. In the current fuel cell system 6 converters are used and there by the output capacitance also is six times bigger, so the voltage drop on the 48V bus would also be worse. See Figure 16.

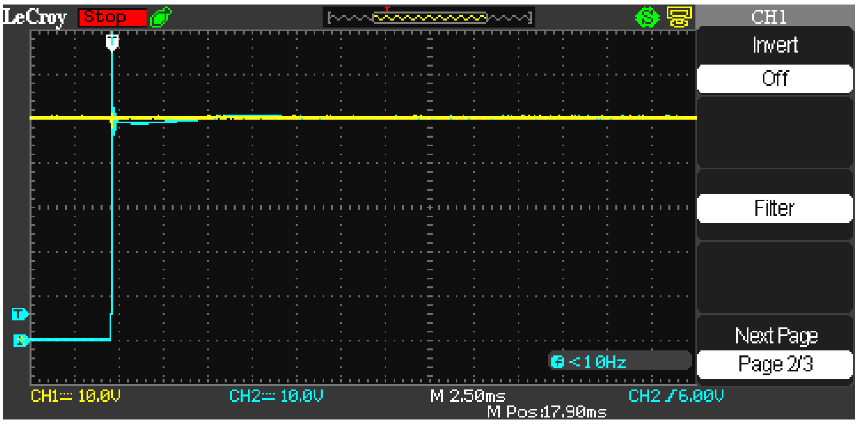


Figure 16 [Yellow is the simulated +48V telecom bus line and Blue is the voltages measured on the DCDC converters output terminals.]

The measurement Figure 16 is when the software solution is implemented and it’s clearly seen that the 48v bus is not interfered.

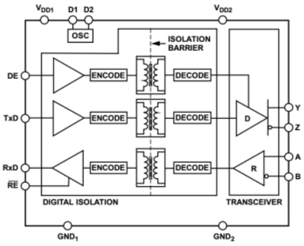
1.5.3.6 WP3.2- FCC/PB improvements RS485 power good for robustness

1.5.3.7 Description of the problem

During production both Fuel Cell Control boards and Power Board are seen failing. The internal 3.3V and 5V supplies are hold down and are not reaching their designated levels. The voltages are kept down for 1 to 30 seconds before the system is starting up. When the system is started up it works as intended. The error is located to be around the RS485 drivers, because if the RS485 driver is replaced on a bad board the error is removes at the board is working normally.

1.5.3.8 Investigation:

During startup it is seen that the RS485 driver is holding the supply voltages down.
A closer look at the driver shows that the driver is trying to switch D1 and D2 before it locks up, sometime only one of them make a pulse and sometime two or three pulses before it locks up. The startup comes already at 1.4-1.5V where the typical startup voltage for the driver is 2.2V. So it seems that and internal oscillator is starting up before the voltage is high enough and because of the low input voltages it cannot continuum switching and locks up.
See picture below. Figure 17.



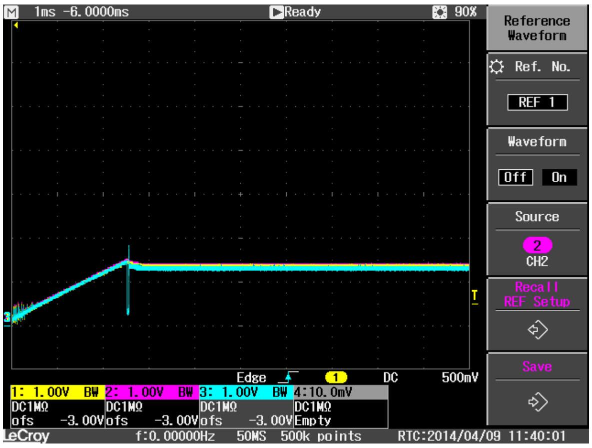


Figure 17 [Yellow and red is the supply voltages and blue is D1]

The layout around the RS485 driver is not done as recommended in the datasheet so to see if this was the cause of the problem a demo board was ordered and tested. The demo board did also have the same problem.

On the demo board, it could be seen that if the laboratorial power supply was switched on while connected to the board the error occurred. We observed that, if a hard switch was done, the error was gone.
It showed that, if the raise time of the supply voltages was to slow, we had the problem and a faster raise time did solve the problem. This could also be seen on the Power Board.

On the Power Board we could see, that it was not the linear 3.3V supply that directly supplied the driver that caused the problem, but the 5V DCDC that supplied the 3.3V regulator that was starting to slow. See Figure 18.

