CONFIDENTIAL

REST

Reliability **EST**imation of hydrogen and fuel cell systems

Final report

1.1 Project details

Project title	REST - Reliability ESTimation of hydrogen and fuel cell systems
Project identification (program ab-brev. and file)	64014-0174
Name of the programme which has funded the project	EUDP 14-I
Project managing company/institu-tion (name and address)	Ballard Power Systems Europe A/S Majsmarken 1 9500 Hobro
Project partners	Nel Hydrogen A/S Aalborg University LeanEco A/S
CVR (central business register)	Ballard Power Systems Europe A/S | 30804996 Nel Hydrogen A/S | 26933048 Aalborg University | 29102384 LeanEco A/S | 30559150
Date for submission	July 2017

Indholdsfortegnelse

1.2 Short description of project objective and results

The REST project focus is to strengthen reliability of Hydrogen refuelling stations (HRS) and Fuel Cell systems (FC). Specific project activities have included:

- the development of a new reliability assessment methodology and associated models;
- accelerated reliability testing of FC systems and sub-components to validate the models and induce improvements into the systems;
- the development and testing of a new advanced Control and Monitoring System (CMS) for HRS enabling intelligent self-diagnostic and correction of failures

All objectives have successfully been accomplished with great result. Reliability in both FC and HRS has improved, and CMS have been implemented in the HRS. The accelerated testing of BOP components has made it possible to improve CMS in the FC system.

REST projektets fokus har været at øge pålideligheden af Brinttankstationer (HRS) og brændselscelle systemer (FC). Specifikke projektmål har været:

- udvikling af en ny pålideligheds vurderingsmetodologi og tilhørende modeller.
- Accelererede pålidelighedstest af FC systemer og underkomponenter for at validere modellerne og for at introducere forbedringer til systemet.
- Udvikling og testning af et nyt avanceret Kontrol- og overvågningssystem (CMS) til HRS for at muliggøre intelligent selvdiagnostisering og korrektion af fejl.

All mål er blevet udført med succes og et godt resultat. Pålideligheden for både FC og HRS er Blevet forbedret, og CMS er blevet implementeret i HRS. De accelererede test af Balance of Plant BOP komponenter har muliggjort forbedring af CMS in FC systemer.

1.3 Executive summary

In the REST project, a new Fuel Cell CMS system for back-up power systems has been developed by Ballard Europe (former Dantherm Power) and a new CMS for Hydrogen Refueling Stations (HRS) by Nel Hydrogen A/S (former H2 Logic).

Development and test of new CMS for fuel cell systems

Through the REST project, BPSE has been able to improve the system reliability: several components and full scale systems have been tested in accelerated test and critical environment. This has helped us improve:

- The reliability of the backup system and UPS at a rate of 98%
- The FC-based backup power system is now at Technology Readiness TRL 8 (system complete and qualified)
- Reliability testing has been done to asses long-term failure modes on BOP and system level.
- A reduction in warranty costs has been made by the improve reliability and the improved CMS in the FC system. The system can perform better self-diagnostics; this allows the service technicians to be able to handle several errors without visiting the site.
- Cost competitive at a market price of 14.520 DKK/kW at 5 kW in year 2017 has not been possible to achieve. Currently, we are at 18.500 DKK/kW. The price of the Fuel Cell stack has increased due to dollar currency.
- The benefit of using FC system instead of batteries has eliminated the need for customers to have air conditioning installed in the technical shelters. Especially the new site installations are installed with only a ventilation system.

- In the REST project, we have improved how we collect our field data. We have built a database where all systems (with service contract) field data is stored. It is now possible to monitor irregularities and prevent errors and performance loss.
- Demonstration of the project developments had a goal of being deployed in 5-10 FC-based backup power systems. This goal has been exceeded with 25 site installations at our local customers in Denmark (EnergiMidt, SEAS-NVE and NRGi). 5 systems have also been installed in Scandinavia: Norway and Sweden.

Development and test of CMS for Hydrogen Refuelling Stations

As part of the REST project, Nel Hydrogen has successfully managed to develop and test a new HRS CMS with substantial advances compared to the previous state-of-the-art:

- A new HRS CMS has been developed with more intelligent self-diagnostics and correction intelligence, reducing the number of operation interruption events
- Number of operation events/alarms has been reduced with 90%, helping to reduce costs for service personnel required for operation monitoring and troubleshooting with more than 25%. This has also been achieved by a new KFI tool that allows service personnel to analyze and trouble shoot events much faster.
- HRS availability/reliability has been also stabilized above 98%, compared to previous fluctuations of 70-98% due to a long trouble shooting time
- A new fully automated KPI reporting system has reduced personnel time required for each report from 10 hours down to few minutes – providing greater convenience and less costs for customers (HRS operators).
- The new HRS CMS has been tested on 9 HRSs based on the 1^{st} Gen. H2Station® product from Nel Hydrogen, across Denmark in live operations, substantially more than the original project target of test on only 1 HRS.
- The HRS CMS has successfully been implemented across all 1^{st} Gen. H2Station® in operation in seven countries across Europe.
- The HRS CMS from REST has also been used in a new 2^{nd}. Gen. H2Station® product launched during 2016, where sales and installations in Europe has already been secured. In addition, Nel Hydrogen was recently awarded an order of 120 million DKK from Shell for stations to be installed in California.
- Since commencing of the REST, 10 more employees have joined Nel Hydrogen, and with an outlook of a 10% increase per year going forward, thanks to the results of REST. Also, Nel Hydrogen targets to grow annual sales with 30% on the new 2^{nd} Gen. H2Station®, made possible by the HRS CMS developed in REST. Many the annual sales are expected to be export outside of Denmark.

1.4 Project objectives

Description of the project objectives and the implementation of the project. How did the project evolve? Describe the risks associated with the project. Did the project implementation develop as foreseen and according to milestones agreed upon? Did the project experience problems not expected?)

The objective of the REST project has been to address the current limitations on reliability estimation and testing across several application segments for H2 and FC technology – especially backup power and hydrogen refuelling stations (HRS).

The project has also leveraged reliability related know-how from other applications, namely FC systems for electric vehicles (FCEV) and for material handling vehicles (MHV) – promoting the transfer of knowledge between application segments.

Specific project activities have included:

- the development of a new reliability assessment methodology and associated models;
- accelerated reliability testing of FC systems and sub-components to validate the models and induce improvements into the systems;
- the development and testing of a new advanced Control and Monitoring System (CMS) for HRS enabling intelligent self-diagnostic and correction of failures

The project has been based on an industrial platform comprising three companies – Ballard Power Systems Europe (previous Dantherm Power), NEL (previous H2 Logic), and LeanEco – which have been at the forefront in the development and demonstration of H2 and FC systems.

The REST project has focused on improving reliability assessment and growth across various hydrogen and fuel cell market applications with the aim to reduce costs for operation and warranties and improve customer services.

The key objectives and targets for the REST project have been the following:

- **Development and test of new CMS for fuel cell systems**
  - Be able to prove a reliability of the backup system and UPS at a rate of at least 99.95%, compared to existing reliability on 87%-90% in some cases where diesel generators are used.
  - Move FC-based backup power and UPS systems from Technology Readiness Level (TRL) 6 (technology demonstrated in relevant environment) to TRL 8 (system complete and qualified)
  - Reliability testing, in particular accelerated testing, on fuel cell systems and sub-components to assess the long-term failure modes resulting from long-term operations of the systems in the field
  - Add benefits by reducing the warranty costs for the manufacturer to 1.200,00 DKK/system at 5 kW system in year 2017 (75% reduction) and the service costs for the end user after the end of the 2-year warranty period to 1.118.00 DKK/system/year (75% reduction) at 5 kW system in year 2017
  - Be cost competitive at a market price of 14.520 DKK/kW at 5 kW in year 2017
  - Add benefits by saving 20% to 80% on air conditioning enabled by removing the batteries
  - Systematic collection and analysis of existing operational and failure data from fuel cell systems, including demonstration units
  - Demonstration of the project developments in 5-10 FC-based backup power demonstration units deployed at the three end-users supporting the project (EnergiMidt, SEAS-NVE and NRGi)

- **Development and test of new CMS for Hydrogen Refuelling Stations**
  - R&D of new improved CMS for hydrogen fuelling stations featuring:
    - Intelligent self-diagnostic & correction (improving reliability)
    - Automated data/failure analysis & KFI (reducing operation monitoring cost)
    - Automatic online KPI report (improving customer service)
  - Improve reliability to >98% compared with today's fluctuating reliability of 70-98%
  - Reduce personnel cost for operation monitoring with 25% – reduction from approx. 3% of HRS CAPEX per year to approx. 2%)

- Improve refuelling performance to close to 100% – as experienced by end-users (% of successful first refuelling attempts) – by conducting continuous analysis of HRS compiled data
- Improve service for customers by providing automated KPI reporting – reducing cost of reporting with 50% (reduction from 10 hours/report to 1 hour/report) and enable instant reporting

Test and implementation at a HRS in field operation in order to verify reaching of targets

1.5 Project results and dissemination of results

The REST project has involved three key tasks listed below:

1) Development of a FC reliability assessment methodology and model
2) Development and test of new CMS for fuel cell systems
3) Development and test of new CMS for Hydrogen Refuelling Stations

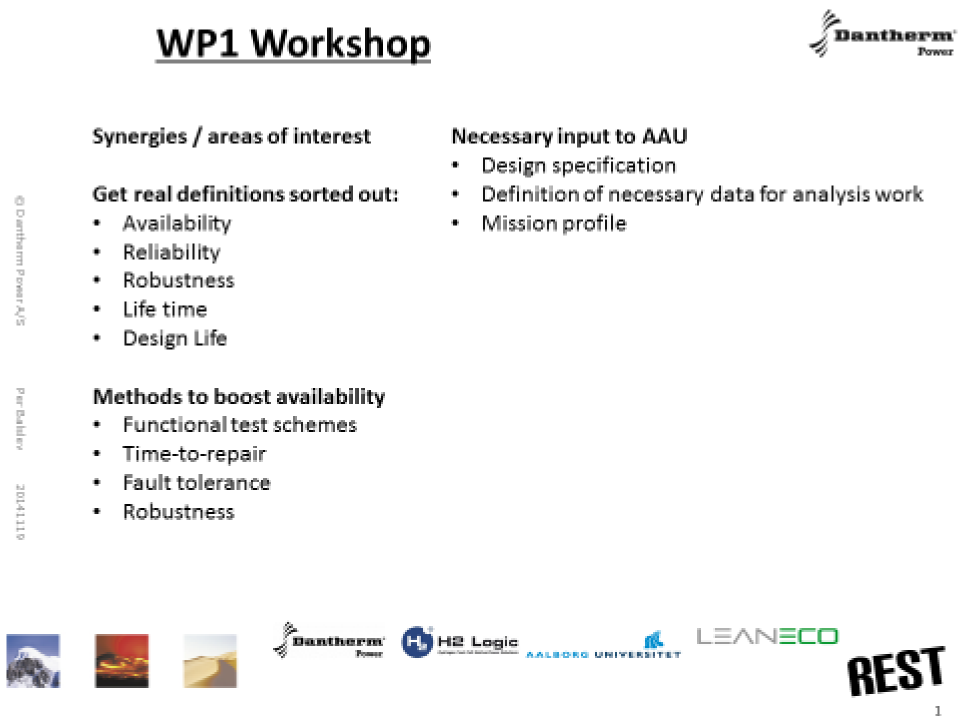
Results from each work package below elaborates further the dissemination activities and will address the three main objectives.

1.5.1 WP 1 Specification & coordination across market applications *(Ballard)*

Ballard Power Systems Europe (Dantherm Power) arranged workshops and steer group meeting throughout the project., where the project findings and challenges were discussed. The knowledge and experience exchange has worked well in the project period.
For example, the first work shop highlighted the main challenges for all tree partners.

Main areas for reliability challenges:

1. Electronics
2. Fuel cell stack
3. BoP Components



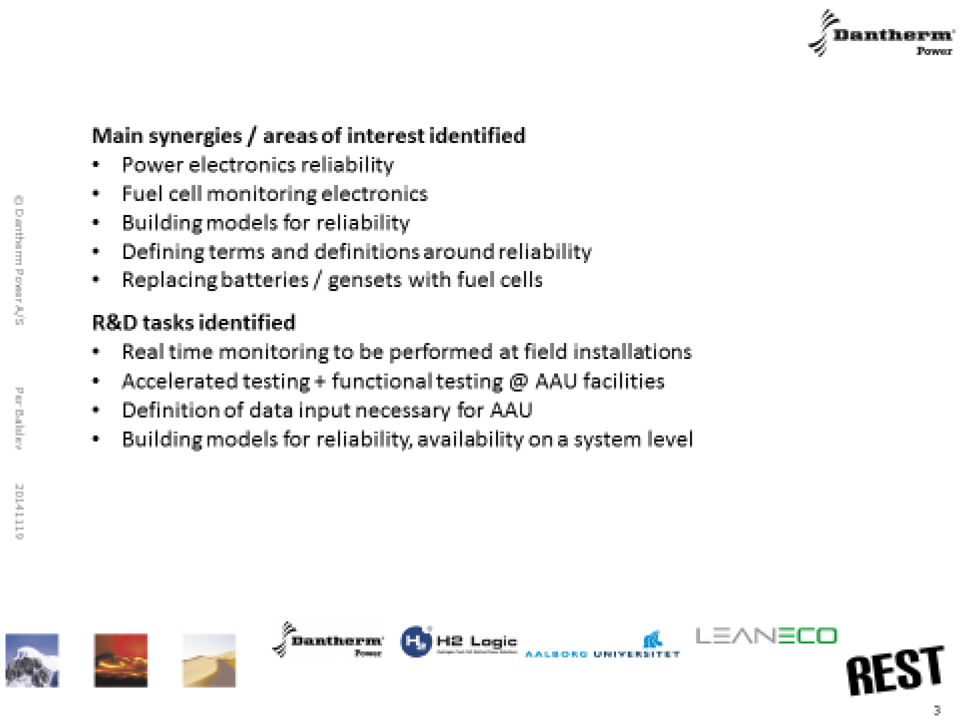


Figure 2 Synergies where found and common areas of interest.

The workshop helped find synergies and common areas of interest; this helped align how the results in the work packages could benefit all partners.

1.5.2 WP 2 Development of a Reliability Assessment Methodology (*AAU)*

1.5.2.0 Mission profile failure mode and effect analysis (FMEA)

This section describes the structure of a fuel cell system used in backup power, and particularly addresses the system overview and the specification of 5 kW DBX5000 from Dantherm Power. By dividing into three sub-systems (fuel cell stack, balance of plant, and power electronics converter), the failure modes and failure consequence of the critical components are identified and analyzed. Accordingly, the main stressors causing the sub-system reliability are then mapped. Since DBX5000 are mainly installed in Denmark and India, the mission profiles are analyzed and compared in terms of grid stability, ambient temperature and humidity. In a word, this section is dedicated to the input analysis of the system reliability toolbox.

A system overview of 5 kW fuel cell backup power DBX5000 from Dantherm Power is shown in Fig. 1. It is noted that three hydrogen inlets are available before the hydrogen enters pressure regulation channel. Simultaneously, two independent fuel cell stacks are contained in fuel cell module. In addition, six 1 kW dc/dc power converter are redundantly extended for 5 kW application.

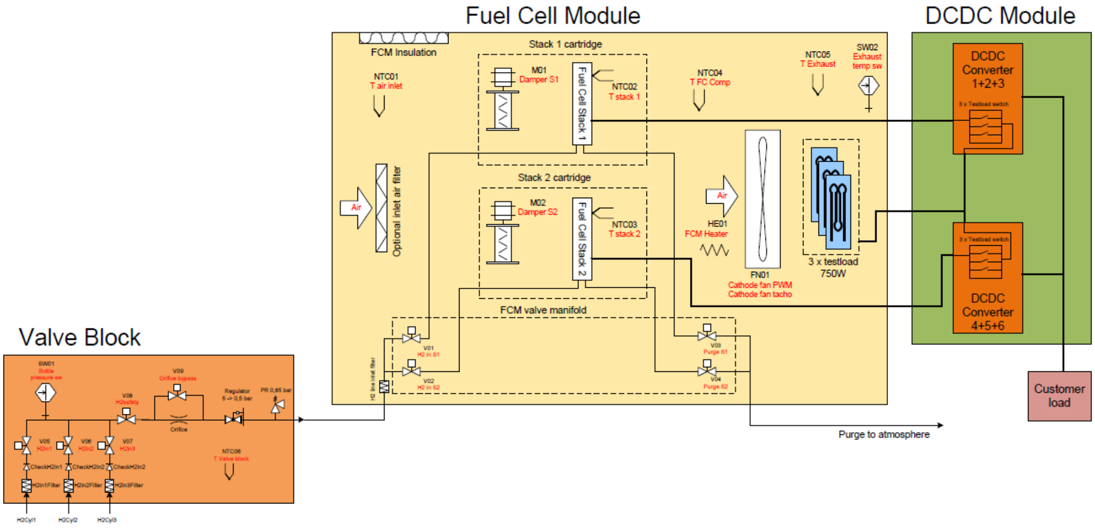


Fig. 1. Fuel cell system structure of Dantherm DBX5000 used for telecom backup power.

The Failure Modes and Effects Analysis (FMEA) is a structured methodology for identifying potential modes with objectives of the potential hazards identification, and remedial proposals. The failure mode is a manner or mechanism, where the component fails to meet or deliver the intended function. The effect of the failure mode is determined by the system's response to the equipment failure. The FMEA is performed at the component level, where the likelihood of potential failure occurrence and potential severity of the impact are also concerned.

For example, two failure modes of the humidifier in a FC system have been identified: fail to provide water to the FC stack and flooding, whose effects are severe damages to the FC stack. Hydrogen filter, valves, fans, humidifier, heater, FC stacks, capacitors, and power switches are included in the FMEA as shown in Table I. It is a simplified version, as the operational mode, detection of failure, effects on the subsystem are omitted.

Table I. Failure Modes and Effects Analysis (FMEA) of fuel cell system used in telecom backup power

No.	***Description***			
	Unit	***Function***	***Failure mode***	***Effect on the system***
1	Hydrogen filter	Removing impurities	• Fail to strain properly	• Low output
2	Hydrogen inlet valve	Hydrogen supply	• Fail to open • Leakages • Spurious operation	• Low output
3	Hydrogen safety valve	Emergency shutdown	• Fail to open on demand • Leakages • Spurious operation	• Over pressure • System damage • Explosion
4	Hydrogen pressure valve	Hydrogen pressure regulation	• Fail to regulate • Leakages • Spurious operation	• Over pressure • System damage • Explosion

No.	Description			
	Unit	***Function***	***Failure mode***	***Effect on the system***
5	Fan	Supply cooling air	• Fail to supply air • Fail to cool down	• Over heating
6	Humidifier	Provide water to FC stack	• Fail to supply water to FC stack • Flooding	• Fail to generate electricity
7	Heater	Heat up FC to optimized temperature	• Over heating • Freezing	• Fail to generate required power
8	FC stack	Electro-chemical reaction	• Chemical, thermal, and mechanical degradation	• Fail to generate electricity

As the failure of a component may be caused by several failure mechanisms, various stressors can simultaneously contribute on the degradation of the component. However, each stress (e.g. thermal, humidity, vibration or contamination, etc.) could have its own degradation model and lifetime model. It is worth to classify failure stressors into specific groups. The critical components and main stressors of the fuel cell backup power system are listed in Table II. It can be emphasized that thermal stress and humidity stress can be regarded as the most two important stressors.

