Final Public Project Report

Competitive µCHP for H2omes

Grant agreement no.: EUDP-11-I J.N°: 64011-0051

Project duration: 1-Jul-2011 to 31-dec-2015

Project Coordinator: Laila Grahl-Madsen

Beneficiary no.	Beneficiary full name & address	Beneficiary short name	CVR
1 Coordinator	IRD A/S Emil Neckelmanns Vej 15 DK-5220 Odense	IRD	1468 9605
2	SEAS-NVE Holding A/S Hovedgaden 36 DK-4520 Svinninge	SEAS	2578 4413
3	TREFOR Entreprise A/S Kokbjerg 30 DK-6000 Kolding	TREFOR	1906 5472
4	AVL List GmbH A-8020 Graz, Hans-List-Platz 1	AVL	

Contributors to the Final Report:

Laila Grahl-Madsen (IRD)
Henrik Lunde (TREFOR)
Martin Vesterbæk (TREFOR)
Jens Ole Phil (SEAS)
Vincent Lawlor (AVL)
Katharina Renner (AVL)

Report submitted to EUDP on the Thursday, 21 January 2016

SHORT DESCRIPTION OF PROJECT OBJECTIVE AND RESULTS

English abstract:

The overall objective was to develop and test a new generation of IRD's 1 kW micro-combined heat and power (µCHP) unit based on low-temperature polymer electrolyte membrane fuel cells (LT-PEMFC). This improved unit should be much more robust and have prolonged lifetime compared to previous versions. Good results are obtained; 28-units of the developed µCHP has been tested some solely in the laboratory, but the majority of units has been demonstrated in a true end-used environment, more than 85,000 accumulated operational hours are obtained. The lifetime potential of the new µCHP has been substantially increased and a lifetime of more than 11,000 hours has been demonstrated. The obtained cost reduction of the developed µCHP is 36% very close to the target reduction (40%).

Dansk abstrakt:

Det overordnede projektmål var, at udvikle og afprøve en ny generation af IRDs 1 kW mikrokraftvarme (µCHP) enhed baseret på lav temperatur PEM brændselsceller (LT-PEMFC). Enheden skulle være mere robust, have længere levetid og være væsentligt billigere end tidligere µCHP versioner. Gode resultater er opnået eg. 28 enheder af den udviklede µCHP er blevet testet enten i laboratoriet eller hos rigtige slutbrugere (enkelt familie husstande), samlet er opnået mere end 85.000 akkumulerede testtimer. Levetidspotentialet i den nye µCHP er øget betragteligt i forhold til tidligere versioner; levetid på mere end 11,000 timer er demonstreret. Den opnåede kostreduktion af µCHPen er 36% meget tæt på projektmålet på 40%.

EXECUTIVE SUMMARY

The main objective of the project was to develop a new generation of IRD's low-temperature polymer electrolyte membrane fuel cell (LT-PEMFC) micro combined heat and power (µCHP) system, to demonstrate it, and to prepare for mass production to obtain a significant price reduction. The µCHP plant is hydrogen-fuelled, and the fuel cell (FC) system may be combined with a PEM electrolyser-cell (EC) module to create a self-sufficient household system. The specific project targets regarding lifetime and cost correspond to the national Danish roadmap targets.

The project consortium consist of the following four (4) partners: IRD (coordinator, system developer); SEAS NVE (DSO, specification of relevant test); TREFOR (DSO, specification of relevant test, tester) and AVL (consulting engineering company; evaluating system components and optimising the operational strategy). The project was initiated July 2011 and completed by December 2015.

The developed µCHP has a nominal AC-power of 1 kW and an additional heat production of 0.8 kW. The unit has been CE-certified by DGC that also measured the BoL (Beginning-of-Life) efficiency to be 50% electric (LHV) and 41% heat. 28 H2omes µCHPs have been tested for in total 85,123 hours shared among the following:

- Three (3) units was tested for in total 18,013 h solely in the laboratory
- Four (4) units was tested at a professional end-user for in total 7,053 h
- 21 units was tested in a real end-user environment for in total 60,057 h

The project µCHP system proved to be a solid, durable system that facilitates fuel cell degradations well in-line with the reported current international state-of-the-art. The lifetime potential of the developed µCHP has been substantially increased compared to previous versions of IRDs µCHP and a lifetime of more than 11,000 hours of one unit has been demonstrated. A small number of system weaknesses was discovered during the test, all but a few was corrected and mitigation strategy for the last formulated. The test program included several operational patterns of which one pattern was designed to investigate the 'smart-grid' capability of the µCHP. The conclusion is based on a unit that has been exposed to ≈3,000 start/stop cycles and 3,300 nominal operational hours. The calculated degradation is well in-line with the degradation in similar systems exposed to less than one-third of the number of start-stop cycles and it is therefore concluded that the developed µCHP is well suited for a future smart-grid.

The obtained cost reduction of the developed µCHP is 36% very close to the target reduction (40%).

The hydrogen fuelled µCHPs host a potential for a significant reduction of the CO_2 emission compared to conventional oil- and natural gas fired boilers. The CO_2 savings are estimated by DGC[1] to be 0.75 kg per kWh_{AC} and 0.204 kg CO_2 per kWh_{Th} produced when NG-boilers are displaced. The yearly CO_2 savings for a single family household would, if the µCHP on a yearly basis should cover the electricity consumption (5,000 kWh) and the hydrogen is produced by electrolysis made with surplus RE e.g. wind then be 4.5 tons CO_2.

The project results has been disseminated in a joint effort with the parallel IRD activities. The dissemination comprises several presentations in Denmark (8 oral presentations and several demonstrations at national exhibitions) as well as 8 oral presentations at international events.

[1] http://www.dmkv.dk/downloads/MKV_Baggrundsanalyser.pdf & Jan de Witt pers.com. 2014

TABLE OF CONTENT

INTRODUCTION

Project Objectives

The objective of the 'Competitive µCHP for H2omes' project was to develop an attractive, reliable, and environmentally friendly µCHP-unit that can substitute oil-fired boilers and ensure a green solution for households outside the public heat and natural-gas supply networks. The aim was to take advantage of the valuable knowledge gained through previous public and privately funded projects to create a high-quality product and in this way to contribute to the fulfilment of the national political ambitions and international obligations in the fields of energy resources and environmental protection.

The specific project targets (Table 1) are well in-line with the national Danish road-map targets.

Project Overview

The project was initiated in July 2011 and originally scheduled for three (3) years. Progress delays caused the project to be extended with in total 18-month mainly due to lack of mechanical engineering resources at IRD, which accounted for at least 1-year of delay, and expansion of the consortium when AVL upon request from EUDP entered the consortium in 2013. SEAS NVE decided Medio 2014 to withdraw from the remaining project tasks that solely comprised end-user test. TREFOR and IRD took over these obligations.

The most recent defined Gantt including WP-leaders (main actors) is shown in Fig. 1. Defined milestones (incl. deliveries) are listed in Table 2. All milestones are accomplice except the two cancelled milestones.

Table 1 Key target values for the 1 kW_{AC} µCHP in the 'Competitive µCHP for H2omes' project.