1.5.3.9 Possible solution

The 5V DCDC was not designed as described in the datasheet.
Redesigning the DCDC, so it worked as described in the datasheet, did make the supply voltages raise faster and the problem with the driver disappear.
This solution however did also change the power up of all the circuits on the board as well as the power drawn from the 24V supply in front of it would be much different during startup.
What this would have of possible consequences, both on the board corrected and on other boards that the 24V supply is supplying, is difficult to determine and would demand a bigger investigation.
Because of this changing, the DCDC solution will not be implemented and a solution, easier to verify, would be preferred.

1.5.3.10 Switch solution

Building in a switch in front of the RS485 driver could be a solution to make the supply voltages to the driver raise faster.

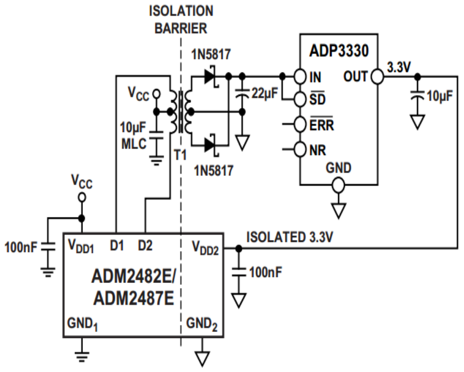


Figure 18 3,3V regulator circuit diagram.

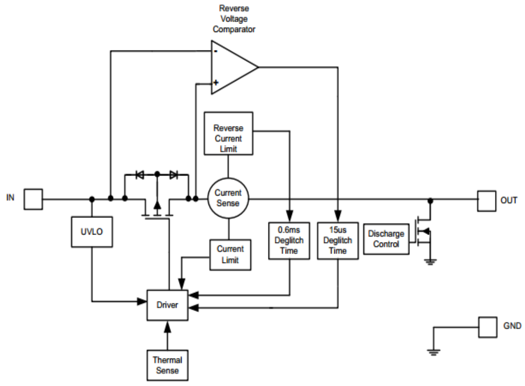


Figure 19 DCDC output switch simplified electrical diagram.

AP2337SA-7 is a high side switch that has an under voltages lookout of 2.00V-2.65V so that insures that the main supply voltages is well above the critical 1.4-1.5V before it is switching on.
The solution has been tested and found to work well. Figure 19

A bypass capacitor between 10nF and 100nF is recommended on the supply for the RS485 driver. The following picture shows the startup with a 100nF connected
See Figure 20.

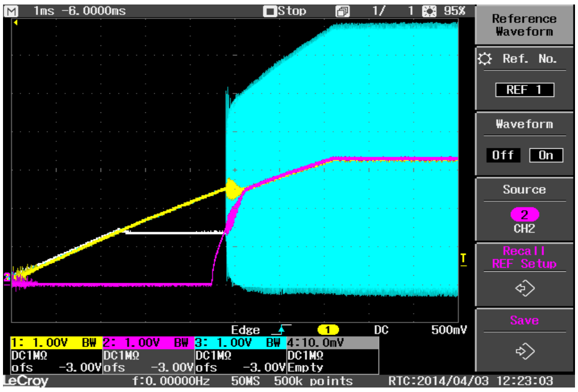


Figure 20 [The Yellow is the main supply voltages, the red is the supply voltages to the RS485 Driver and the Blue is D1. The white ref is the supply when failing to startup without switch.]

The switch has built in current limiting and that slows the raise time.
We will try to make this raise time even slower to ensure that we are not close to a critical condition.
To test this, a 22uF capacitor is connected to the supply input of the Driver, see measurement below Figure 21

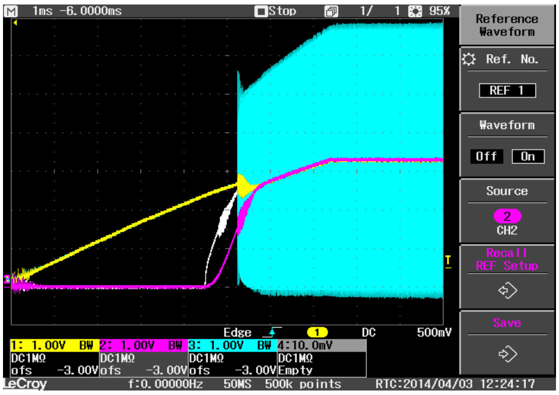


Figure 21 [The Yellow is the main supply voltages, the red is the supply voltages to the RS485 Driver and the Blue is D1. The white ref is driver supply voltages with 100nF bypass capacitor.]

From the measurement it is seen that even if the raise time is slowed by a 22uF capacitor the system is still starting up as intended.
Because we are supplying the driver though a switch a bigger bypass capacitor then the one recommended in the datasheet is desired. We chose 1uF and the measurement is seen below Figure 22.