Table II. Critical components and main stressors

		dT[1]	T[2]	Vibration	Humidity	Contamination
FC stack	Membrane	X	X	X	X	X
	Catalyst			X	X	X
	GDL[3]			X	X	
	Flow plate			X	X	
	Gasket			X	X	
Balance of plant	Valve		X			
	Pump			X		
	Fan					X
	Sensor		X		X	
DC/DC converter	Semiconductor	X	X			
	Capacitor		X		X	
	PCB[4]				X	X

Note: [1] dT denotes the temperature fluctuation; [2] T denotes the absolute temperature;

[3] GDL stands for the gas diffusion layer; [4] PCB stands for the printed circuit board.

Mission profile analysis of the fuel cell backup power system is in focus. It starts with description of a typical loading profile of the telecom application and the frequency of the grid outage (operation frequency of the backup power). Then, since the thermal stress and humidity stress are the most affecting factors, the ambient temperature and the outdoor humidity are analyzed and evaluated in terms of the daily distribution and the annual distribution. Finally, two typical mission profiles, named as benign mission profile and severe mission profile, are summarized and compared.

In order to determine the working condition of the fuel cell system used in telecom backup power, the loading profile and the grid stability are necessary and crucial, as both of them affects the amount of output power and operation time duration of fuel cell. A daily loading profile of the telecom application is shown in Fig. 2, where two hours of full loading and ten hours of quarter loading can be seen, and it is repeated every twelve hours. On the other hand, the annual frequency of the grid outage indicates the switching time between the idle mode and working mode, and the outage time duration affects the loading variation based on the loading profile (full loading, quarter loading, or the loadings between them).

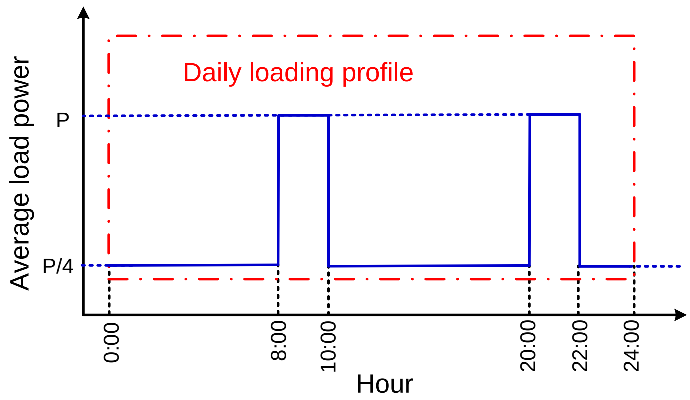


Fig. 2. Typical loading profile for a telecom application.

As the variation of the ambient temperature can be regarded as the thermal stress, they will be described in terms of the daily distribution and annual distribution. Due to the fact that the DBX5000 are mainly operating in Denmark and India, the ambient temperature and humidity distribution of these two countries will be further analyzed.

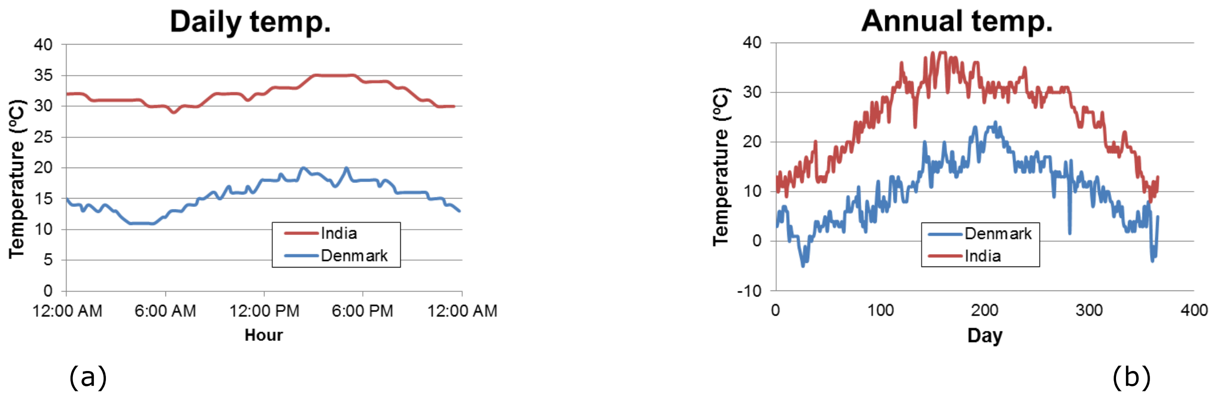


Fig. 3. Ambient temperature comparison between Denmark and India. (a) Daily temperature of Jul. 1st, 2014 with time step of 30 min; (b) Annual temperature of 2014 with time step of 1 day.

The ambient temperature comparison between Denmark and India is shown in Fig. 3, where the daily temperature and annual temperature are both mentioned. It is obvious that regardless of the daily temperature and annual temperature, India is generally higher than Denmark.

Table III. Two typical mission profiles

		Benign (Denmark)	Severe (India)
Grid stability	Annual outage frequency	2	365
	Outage duration	10 min	4 hr
Climate	Range of ambient temperature	-5~25 ºC	10~40 ºC

Two typical mission profiles can be summarized in Table III. It is noted that only two times of grid outage annually occurs in Denmark, while the grid outage happens every day in India. Moreover, the average outage duration in India is 4 hour, much higher than the 10 min of Denmark. Therefore, the benign mission and severe mission profile are used to stand for the Denmark case and the India case.

1.5.2.1 Development of a toolbox for fuel cell system reliability assessment

Hydrogen Fuel Cell (FC) technologies have been developed to overcome the operational and environmental challenges associated with using conventional power sources. Telecommunication industry, in particular, has implemented FC systems for the backup power function. The designers and manufacturers of such FC systems have great interest in verifying the performance and safety of their systems. Reliability assessment is designated to support decision-making about the optimal design and the operation strategies for FC systems to be commercial viable. This involves the properties of the system such as component failures, the system architecture, and operational strategies. This paper suggests an approach that includes Failure Modes and Effects Analysis (FMEA), Fault Tree Analysis (FTA), and Reliability Block Diagram (RBD). For a case study, and the service lifetime of a commercial 5 kW Proton Exchange Membrane Fuel Cell (PEMFC) system is estimated for backup power applications, in terms of the critical components, subsystems and the whole system.

Fig. 4 depicts a hierarchy of the system as well as the critical components of each subsystem.

1) FC stacks are assembly of a number of fuel cells, which convert from the chemical energy to the electricity.

2) DC/DC converter regulates the output from the FC stacks to a fixed DC voltage (e.g., 48 Vdc in telecommunication application).

3) Balance of Plant (BoP) is an instrumented system that is comprised of auxiliary parts, which serves to control both the supply of hydrogen and the thermal condition of FC stacks.

The FC stack generates electrical current from hydrogen, and the power converter conditions the electric power. The BoP is the collection of equipment that is necessary for FCs to operate. The system can be also described with a Reliability Block Diagram (RBD), where each block is connected in series structure. This structure implies all of the three subsystems must function for the system to operate as desired. Each sub-system itself is a block diagram consisting of major components.

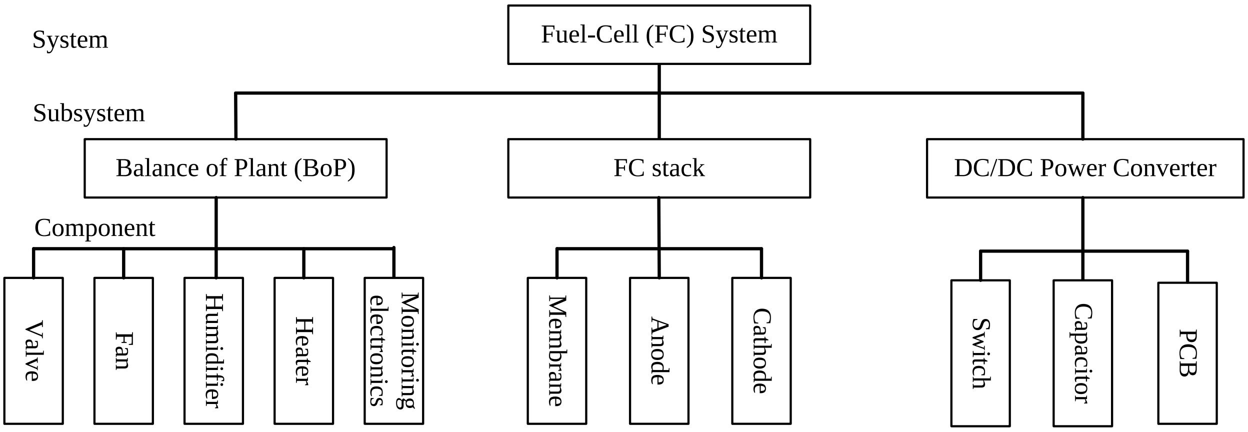
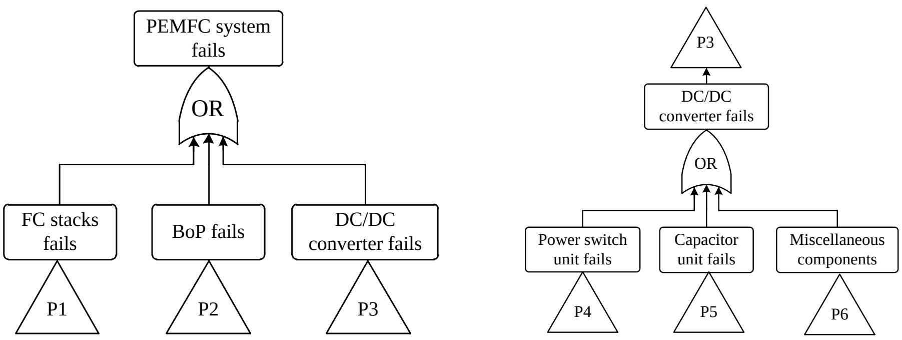
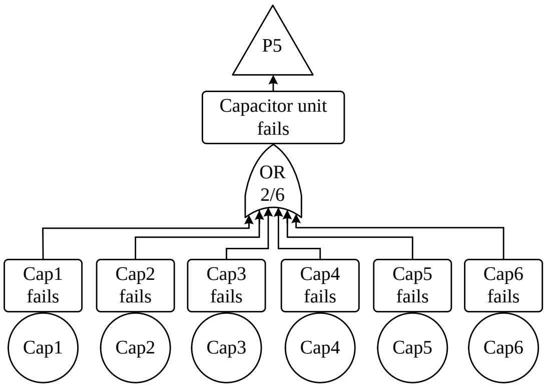


Fig. 4. Critical components of three subsystems in a fuel cell system.

Fault Tree Analysis (FTA) is used to demonstrate how the undesired event, defined as the TOP event, can happen. FTA is a so-called 'top-down' approach, where the TOP event is defined first, and failure causes are identified and connected to the TOP event with logic gate, such as OR gate, AND gate and voting OR gate, which represents for redundancy consideration. In the case study, the PEMFC system failure is the TOP event, as shown in Fig. 5, where the three subsystems of a FC system denote sub-fault trees. Besides, the sub-fault trees P3 and P5 are shown as well.



(a) (b)



(c)

Fig. 5. Fault tree analysis for a fuel cell system.(a) Three sub-fault trees for a fuel cell system; (b) Sub-fault tree for the dc/dc converter unit; (c) Fault tree for capacitor unit failure (P5).

The definition of reliability is probability that a system fails at certain operation time. Since the system experiences ageing and stresses during their lifetime, this probability may be decreasing in most cases, following a specific distribution. Weibull distribution is selected to express the component reliability, which is one of the commonly used distributions. It is flexible to express failure of components with two parameters β and η. β is shape parameter that implies how much a system is prone to a failure. η represents how long a system is expected to survive. The reliability function is

$$R(\mathrm{t}) = \exp[-(\frac{\mathrm{t}}{\eta})^{\beta}] \tag{1}$$

For the failure of the FC stack cell owing to its degradation, $\beta = 3.5$ is used. The η value is assumed 38,000 hours, calculated from the empirical data. For the BoP components, β and η values are assumed in reference to the OREDA handbook, and relevant papers and empirical data. For instance, the failure of the hydrogen inlet valve due to leakage is assumed to follow Weibull distribution with $\beta = 1$, and $\eta = 137{,}000$ hours. For the capacitors, failures due to the open-circuit, short-circuit or wear out, are assumed to follow Weibull distribution with $\beta = 3$ and $\eta = 100{,}000$ hours. The complete list of components with different β and η values are summarized in Table IV.

Table IV. Weibull Parameters of Critical Components in 5 kW FC System

Subsystem	Critical component	Shape parameter β	Scaling parameter η
FC stack	Fuel cell stack	3.5	3.8E4
BoP	Humidifier	1.0	4.65E5
	Purge	1.0	1.40E5
	Fan	1.0	1.29E5
	Hydrogen inlet valve	1.0	1.37E5
	Hydrogen safety valve	1.0	1.27E5
	Hydrogen pressure valve	1.0	6.87E4
	Power switch	2.5	1.200E5

DC/DC converter	Capacitor	3.0	1.000E5

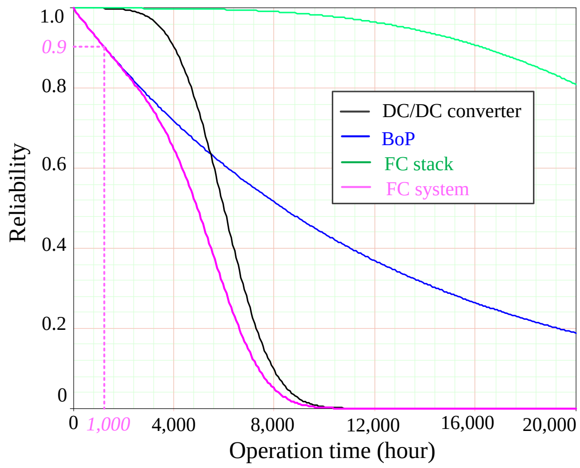


Fig. 6. Subsystem-level and system-level reliability of a PEMFC system.

The values are subjected change as the data from the operator of the systems are updated, or suggested value from expert judgments. Based on the component reliability, the calculation of the subsystem-level reliability can be initially carried out in terms of the FC stacks, BoP and DC/DC power converters. Afterwards, the FC system-level reliability are calculated by using the software ReliaSoft BlockSim as shown in Fig. 6. Thus, B10 lifetime (i.e., the time when the reliability is 0.9 or the time when there is 10% failure), is estimated to be 1,000 hours. Since the analyzed fuel cell system is used for backup power application at the absence of the regular power supply, its calendar lifetime expects to be longer since the system is in standby mode during most of the time. Moreover, the reliability assessment results are based on the component-level reliability data shown in Table II, which need to be updated for specific application case and loading profile.

The suggested framework in this fuel cell system is expected to be practical for the designers and manufactures. This approach is inclusive of critical components in terms of performance and safety of fuel cell systems. The approach is simple and flexible, since the component-level reliability data can be updated by users. The challenges remain due to the uncertainties and lack of reliability data that should be collected from testing and field operations. In the case study, data handbook OREDA is used for obtaining the reliability data of BoP components, which is a credible source in the oil and gas industry. It is therefore considered that more precise reliability estimation can be achieved with using data collected from the FC industry. Regardless of this limitation, the industry will find it practical to follow this approach as a starting point in verifying reliability assessment of a FC system, which satisfies the reliability target required by regulations and industry standards.

1.5.2.2 Validation and demonstration of reliability assessment model for fuel cell system

Reliability performance is critical for backup power applications as the system-level availability is with the high priority. Based on the mission profile of the dc/dc power converter, this section works on a system-level reliability analysis for the power stage used in fuel cell stacks. The time-to-failure distributions of key components (i.e. MOSFETs and capacitors) are predicted according to the long-term electro-thermal stress analysis, lifetime models, and Monte Carlo based variation analysis. Weibull distribution based component-level models are applied for system-level reliability analysis by using the reliability block diagram. A case study in a 5 kW power stage, consisting of six 1 kW power converters, reveals that the B10 and B1 lifetime of the power converter are remarkably reduced compared to the each power semiconductor and capacitor due to the large amount of them are connected in series. Moreover, if a 5-out-of-6 redundancy strategy is applied, the expected operation time of the power stage can be significantly enhanced compared to the case without redundancy.

The power semiconductor reaches the end-of-lifetime when an overlap occurs between its stress level and strength model. From the power cycling perspective, the stress analysis is related to the mission profile (e.g. the ambient temperature, the loading profile, and also the grid availability), while the strength model is determined by the selection of the power device and the associated cooling. Although the approach to evaluate the thermal stress of the power semiconductor at the standby mode and the operation mode is different, only the operation mode is considered since the much higher junction temperature leads to the dominating lifetime consumption compared to the standby mode.

The flowchart to predict the lifetime of the power semiconductor in the case of the operation mode is shown in Fig. 7. Under this circumstance, the junction temperature of the power semiconductor is jointly determined by the ambient temperature and the loading profile. The loss distribution of the MOSFET mainly consists of the conduction loss Pcon and the switching loss, which can be further divided into the turn-on losses Pon and the turn-off losses Poff. Due to the discrete MOSFET, its own heat-sink results in an independent thermal system, neglecting the thermal coupling from the adjacent devices. Considering the ambient temperature of 40 ºC, as the worst-case scenario, the mean junction temperature Tjm and the junction temperature fluctuation dTj can be calculated, based on the thermal impedance from the junction to the ambient.

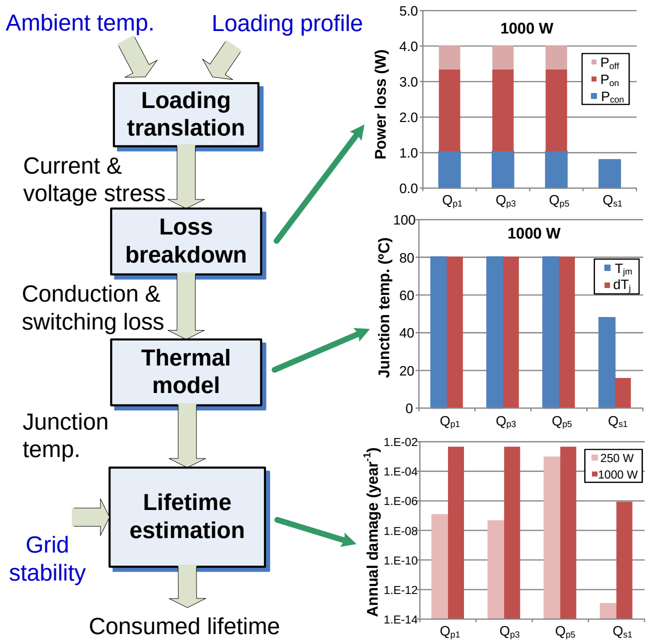


Fig. 7. Flowchart to predict lifetime of power semiconductor in the case of the operation mode.

The previous discussion gives a B10 annual damage of MOSFETs used in power converter, but the uncertainties due to the statistic properties of the applied lifetime model and the parameter variations of the power device should also be considered. Therefore, a statistical approach to analyze the lifetime performance subject to parameter variations is carried out in detail by means of Monte Carlo analysis. Finally, the time-to-failure distribution of the power semiconductors can be estimated by considering the parameter variations.