		δ-µCHP [2014]	δ-µCHP [2016]
Quantity manufactured		100	2,500
η_{EL} ($H_2 \rightarrow P_{AC}$) at BoL	[%]	50	50
P_{AC} @ BoL	[kW_{AC}]	1.0	1.0
η_{TH} ($H_2 \rightarrow P_{TH}$) at BoL	[%]	46	46
Start-up time from cold	[min.]	2	2
System noise level	[dBA]	<40	<40
MEA degradation	[µV/h]	2	2
Inverter cost	[1,000 DKK]	12	4
Heat storage cost, 200 litre	[1,000 DKK]	14	7
1.0 kW µCHP incl. control	[1,000 DKK]	60	27
Total investment cost ex. installation & H_2-fuel	[1,000 DKK]	86	38

Måned	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45
	jul-11	aug-11	sep-11	okt-11	nov-11	dec-11	jan-12	feb-12	mar-12	apr-12	maj-12	jun-12	jul-12	aug-12	sep-12	okt-12	nov-12	dec-12	jan-13	feb-13	mar-13	apr-13	maj-13	jun-13	jul-13	aug-13	sep-13	okt-13	nov-13	dec-13	jan-14	feb-14	mar-14	apr-14	maj-14	jun-14	jul-14	aug-14	sep-14	okt-14	nov-14	dec-14	jan-15	feb-15	mar-15

Projektets arbejdspakker:	
WP 0: Coordination and management	**IRD**
Task 0.1: Management & Coordination	IRD
Task 0.2: Reporting and publication	IRD
Task 0.3: Benchmark study	IRD
Task 0.4: Dissemination	IRD
WP 1: Development of δ-μCHP units	**IRD**
Task 1.1: Process design of LT PEMFC δ-μCHP units	IRD
Task 1.2: LT PEMFC stack modules	IRD
Task 1.3: Inverter	IRD
Task 1.4: Control units	IRD
WP 2: Integration of δ-μCHP units	**IRD**
Task 2.1: Integration and functionality test of δ-μCHP	IRD
Task 2.2: Smart grid [ready]	SEAS
Task 2.3: Integration of the overall control systems	IRD
Task 2.4: CE-certification of the δ-μCHPs	IRD
WP 3: Test and evaluation of δ-μCHP units	**TREFOR**
Task 3.1: Test plans and success criteria	TREFOR
Task 3.2: Implementation of LT PEMFC δ-μCHP units	SEAS
Task 3.3: System manufacturing	TREFOR
Task 3.4: Test	TREFOR
Task 3.5: Post Mortem analysis	IRD
Task 3.6: Evaluation	IRD
WP 4: Test and evaluation of the combined δ-μCHP and the μ-PEMEC u	**SEAS**
Task 4.1: Integration with the μ-PEMEC module	IRD
Task 4.2: System manufacturing	TREFOR
Task 4.3: Test plans and success criteria	SEAS
Task 4.4: Field test	SEAS
Task 4.5: Post Mortem analysis	IRD
Task 4.6: Evaluation	TREFOR
WP 5: Evaluation and exploitation	**TREFOR**
Task 5.1: Efficiency evaluation	IRD
Task 5.2: Up-scale evaluation	TREFOR
Task 5.3: Cost evaluation	TREFOR
Task 5.4: Exploitation	IRD
WP 6: System reliability & lifetime	**AVL**
Task 6.1: System analysis	AVL
Task 6.2: Application & Targets	AVL
Task 6.3: THDA Start-up	AVL
Task 6.4: THDA Measurements	AVL
Task 6.5: Load Analysis	AVL
Task 6.6: Optimisation of operation	AVL

Fig. 1 Project Gantt; the associated milestones are listed in Table 2.

Table 2 List of Milestones. All milestones are completed except the two (2) cancelled milestones.

Milestone	Nature
MS0.1: Public project website and share point established	Access to share-point and public web-site
MS0.2: Yearly scientific report	Report
MS0.3: Yearly scientific report	Report
MS0.4: Yearly scientific report	Report
MS0.5: Final scientific report	Report
MS0.6: Project progress and results presented at >4 international meetings and/or in international publications	Papers and symposium/ conference participation
MS1.1: P&I diagram, solid-works drawings, bill-of-material (BoM), wiring diagrams and design HAZOP completed	Diagrams and design HAZOP
MS1.2: LT PEMFC stack module ready for integration	Component
MS1.3: Inverter completed and certified, ready for integration	Component
MS1.4: Business plan for the inverter	Report
MS1.5: The µCHP control unit ready for integration in WP2	Component
MS2.1: Report on integration and functionality test of the δ-µCHP unit	Report
MS2.2: Report on Smart Grid functionalities	Report
MS2.3: δ -µCHP certified ready for test at professional users	Certificate [CE & Emission]
MS3.1: Report on Test Plans and success criteria's	Report
MS3.2: Two (2) δ -µCHP units constructed ready for test in Task 3.4	Component
MS3.3: Report on the long-term validation test of the δ -µCHP	Report
MS3.4: Post-Mortem analysis completed	Input to the evaluation reports (MS3.5 & MS4.4)
MS3.5: Evaluation report on the δ -µCHP	Report
MS4.1: The integration of the µCHP with the µPEMEC module completed	Component
MS4.2: Two (2) δ -µCHP/µPEMEC units constructed ready for test in Task 4.4	Component
MS4.3: Test protocols completed	Report
MS4.4: Conclusion on field test and post mortem analysis	Report
MS5.1: Report on observed µCHP efficiency and lifetime estimations	Report
MS5.2: Report on the µCHP cost potential	Report
MS5.3: Exploitation reports [one from each partner]	Cancelled
MS5.4: Establishment of suitable facilities for scalable production	Cancelled
MS6.1: Relevant failure modes and duty cycles are determined	Cf. WP6, *ibid*
MS6.2: THDA ready to be operated by IRD	Component
MS6.3: Presentation THDA and Load Analysis results measurements and suggestions for optimising operating strategies	Cf. WP6, *ibid*

WP1: DEVELOPMENT OF δ-µCHP UNITS

The µCHP is divided into the following sections: a) The LT PEM FC stack module integrated in a hydrogen chamber and situated next to b; b) The power electronics (inverter); and c) Both modules, mentioned above (a&b), are placed on top of the water drainage

An optimised design of the 1 kW LT-PEM module has been made. The work was initiated with a design HAZOP review together with DGC (consultant) to assure that the unit operates safely and can be certified latter. The following subjects has in addition to cost, durability, and lifetime been in focus in the new design:

- Easy assembly
- Easy maintains
- Noise reduction upon hydrogen purge (this has been one of the few negative feed-backs from the Vestenskov phase 2 µCHP hosts)
- Passive frost protection of the hydrogen exhaust pipe

The stack module includes the following:

- A LT PEM stack with 41
- A Cell Voltage Monitoring System
- An air fan and an air humidifier
- The control board
- Safety valves e.g. two solenoid valves to fulfil the requirements to the CE-marking
- The primary cooling circuit
- A hydrogen circulation pump

The FC lifetime is significantly increased in the new design, i.a., a hydrogen pump has been implemented to ensure recirculation of humid hydrogen, to avoid local fuel starvation and formation of radicals on the membrane at the hydrogen inlet on the MEA.


A.


B.

Fig. 2 The 'Competitive µCHP for H2omes' inverter with closed cabinet (A) and without cabinet (B). The cabinet dimensions are 30*10*60 cm^3 and the inverter weight is 9 kg (cf. Table 3).

Table 3 Project inverter specification.

		Pro3 25-40/100
Input (DC)		
	Rated DC voltage	30 V
	Input voltage range	25-40
	Max. input current	100 A
Output (AC)		
	Rated power (at 230 V, 50 Hz)	2.0 kW
	Max. AC power	2.3 kW
	Rated output current	9 A
	Nominal AC voltage	230 V_{AC}
	Nominal AC voltage range	207 V – 253 V
	AC power frequency	50 Hz
	AC power frequency range	45 - 55 Hz
	AC power frequency range, Denmark	47.5 - 52 Hz
	Feed-in phases	1
	Connection phases	1
	Power factor	0.95 lead and lag
	Harmonic distortion	<4%
	Efficiency	>95%
Protection		
	DC reverse polarity protection	yes
	AC short-circuit monitoring	yes
	Grid monitoring	yes
General Data		
	Dimensions (W / H / D)	300 / 100 / 600 mm
	Weight	9 kg
	Operating temperature range	0°C - 60°C
	Self-consumption standby	0 W
	Topology	HF transformer
	Cooling concept	Convection
	Galvanic separation	
Features		
	DC terminal	Cables
	AC terminal	Connector
	Control interfaces	CAN 2.0 1 Mbaud

An inverter has been designed, constructed and CE-certified within the project. The inverter consists of two parts, a DC/DC (step-up) converter and a DC/AC inverter. Several prototypes of the IRD inverter has been made. The inverter specification is listed in Table 3. Three (3) final project inverters (Fig. 2) has been manufactured. A variant of the inverter with an altered step-up part (DC→DC) has been developed outside the present project for integration in the SOFC µCHPs that was field-tested in Sønderborg as part of the project ‘Demonstration of Micro CHP Based on Danish Fuel Cells - Phase 2 & 3’. The developed inverters have been CE-certified to enable the field test.