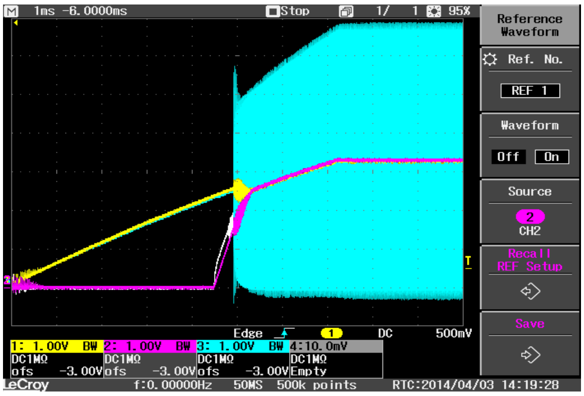


Figure 22 [The Yellow is the main supply voltages, the red is the supply voltages to the RS485 Driver and the Blue is D1. The white ref is the driver supply voltages with 100nF bypass capacitor.]

Using a 1uF capacitor works fine and when we also could do the tests with a 22uF capacitor we are not close to a critical condition.

1.5.3.11 Implementation

The high side switch AP2337SA-7 and a 1uF X7R capacitor are chosen to be added on the Power Board and the Fuel Cell Control board to resolve the problem with slow startup of the 3.3V supply because of the RS-485 driver is locking up during power up.

1.5.3.12 WP3.4 - DC line voltage measurement circuit improvements to able to use overvoltage set point

The fuel cell system is monitoring the output line voltages of the site that it is connected to and if the voltage gets to high the fuel cell system is able to turn itself off for protection.
The measurement circuit is implemented in hardware and readout is done by the CPU placed on the Power Board and from there the converted voltage is send to the Fuel Cell Control unit for processing.

The hardware circuit is designed so it maximum can measure 58V and, if all tolerances in the hardware circuit and aging is included, it can, in the worst case, only measure a line voltages of 56V.

To improve robustness, the maximum measurement of the hardware circuit is raised. This allow bigger headroom before the fuel cell system is closing down and more margins for noise and minor errors on the connected DC bus line.

Software for the CPU placed on the PB also needs to be changes so it can do the right conversion between the hardware readout and the value passed on to the Fuel Cell Control unit. To be able to use the same software for both new and old power board hardware also an ability to distinguish between new and old hardware is implemented into the power board software solution.

1.5.3.13 WP3.6 - FCC CAN circuit improvements to support SNMP communication

The SPI interface that is going to be implemented in WP4 shall run on the CAN interface that is placed on the Fuel Cell Controller. The CAN interface has not earlier been implemented into a product, so fully verification and the last adjustments shall be done to get this circuit ready for WP4.

The small DCDC converter that is supplying the CAN circuit has input and output capacitors that are not according to the applications notes. To insure good operation and robustness these capacitors needs to be adjusted. Opening up the capacitors design also makes it possible to changes the type to ceramic capacitors that have a much better reliability then the tantalum capacitors used in the original design.

We have to reduce the capacitance value, but despite that we actually get better performance because of the better type of capacitor. This is seen by that the ripple voltage on the 5V_CAN output is getting smaller. Figure 23.

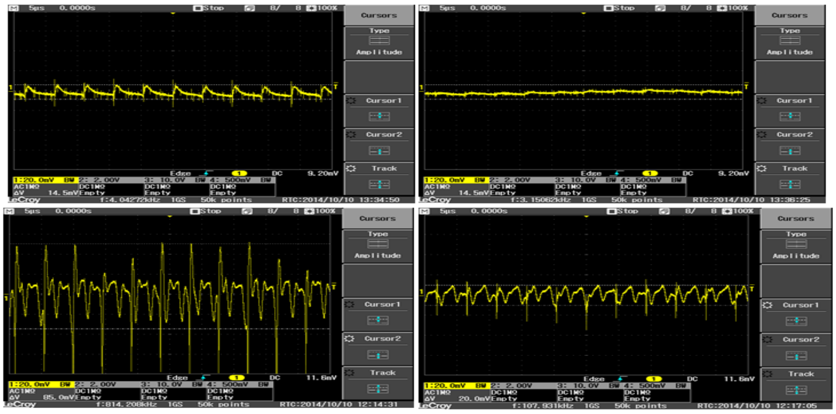


Figure 23 5V CAN voltage before and after optimizing circuit with different capacitor. Left is before and right is after. It can be seen that ripple is reduced.