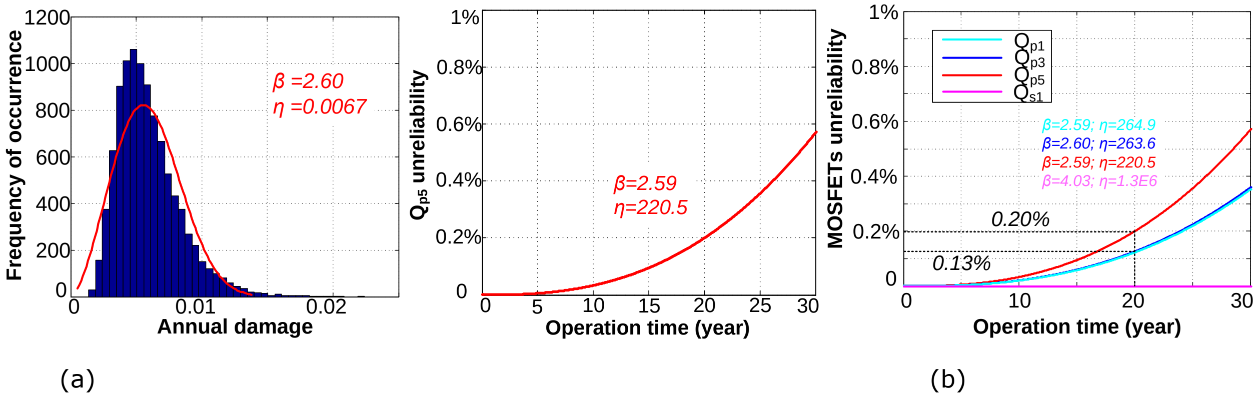
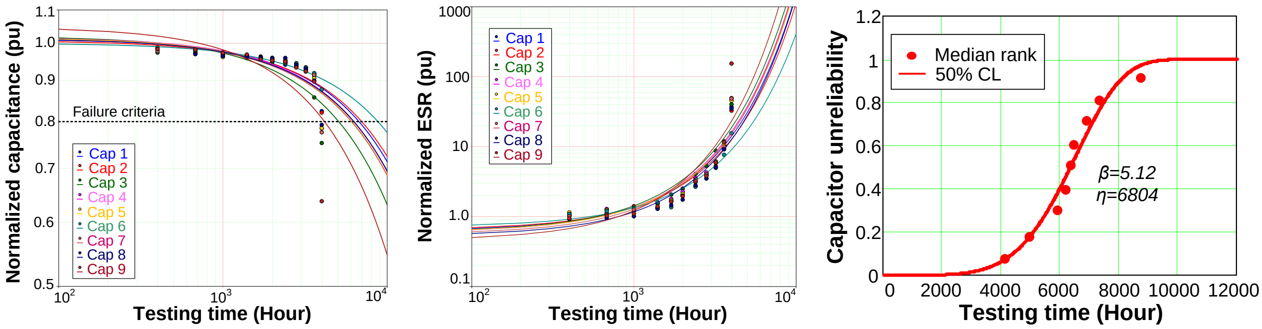


Fig. 8. Monte Carlo analysis considering all parameter variations from the stress evaluation and lifetime model for the most stressed MOSFET Qp5. (a) Annual damage distribution; (b) Accumulated percentage of failure (i.e. unreliability) along with the operation time; (c) Four typical power switches in terms of the accumulated failure.

Since the lifetime model is obtained from the accelerated testing results based on a specific number of testing samples, there is uncertainty of the derived constant parameters. The coefficients of the Bayerer model are fitted by many test data, and they are given within a certainty range. All the parameters in the lifetime model are distributed by means of Normal probability density function (pdf), if A and β1 experience a variation of 5%. The second type of uncertainty exists due to variances in the manufacturing process (like the typical, maximum and minimum on-state resistance of the MOSFET), which results in the variation of the mean junction temperature and the junction temperature fluctuation. To illustrate this, Qp5 is selected as an example. The junction temperature fluctuation experiences a variation of 5%. Each distribution is sampled by using Monte Carlo analysis, whose sample numbers results in the accuracy of the output distribution. Therefore, 10,000 samplings are chosen to establish the accumulated damage distribution.

With the static equivalent values of each component, the lifetime distributions of the key MOSFETs can be calculated, considering 5% parameter variations from the lifetime model and the stress analysis. Since the scale parameter of the Weibull function denotes the value when 63.2% failure occurs, it is predicted that Qp5 has the lowest scale parameter of 220.5 according to the accumulated damage estimation as shown in Fig. 8. For the accumulated failure, it can be seen that 20-year operation (i.e desired lifetime of the MOSFETs) results in 0.20%, 0.13%, and 0.13% failure in Qp1, Qp3 and Qp5, respectively.

Due to the lack of the complete failure data, the previous starts to calculate the B10 lifetime of the power semiconductor, and then the lifetime distribution can be obtained by considering the parameters deviation. In this part, the lifetime distribution of the dc capacitors is studied, and this is based on the complete failure data of the capacitors.



(a) (b)

Fig. 9. Capacitor degradation testing results at the rated voltage, rated ripple current and upper category temperature. (a) Normalized capacitance; (b) Normalized ESR; (c) Time-to-failure of capacitors at 50% Confidence Levels (CL) by using Weibull distribution in the case of 105 ºC.

The capacity change, dissipation factor and leakage current are generally considered as key indicators during the healthy condition of the electrolytic capacitors. To obtain the failure statistics of the used capacitor, a degradation test is performed with a series of 9 capacitors (56 μF/ 35 V) at the rated voltage, upper category temperature (105 ºC) and rated ripple current, and the normalized capacitance and Equivalent Series Resistance (ESR) are regularly measured with 4,000 testing hours. As shown in Fig. 9, the results are analyzed by using the software tool Weibull++. It can be observed that, during the process of the testing hours, the initial capacitance and ESR increase or decrease smoothly until they reach the turning point around 4,000 hour. This agrees with the end-of-life criteria of the individual capacitor – 20 % drop of initial capacitance. Generally, the exact reliability and the probability of the failure can never be known unless the failure data of every unit in the population can be obtained. Since this usually is not a realistic solution, the testing with a certain number of samples is used to estimate the reliability, which introduces the Confidence Level (CL) – a range within which these reliability values are likely to occur with a certain percentage of the time. The widely-adopted 50% CL is applied by using Median Rank (MR), where the lifetime is not neither overestimated nor underestimated. The time-to-failure of 9 samples are located as shown in Fig. 9, and they can be fitted in terms of the Weibull distribution with a shape factor of 5.12 and scale factor of 6,804. Thus, BX lifetime at any condition can be calculated.

According to the loading condition and thermal model of the electrolytic capacitor, the operation temperature of the capacitor can be calculated in the cases of the standby mode and the operation mode. Afterwards, based on the lifetime model of the capacitor, the expected BX lifetime for the input-side and output-side capacitor can be calculated.

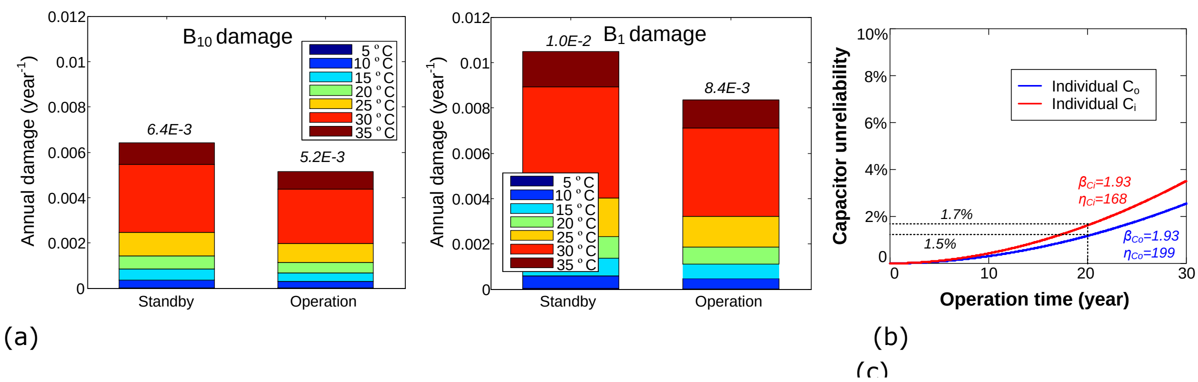


Fig. 10. Annual damage of the output-side capacitor in the case of the standby mode and operation mode. (a) B10 damage; (b) B1 damage; (c) Time-to-failure of individual input and output capacitors within 20-year operation.

Although the types of input-side and output-side capacitor are different with the tested capacitor, all of them belong to the family of the radial electrolyte capacitor, whose lifetime expectancy is 5,000 hour as mentioned in their datasheet. Consequently, the lifetime model as shown in Fig. 9 is suitable for both the input capacitor and the output capacitor. Based on the B10 and B1 lifetime model, the damage of the output-side capacitor is shown in Fig. 10, in which the standby mode and the operation mode are compared. Although the loading condition leads to a rise of the capacitor temperature, when the B10 lifetime is considered, the higher proportion of standby mode causes a higher annual damage of 6.4E-3 compared to the operation mode of 5.2E-3. Meanwhile, if the B1 lifetime model is considered, the annual damage in both the standby mode and the operation mode is higher than the B10 because of its lower cycle-to-failure at the same stress level. Similarly, the same approach can be extended to the input-side capacitor, and the B10 and B1 damage can be calculated as well.

With the calculated B10 and B1 lifetime for the input-side capacitor and output-side capacitor, the key Weibull parameters of their time-to-failure curve can be fitted. It is noted that the shape factor and the scale factor for the individual input capacitor are 1.93 and 168, while these factors for the individual output capacitor are 1.93 and 199. Similarly, in the case that the 20-year operation (desired lifetime of electrolytic capacitor) is in focus, the unreliability of the capacitor along with the operation time is shown in Fig. 10. It is evident that 20-year operation of the fuel cell system induces 1.5% and 1.7% failure for the input capacitor and output capacitor, respectively.

In order to assess the reliability metrics of the whole power stage in the fuel cell system, major steps can be divided into the reliability analysis of a 1 kW power converter and a 5 kW power stage. By using the RBD, the procedure to calculate the reliability function is shown in Fig. 11. The reliability evaluation of the total power semiconductors and capacitors is calculated by each component. Afterwards, the 5 kW power stage can be investigated based on the 1 kW power converter. Due to the same time-to-failure characteristic of the used power devices and dc capacitors, only these representing components are considered.

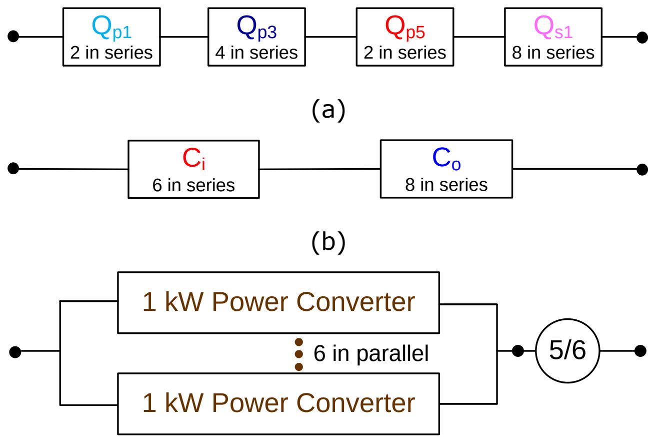
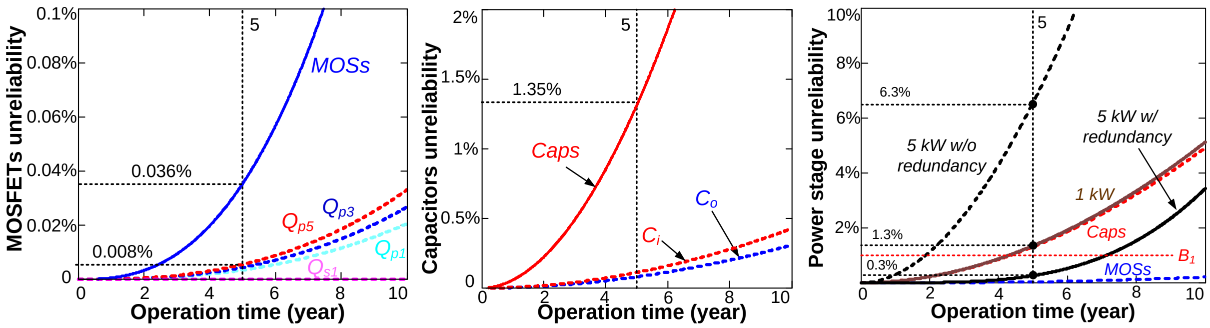


Fig. 11. System-level reliability calculation by using reliability block diagram. (a) Composition of MOSFETs in 1 kW power converter; (b) Composition of capacitors in 1 kW power stage; (c) Composition of 5 kW power stage considering redundancy.

As mentioned before, the MOSFETs are not evenly stressed and the four representing MOSFETs can be found. The reliability of 1 kW power converter can then be calculated by considering all the MOSFETs used in the primary-side and secondary-side. As shown in Fig. 12, the reliability of the total MOSFETs can be deduced from each component. The damage of the 5-year operation (desired life-time of the backup power) increases from less than 0.01% of the most stressed MOSFET to almost 0.04% of all the MOSFETs existed in 1 kW power converter. Meanwhile, the reliability of the total capacitors from the input capacitor and output capacitor is shown in Fig. 12.



(a) (b)

Fig. 12. Accumulated percentage of unreliability from component-level to system-level. (a) From MOSFETs to 1 kW power converter; (b) From capacitors to 1 kW power converter; (c) From 1 kW power converter to 5 kW power stage with and without redundancy.

The unreliability of the whole power stage is shown in Fig. 12, where the cases with and without redundancy are compared as well. Since five reliability blocks are series connected in the condition without redundancy, the lifetime of the power stage is significantly reduced compared to the 1 kW power converter. However, in the case of using redundancy, the reliability of the power stage can be enhanced compared with no redundancy. For instance, the B1 lifetime of 1 kW power converter is 4.5 years. At the same time, the expected operation time of the power stage without redundancy is around 2 years, while the expected lifetime with N+1 redundancy can be enhanced to 7.5 years. It is noted that 5-year operation results in 1.3% failure of 1 kW power converter, while it consumes 0.3% and 6.3% failure whether the redundancy is applied or not. It is concluded that, to fulfil the high reliability (i.e., 0.99) within a service life of 5 years, the N+1 configuration has to be employed. Alternatively, it can be achieved by sizing the more reliable dc capacitors.

Overall, a system-level reliability analysis method of dc/dc converters for the power conditioning stage of fuel cell stack is proposed in this WP. It is mission profile and Weibull distribution based by analyzing the long-term electro-thermal stress profiles and the time-to-failure distribution of key components. A case study of an industry design of a 5 kW fuel cell system with multiple dc/dc converters is presented. The reliability curves of the MOSFETs and capacitors used in the dc/dc converters is predicted by considering the associated electro-thermal loadings and statistical properties in lifetime models and component parameters. The predicted B10 lifetime with 50% confidence level of the group of 16 MOSFETs and the group of 14 capacitors in a single dc/dc converter are 50 years and 15 years, respectively. Without redundancy, the B10 lifetime is 6 years for the power conditioning stage with five 1 kW dc/dc power converter. To extend its lifetime, a redundant design with one more 1 kW dc/dc converter is analyzed with the increase of B10 lifetime to 14 years, which allows a further study for the trade-off design between the lifetime extension and cost. Although the study case is carried out in a fuel cell application, it is a general approach to evaluate the system-level reliability. By knowing the mission profile, and thermal stress of the critical components, the reliability of the power converter used in the popular applications (e.g. renewable energy system, drive system, etc.) can be investigated in the similar manner.

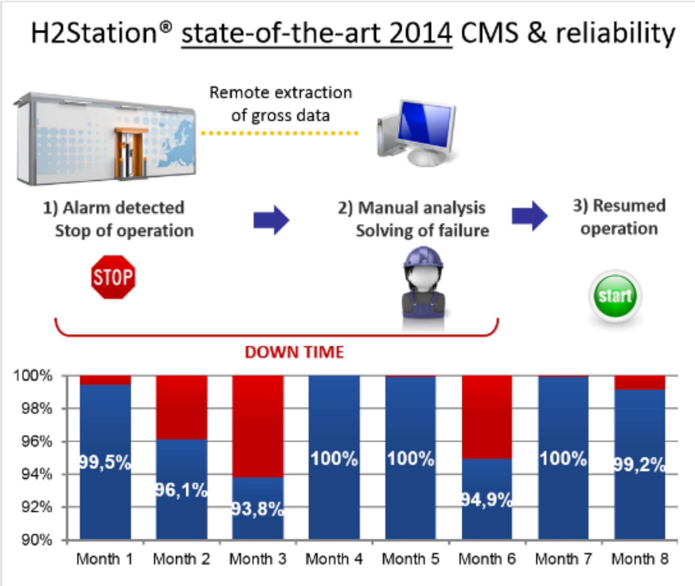
1.5.3 WP 3 Development & test of new CMS for Hydrogen fuelling Stations (H2Logic)

Nel Hydrogen (former H2 Logic) has developed and tested a new Control and Monitoring System (CMS) for Hydrogen Refuelling Stations (HRS) as part of the rest project. Below sections outlined the project process and results. The CMS has been developed for the H2Station® product range from Nel Hydrogen.

1.5.3.0 Background and objective

The background for the REST efforts has been to both improve reliability of HRS and reduce involved personnel resources in the operational handling and monitoring.

In 2014 (at the start of REST), the state-of-the-art CMS was a mainly manual process as outlined in the figure.

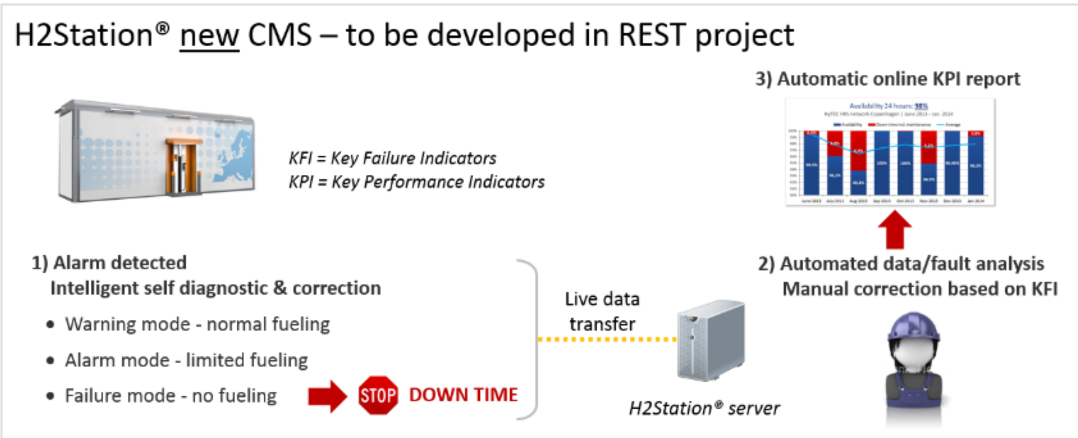


When an alarm or stop of operation was detected, a service technician had to conduct manual failure analysis and solve the failures. Besides requiring substantial resources, it also increased the down-time resulting in a fluctuating reliability.

Also no intelligence was built into the control of the HRS, thus many small alarms caused the HRS to go off-line, despite it easily could have continued operation. Many major alarms were only detected when it was too late (the station going out operation), instead having intelligence that could monitor and understand when an alarm might be pending soon.

Also, reporting to customers on KPI's was a complicated and very manual process taking up to 10 hours, as substantial amount of data had to be processed manually.

The aim of REST has therefore been to develop a new CMS for the HRS, as outlined in figure below. The rationale has been to build in more intelligence in the HRS control software, so it both can detect upcoming alarms earlier and sort in the relevance of alarms, avoiding the station to go out of operation due to smaller errors, not affecting safety or ability to conduct a fuelling. The data handling process was to be more streamlined and automated by introducing a central server where data are pushed to from the station.



In addition, a software tool had to be developed that would enable a more automated failure solving for service people (identifying Key Failure Indicators), as well as a fully automated Key Performance Indicator (KPI) reporting system.

1.5.3.1 KFI/KPI definition and specification

As a first effort in the project, a detailed list of KFI and KPIs was developed, to act as back-bone specification for the various software. In total, a list of 300 items were developed, grouped into different categories as outlined below.
The categories covered single static data as well as dynamic calculation of new data based on static data.