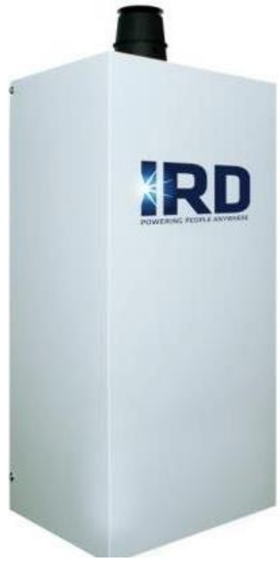


Fig. 3
Picture of gamma up-date µCHP. The listed system power and efficiencies are measured by DGC as part of the certification.

Nominal Power	1.0 kW_{AC}
Nominal Heat	0.8 kW_{TH}
Electrical efficiency, LHV ($H_2 \rightarrow P_{AC}$)	50%
Heat efficiency, LHV ($H_2 \rightarrow P_{TH}$)	41%
Combined efficiency	91%
Size (D x W x H)	45 x 87 x 106 cm^3
Weight	85 kg
Amount of cooling DI H_2O	1 litre

WP2: Integration of δ-µCHP units

The project µCHP was integrated into a cabinet aimed for wall installation similar to the gamma µCHP (DK-µCHP, phase 3 unit), (Fig. 3). The only difference from a customer point of view is that the inverter now is integrated into the cabinet and no longer freestanding, and that the cooling circuit has been changed so the circulation pump between the heat storage and the µCHP now is integrated into the µCHP. The first systems were made with a German HF inverter (SMA).[2]

The IRD control software has been further developed in such a way that it is reusable across different platforms (µCHP, PEMEC & DMFC). As such some of the described advances have been developed in cooperation with other projects. The EUDP project 'HyProvide the LT PEM track' is for instance also concerned about "Smart Grid" compliance. The European standard for Smart Grid support, IEC-61850, is a complex and diverse definition of protocols and data formats, that describes the communication between Smart Grid clients and servers. An integrated solution from Beck IPC was chosen our first Smart Grid support. IRD has implemented a light smart-grid functionality in the software that allows the µCHP to be controlled using a simple input that is similar to the smart-grid control currently available for some heat pumps.

The developed µCHP, although equipped with the commercial available SMA-inverter has been CE-certified by DGC. The following documentation has been made as part of the certification:

- A P&I Diagram
- Component specifications sheets and manufacture declarations
- Instrument data sheet
- Handling, Transportation and Storage
- Installation manual (in Danish)
- Operation and maintenance manual (in Danish) incl. troubleshooting

[2] The SMA inverter aimed for fuel cell µCHPs is no longer available

WP3: TEST AND EVALUATION OF δ-μCHP UNITS

DGC has as part of the CE-certification, and as an independent evaluator tested the μCHP. They tested the performance at two different temperature settings on the external cooling (37ºC and 47ºC). DGC measured electrical efficiencies[3] ($H_2 \rightarrow P_{AC}$) of 50% and 48% for each of the two (2) temperature settings with the corresponding total efficiencies (LHV) of 91% and 85% respectively. The electrical efficiency target of 50% (Table 1) has been reached.

Two (2) gamma up-date μCHPs have been long-term tested at IRD (Fig. 4-5). Both units are equipped with the THDA analytical tool (WP6, *ibid*). Different operational strategies has been tried. One unit has within the last 5,000 operational hours been operated with only four (4) hydrogen purges per hour (Fig. 4), in contrast to the previously applied purge strategy with 30 hydrogen purges per hour (Fig. 5). The reduced purge frequency has been possible due to implementation of a hydrogen circulation pump, and facilitates even higher fuel utilisation (efficiency) than the unit tested by DGC and reduced safety concerns.

The average MEA degradation is shown in Fig. 4B & 5B. The overall degradation is decreasing with operational hours reaching minimum values of 1-2 μV/h (corresponding to a projected lifetime of ≈40,000 h's). The occasional increase in degradation rate reflects malfunction BoP-components. The degradation development has proven to be a sensitive measure for the BoP functionality.

Part of the present project was running in parallel with the phase 3 of the DK-μCHP project. The developed μCHP for the phase 3 demonstration was equipped with a commercial available SMA-inverter. However, this inverter was no longer in production when the last phase 3 units was about to be manufactured. A new high-frequency SMA inverter had replaced the old design, but the new inverter was not CE-certified and smaller in power (1.0-1.2 kW). IRD therefore decided to manufacture the μCHP's that was developed within the present project for the phase 3 demonstration in Vestenskov. This implies that the phase 3 demonstration in Vestenskov comprises in total 32 installations of which 21 units are of the version developed within the present project although without the project inverter. IRD has for this reason obtained a significant experience. The units in Vestenskov had different operational patterns implemented with different numbers of daily start/stop cycles, as further explained in WP4 (*ibid*).

The cost target within the present project (Table 1) is well in-line with the national Danish road map targets. The target cost in the present project was 60 kDKK for the μCHP plant excl. heat storage by the end of 2014 at a production of 100–1,000 units. The obtained cost of the developed μCHP is 64 kDKK excluding inverter, but including labour when manufactured in quantities of +100. The obtained cost division (Fig. 6) of developed μCHP is further elaborated in the confidential MS5.2 report.

The THDA that was connected to uCHP056 (Fig. 5) failed during a start-up, loading the fuel cell stack with 400 A's, which is 10 times the nominal load, without supplying the necessary gasses. The fuel cell stack was therefore both air and fuel starved causing cell reversal and instant development of substantial membrane crossover. The uCHP056 test was for this reason terminated. However, the

[3] Using the energy value of the 'Lower Heating Value' (LHV)