Also on the input to the DCDC converter we see a significant improvement.
The improvement on the input of the DCDC converter is not only imported for the way the DCDC converter works, it's also important for other circuits connected to the +24V supply. The lover ripple the les interference will the other circuits see and the less is the probability that they will be critical disturbed and overall robustness is improved.
To illustrate this, the ripple on the +24V supply is also measured a little away from the DCDC Converter, on L1, 4-5cm away. Also here the improvement have made the ripple voltages fall significant Figure 24

Figure 24 5V CAN Ripple measurement before and after better capacitor is added.

It can be seen that improving the capacitor choices has a number of positive effects.
- Less ripple/noise on the +5V can supple -> Improves robustness of the CAN circuit
- Less ripple/noise on the +24V supple -> Better robustness of other +24V circuits
- Better reliability of the capacitors -> Better overall reliability / System robustness
- Les capacitance makes the DCDC converter startup easier -> Better CAN robustness.

Beside the Capacitor on the CAN supply also the filtering of the CAN signal is improved to insure better signal integrity and robustness of the CAN communication.

1.5.4 WP4 - Development of communication interface

To an end-user, the communication interface is a core attribute of a power backup system as reliability and knowledge of system status is highest priority. The fuel cell module must be possible to implement in an overall operations structure at any given operator. The interface must live up to demands for type on protocol and call out strategy. The novel communications protocols for network integration must be identified and incorporated into the modular design. The communication interface will be developed on the basis of the new communications protocols for network integration identified in the PRD (SNMP expected from WP1).
The outcome is a complete variety of communication options either as standard or as an option with slight modifications. It is imperative that all demands can be met by configuring or adapting the standard solution. Both integrated solutions and external add-on solutions must be explored.

Scope

Goal was to develop an reliable communication interface that made it possible for the customer to monitor the fuel cell systems status alarms and performance in order to make an more reliable backup system for the end user. Below picture show the finished SNMP user interface that supports SNMP communication to 1.7kW fuel cell system that also will be tested in field test in WP6.

System setup description FCgen® -H2PM SNMP

The FCgen® -H2PM SNMP v2c User Interface is a remote communication interface, intended for use with FCgen® - H2PM 1.7 kW and 5.0kW systems.

The SNMP interface is powered from the 48 VDC bus of the FCgen® -H2PM system through a 1A circuit breaker. The FCgen® -H2PM SNMP Interface communicates with the FCgen® -H2PM systems via a CAN connection and communicates via an Ethernet connection to an SNMP manager PC program placed in the customer network operation center (NOC) or a standalone PC. See typical system setup in Figure 25.

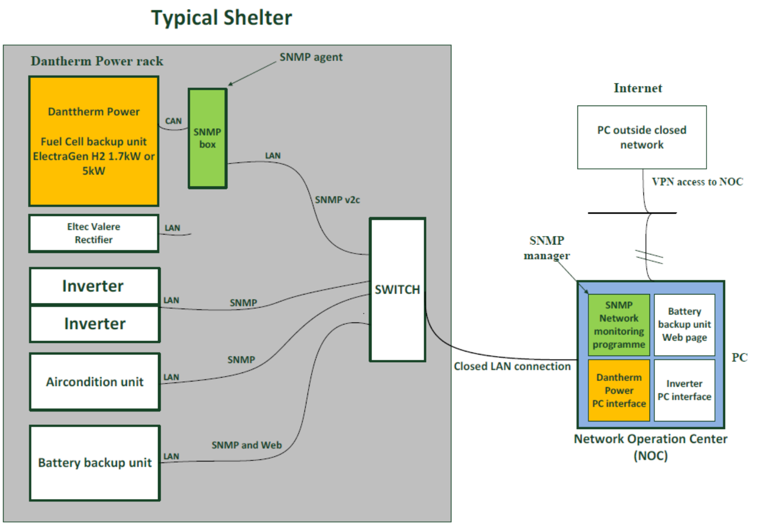


Figure 25 Functional block diagram for SNMP implementation in typical shelter system.

The FCgen® -H2PM - SNMP User Interface consists of two PCB boards and a mechanical enclosure. The LCD board PCB is the brain in the system and communicates with the FCgen® -H2PM H2 systems over CAN and converts to SNMP that which is communicated via LAN. The SNMP Connector Board PCB consists of a 48/24VDC power supply that supplies the LCD board. Besides that, the SNMP Connector Board PCB consists of interconnections between the connectors in the front of the SNMP box to the LCD board PCB. See Figure 26.