H2Station® KPI/KFI specification

No.	Main parameter	
A.	Specification data	Static data fixed at Start of Operation - updated when relevant
B.	Fueling specific data	Static data recorded for each Fueling
C.	Event specific data	Static data recorded for each Event
D.	Operation specific data	Static data recorded for various operation parameters
E.	Fueling performance data	Dynamic accumulation and/or calculation of data for a variable period
F.	Event performance data	Dynamic accumulation and/or calculation of data for a variable period
G.	Operation performance data	Dynamic accumulation and/or calculation of data for a variable period

B. Fueling specific data

B.1	Main parameter	Unit
B.1.1	Fueling pressure	MPa
B.1.2	Dispenser no.	Number
B.1.3	Hose no.	Number
B.1.4	End-user interaction start time	dd.mm.yyyy hh:mm:ss
B.1.5	Dispensing start time	dd.mm.yyyy hh:mm:ss
B.1.6	Dispensing end time	dd.mm.yyyy hh:mm:ss

1.5.3.2 Definition of advanced alarm modes

To achieve more intelligence in the HRS control software, new operation modes with more advanced alarm modes were developed.

The H2Station® CMS determines autonomously what impact an event should have:

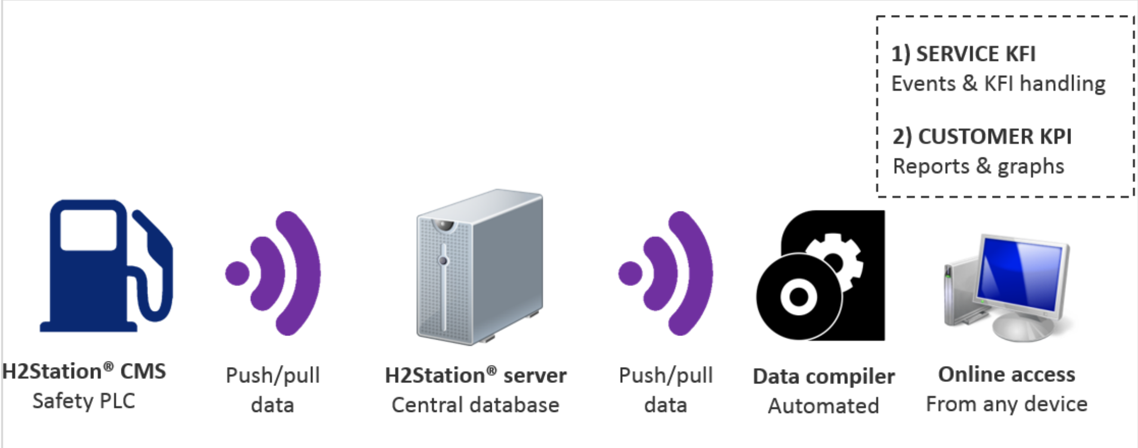
- **Warning:** Event not safety relevant and no performance impact
  Can be addressed by service personnel when relevant
- **Alarm:** Event not safety relevant but performance impacted
  Fuelling still possible but e.g. less capacity
- **Failure:** Event may affect safety – fuelling is not possible
  System in emergency shutdown (fail-safe-mode)

The aim has been to avoid that smaller alarms cause the HRS to go out of operation.
The table below provides further detail on the developed alarm modes.

H2Station Operation Modes	Status description	Alarm / situation examples
Operation mode	Ready for fueling	None
Warning mode	Ready for fueling – Warning on potential upcoming alarms.	E.g. a transmitter has reached a warning level, but not a critical level (alarm) where action is taken.
Alarm mode	Limited fueling – Alarm and/or shot down of sub-systems	E.g. alarm that results in shut-down of compressor, but refueling from cascade is still possible.
Failure mode	Not ready for fueling – Alarm affect-ing safety – emergency shutdown entire system.	E.g. alarms on detection of hydrogen, smoke, flames or other safety critical situations.

1.5.3.3 Overall data structure specification

An overall data structure was also specified as outlined in figure below.



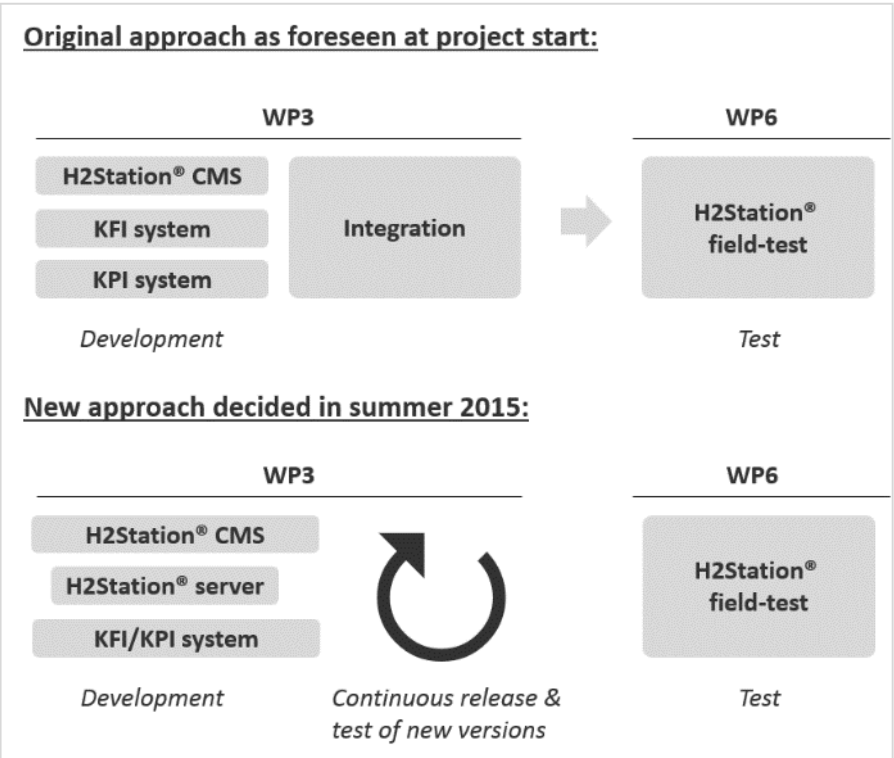
Each HRS will push or pull data from a central server data base, thus avoiding the need for large memory capacity at each HRS. It also enables a safer storage of data centrally.

On top of the data base, a data complier software will be used to, intelligently and in an automated way, compile relevant data for two purposes:

- **Service KFI:** To allow service people to identify relevant KFIs instantly and thus, allowing for a faster failure solving
- **Customer KPI:** Interface allowing for instant generation of KPI reports and graphs for customers (HRS operator)

1.5.3.4 Software implementation and test approach

At the start of REST, it was originally foreseen that the developed CMS where to be tested on one HRS in the field. However, during the project a new approach was decided as outlined in figure below.



To gain as much field operational experience as possible, the new CMS will be introduced through several software releases and on all HRSs in field operation in Denmark.

The step-wise approach will allow for gradual improvement during the project, based on the field operation results. And by implementing it on HRS's in Denmark instead of only one, much more data and experience would be collected.

1.5.4 WP 4 Accelerated reliability testing of FC-BC system (Ballard)

The objective is to perform accelerated tests of sub components and full scale systems. Data from the test is also used to validate the reliability model developed in WP2.

1.5.4.0 WP 4.1 Definitions of test types and test equipment

The ability to accelerate test is done with some of the BOP components. The full-scale systems reliability is tested in several possible conditions observed in the field.

Most of our back-up systems are located in technical shelters owned by the customer. A copy of a common shelter is located at Ballard Power Systems Europe (BPSE), which has been modified, to conduct a variety of tests. Accelerated tests and reliability, in the same conditions the system normally is operating in, are done in the shelter. To accelerate some of the tests, the shelter is slightly modified. The air inlet to shelter is modified to simulate different temperatures.

Figure 1 shows the technical shelter. With two cooling containers running in cascade, a stable cooling for long periods of time is possible.
The technical shelter is equipped with two types of ventilation.

- Positive pressure ventilation
- Negative pressure ventilation

The system placed in the field shows that the ventilation in the shelter can affect the performance and reliability of the system.
The Containers can supply the shelter with air and deliver -40°C to +30°C air temperature.
The shelter setup hosts many of the system tests performed in this project. The versatility with the control of the climate and ventilation will be used in variety of tests.
The shelter can be used to simulate process air used from inside the shelter. The container give the possibility to simulate different outside temperatures how this effects the system performance and reliability.

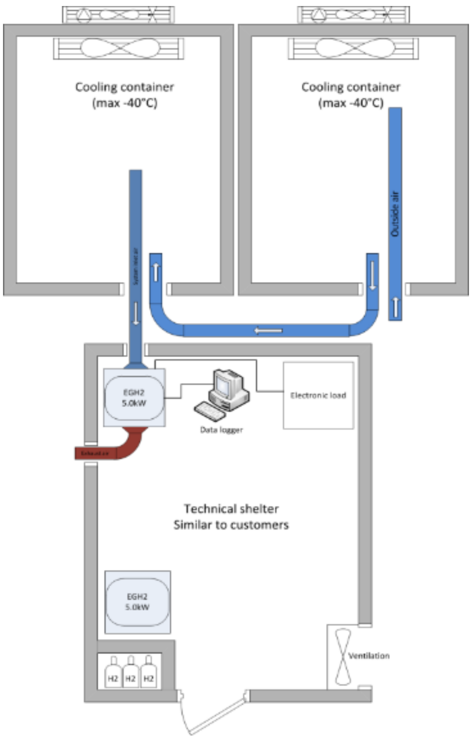


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Figure 3 Technical shelter setup

Figure 5 Refer containers and technical shelter setup

Figure 4 Image of test setup inside the technical shelter

Figure 5 shows the inside of the shelter, with a FCgen®-H2PM 5.0 kW/48V system in a climate test simulation test. The computer and electronic load is used to create accelerated tests.
The computer is operating the system load and logging all the temperatures relevant for the different tests (Figure 5). In the climate test, the reliability and stability of the system is monitored with fuel cell.

A small climate chamber was used for accelerated testing of different bottle regulators for our fuel cell systems. The test setup is created so that it is possible to test regulator performance from -60°C to 100°C.

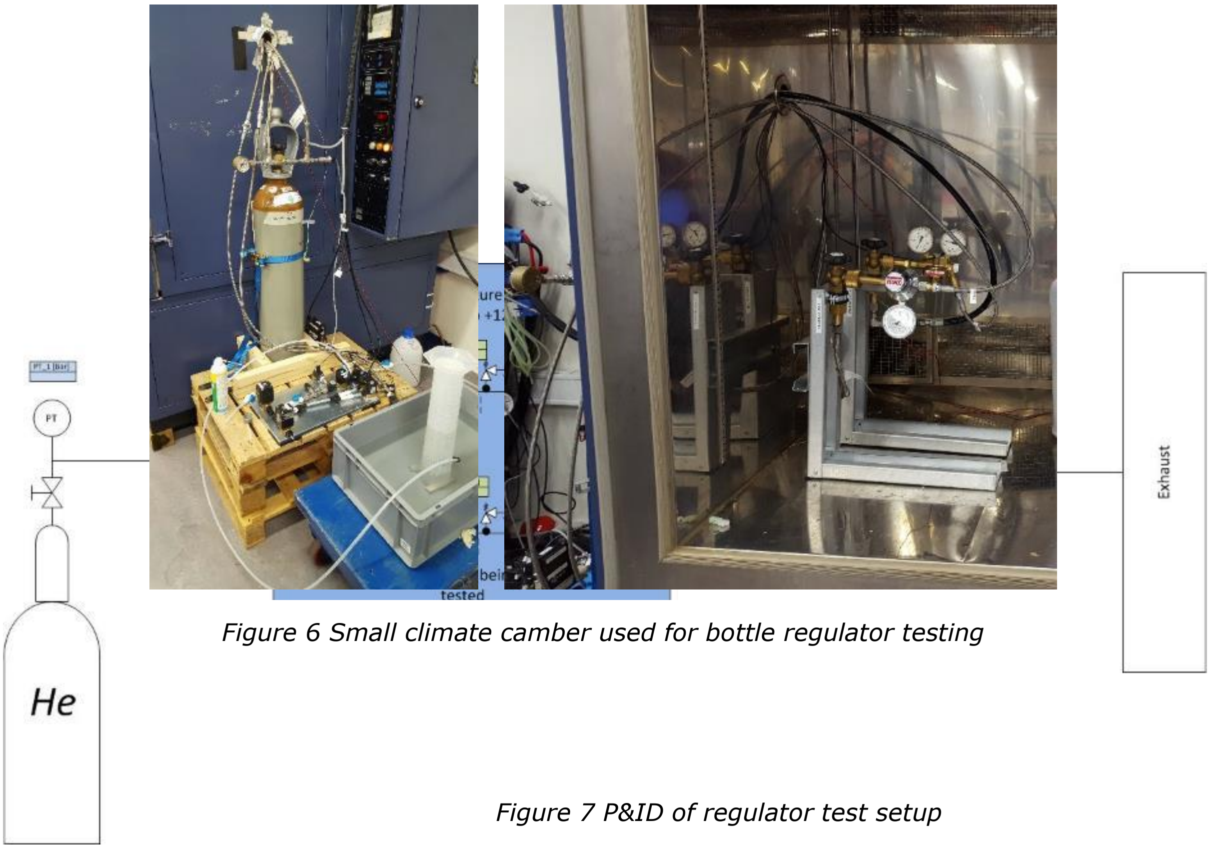


Figure 6 Small climate camber used for bottle regulator testing

Figure 7 P&ID of regulator test setup

The test setup can operate the regulators with several open and close sequences. The regulators are used in different system configurations, meaning that the flow variations of the regulator are very important to test.

1.5.4.1 WP 4.2 Selection of components to be tested

A study of the errors observed on fuel cell backup systems in the field shows the areas where reliability could be improved.

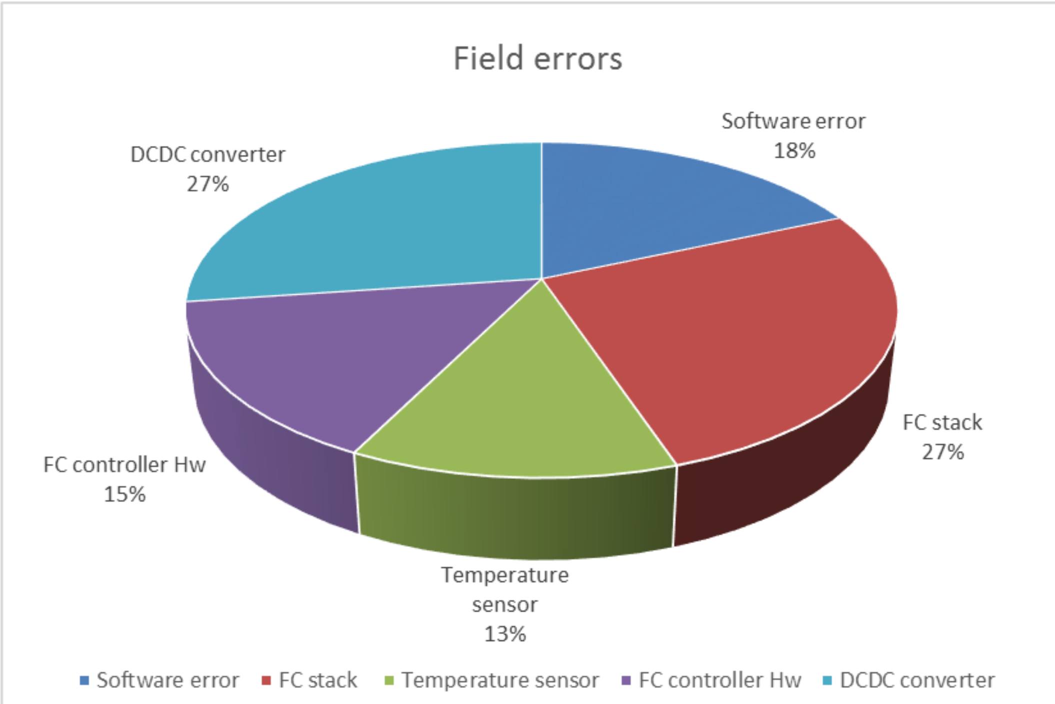


Figure 8 Field errors on fuel cell back-up systems (2014)

The list of components to be tested is mainly selected from this study. Figure 9 shows that the DCDC converter is responsible for 27 % of the errors observed in 2014. The work done in this project has focus on testing the reliability of the most common components to fail in a DCDC converter. The reliability assessment model in WP 2 has used components on from the DCDC converter to verify the model and calculations.

The software is also a big challenge. The software errors can in some cases cause the failure of the FC stack, FC controller and DCDC converter. The system reliability testing has therefore focused on testing the software and software improvements before they are released.

The FC stack is not directly in focus in this project, but the BoP components that manage the stack and secure the reliability and performance are. The 27 % reveals that there are areas of stack management that need to be improved.
Task 4.3 is looking directly at the start up time and hydration of the stack.

1.5.4.2 WP 4.3 start-up time

The correlation between the impedance and the relative humidity of the fuel cell membrane in determining the fuel cell's start-up time

Fuel cell-based backup units are characterized by long standby periods but they must be ready to start at any instant in the shortest possible time. In the case of low temperature proton exchange membrane fuel cells, the estimation of the hydration status of the fuel cell's membrane during standby is important for determining the cell's ability to perform a fast and safe start-up. In work package 4, a non-conventional electrochemical impedance spectroscopy (EIS) was suggested and investigated as a method to estimate the membrane's hydration status. The proposed technique

differs from standard EIS in that the current through the fuel cell cannot contain a DC component, since hydrogen is absent.
In brief, the idea was to symmetrically feed with air a fuel cell stack, whose temperature and relative humidity are controlled, and its complex impedance is measured at different frequencies and for different values of relative humidity at constant temperature. Power regression models can be applied to the data, and the relationships between complex impedance and relative humidity can be found.

The constant temperature characterization of fuel cells using impedance measurements is presented in [1] *(Reference to previous publish document see page 29)* while the variable temperature characterization is described in [2]. As the results show, the proposed technique is a viable way for estimating the membrane hydration status of a fuel cell stack during standby. Moreover, the most suitable frequency values, at which the measurements should be performed, can be defined.

This work presents a method and a setup that has been proposed and built to measure the start-up time of the fuel cell standing in stand-by mode for a longer time in different environmental conditions (temperature and relative humidity set points). The results can lead to a correlation between fuel cell impedance in standby mode (based on humidity and temperature measurements presented in [2] and the possible start-up time after the standby period.

Start-up time measurements

The overall goal of the work is to find a correlation between the hydration status of the fuel cell membrane and the fuel cell start-up time through analytical equations. It has already been presented in [2] that the impedance of the fuel cell in stand-by mode correlates to the relative humidity of the membrane. From this, an assumption can be made: by replacing the stand-by fuel cell with one connected to the hydrogen supply system and by reproducing the same environmental conditions as described in the previous publication [2] it is possible to perform the start-up procedure on a fuel cell having the same impedance as the one measured in stand-by condition.

As a more accurate definition of the PEM fuel cell start-up time was not found in the literature, hypothetically the start-up time was defined as that time interval during which the fuel cell reaches its operating load current with fixed output voltage and its temperature increases and stabilizes within a 1% error band around the stabilized temperature value.

The experimental setup

The main element of the experimental setup (Figure 11) is a climatic chamber which ensures variable environmental conditions. An Angelantoni 1200CY climatic chamber is used for this purpose. The chamber volume is equal to 1152 l, the temperature range with no relative humidity control is [-75; 80] °C, and temperature and relative humidity ranges with humidity control enabled are [1; 95]°C and [2; 90] %. The chamber can be controlled with the software WinKratos, provided by the manufacturer of the chamber, in which the operating conditions can be defined and changed in automatic or manual mode.

A 36 cell Ballard low temperature PEM fuel cell stack was placed inside the climatic chamber, connected to the laboratory hydrogen supply system (Figure 10). The hydrogen pressure is regulated to 0.5 Bar (50 kPa), according to the datasheet.