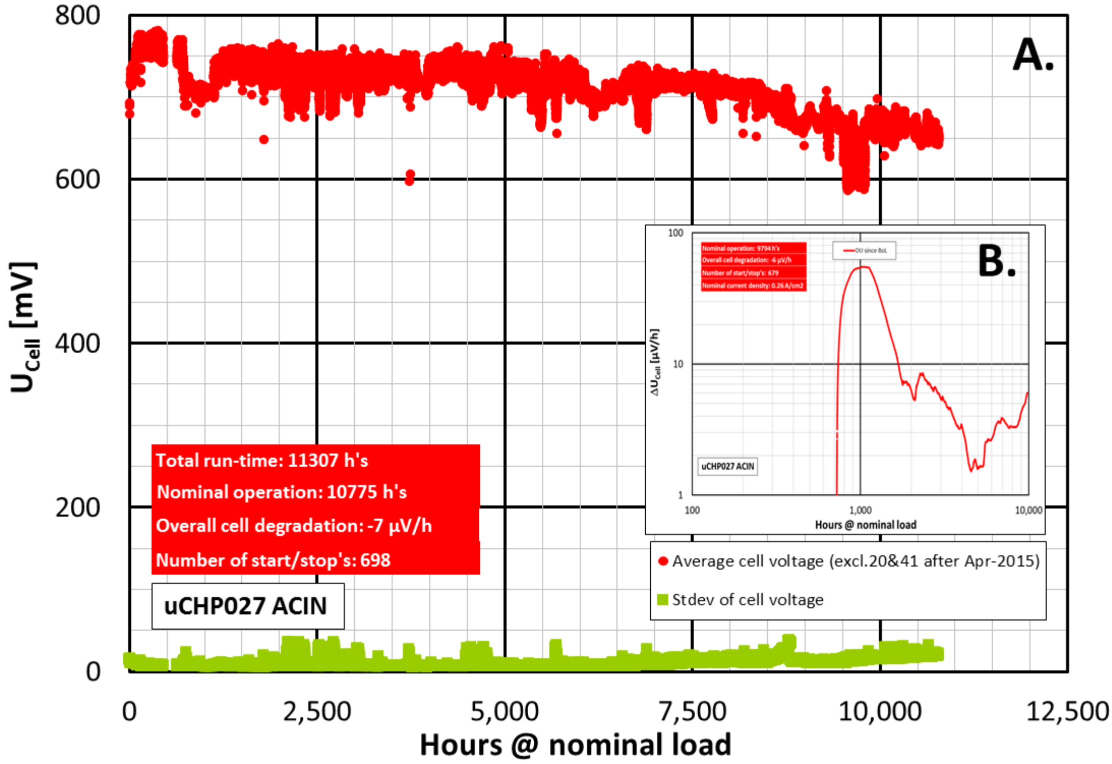


Fig. 4 Overview of one of the long-term µCHP laboratory test at IRD (A); and the calculated average MEA degradation (B).

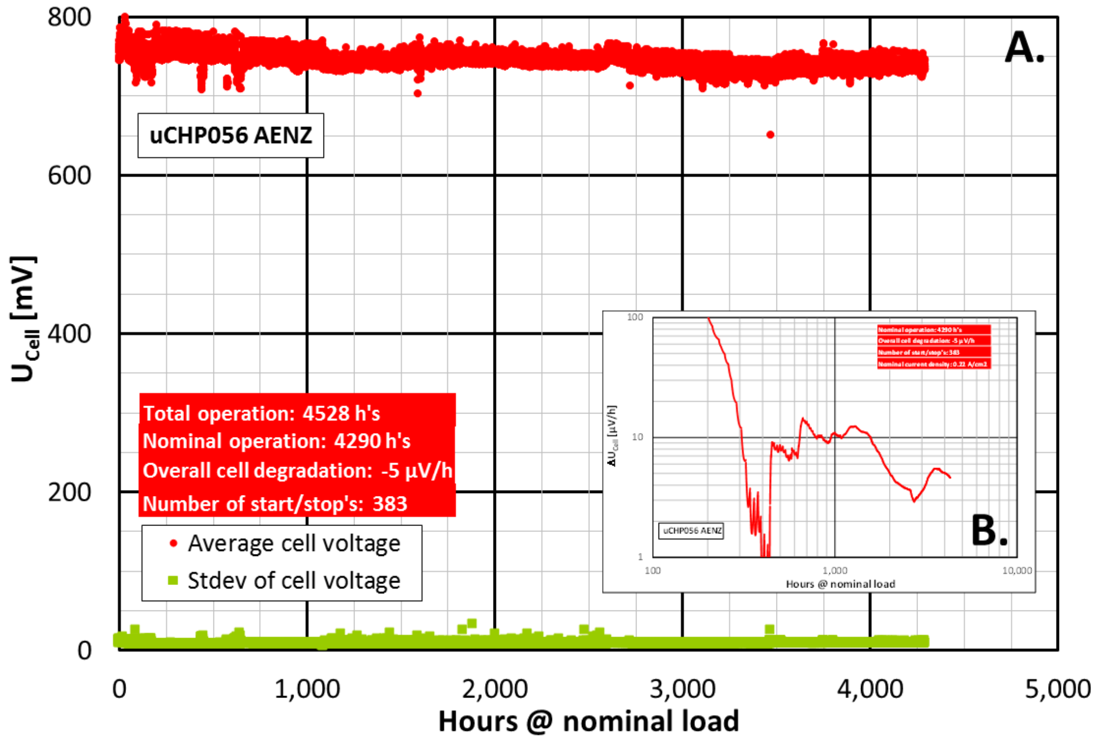


Fig. 5 Overview of one of the long-term µCHP laboratory test at IRD (A); and the calculated average MEA degradation (B).

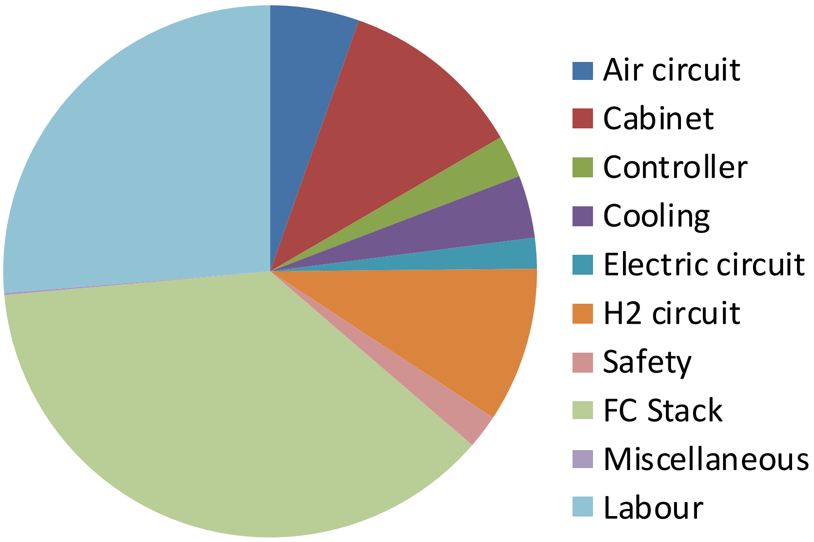


Fig. 6
The cost division of developed µCHP manufactured in a by-the-piece numbers at IRD.

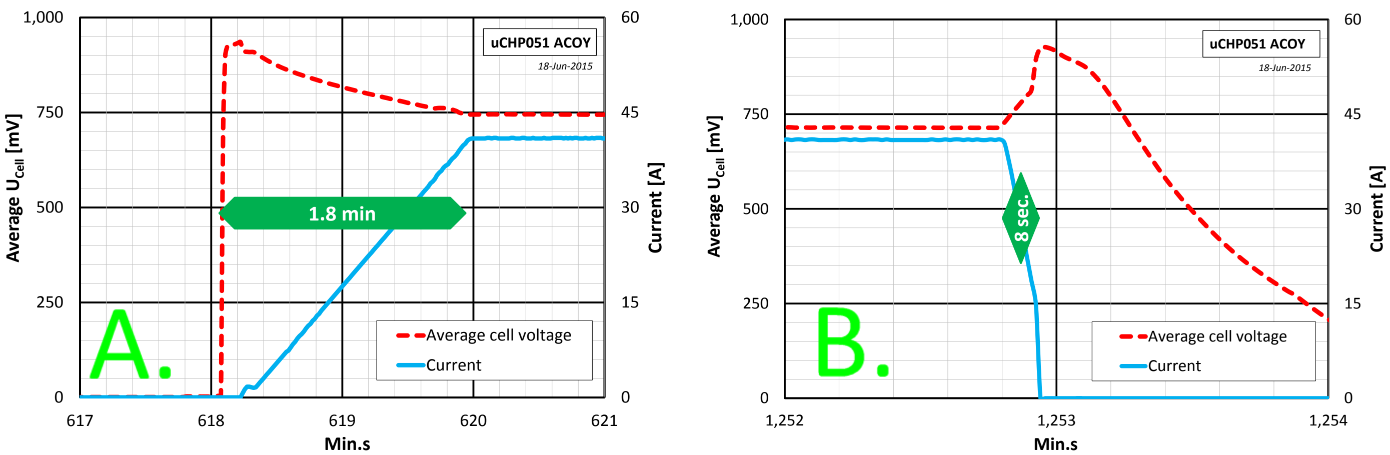


Fig. 7 An example that illustrate that the µCHP takes <2 min.s from the-signal-to-start to reach full power (A), and <10 sec.s to close down (B).

test proved that an optimal operational pattern was achieved and stable cell performances proven for more than 4,000 operational hours (Fig. 5).