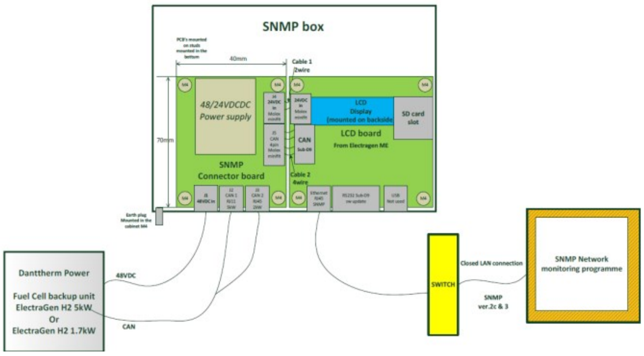
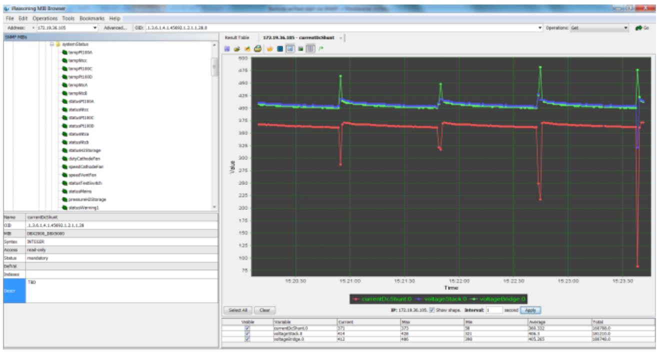


Figure 26 SBNPbox internal layout and connection to fuel cell system and remote monitoring via SNMP manager installed at remote PC.

SNMP sw. and SNMP manager description

In order to communicate with the SNMP box you need to install an SNMP manager program on your PC. The SNMP manager program is the program where you monitor your SNMP agent which in this case is the SNMP box for the EGH2 fuel system. There are several SNMP programs available on the market, which one you use is not important for SNMP box since it works according to an generic SNMP 2c standard which the SNMP manager program also must work according to. Below there is shown an example of the setup of an SNMP manager program from iReasoning which is freeware. It's also shown how MIB file which is unique for the Dantherm Power EGH2 SNMP User Interface, can be loaded. If you use another SNMP manager program this procedure might be different. On the picture below SNMP manager program is seen monitoring a self-test started manually remotely from Ballard local network to SNMP box mounted at Stofa field test site. Access to Stofa network is made with VPN connection. Figure 27



Name currentDcShunt

Syntax INTEGER

Access read-only

Status mandatory

Descr TBD

Figure 27 Screen dump from SNMP manager remote connected to field system while it runs in self-test

Result

SNMP communication interface was developed and finished and 5 SNMP box prototypes was successfully tested during field testing in Fc2scale see Figure 28

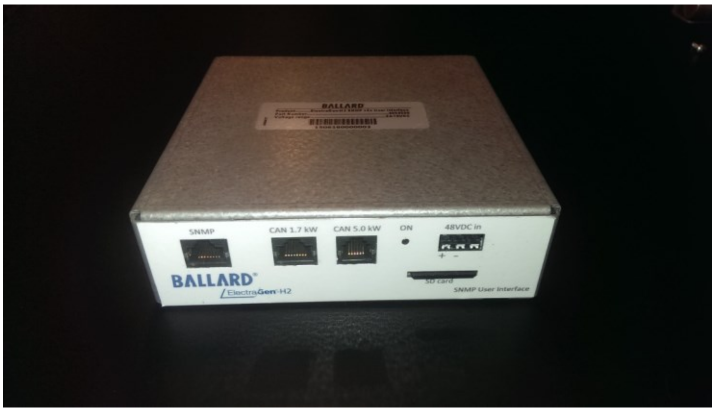


Figure 28 SNMP box

1.5.5 WP5 - Technology integration, testing and prototyping

WP5 description

Task 5.1: Mechanical integration of core fuel cell module (Task Leader: Dantherm Power).

Taking the prototype design from task 2.2 as a departure point, the overall system will be optimized towards scalability as defined in WPs 2-4. The fuel cell module must be designed for easy assembly in production and on-site integration into any installation plenum or application needed.

The focus is on allowing continuous upgrading as power consumption on the site increases and on ease of installation, integration and commissioning.

Task 5.2: Design and integration of complementary enabling features (Task Leader: Dantherm Power).