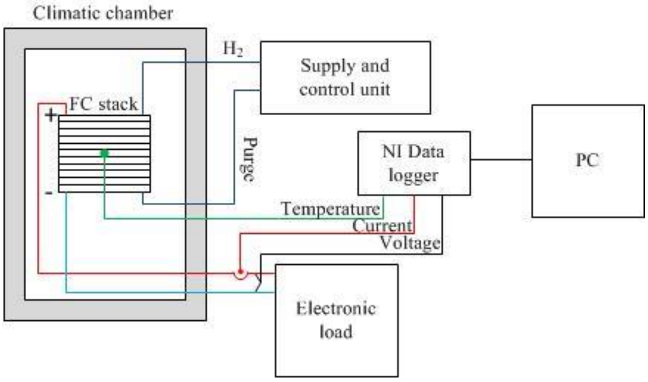


Figure 10 Schematic of the experimental setup

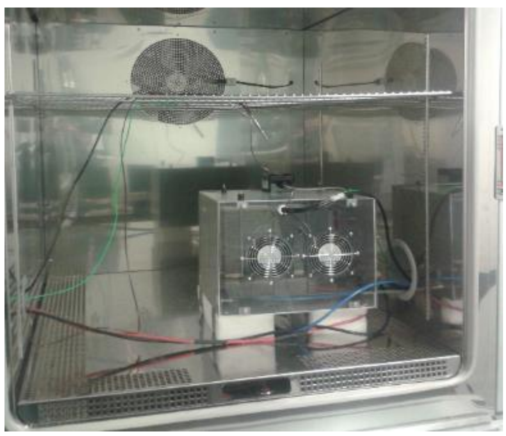


Figure 9 The fuel cell inside the climatic chamber

Knowing that the climatic chamber is an almost isolated system, for the oxygen consumed by the fuel cell for the chemical reactions has to be compensated additionally. For this purpose, a Bürkert mass flow controller is used, connected to the laboratory compressed air supply system, to ensure 0-40 Nl/min controlled air flow. The hydrogen supply of the stack is ensured with electronic valves, controlled manually by a relay switch – enable or disable the H_2 valve. A similar relay starts a timer that enables the purge valve of the fuel cell after each 60 second time interval for a 100 ms purging. The cooling of the fuel cell stack is realized with two 24 V fans that are connected to a temperature control unit. The fans are always turned on when H_2 supply relay is ON and working with a low speed. Based on the temperature of the stack, the fan speed is increased by the temperature controller (Figure 13).

Figure 12 Fuel supply and fuel cell stack temperature control platform

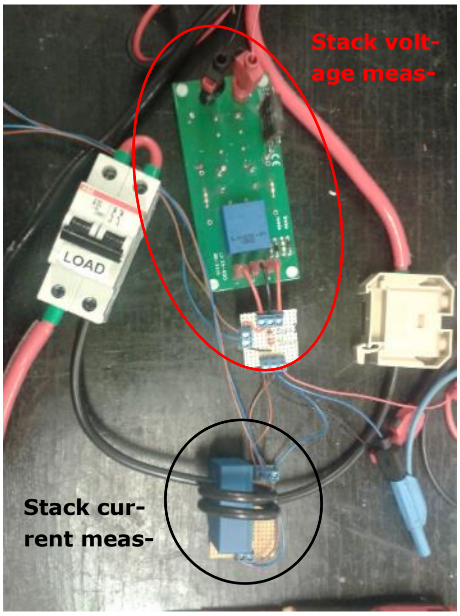


Figure 11 LEM transducers for voltage (upper ellipse) and current measurement (lower ellipse)

Results and discussion

In Fig. 1 the measurement results at 15°C are shown. On the top graph, the temperature waveforms are presented. In the middle graph the stack current is shown. The 1 minute purge time in the waveform can be seen. In the bottom of the graph, the output voltage is presented, which is a controlled 18 V with load turned on and 36 V with no load (in the turn on sequence of the measurements). Similarly, the start-up time variation is presented for 30°C and 50°C in Fig. 2 and Fig. 3. The voltage waveforms are not included in the presentation as they look like the ones presented in Fig. 1.

As stated before, the start-up time is that time interval during which the temperature and the stack current of the fuel cell reaches a certain value, which is considered the stable operating temperature and current. In average, these values are:

- 52°C and 64A at T=15°C starting condition
- 54.5°C and 66A at T=30°C starting conditions

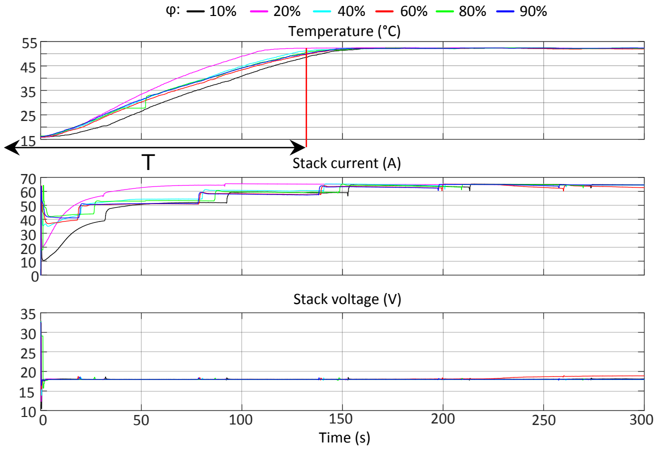


Fig. 1. Stack temperature, current and voltage waveforms measured at T=15°C and with various relative humidity values. T_s represents the start-up time.

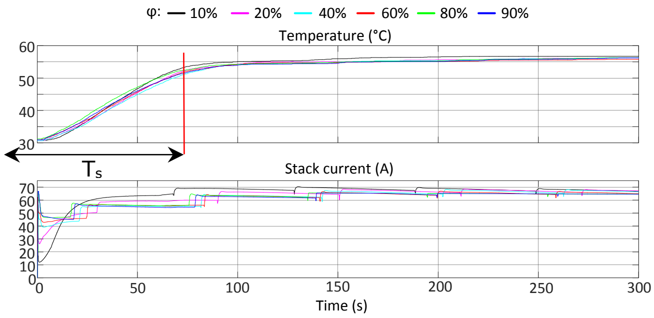


Fig. 2. Stack temperature and current waveforms measured at T=30°C and with various relative humidity values. T_s represents the start-up time.

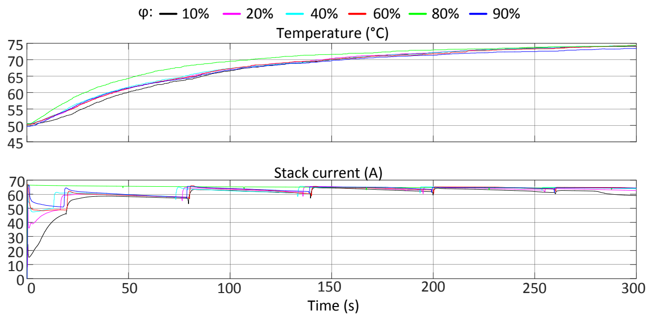


Fig. 3. Stack temperature and current waveforms measured at T=50°C and with various relative humidity values. T_s could not be defined as the temperature was in increase.

The temperature did not reach a stable value with the current setup when the initial temperature was 50°C. This can be explained by the fact that the fuel cell stack cooling system is underestimated and cannot pull the initially warm air through the stack with enough speed to stabilize the stack temperature, even though the chamber is trying to keep the environment temperature constant and reduce the humidity surplus released by the stack.

Based on the numbers from the measurements and looking to the figures above, the average start-up time measured with the presented setup is:

- around 150 s with T=15°C starting conditions
- around 85 s with T=30°C starting conditions

With T=50°C starting temperature, the value of the start-up time could not be defined because the temperature did not stabilize during the measurement time interval. The different deviations from the average values could be related to the procedure errors introduced by limitations of the measurements and are explained in the following sub-sections.

Conclusions

- The impedance of the fuel cell in stand-by mode correlates to the relative humidity of the membrane.
- By measuring the start-up time of the fuel cell connected to the hydrogen supply system in the same environmental conditions as described in the previous work, a correlation can be made between the relative humidity of the fuel cell and its start-up time through its impedance.
- A method for measuring the start-up time of an on-line fuel cell with different environmental conditions was described.
- The constraints and limitations of the experiments were also presented.

Future work possibilities

- Most important improvement in the future the automation of the system and synchronization
- Future work should also include measurements in the sub-freezing temperature area.
- Through analytical calculations, the equations that will give the value of the start-up time in function of the fuel cell impedance will be derived after merging all the data from previous and current measurements.
- A design of a diagnostic and control system will then follow including the low-cost impedance measuring device and humidifying control system to keep the membrane hydration status at its optimum value during stand-by to obtain the optimum start-up time.

References and relevant publications

[1] B. Bidoggia and S. K. Kær, "Estimation of membrane hydration status for standby proton exchange membrane fuel cell systems by complex impedance measurement: Constant temperature stack characterization," *International Journal of Hydrogen Energy,* vol. 38, no. 10, pp. 4054-4066, 4/1/ 2013.

[2] B. Bidoggia and S. K. Kaer, "Estimation of membrane hydration status for standby proton exchange membrane fuel cell systems by impedance measurement: First results on variable temperature stack characterization," in *Ecological Vehicles and Renewable Energies (EVER), 2013 8th International Conference and Exhibition on*, 2013, pp. 1-10.

[3] L. Török, S. L. Sahlin, S. K. Kær, and B. Bidoggia, "Estimation of membrane hydration status for active proton exchange membrane fuel cell systems by impedance measurement: Start-up time measurements," in *2016 IEEE 16th International Conference on Environment and Electrical Engineering (EEEIC)*, 2016, pp. 1-5.

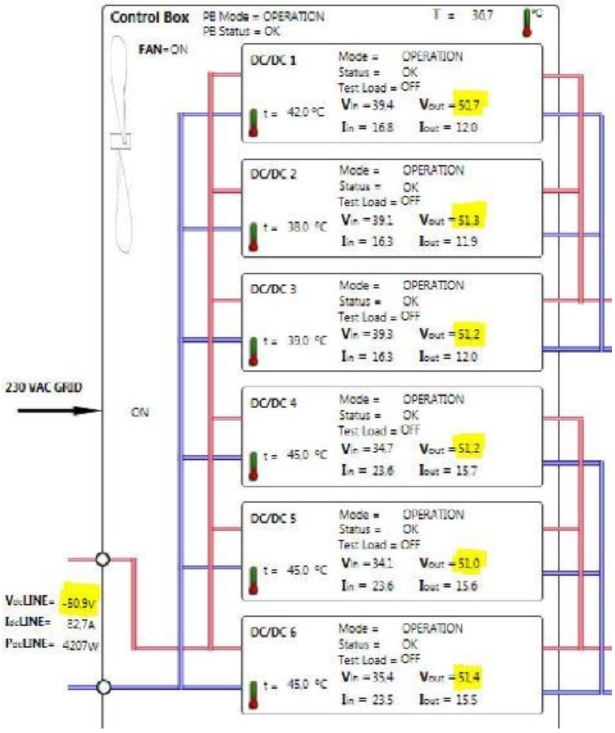
1.5.4.3 WP 4.4 Accelerated testing

DCDC output measurements temperature stability

Description of the problem

The 5kw system is build-up of 6 DCDC converters, 3 on each stack of the two stacks. The output of the DCDC converters are all connected to the same 48V bus, which also serves as the output from the system. The DCDC converters are measuring the output voltages and this measurement is calibrated in the production of the DCDC converters. Even though, it has been observed on systems in the field, that the DCDC converters show different output voltages. The difference of the measurements was as high as 1V and far more than the tolerances in the system should allow.

The measurement is only an internal measurement; the customer voltage is controlled by a direct measurement on the 48V output bus. But during start up, the difference is resulting in that the DCDC converters have problems current share correct and first after the current share algorithm has adjusted the DCDC converters in place, the DCDC converters shared the load correctly. This adds extra stress to the DCDC converters that take the most load during start-up.This situation should be avoided to improve the reliability.



1 The six DCDC converters measurements variation in a system

Calibration improvement

The first question was if the Factory Acceptance Test (FAT) did calibrate the DCDC converters good enough. The calibration of the DCDC converter is done in two points, a low voltage point and a high voltage point.

When the DCDC converter is not calibrated, the tolerances in the measuring circuit is big, so that the DCDC converter might be damaged if switched on at its limits. Because of this, the DCDC converter is first switched on in the middle of its output range and calibrated in a narrow span.

To improve the calibration, an extra calibration routine was implemented. After the DCDC converter had been calibrated in the narrow span, the DCDC converter was also calibrated at two points near its limits.

This improved the measuring accuracy on measurements made right after, still in the FAT test system.

But mounted in a product, the output measurements on different DCDC converters were still not the same.

2 Factory Acceptance Test System was added extra calibration routine

Control box calibration

That the DCDC converter measurements were not the same in a system, as they had been in the FAT test system, could be explained by in the FAT test system the DCDC converters did not have the same cooling as they have in the system. The test time, until the DCDC converter measurements got calibrated could variate a little, so this might result in that the DCDC converter output measurements were calibrated at a bit different temperature.

The solution was to calibrate the DCDC converter output measurements while they were mounted in the control-box. In this way, we insured that the DCDC converter output measurements were calibrated at conditions as close to the real world as possible. To make this test and calibration possible, a new test and calibration system was developed. It contains both power supply to supply the control box (where the DCDC converters are mounted) and precision measurement equipment. The test and calibration system is controlled by a PC and dedicated software was developed for control in Lab View.

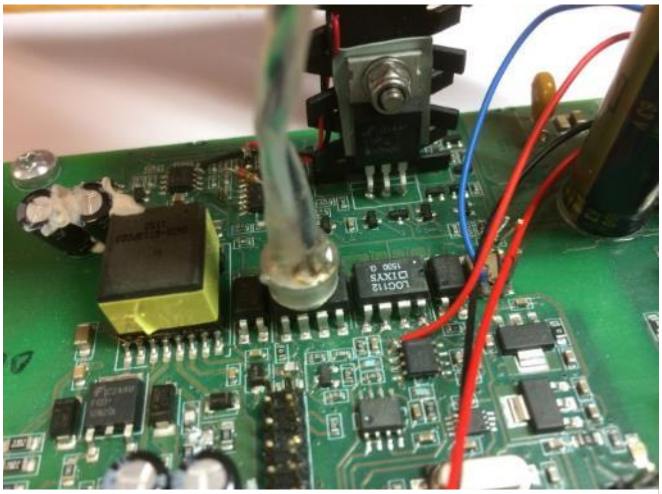
3 The calibration and test system capable of calibrating six DCDC converters while mounted in the control-box

Although the DCDC converter output measurements showed the same in the test system, they drifted apart when the temperature changed. This indicated that the DCDC converter output measurement was not only temperature sensitive, the temperature sensitivity varies from converter to converter.

Investigating temperature stability

The DCDC converter output measurement circuit consists of multiplied components and the task was to identify witch of these components contributed most to the large temperature sensitivity in the output measurement.

Heating the DCDC converter PCBA with a heat blower, quickly showed to be inadequate because multiplied components were heated at the same time. This resulted in the development of a special heating element that held a constant temperature on a small metal surface. This heated surface could then be placed on a single component to heat it. The temperature was kept at a maximum of 50°C to insure the integrity of the component under test.



4 The Heating element on the linear optocoupler and test wires added for measuring the result

This quickly revealed that it was a linear optocoupler that by far added to the temperature sensitivity of the DCDC converter output measurements.

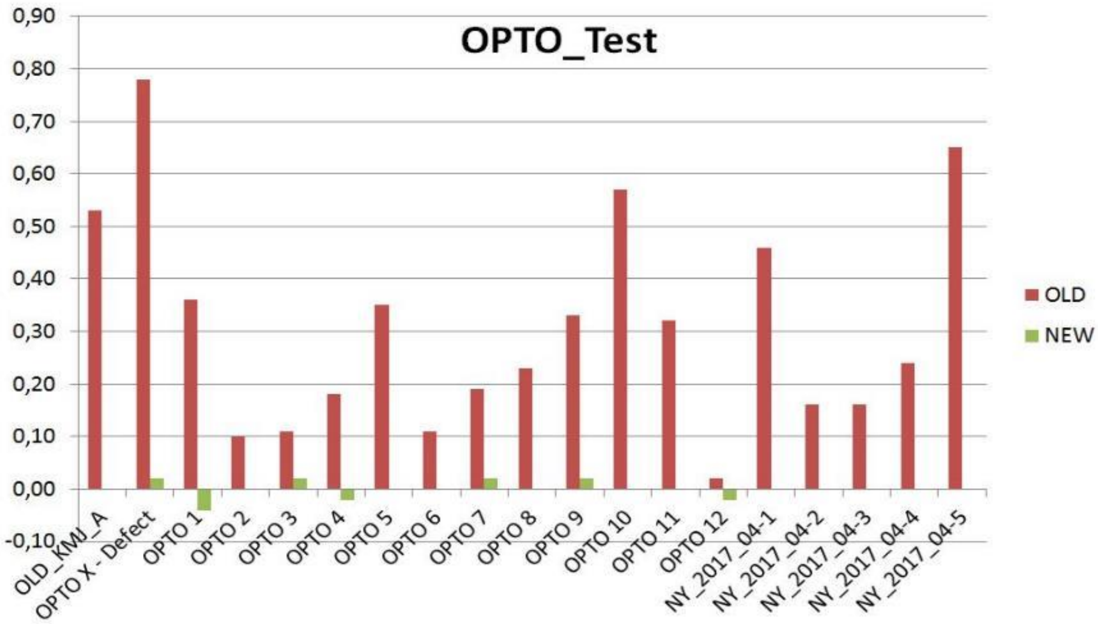
Testing was done on several DCDC converters and it showed a big spread in the sensitivity. A few hardly moved while others deviated nearly 1V and this by only raising the temperature on 25°C.

5 Measurement where the heating element is added and then removed again. The measurement changes 1.7%

Solution

Calculations showed that the sensitivity of the linear optocoupler was much higher than it should be according to its datasheet. This resulted in the decision of trying a linear optocoupler from another manufacturer. To do this, a redesign of the circuit around the linear optocoupler was needed.

The redesign and implementation of the new linear optocoupler resulted in a significant improvement of the temperature sensitivity of the DCDC converter output measurements and it was decided to implement this solution in the product.



6 We here compare the variation of the DCDC converters output voltage measurement, when the temperature on the linear optocoupler is changed to 25°C The red bar shows original solution and the green bar shows the same DCDC converters after update to the imp

Testing the solution

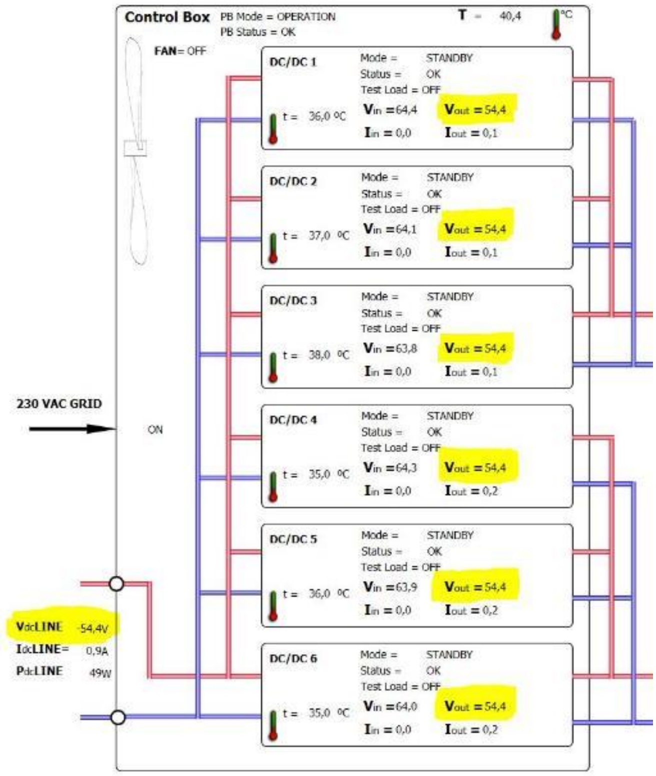
To test the new linear optocoupler solution, two systems were updated and, after passing all internal production tests, the systems were put out in a shelter for long time testing. Here, the two 5kW systems were setup as a 10kw system and tested. In a period, the temperature in the shelter changed with the outdoor temperature to simulate real life conditions. After this test was passed, the temperature in the shelter was raised to stress the system. During both tests, the system operated in standby as well as started up and running in pre-defined intervals. After the system passed both tests, the solution was released for production.