Hydrogen fuelled UPS based on the LT PEMFC technology is commercial available. These UPS' are all equipped with either batteries or a supercap to be able to deliver power within ms. The developed µCHP has not been optimised with respect to start-up and shutdown time (Fig. 7A). The start-up time without batteries or a supercap cannot be optimised significantly further due to the speed of BoP components as distribution of feed gasses particular air supply. The optimised shutdown takes 8 sec.s (Fig. 7B) and can further reduced down to the speed of the communication (<1 s). The µCHP can, if batteries or supercaps are integrated, be optimised to respond as a first power reserve (0-15 min.) in the growing Danish RES.

The accumulated number of test hours within this WP is:

- 60,057 hours obtained with 21 units feed with hydrogen from an alkaline electrolyser

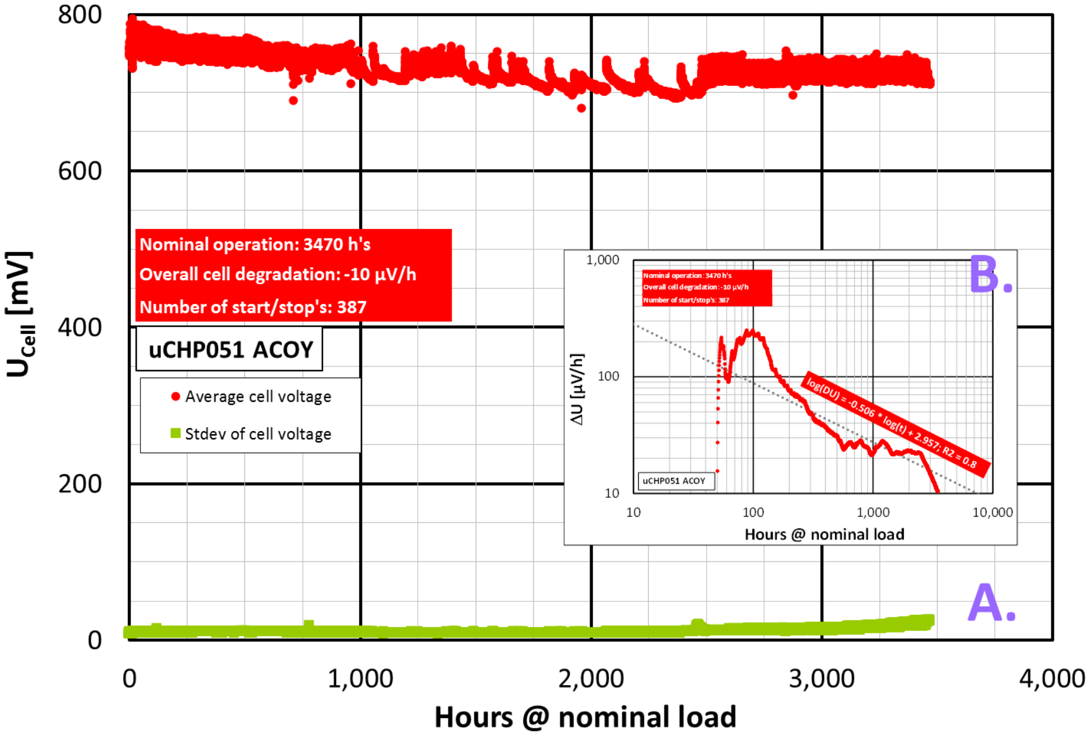


Fig. 8 Average cell voltage @ 0.25 A/cm^2 for a unit that has solely been feed with hydrogen produced by the HyProvide PEM-electrolyser (≥99.995% pure hydrogen) (A). The accompanying average cell degradation is shown in Fig. 8B.

Fig. 9 Show-room with one of the µCHP test set-up at TREFOR premises.

Fig. 10 Work-/test-room at TREFOR premises with installation for simultaneous test of in total four (4) µCHPs.

- 18,013 hours obtained with 3 units feed with hydrogen from industrial grade hydrogen on 200-bars bottles

WP4: TEST AND EVALUATION OF THE COMBINED δ-µCHP AND THE µPEMEC UNITS

TREFOR has made a number of improvements to their test facilities in-order to be able to test the µCHPs (Fig. 9-10). Four (4) µCHP units have been extensively tested at TREFOR. These µCHPs were fed with hydrogen produced by the PEM electrolyser developed within the parallel running EUDP-project 'HyProvide – the LT PEM track'. Three (3) of the µCHPs in test at TREFOR were previously in Vestenskov and one (1) unit was solely tested with the PEMEC hydrogen at TREFOR (Fig. 8). The four (4) units were operated for 7,053 hours in total on PEMEC derived hydrogen without any problems. This was also anticipated as the PEMEC derived hydrogen is much more pure ($\geq$99.995%) than the normal industrial grade hydrogen (99.6%) used in the other test (WP3, *ibid*).

The µCHPs are operated after different schemes. One (1) of the units that has been transferred from the Vestenskov field test has presently been exposed to ≈3,000 start/stop cycles (Fig. 11A). This FC-stack was cooled to ≈35ºC between each cycle this experimental condition might be more harmful to some MEA components and less harmful to others in comparison to a steady state operation (cf. WP6, *ibid*). A low cool-down temperature will increase the chemical and mechanical membrane degradation, while a high cool-down temperature facilitates hydrophobicity loss in the MPL, the GDL, and in the electrode due to washout. The catalyst degradation is also facilitated by a high idle temperature this is further elaborated in WP6, *ibid*. The main challenge observed has been the