In addition to the power management system (WP3) and communication interface (WP4), a set of other enabling elements are required around the core fuel cell module. This task will focus on studying and designing those enabling features that are needed to ensure the integration of fuel cell core modules into a complete safe and rugged solution. The following elements will be covered:

- Housing and physical placement/arrangement of the diverse components of the power backup system. The physical placement can wither be external enclosures in combination with existing equipment, or new enclosure with possibility for new equipment. The mechanical design must have into account the possibility of upgrading to higher power and runtime demands (given the focus of the solutions on scalability). Moreover, design must account for simplicity and cost-effectiveness of installation procedures, since one of the cost drivers is time and resources spent on installing the system. Finally, housing design must regard the need for safe and flexible hydrogen (fuel) storage and refueling.
- Ventilation for intake and exhaust in air cooled systems. Design requirements include avoid blocking by outside factors and adequate size/capacity to facilitate the maximum airflow of the systems.
- Cooling system design. By replacing batteries, the fuel cell-based power backup solution significantly reduces the cooling demands (which basically will only be required for the electronic systems). Therefore, the cooling system will be redesigned to the requirements of the new solution.

In most cases the compressor or active driven cooling will be used much less than with a battery system, and this change in demand enables the switch to new cooling technology, namely the free cooling concept using forced air to cool majority of temperature conditions with the active cooling to be utilized 5-10% of the time. The reduced cooling requirement relates to the entire radio base station when no batteries are present.

The outcome of tasks 5.1 and 5.2 is an integrated mechanical design with the ability to be assembled and installed with speed and ease in any installation. Both materials and techniques for the fuel cell module and enabling elements must be explored without compromising cost and functionality.

Task 5.3: Building and testing the complete integrated solution

The flexible, modular and cost optimized fuel cell backup power solution is built and lab-tested according to test specifications based on the PRD (WP1), and verified by end-users.

The outcome is a complete solution tailored to meet the demands of the operators and the complete catalogue of solutions that describes all different variants. The solutions are tested against the relevant tests standards and evaluated from a solutions point of view.

Overview of WP5 M6 – Prototype power backup systems lab *tested ready for field trails.*

After development of scalable systems in WP3 the systems were integrated in a complete system with rectifiers and inverters in the DESITEK UPS rack see pictures below. Scalable fuel cell system was tested and verified according to performance parameters found in WP2 – in short words ‘could the scalable fuel cell perform as good as the standard fuel cell’? prototype testing showed that it could. See field system setup at Figure 29 & Figure 30.

Figure 29 Field system setup tested in lab before its installed at Billund site. At the left UPS rack from Desitek, and at the right the fuel cell system.

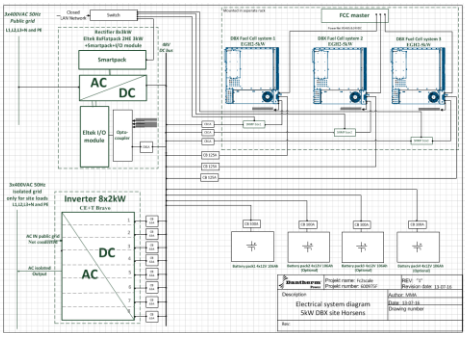


Figure 30 Field test system block diagram

1.5.6 WP6 - Field trials

The systems are installed together with project partners for field trial and proof of concept. The installations are done in live networks, and a series of network field trials with all elements of a roll out incorporated is planned to ensure all stages of the trials are covered, and this will at the same time determine if all solutions and designs are meeting specifications. It is expected the installation and testing of 8 systems – two systems of 1 kW, two of 2 kW, two of 3 kW and two of 4 kW. According to the marketing strategy, the solution is positioned and disseminated for broader roll out.

Field test system setup at Stofa sites

The drawing below shows the complete field test system Figure 31. The test system is installed in Intego shelters already used by Stofa to contain the broadband electronics and the UPS battery rack. In the Fc2scale field test the fuel cell rack is installed an integrated to the existing UPS battery system from Desitek. The H2 bottle room is specially integrated in the Intego shelter ensuring higher integrity and more direct connection to the fuel cell system giving more reliable system operation in the end.

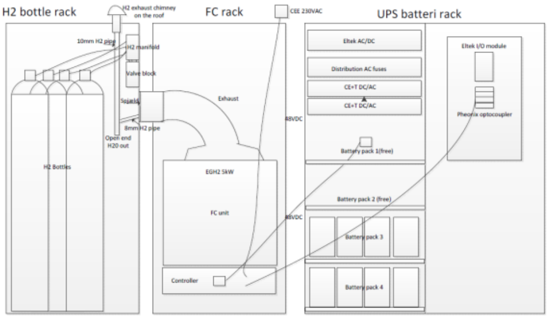


Figure 31

Complete field test system setup. Intego shelter is equipped with room for H2 bottles making the whole installation more integrated and safer. Fuel cell system rack is installed next to the existing UPS rack with batteries, inverters and rectifies.