Test results

The testing revealed that the DCDC converter output measurements now are much more stable and on our remote access software this is also clearly seen as the DCDC converter output measurements now shows the same or only 0.1V apart. Furthermore, the testing also showed better current sharing during start up, as expected, and thereby less stress of the DCDC converters.

Further testing

Having the test system setup in the shelter, it was desisted to continuing the long-term testing to see if it could reveal any other weakness in our system. So far, nothing else was found, but the test continues.



7 After the improved solution for the DCDC converter output measurement, it is seen that the output voltage measurements are the same as the main output measurement

System testing

The focus of the system testing was to monitor the system performance and reliability at extreme temperatures. The fuel cells inside the system were fitted with extra temperature sensors Figure 15a and Figure 15b. This would help understand the air distribution and help detect failures before system failure.

Figure 14a Fuel cell stack equipped with extra temperature sensors

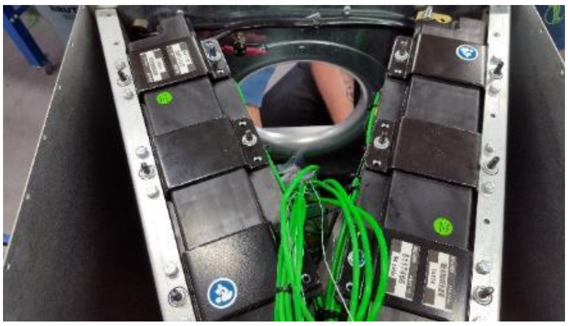


Figure 14b Fuel cell system with two stacks with extra temperature sensors.

The test revealed that, in cold climate, the temperature distribution was very large compared to normal operation temperature on 0- 25 °C.

The temperature highlighted with the dotted circle in Figure 16 is the temperature monitored by the fuel cell system itself. This

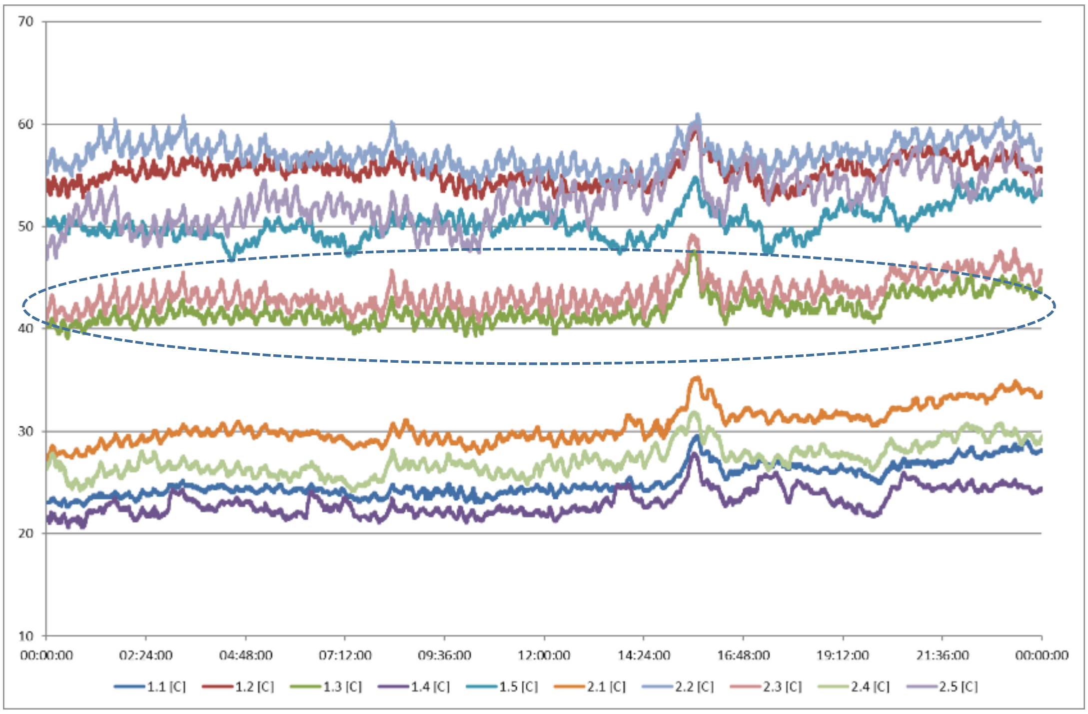


Figure 15 Temperature distribution in fuel cell stack at cold climate operation

means that, in the situation of cold operation, the fuel cell stack is not observing the higher temperature or the colder temperature in some areas in the stack.

The temperature distribution is a clear indication of possible system failure. The problem starts to occur when the stack can't produce enough heat to keep the reaction and water removal stable. Temperature in different areas of the stack starts to drift. This can be seen on Figure 17, where a huge temperature deviation occurs. In some cases, the temperature normalises again, but the test

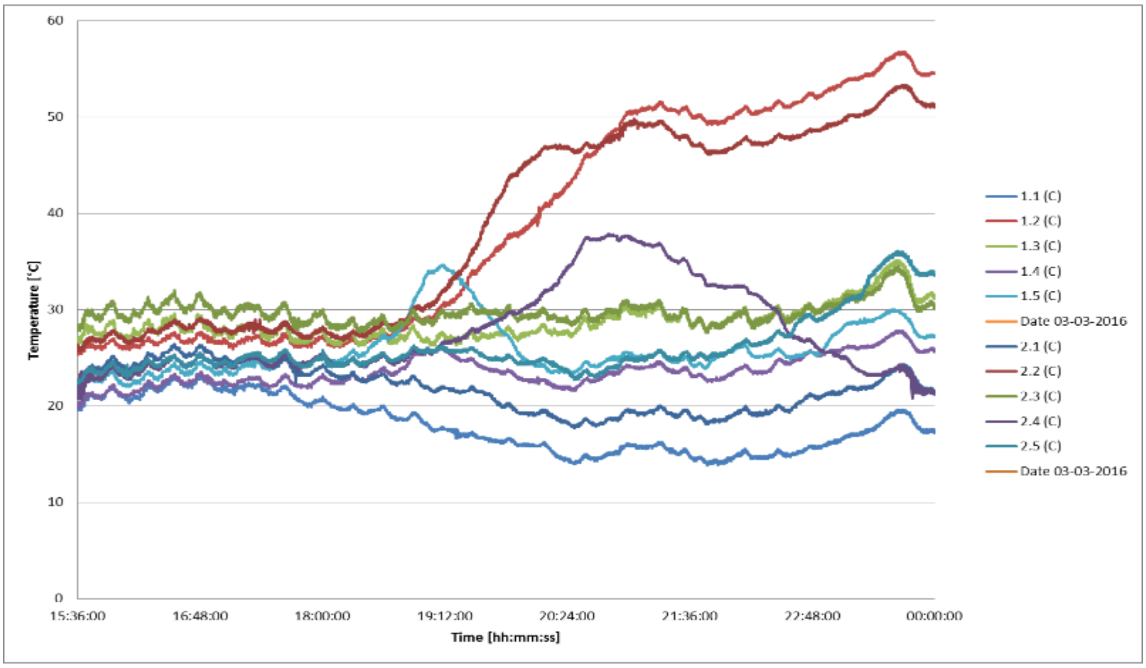


Figure 16 Backup test fail -20° 2500 W (day 1)

shows that, in most cases, if not stopped in time, the areas with high temperature can reach critical temperature limits where the stack membrane is permanently damaged.

The test results were used to create the Go/No go graph shown in Figure 18. The graph shows the relation between inlet temperature and the stack load.

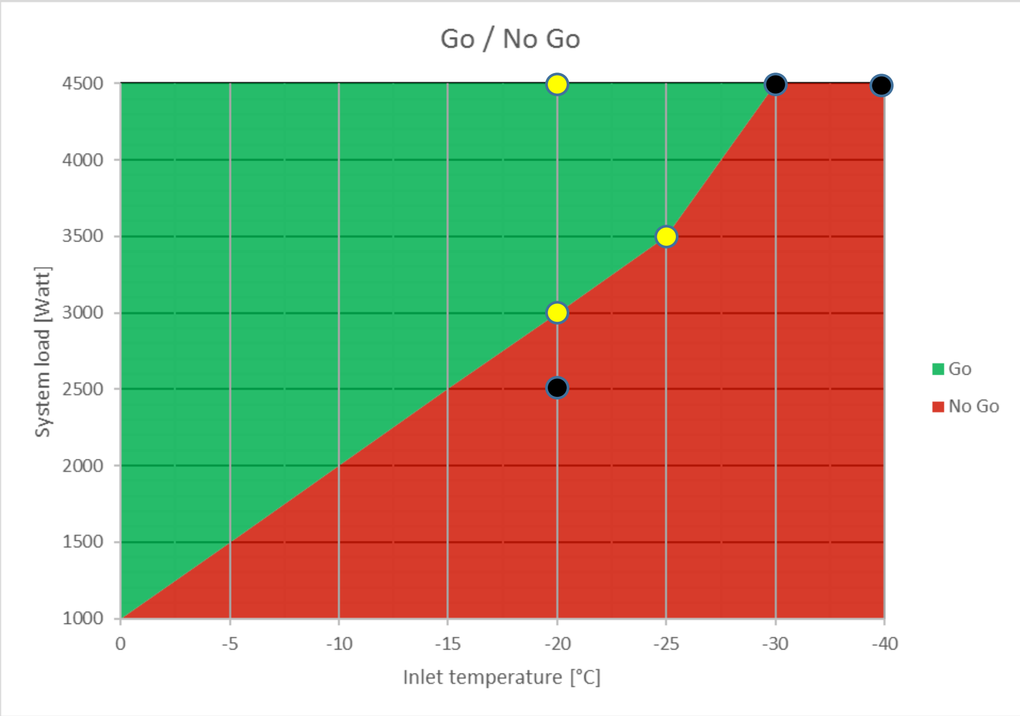


Figure 17 Go/ No Go Graph

The green area is where the system can stable operate, with no performance loss. The red area is where the system needs a cold climate kit add on to perform stable over a longer back up period. In the red temperature range above -20°C, the system can operate without cold climate kit in back up periods shorter than 6 hours.

Regulator test

The increasing focus on higher storage pressure to increase backup time and decrease service intervals results in finding a replacement for our current 200 barg regulator. The bottle regulator is one of the most vital BoP components. The regulator delivers a stable 5 barg hydrogen pressure from the 200 barg bottle.

The regulators are installed in the climate chamber *Figure 19.* In the chamber, the regulators are tested down to -40°C and up to 60°C.

Figure 18 Regulators installed in climate

Figure 19 Regulators in -40°C storage test

The graph in *Figure 21* shows how the output pressure increases when the inlet pressure decreases.

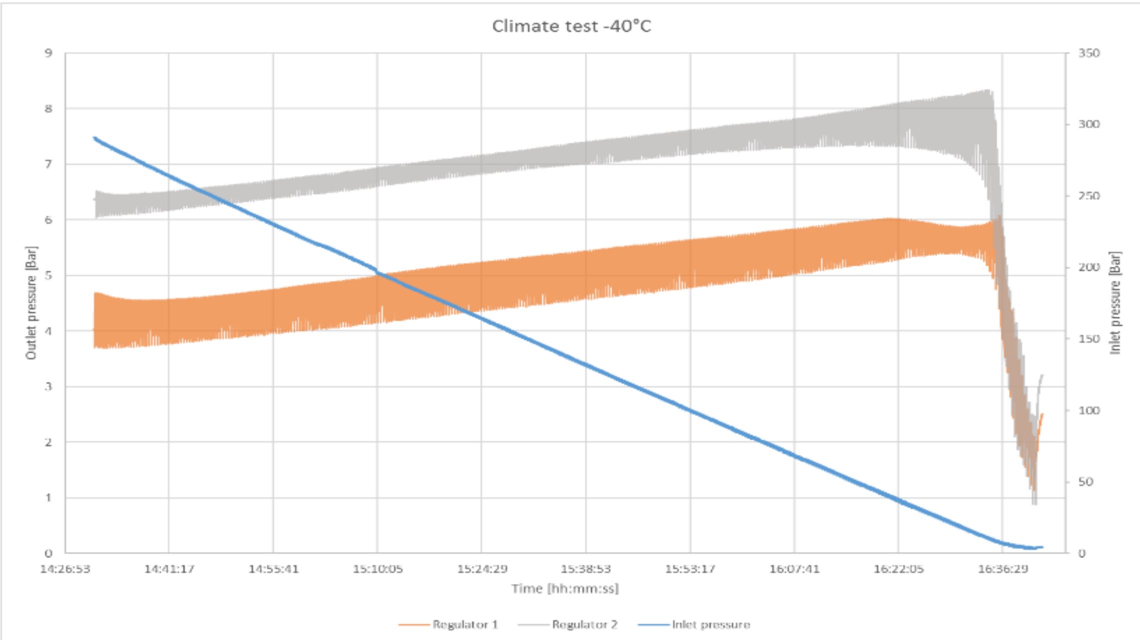


Figure 20 Regulators tested from 300 - 5 bar in -40°C

This is normal, but when comparing the two regulators' outlet pressure, there is a huge difference between the static pressure and the dynamic pressure of regulator 1 compared to regulator 2. Both regulators used in this test have, prior to the cold test, undergone a test to verify the flow qualifications of the regulator. To increase fuel cell life time and reliability the flow and pressure of the hydrogen is critical each time the fuel cell system purges (flush the fuel cell stack with fresh hydrogen). In the high flow test regulator, instability was observed, and the further test in the climate test revealed differences in the regulator performance.
In the high flow test, the Regulator 1 did open the relief valve. This caused the outlet pressure to drop from 7,5 to 4,8 bar. Regulator 2 has also undergone the high flow, but this regulator passed the test with no opening of the relief valve. It kept the high outlet pressure (7- 7,5 bar).
The test shows how Regulator 2 has a more stable dynamic outlet pressure.

Regulator 1 has larger variations between static and dynamic pressure. This test indicates that something inside the regulator is damaged under the high flow test when the relief valve opens. Further inspection of the regulators showed that the needle inside the regulator was damaged.

Figure 21 The needle that sits inside the regulator housing is bend.

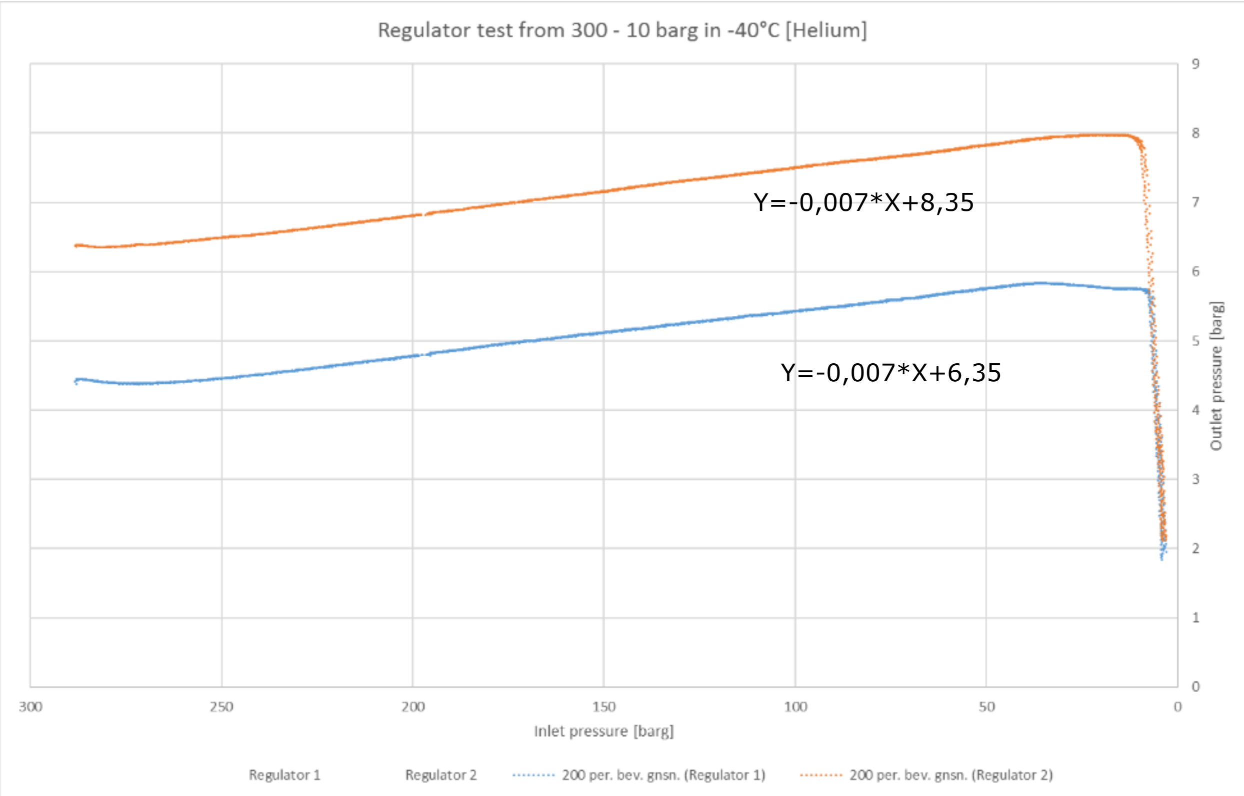


Figure 22 Outlet pressure according to decreasing inlet pressure 300-10 barg in -40°. Test done in climate

Several regulators where tested and one of the indicators used to compare the regulator performance is the slope of the regulators creep of the outlet pressure when the inlet pressure is decreasing. Figure 23 is an example of the slope being measured. The slope is a good indication of the regulator quality and balance between spring tension and pressure range.
Three of the regulator brands tested is listed below in Figure 23.

Regulator	Slope in 20±5°C [**a**] (y=**a***x+b)	Slope in -40±2°C [**a**] (y=**a***x+b)
Concoa	0,005	0,006
Kayser	0,005	0,007
Genie	0,012	-

Figure 23 Regulators slope

(In the graph Figure 23 the slope is negative due to the inverted axes)

The results of the accelerated regulator test revels that a high slope is a problem when the regulators have to work with the fuel cell system valve block. The high flow and climate test was done with Helium for safety reasons. The test with a low-density gas reveal some design flaws in different manufactures' regulators. The manufactures typically test with air, but since hydrogen and, in this test Helium, is a very low density gas, it caused problems with the regulator performance at high flow and storage at low temperature. Without these accelerated tests, the errors could in the field have caused system failure.