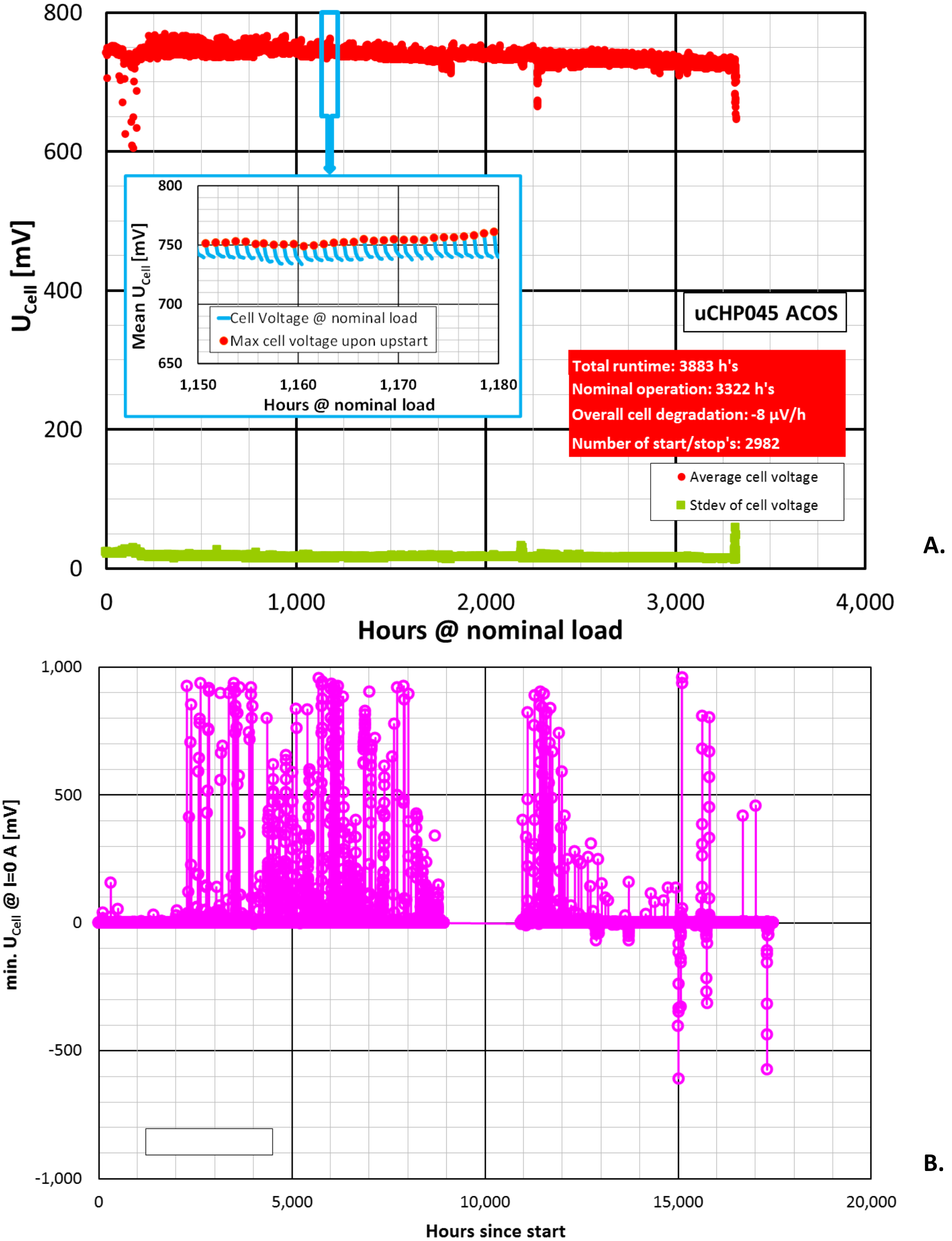


Fig. 11 Average cell voltage @ 0.25 A/cm^2 for a unit that has been exposed to 2,982 start/stop (S/S) sequences (A). The first ≈2,000 S/S's was performed in Vestenskov, while the last 1,000 S/S's and 1,000 hours of nominal operation has been done within the present project. The cells unfortunately developed crossover due to cell reversal during standby/idle-mode (B).

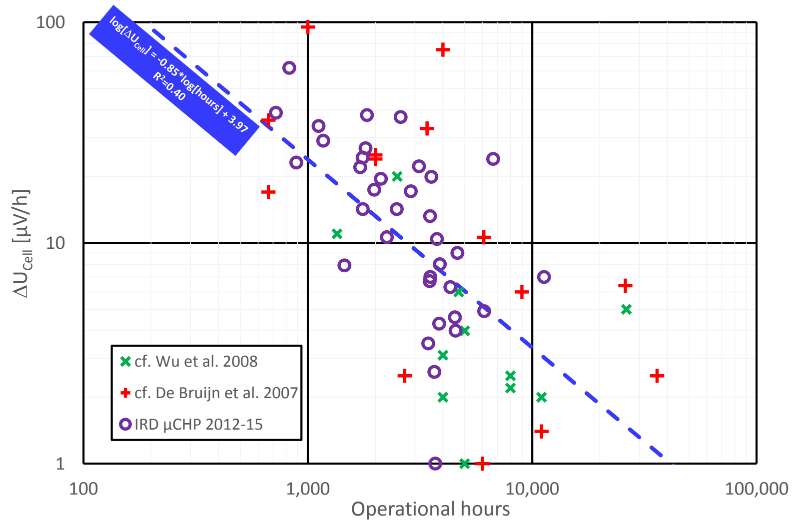


Fig. 12
Calculated degradation rate versus operational hours for hydrogen fuelled LT PEMFC stacks and systems. The figure includes data obtained within the present project as well as data from the literature[4-5] and Vestenskov phase 3 field demonstration.

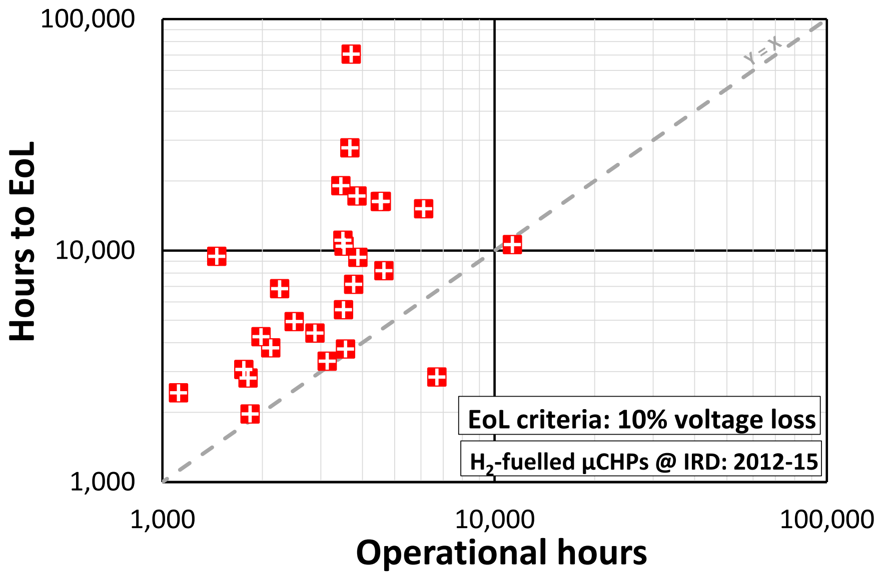
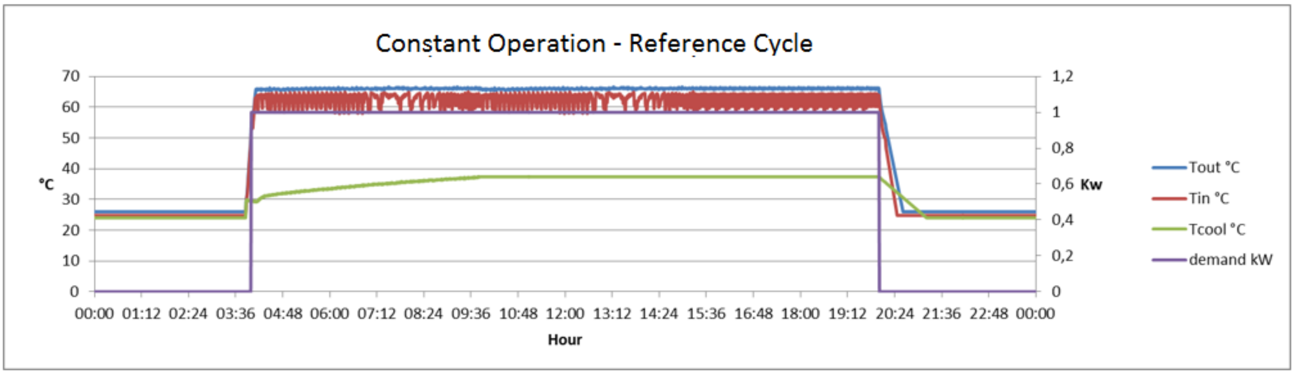


Fig. 13
Estimated lifetime versus operational hours. The lifetime estimates are based on the calculated degradation rates of the hydrogen fuelled µCHPs (Fig. 12) and the academic definition of 10% voltage as EoL.

lifetime of the hydrogen circulation pump where the membrane has been exchanged after 1,500 start/stop and the full pump after ≈3,000 operational hours. However, the fuel cell stack in the latter mentioned µCHP has developed crossover due to fuel starvation as a consequence of power failure at three (3) events, these incidents caused cell reversal (Fig. 11B).