- **Scalable system in Løgstør 2x1.7kW**

This system consists of 2 1.7kW systems in parallel installed with the existing UPS battery rack. One SNMPbox is installed for each 1,7kW system. The whole system is installed in an new Intego shelter with integrated room for H2 bottles see Figure 32

2x1,7kW system with 2xSNMP box

Figure 32 Løgstør system site with 2x1,7kW fuel cell systems installed in a Intego shelter with integrated H2 bottle room.

• Scalable system in Billund, STOFA site

This system consists of one 5kW systems in parallel with scalable system 3,2kW with a Master controller to combine the two systems. Fuel cell system is installed with the existing UPS battery rack. One SNMP box is installed with the 3,2kW system. The whole system is installed in an old shelter with H2 bottles rack mounted outside (see Figure 33)

Figure 33 Billund system site with 5kW system in parallel with 3,2kW system and Master controller installed in a old shelter with integrated H2 bottle rack mounted outside..

Test results from field test

The stack performance is evaluated according to beginning of life polarization curve BOL see below. Table below see Figure 34 with the evaluation point 'stack performance compared with nominal BOL'. All stacks has been performing as they should within +/- 3% of the BOL polarization curve see Figure 35.

All systems passed the field tests. The scalable system in Billund stopped operation several times during the self-test. The root cause for this was to high load in self-test which was caused by the fact that system had 2kW test load heater and 3dcdc's on each 46cell stack. With a stack nominal load of 1,8kW the self-test test load was too big. For future scalable systems test load should be adjusted to the stack nominal load either by reducing the number of DCDC's or another test load.

Site location	Installation date.	No. Of start/stop	Running hours	H2 consumption Backup.	Life time left start/stop & running hours New stack 500 start/stop 1500 running hours	Stackperformance compared with nominel	SNMP box status
Billund 1x3,6kW	6-5-2015	21 = 17 selftest (2x10min) Approx. 4 backups	5,7 hours selftest 0,5hours backup	12kWh	479 start/stop left 1493 running hours left	OK	OK
Billund 1x5kW	6-5-2015	21 = 17 selftest (2x10min) Approx. 4 backups	5,7 hours selftest 0,5hours backup	14kWH	479 start/stop left 1493 running hours left	OK	OK
Løgstør 1 1x1.7kW	16-03-2016	8 = 7 selftest (2x10min) Approx. 1 backups	2,3hours Selftest 0,1hours backup	2,5kWH	492 start/stop left 1497 running hours left	OK	OK
Løgstør 2 1x1.7kW	16-03-2016	8 = 7 selftest (2x10min) Approx. 1 backups	2,3hours Selftest 0,1hours backup	2,5kWH	492 start/stop left 1497 running hours left	OK	OK
Silkeborg 1x5kW	7-4-2016	7 = 6 selftest (2x10min) Approx. 1 backups	2,1hours Selftest 0,1hours backup	4,1kWH	493 start/stop left 1497 running hours left	OK	OK
Horsens 1x5kW	20-6-2016 Not put into operation but running selftest	5 = 4 selftest (2x10min)	1,8hours Selftest	3,6kWH	495 start/stop left 1498 running hours left	-	OK

Figure 34 Test results from field test at Stofa sites.

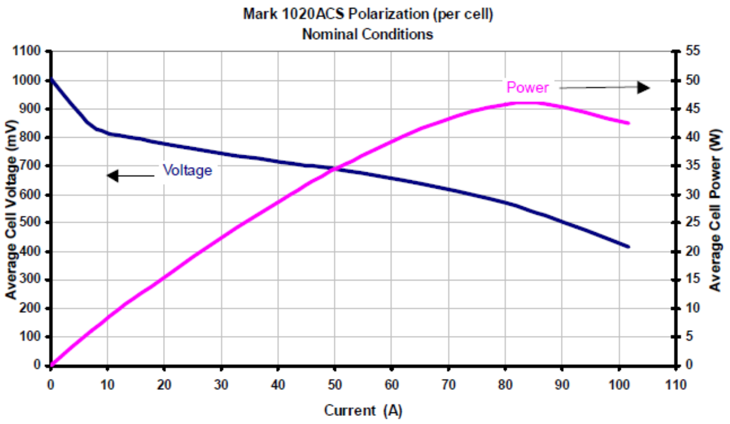


Figure 35 Fuel cell stack polarization curve beginning of lif BOL. Stack performance from field test systems are compared and evaluated with this BOL polarization curve.