1.5.5 WP 5 Test & implementation of FC system improvements (Ballard)

1.5.5.0 Planning of FC-BP demonstration trails

The demonstration of the Fuel cell back system has in the project period been done on existing sites where upgrades and improvement have been installed. Customers involved in the pro-

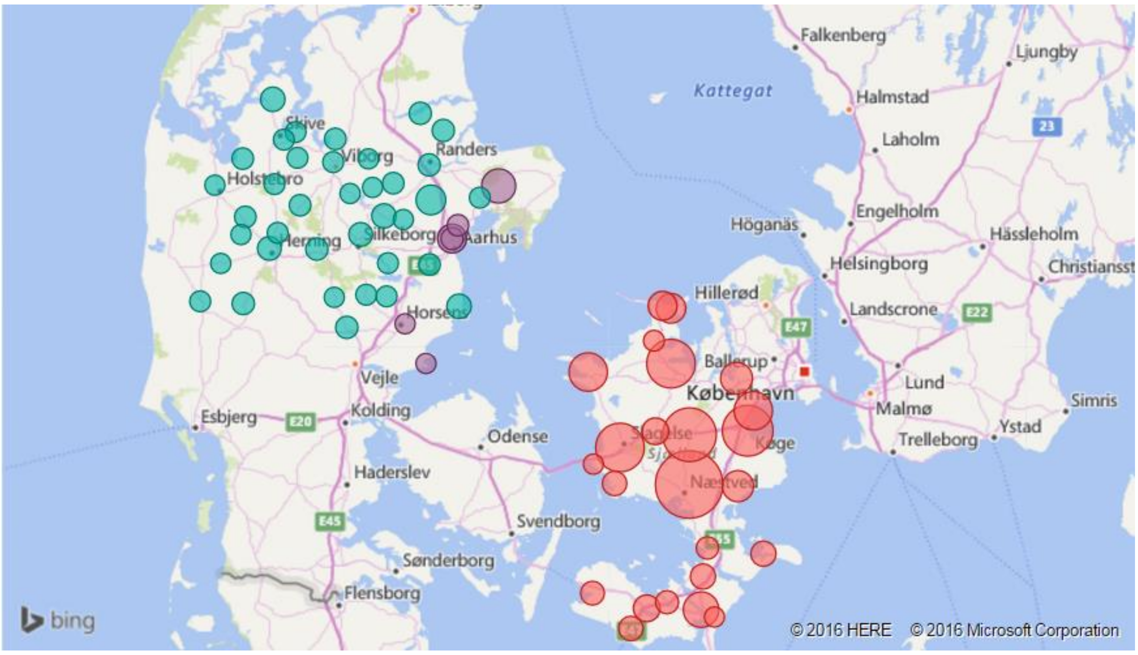


Figure 24 Site installations in Denmark, (Circle size indicates number of systems installed)

ject:SEAS-NVE, NRGI and EnergiMidt (Eniig) have, in the project period, installed fuel cell back systems on new sites. The project test results and improvements have been used on new demonstration site installations at customers in Norway and Sweden.

1.5.5.1 Implementation of improvements to units deployed in the field

The improvements developed to the system were installed when they had passed lab testing, and accelerated testing in the technical shelter at the Ballard Europe facility. Most of the improvements installed during this project were software updates, with improvements done to error handling and self-diagnostics. The accelerated testing has reduced the time for a component or update qualified for field integration. The testing has also reduced the possibility of components being installed before they were proper qualified.
The improvements have been implemented during the yearly service visits. If the error could cause a permanent performance loss or prevent the system from operating in a back-up situation, the service team have implemented the improvement.

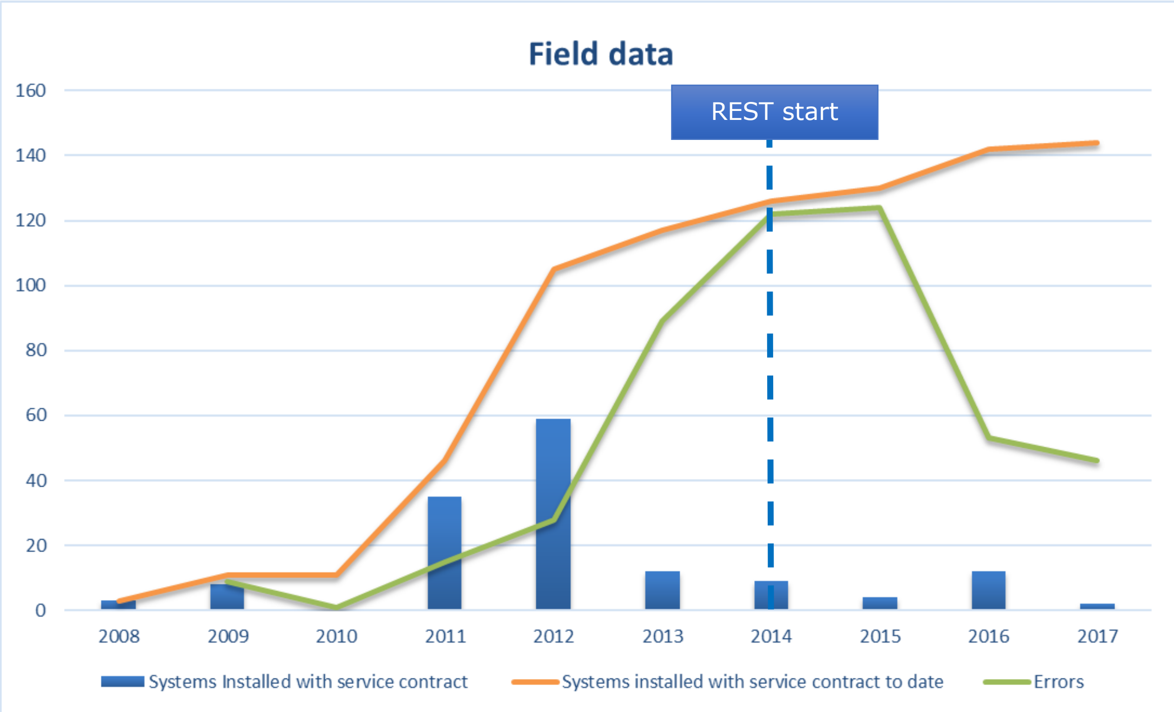


Figure 25 FCgen®-H2PM 5.0 kW/48V systems installed with service contract

The field data (Figure 26) show how the improvements implemented in the REST project have helped reduce the number of errors seen in the field. The graph shows all errors where a service technician was called. In the end of 2015 and beginning of 2016, the software upgrades and implementations have made it possible for the technician to handle some of the errors remotely. The error curve in 2017 is slightly misleading as most of the errors are related to less conservative approach on stack performance. The new stack performance parameters call for a technician to boost the stack performance with a new regenerative software tool. This is a trail period where the performance gain from this procedure should extend stack performance for a longer period instead of replacing them.

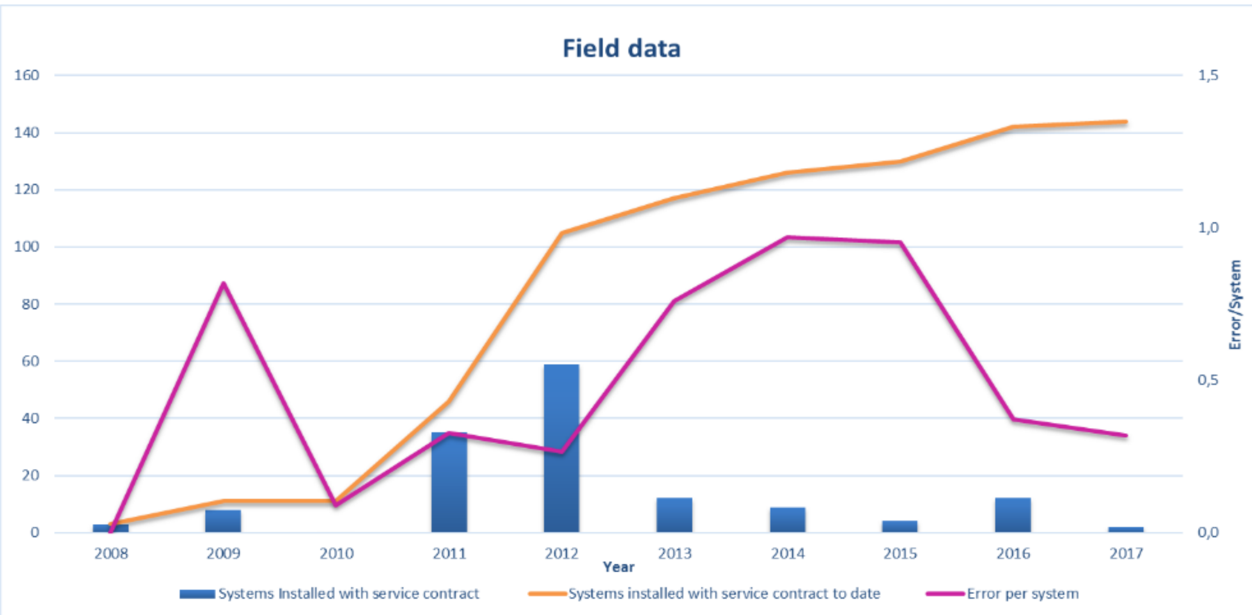


Figure 26 FCgen®-H2PM 5.0 kW/48Vsystems Errors / system installer with service contract

1.5.5.2 Implementation of diagnostic capabilities

The system is performing a self-diagnostic test every month. The test helps boost stack performance and will raise the system readiness level. If an error occurs the system will try to self-diagnose and if the system is not able to resolve the error a service technician is called.

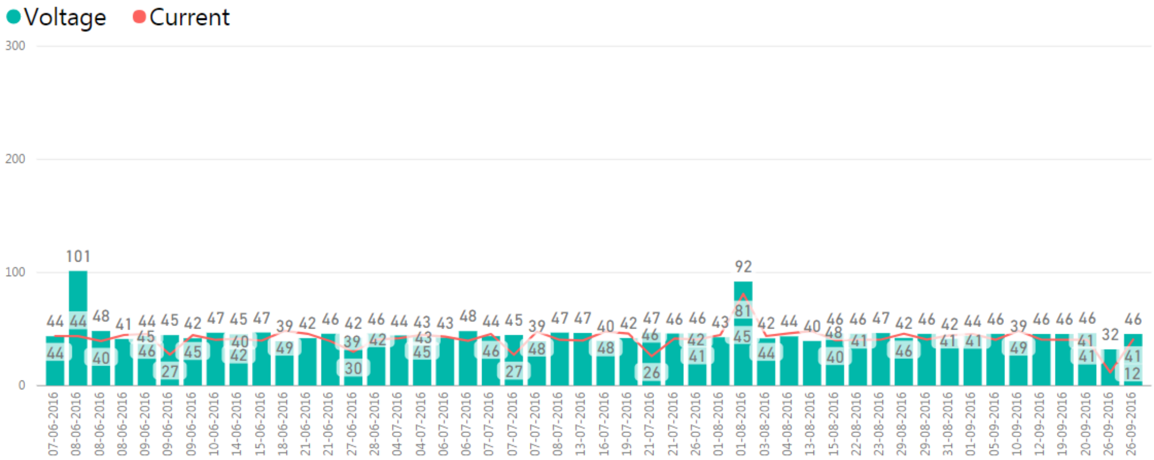


Figure 27 Plot of stack performance from all sites with service agreement.

The graph Figure 28 shows system performance in the field over 3-month period. With this new possibility to monito the data is possible to detect performance irregularities. Right now, we must manually monitor the performance and sport irregularities. The next step is to develop algorithms that flags the systems where an error could occur soon.

1.5.5.3 Operation of the demonstration units and operational data collection and analysis

The failure reports from FCgen®-H2PM 5.0 kW system in the field (Figure 28) show the type of errors and how many times this types have occurred. The number of errors has been reduced during the REST project period. The implementation of upgrades to the DCDC converter can be seen in the reduction of errors from 2014 to 2016. In 2014, the DCDC errors accounted for 30 % of all errors that year. In 2016 the DCDC converter only stood for 9%.

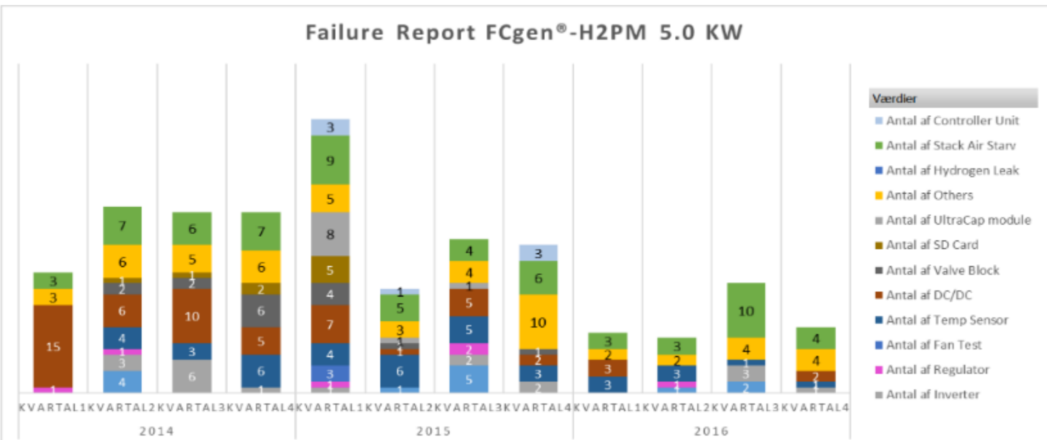


Figure 28 Failure report on FCgen®-H2PM 5.0 kW Systems with service contract

The FCgen®-H2PM 5.0 kW system reliability has improved during the REST project. This has been achieved with the continues improvements done to BOP and software.

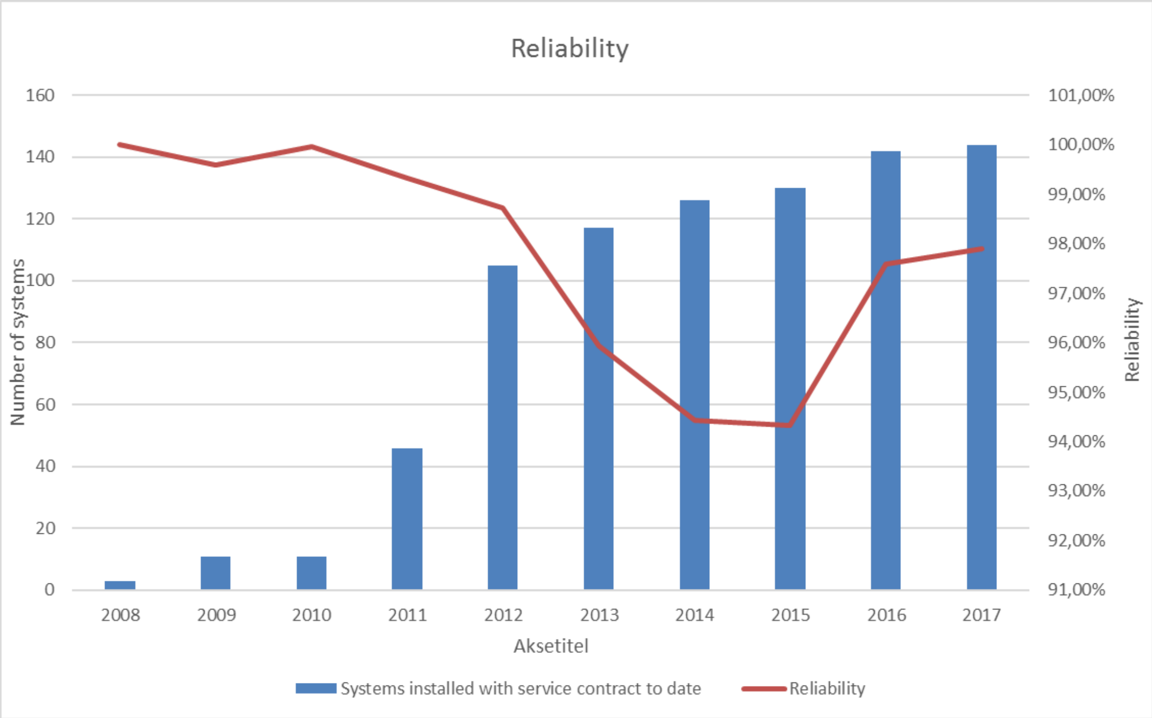


Figure 29 Fuel Cell backup system reliability 1 gen and the from 2011 the new generation FCgen®-H2PM 5.0 kW system reliability

The effort forward will be to increase the reliability by implementing the last updates created in the project. The new knowledge about environment impact on the system will be included in new integrations of fuel cell systems at customers.

1.5.5.4 LeanEco

Short description of project objective and results

LeanEco has focused on the bridging between power and digitalisation to enable a unique interactive management framework that may be associated with big data, tools and new services.
The key outcome of the project is a projected architecture of which direction to develop the means of communication and user interfaces.

Executive summary

The objectives are to enable building a variety of new features and services like

- A generic, simple sales tool that does not require any expert knowledge
- Remote service and maintenance (interactive)
- On-the-fly updates (new functions, new services, more languages etc.)
- Analyses and optimisation based on big data (like preventive maintenance)
- Remote interactive response to e.g. faults or other events (remote setup, or autonomous response according to user presets)
- Remote, non-invasive setup of SmartGrid services
- Etc.

The LivingPower™ platform itself also allows to reduce the number of power converters, typically 1.5-3X less converters for similar function and capacity. This offers improved reliability, higher availability, reduced space and CAPEX. It may be compared to server virtualisation with similar (although less) advantages in terms of resource utilisation, thus the technology is also called Power Virtualisation.

Project objectives

The original project objective was to build a reliability/availability model of the LivingPower™ platform.

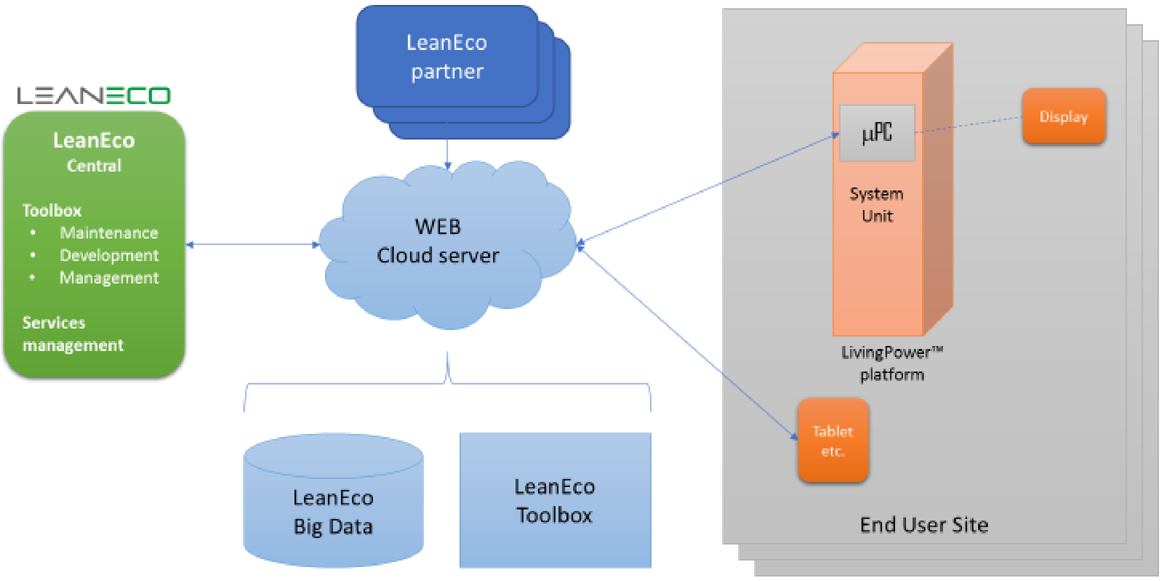
However, due to the almost endless number of different states and operating conditions of such a system, this task was analysed and judged too comprehensive for the available resources of this project.

Instead, efforts were spent to pursue the digitalisation field in order to draw the first road map of configurator developments, primarily to support boosting the availability of the solutions like

- A tool box: The use of Big Data for analyses, preventive maintenance and other similar efforts
- Interactive means to cope with "situations" (faults, overloads, problematic loads, high inrush current, fuse clearing and more).

Project results and dissemination of results

The project has derived an architecture that is intended to serve as a platform for numerous future developments.