[4] de Bruijn, FA; Dam, VAT & Janssen, GJM (2007): Review: Durability and Degradation Issues of PEM Fuel Cell Components. Fuel Cells 08(1)3–22

[5] Wu, J; Yuan, XZ; Martin, JJ; Wang, H; Zhang, J; Shen, J et al. (2008): A review of PEM fuel cell durability: degradation mechanisms and mitigation strategies. J Power Sources 184(1)104–19



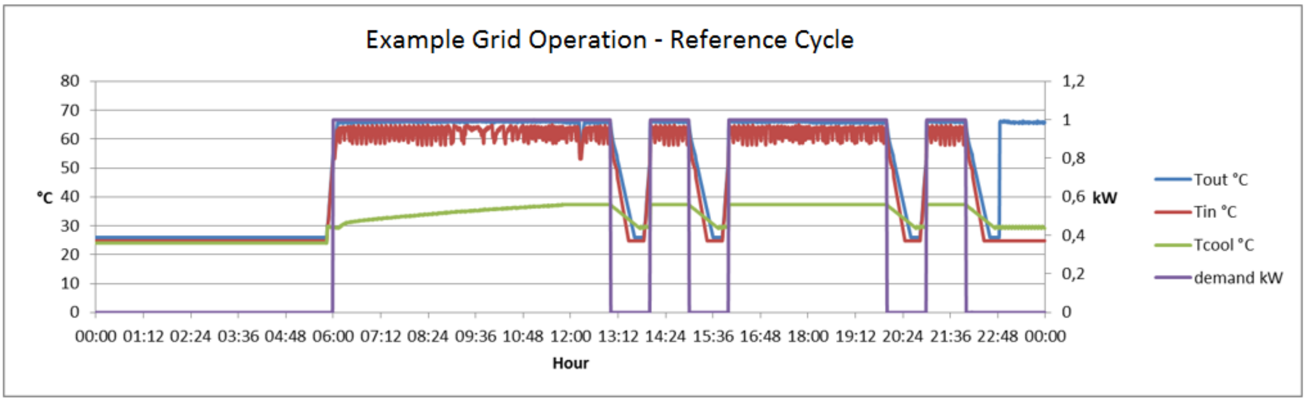


Fig. 14 Example reference cycles as start point for deducing an optimized strategy for reliability and durability.

WP5: EVALUATION AND EXPLOITATION

The calculated degradation rates in the µCHP tests are well in line with the reported values in the literature (Fig.12). The international accepted academic EoL is presently defined as a voltage loss of 10% at nominal operation. This does not necessarily means that the fuel cells does not function afterwards, but higher voltage loss might be a challenge for the power electronics. The implication of the calculated degradations on lifetime is illustrated in Fig. 13. Here it is clearly illustrated that lifetimes estimates based on a short test period can be rather misleading.

The hydrogen fuelled µCHPs host a potential for a significant reduction of the CO_2 emission compared to conventional oil- and natural gas fired boilers. The CO_2 savings are estimated by DGC[6] to be 0.75 kg per kWh_{AC} and 0.204 kg CO_2 per kWh_{Th} when NG-boilers are displaced. This means that the hourly CO_2-savings (assuming that the hydrogen is produced by electrolysis made with surplus RE e.g. wind) is 0.91 kg CO_2 per hour (1 kWh_{AC}: 0.75 kg CO_2 plus 0.82 kWh_{Th}: 0.17 kg CO_2). The yearly CO_2 savings for a single family household would, if the µCHP on a yearly basis should cover the electricity consumption (5,000 kWh[7]) then be 4.5 tons CO_2.

The exploitation of the project results are described in the mandatory section "Perspective and Utilization of project results", *ibid*.

[6] http://www.dmkv.dk/downloads/MKV_Baggrundsanalyser.pdf & Jan de Witt pers.com. 2014

[7] http://www.seas-nve.dk/privat/spareraad/dit-energiforbrug/elforbrug-i-boligen (4 persons)

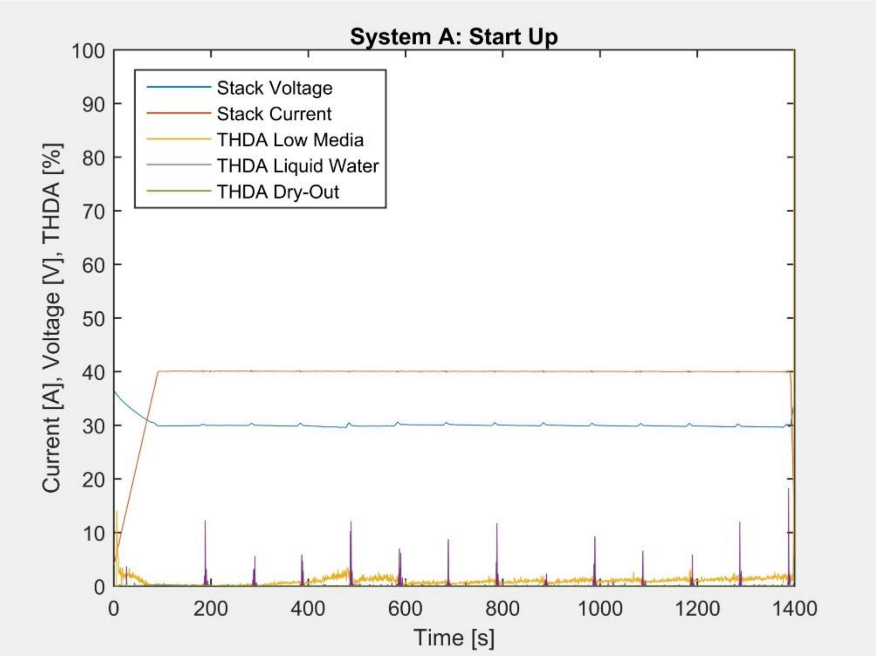


Fig. 15
Start-up of uCHP027 at room temperature.

WP 6: SYSTEM RELIABILITY & LIFETIME

Continuously fuel cell stack monitoring usually means that all single cell voltages have to be measured and analysed separately (CVMS). AVL has developed a simplified alternative stack monitoring system (THDA), feasible for fully integration into existing system components like electronic control unit and inverter. The THDA is based on the analysis of effects of voltage drops or voltage fluctuations instead of its direct measurement. Since electrical auxiliaries of the fuel cell system and other electrical components from the vehicle can interfere with the formation of harmonics, comprehensive compensation algorithms have been developed. These compensation algorithms vary from system to system. In addition, AVL has developed an approach for the classification of identified critical issues into water droplets, (membrane) dry-out and low media supply issues. Separate output signals are continuously calculated and provide this extra information. These outputs are generated by the sophisticated interpretation of the correlation between collected electrical parameters and its typical characteristics during exceptional operating. In this project the THDA methodology is applied to improve operating conditions of the µCHP system in order to avoid critical conditions during operation and to optimise operating parameters to increase the systems lifetime.

Two (2) THDA devices have been installed at two (2) µCHP units (uCHP027 & uCHP056, Fig. 4-5) at IRD. The hardware installation of the THDA measurement device was very straight forward. The goal of the calibration procedure was to bring the system into critical operating conditions (dry out, low media, flooding) on purpose. During those tests *dry out* was in-forced by changing the stack temperature and increase the air flow. *Starvation* on cathode side was done by reducing the air lambda and the same was done on the anode side by changing the pump speed of the hydrogen pump. As already expected the final analysis proofed that during the calibration tests it was almost not possible to flood the systems on purpose, which is definitely a good sign for the system and stack design, but also lead to the results, that the THDA flooding channel might not be calibrated good

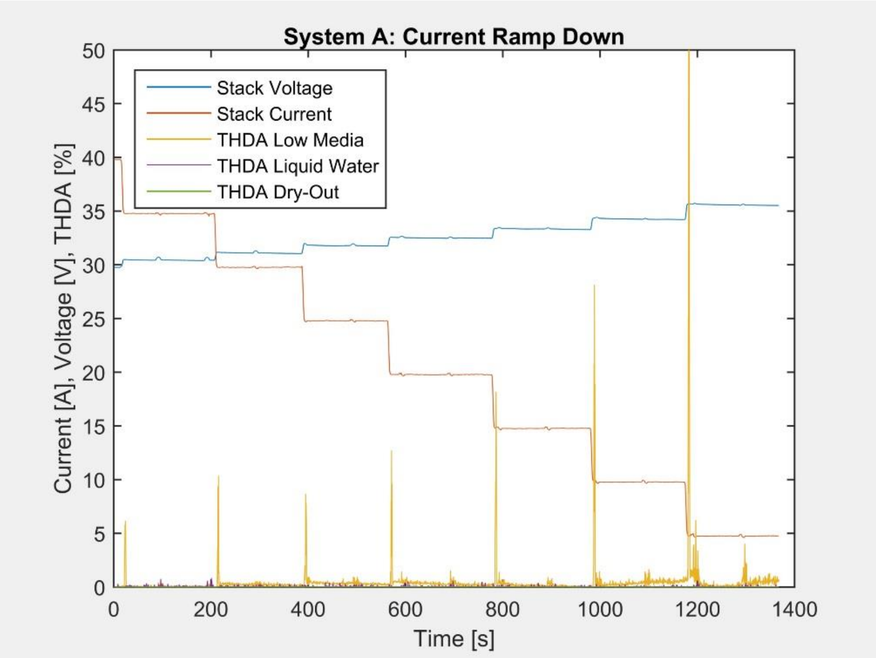


Fig. 16
Results from a THDA measurement of a current – step run. At each down-step of the current, the THDA device indicates media starvation.

enough. The result of the analysis is a set of diagnostic functions that allow an online monitoring of the stack during operation.