1.5.7 WP7 - Project Management and Dissemination

WP7 description

Task 7.1: Overall management and risk contingency planning.
The appointed Project Manager (PM) Morten Madsen, in cooperation with the Business Development Department of BPSE, have been responsible for coordinating the technical progress and ensuring that the project schedule is met. This means reviewing all reports and project progress, solving potential partnership problems and mediating in case of conflict, planning and organizing the regular meetings.
BPSE has been responsible for managing all relevant documentation and for the financial administration of the project, including distribution of funding to partners and reporting to EUDP. The PM has continuously reviewed reports to verify consistency with the project tasks and deliverables before transmitting them to the EUDP. Deviations from the project

plan have been reported to the Steering Committee (SC), which has decided which measures to be taken and which changes were necessary for the fulfillment of the project objectives.
During the project period, several risk analyses were made in order to ensure that no critical factors influence the project achievements. This is why, several amendments had been implemented in the project lifetime.

Task 7.2: Dissemination of project results.
The project management team, in dialogue with all consortium members, decided how to disseminate the project results in the best way.
The dissemination activities included participation in conferences and meetings, presentations, and active engagement in contacts with customers, investors, academia and regulators/policymakers. In particular, the project results have presented both at national (as, fx: Danish Hydrogen and Fuel Cell Day, November the 10th, 2016, Odense; IDA Energy Technical Group, October the 13th, 2016) and international level (fx. FCH-JU events; The European Hydrogen Association), at relevant technical and trade seminars within the telecom and IT sectors. The project team prepared a dissemination plan with the input from all partners which was used as guidelines for the dissemination activities.
Specific strategies were defined for groups or target audiences – among these the three sectors within the telecommunications market, i.e. OEM customers, distributors (VARs) and operators (end-users).
During the field trials phase, specific dissemination activities were organized, including presentation of the key results and summary reports. During the project period status report, financial reports and other project relevant documentation had been produced and managed.

1.6 Utilization of project results

The project has reached its goal by investigating the technical and economic advantages in scalable fuel cell systems. Technical investigations have shown that scalable systems are possible to build without compromising with the system performance and integrity. Besides that, it has documented the economic advantages in scaling the system.
However, the project has also reached the conclusion that scalable sizes below 5kW is not needed based on feedback from Stofa looking at costumer requirements since the project start.
The project has pointed out the importance for a reliable and self-maintaining system which has led to up to 80% less service time pr. System. The remote monitoring SNMP communication interface which has been developed in this project, has open up our eyes for the advantages in this tool. Preventive maintenance is what remote monitoring is opening up for and with that it's possible to increase the reliability even more, because error's can be fixed before they happen and system breakdown be avoided.

1.7 Project conclusion and perspective

Development and field test of the scalable system showed that the concept works from a technical point of view. There are significantly cost reductions for scalable fuel cell systems because the 3 main components fuel cell stack, DCDC converter and ultra-capacitor module (BP) are reduced in size and numbers. But based on feedback from project partner Stofa scalable fuel cell systems don't make sense below 5kW because of initial installation cost and because of the power requirement from the site equipment.
The project has succeeded to improve the system reliability and system self-maintenance by major software development as well as hardware development.
SNMP remote monitoring communication interface developed in the project has proven its advantages in field test. The SNMP interface is giving the customer and the service provider the possibility to be more efficient in the service and hereby increasing the overall system 'Up time'.

Commercial perspective general
Business perspective
Fuel cell systems developed during Fc2scale project has proved their worth and Ballard Europe has sold new systems to Stofa. The project has hereby initiated an professional cooperation between Stofa and Ballard Europe and its expected that Stofa will buy more systems in the coming time leading to fact that Stofa not only will be a good project partner but will be one of the biggest Danish customers for fuel cell backup systems.

Technical perspective
- Fuel cell system integration with other energy sources, batteries, PV panels.
- Communication interface makes it possible to make service more efficient, hence reducing maintaining cost.

Cooperation perspective
- Improved cooperation between partners will give more efficient cooperation in the future

Commercial perspective // Future work

Desitek

The project has opened a perspective for hybrid solutions where different backup sources like batteries, fuel cells, PV are combined and an overall control system will insure that each backup source is used as efficient as possible giving an more reliable and efficient backup system.

Ektos

EKTOS A/S has during the project increased our knowledge about scalable control systems and monitoring of energy systems. This knowledge can hopefully be reused in new challenging projects within energy systems.

STOFA

The project has showed the advantages of combined backup sources like fuel cells and batteries in a combined system and this opens up for the use of similar systems in backup applications where higher level of reliability is required.

Ballard Power Systems Europe

The project has showed that fuel cell system integration with other energy sources, batteries have potential advantages.

Communication interface makes it possible to make service more efficient,

Fuel cell systems developed during Fc2scale project has proved their worth and Ballard Europe has sold new systems to STOFA.