The unique value creation is driven by the fact that the LivingPower™ platform is interactive. Thus, the management environment is capable of

1. Analysing, judging, deciding, administrating – based on
    a. Reading data from the unit itself
    b. Data and control from partners
        i. Aggregators (SmartGrid services)
        ii. Server Room Management Software (making the unit part of the virtual family)
        iii. Value-Added-Resellers (remote service and maintenance)
    c. Data and control from the end user / operator
    d. Data and control from LeanEco direct
2. Specific actions, changes, corrections etc (autonomous as well as manual) based on 1).

A major task is to ensure that the communication between the Cloud Server and each Unit is secure and robust against intruders or disturbances.

The units will continue to operate autonomously when there is no network connection, limited to local interaction.

Utilization of project results

LeanEco is targeting the global UPS market, initially starting in Germany, Holland and Belgium.

The LivingPower™ platform is rather complicated to describe. The number of functions and applications is huge, a simple descripting of the possibilities is hard to make.

Therefore, the IT-based user interface is the key tool to create awareness, to educate, to sell and to manage. I.e., it is the perfect basis for all life cycle phases of the products.
The patented LivingPower™ platform seems also to offer important value creation in other segments like wind power, smart building, renewable energy systems. Such directions will be pursued through selected partners to utilise their momentum and to accelerate the commercialisation.
This outcome of this project matches all such applications and will be the foundation for many future developments to pursue.

Project conclusion and perspective

Going forward, there still is the need to make an in-depth analysis of the availability performance of the LivingPower™ technology.
Obviously, the technology will outperform traditional UPS approaches due to its ability to autonomously react to faults ("self-healing"), and since time-to-repair may be substantially shortened by letting the system respond to faults and other situations.
However convincing, it would be beneficial from a commercial point of view to get an independent, university-based blue stamp of the intrinsic performance of the technology.
Based on the directions set out in this project, LeanEco will initiate several developments with the objectives to

- Visualise the opportunities – an intuitive user interface to be used for sales, installation, operation and changing
- Utilise Cloud solutions
- Obtain secure solutions
- Evolve a palette of new services like SmartGrid.

Summary of work description (LeanEco)

The overall objective of the project is to increase the participant's ability to successfully enter the competitive markets of un-interruptible power supply solutions for mobile networks, fiber networks and railroads –– and at the same time to establish a unique and sustainable competitiveness.
The project focusses on interfaces and power converters handling the boundary among one or several fuel cell modules and the UPS system. At the same time, we will adopt the latest achievements within power conversion energy efficiency and reliability. The project develops a multifunction high-efficiency power converter that is capable of operating in three different ways. As such, identical converter modules can operate as rectifiers, inverters – or DC/DC converters. Thereby, the system can supply power to AC equipment (IT) as well as DC equipment (Telecom) – using physically identical power modules. This also allows the system on-the-fly to optimize performance by autonomously moving or re-configuring power modules.
The aim is overall increased up-time (availability), higher reliability, less space, reduced power losses, lower initial cost and reduced maintenance cost – at the same time. The project will build, install and operate a system in a specific realistic customer application. The project results will be available after a test period for direct comparison with existing installations.

Status on the project achievements

The project is progressing well, trying to catch up with the delay in the development of the DC/DC converter (6 months) due to initial technical challenges and a late start. The demonstration unit is now ready for installment at end customer in November 2016.
The project has successfully been operating with two parallel tracks of activities towards the demonstration phase:

1. Improving the fuel cell reliability by optimizing the state of health of the fuel cells using "load management". The concept will be demonstrated in the prototype installation for the field trial.

2. Developing a flexible and efficient converter solution in relation to the UPS-system, in order to strengthen applicability for utilization within back-up power for telecom, fiber networks, railroad signaling and electric utilities. A prototype DC/DC solution is being developed and is integrated into the demonstration unit for field trial.

New challenges and new opportunities

The **challenge** in the current project is that the original project plan will allow only few weeks of demonstration to gather field data for final evaluation of the system. A data evaluation as described in the project description is possible, but a longer demonstration period would allow for better data collection and a better chance for more detailed customer feedback for the development partners.

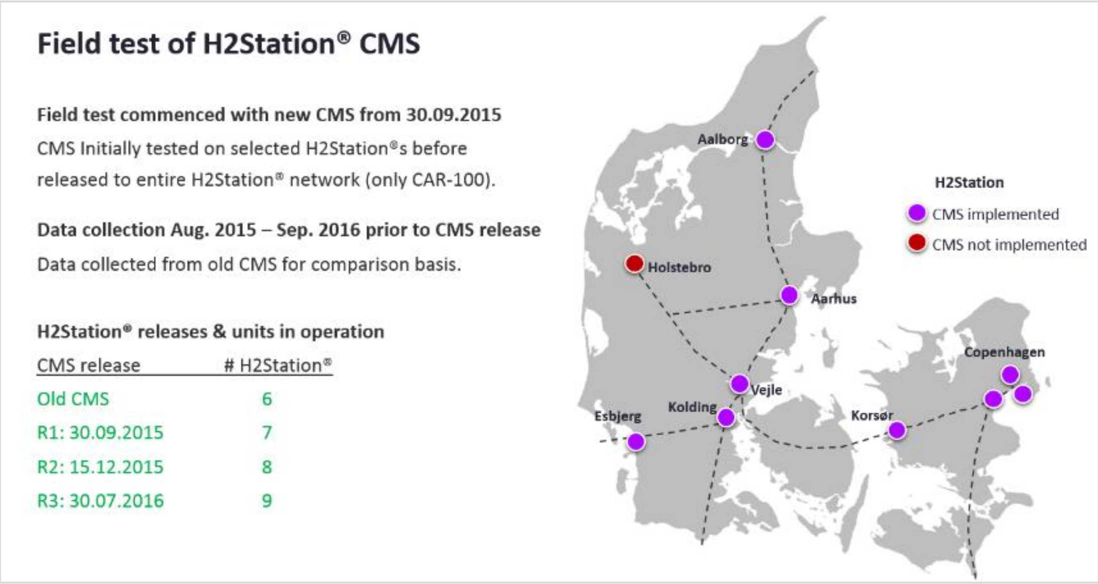
These new **opportunities** have arisen during the course of this project:

1. To employ the new UPS solution to adapt in an uncomplicated way to existing battery installations and to new backup generator technologies like fuel cells or solar panels.
2. To reduce end customer OPEX even further through a remote diagnostics tool optimizing preventive service, reduce number of faults and reduce number of service visits. The peer-to-peer remote communication product Nabto has been identified as a possible new IT tool to ease access and retrieve state-of-health (SOH) data from the fuel cell system to the service staff, not intervening with the network owners' NOC system.

1.5.6 WP 6 Test & implementation of CMS at HRS in field operation (H2 Logic)

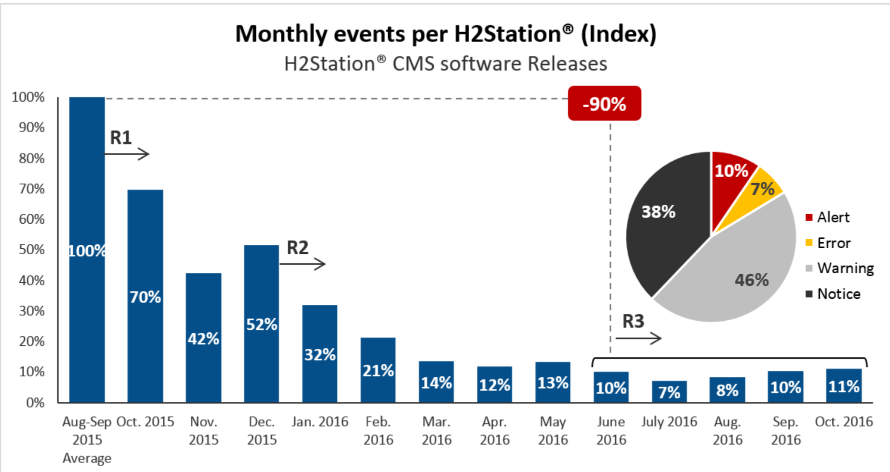
1.5.6.0 Field test implementation of HRS CMS

The developed HRS CMS was firstly implemented on a selected H2Station® from Nel Hydrogen, before being dispatched to seven HRSs across Denmark in September 2015, representing software release 1 (R1). In December 2015, an R2 was released expanding the tests to 8 HRS, followed by a final R3 in July 2016 expanding to 9 HRSs. The field test implementation is shown in figure below.



1.5.6.1 Field test results

The field tests have shown a successful achievement of the major project objectives as shown in figure below, with regards to reduction in monthly events per HRS.

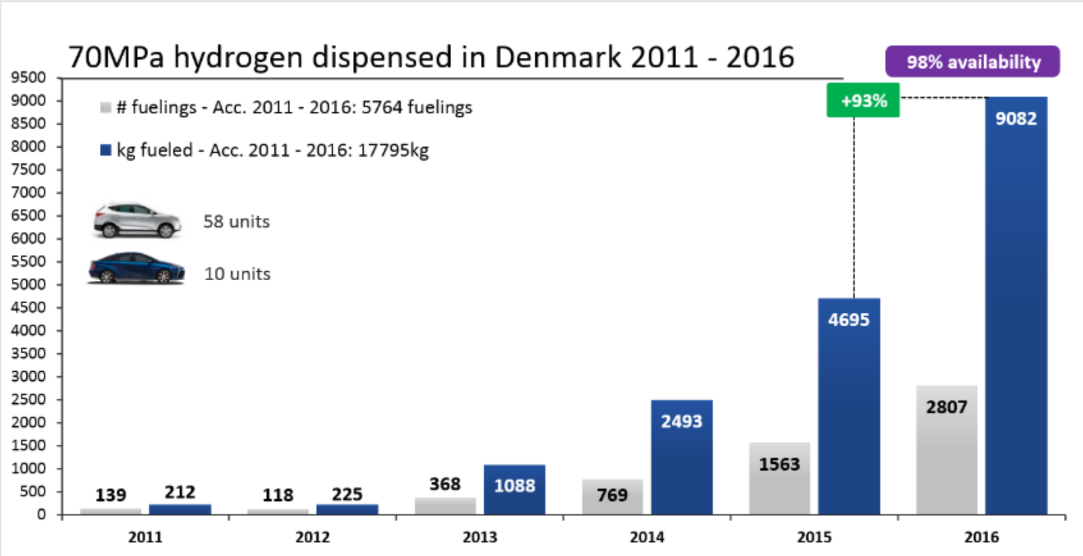


The number of monthly events (alarms) recorded per HRS on average, has been reduced with 90% during the test period. Generally, the number of events dropped significantly after each CMS software release.

In addition, implementation of the alarm modes has helped reduce the number of events that cause outage of the HRS – with most alarms now being warnings or notices that do not affect the HRS performance or availability.

The 90% reduction in number of events has helped reduced personnel costs for operation monitoring well above the REST target of 25%.

The reduced number of events as well as the automated KFI tool has also helped service personnel to respond faster to down-time events, which has helped to stability the average HRS availability to above 98% for the Danish HRS network.



The increased availability has been achieved despite that the annual quantity of dispensed hydrogen in Denmark has been more than doubled during the test period, as shown in graph above.

The KPI reporting tool has reduced the personnel time required to assemble customer reports, from 10 hours, down to a fully automated and instant generation of complete reports in PDF format.

1.5.7 WP7 – Project management, dissemination and exploitation

Dissemination efforts during the project period has focused on the Danish stakeholders within the Danish Hydrogen & Fuel Cell Partnership.

Project progress and results have been disseminated on a continuous basis during the projects in the meetings of the working groups "Fuel Cells" and "Transport".

The project results on the CMS for HRS have been used to update the Danish national R&D strategy within the transport groups, in 2014.

The partners have also ensured dissemination through the European Fuel Cells & Hydrogen Joint Undertaking, by participating and contribution to similar working groups on a European scale.

Specifically, for results on the CMS for HRS, this has also been disseminated through various international networks such as:

- *"CT2/Transport Infrastructure"* working group of the European Fuel Cells & Hydrogen Joint Undertaking www.fch.europa.eu
- *"Station Developers"* working group of the California Fuel Cell Partnership www.cafcp.org
- The Fuel Cell and Hydrogen Energy Association (US) www.fchea.org
- The H2USA initiative www.h2usa.org

Specifically, for partners at Aalborg university

The general achievements and academic publications are summarized in the following:

Achievements:

- ✓ Reliability assessment of FC system in terms of component-level, subsystem-level, and system-level
- ✓ Mission profile based component-level reliability at standby mode and operation mode
- ✓ Power switches: With limited life data, Monte Carlo analysis considering the uncertainties in the component parameters
- ✓ Dc capacitors: Analytical lifetime model from the complete failure data is applied based on physic-of-failure understanding
- ✓ System-level power stage reliability can be analyzed by considering redundancy effect

Dissemination (conference papers)

1. D. Zhou, H. Wang, F. Blaabjerg, S. K. Kaer, and D. Blom-Hansen, "Real mission profile based lifetime estimation of fuel-cell power converter," *in Proc. of IPEMC-ECCE Asia 2016*, pp. 2798-2805, 2016.
2. D. Zhou, H. Wang, F. Blaabjerg, S. K. Kaer and D. Blom-Hansen, "System-level reliability assessment of power stage in fuel cell application," *in Proc. of ECCE 2016*, pp. 1-8, 2016.
3. S. Lee, D. Zhou, and H. Wang, "Reliability assessment of fuel cell system – a framework for quantitative approach," *in Proc. of ECCE 2016*, pp. 1-8, 2016.
4. D. Zhou, H. Wang, and F. Blaabjerg, "Lifetime estimation of electrolytic capacitors in a fuel cell power converter at various confidence levels," *in Proc. of SPEC 2016*, pp. 1-6, 2016.
5. D. Zhou, H. Wang, F. Blaabjerg, S. K. Kaer, and D. Blom-Hansen, "Degradation effect on reliability evaluation of aluminum electrolytic capacitor in backup power converter," *in Proc. of IFEEC 2017 - ECCE Asia 2017*, accepted, 2017.

References and relevant publications

[1] B. Bidoggia and S. K. Kær, "Estimation of membrane hydration status for standby proton exchange membrane fuel cell systems by complex impedance measurement: Constant temperature stack characterization," *International Journal of Hydrogen Energy,* vol. 38, no. 10, pp. 4054-4066, 4/1/ 2013.

[2] B. Bidoggia and S. K. Kaer, "Estimation of membrane hydration status for standby proton exchange membrane fuel cell systems by impedance measurement: First results on variable temperature stack characterization," in *Ecological Vehicles and Renewable Energies (EVER), 2013 8th International Conference and Exhibition on*, 2013, pp. 1-10.

[3] L. Török, S. L. Sahlin, S. K. Kær, and B. Bidoggia, "Estimation of membrane hydration status for active proton exchange membrane fuel cell systems by impedance measurement: Start-up time measurements," in *2016 IEEE 16th International Conference on Environment and Electrical Engineering (EEEIC)*, 2016, pp. 1-5.

1.6 Utilization of project results

The participating companies has successfully ensured continued R&D and commercialisation activities of the technologies developed in the REST project.

1.6.1 *Continued R&D and Commercialisation of CMS for fuel cells*

The REST project have helped improve the CMS in the FCgen®-H2PM 5.0 kW system. This have reduced service cost by enabling the service technician to remotely handle and prevent errors in the field. The optimized self-diagnostics capabilities have minimized performance related errors. The collection of field data in a database has made it possible to analyse system performance over its life time. Future R&D efforts will be used to create algorithms that could compare system irregularities to the rest of the systems.

The reliability model developed have highlighted areas where potential reliability increase could be obtained. The model has in this project focus on DCDC converters. A detailed analysis of DCDC converters operating in Indian compared to Danish environment have revealed some reliability challenges on the DCDC converter. Improvement was implemented in the REST project bringing the number of errors on DCDC converters down from 30 % to 9 %. Further improvements were developed in the end of the project these will be implemented in the next production of DCDC converters.

The extensive accelerated testing made it possible to control BOP components better to minimize performance loss on the FC system. The full-scale climate testing help find the boundaries for the standard system. The learnings allowed us to develop improvements to the FC software to handle these situations better and to prevent damage to the system.
The simulation also opens up for the development of a new way of handling the exhaust and intake air. The test results and learnings was used in the latest installation of a FC back up system in Sweden where requirements of cold climate operation are a must.

1.6.2 *Continued R&D and Commercialisation of CMS for HRSs*

The REST results on the HRS CMS has successfully been implemented in the 1st Gen. H2Station® product from Nel Hydrogen, currently operating in seven countries across Europe.

The HRS CMS from REST has helped position H2Station® from Nel Hydrogen as one of the most reliable HRS products on the global market and has enabled substantial additional commercial sales and export revenue.

Also the HRS CMS developed in REST, has been used for the development of a 2nd Gen. H2Station® product that was launched during 2016.

Nel Hydrogen has already secured sales and installation of the new 2nd Gen. H2Station® in Europe, and was recently awarded an order of 120 million DKK from Shell for stations to be installed in California[1].

Since commencing of the REST 10 more employees have joined Nel Hydrogen, and with an outlook of a 10% increase per year going forward, thanks to the results of REST. Also Nel Hydrogen targets to grow annual sales with 30% on the new 2nd Gen. H2Station®, made possible by the HRS CMS developed in REST. The majority of the annual sales are expected to be export outside of Denmark.

[1] https://fuelcellsworks.com/news/nel-hydrogen-solutions-awarded-frame-contract-for-multiple-hydrogen-fueling-stations-in-california-b/

1.7 Project conclusion and perspective

State the conclusions made in the project. Try to put into perspective how the project results may influence future development.

The REST project has secured key results on two areas that enables a continued use by the partners and the Danish hydrogen sector.

1.7.1 CMS for fuel cells

Ballard Europe (Dantherm Power) has in the REST project improved system reliability and the CMS have help decrease the number of service visits to sites in the field

- Reliability of the FCgen®-H2PM 5.0 kW have increased to 98% compared to the 87%-90% in the beginning of the project.
- Number of systems deployed in the field in the project period was set to 5-10. This has been exceeded with 25 systems installed in Denmark and 3 system installed in Scandinavia.
- The warranty cost and service cost for end user has been reduced with the increased reliability and with remote diagnostic and error handling capabilities.

1.7.2 CMS for Hydrogen Refuelling Stations

As part of the REST project, Nel Hydrogen has successfully managed to develop and test a new HRS CMS with substantial advances compared to the previous state-of-the-art, prior to the project:

- A new HRS CMS has been developed with more intelligent self-diagnostics and correction intelligence reduction number of operation interruption events
- Number of operation events/alarms has been reduced with 90%, helping to reduce costs for service personnel required for operation monitoring and trouble shouting with more than 25%. This has also been achieved by a new KFI tool that allows service personnel to analyze and trouble shoot events much faster.
- HRS availability/reliability has been stabilized above 98% compared to previous fluctuations of 70-98% due to a long trouble shooting time
- A new fully automated KPI reporting system has reduced personnel time required for each report from 10 hours down to few minutes – providing greater convenience and less costs for customers (HRS operators).
- The new HRS CMS has been tested on 9 HRSs based on the 1st Gen. H2Station® product from Nel Hydrogen, across Denmark in live operations, substantially more than the original project target of test on only 1 HRS.
- The HRS CMS has successfully been implemented across all 1st Gen. H2Station® in operation in seven countries across Europe.
- The HRS CMS from REST has also been used in a new 2nd. Gen. H2Station® product launched during 2016, where sales and installations in Europe has already been secured. In addition, Nel Hydrogen was recently awarded an order of 120 million DKK from Shell for stations to be installed in California.
- Since commencing of the REST 10 more employees have joined Nel Hydrogen, and with an outlook of a 10% increase per year going forward, thanks to the results of REST. Also Nel Hydrogen targets to grow annual sales with 30% on the new 2nd Gen. H2Station®, made possible by the HRS CMS developed in REST. Most the annual sales are expected to be export outside of Denmark.