An example of a THDA diagnose is illustrated in Fig. 15. During this test, the system is heated from RT (≈20°C) up to 80°C. During this test, a correlation between the Liquid Water Signal and the air purges is noticeable. At this stage, it is very important to mention that the calibration tests did not allow a precise calibration of the THDA Liquid Water channel. Nevertheless, a possible explanation for water indication during air purge could be that lots of small droplets or a light water film in the channels, which are tried to “blast out” with a purge, gather and form slugs very often at corners in the flow plates. When the slugs are formed and pressure builds up behind them then they get blasted out of the channels. Before this point, the droplets are just slowly pushed along the channels by the high airflow. Once the slug is formed, it will collect all the water droplets behind it and remove them[8]. The Liquid Water indication peaks could be the point where the slugs form. This Liquid Water indication during air purge so far only occurred during this start-up test. It is possible that little more water has accumulated in the cold system before start-up. Another result of the THDA analysis indicate fuel starvation upon current step-down operation (Fig. 16).

A Load Matrix methodology has been applied by AVL. This methodology is very powerful and a well-known tool in the automotive sector. The goal of this methodology is to generate accelerated test procedures/load cycles for durability and reliability validation test program design. The basis for those accelerated tests are the so-called damage models, which describe mathematically the physical and chemical processes leading to failure of single components or the whole system.

During a workshop in 2013 a total of 377 failure modes were identified and 21% of those were deemed to satisfy the priority 1 allocation. Since this equates to 66 failure modes, and given the

[8] E. Colosqui, M. Cheah, I. Kevredkidis, J. Benzinger, Droplet and slug formation in polymer electrolyte membrane fuel cell flow channels: The role of interfacial forces, Journal of Power Sources 196 (2011) 10057-10068

Table 4 Selected failure modes for the 1,000 cycles test analysis.

Subsystem / component	Failure mode	Failure Location	Cause of failure	Effect on system level	Damaging Operating Conditions	Aggravating conditions	Measurable parameters
Stack / Membrane	degradation	Membrane	cracking by OH^- ions	pinhole formation, crossover, cell degradation	operation, peroxide formation		
Stack / Membrane	Mechanical degradation	membrane interface to channel plate	Excessive or non uniform mechanical stresses due to fluctuations of the water content in the membranes	decreased membrane conductivity and mechanical strength, reduced ductility, formation of perforations or tears	local water distribution	stack loading	local water distribution, clamping force, membrane conductivity, OCV
Stack / GDL	Washout (errosion)	GDL	Over time water circulation errodes the GDL.	leeds to increased contact resistance and blockages. may even cause failure to support the catalyst layer. Overheating.	temperature, water flow/amount through the GDL and GDL compression	Wet dry cycles	contact resistance
Stack / Electrocatalyst and catalyst layer	starvation	ACL, CCL	unsufficient media supply	unwanted reactions (oxidation, reduction), damaging of the MEA	high fuel and oxidant utilisation		I/V curve, temperature
Stack / GDL	loss of hydrophobicity	GDL	loss of coating, aging, loss of end groups	unbalanced water management, flooding. Overheating.	elevated temperature, flow rate, high humidity		Unstable voltage due to water clogging, increased back pressure
Stack / Electrocatalyst and catalyst layer	Ageing	Catalyst surface	Pt agglomeration and loss into the membrane	Loss in fuel cell electrical efficiency	Operating temperature	high humidity, low pH values, dynamic loads - oxidizing or reducing environment	Temperature, Humidity, gas composition, cell voltage, membrane resistance
Membrane humidifier (DPOINT PX1-114)	Mechanical degradation	membrane interface to channel plate	Excessive or non uniform mechanical stresses due to fluctuations of the water content in the membranes	decreased mechanical strength, reduced ductility, formation of perforations or tears	local water distribution		
H2 Recirculation pump (Thomas 107cdc20)	fatigue	membrane	membrane movement	pump failure	pumping cycles		deflection, rotational speed
Stack / micro porous layer	Washout (errosion)	MPL	Over time water circulation errodes the MPL.	leeds to increased contact resistance and blockages. may even cause failure to support the catalyst layer. Overheating.	temperature, water flow/amount through the GDL and GDL compression cycling.	Wet dry cycles	increased back pressure, changes in species limited part of I/V curve

Table 5 Comparison of the different cycles.

	Ref. Cycle: “1.2 kW, cool-down to RT”	“35°C cycle”	“50°C cycle”	“35°C cycle”
Power dissipation	1.2 kW	1.2 kW	1.2 kW	1.0 kW
Cool-down temperature after each ON – period	24°C	35°C	50°C	35°C
Complete Load Cycle duration	2,665 h	1,654 h	1,143 h	1,885 h
Total Energy dissipation	1,160 kWh	1,160 kWh	1,160 kWh	1,160 kWh

scope of AVL’s tasks in the project, this number was pared down to 10 failure modes for inclusion in the validation. In order to establish damage evolution acceleration factors for the 10 failure modes (Table 4), “A type” (very simple models to provide a starting point) models have been assigned to each failure mode. A more complex model with in-depth consideration of physical phenomena (B type) has been made for 10 selected failure modes. Two (2) reference cycles have been defined by AVL & IRD, which will be used as a basis in order to deduce an optimized operating strategy. In order to evaluate those test cycles, the damage models are applied to a test cycle and to a reference cycle and the calculated damage caused by both cycles is evaluated. The difference between the resulting damage in both cycles gives then finally the relative damage or acceleration factor of this failure mode respectively. The advantage of this method is that by simply comparing two cycles, some unknown material parameters or constants in the physical and chemical description of failure modes will cancel out. This allows describing the trend of damage processes, where a complete mathematical description would not be possible or too computationally intensive. As an example, just two (2) damage modes are described at this point to demonstrate two different types of failure modes.

One example for a “damage based” failure mode is the damage model for the membrane swelling failure mode. In the damage-based method, the damages is estimated based on a function that closely estimates the actual damage. The membrane swelling depends on the relative humidity and temperature[9], and so does the young’s modulus and the yield strength. However, the damage occurs only, if the stress as a function of swelling and Young’s modulus exceeds the yield strength:

swelling, Young’s modulus, yield strength = f(RH,T)

$$\mathrm{swelling, young's modulus, yieldstrengh} = \mathrm{f(RH, T)}$$

$$DI = \sum_{stress\ cycles} stress\left(stress > yield\ strength\right)$$

For this failure mode the damage does not accumulate continuously but just occurs for certain operating parameters.

Different to the failure mode type above are the “load based” failure modes, where the damage is estimated based on the boundary conditions or in other words load, the operating parameters just determine how fast this process is happening. An example for this type is the “loss of hydrophobicity”

[9] Tang et al., Materials Science and Engineering A 425 (2006) 297–304

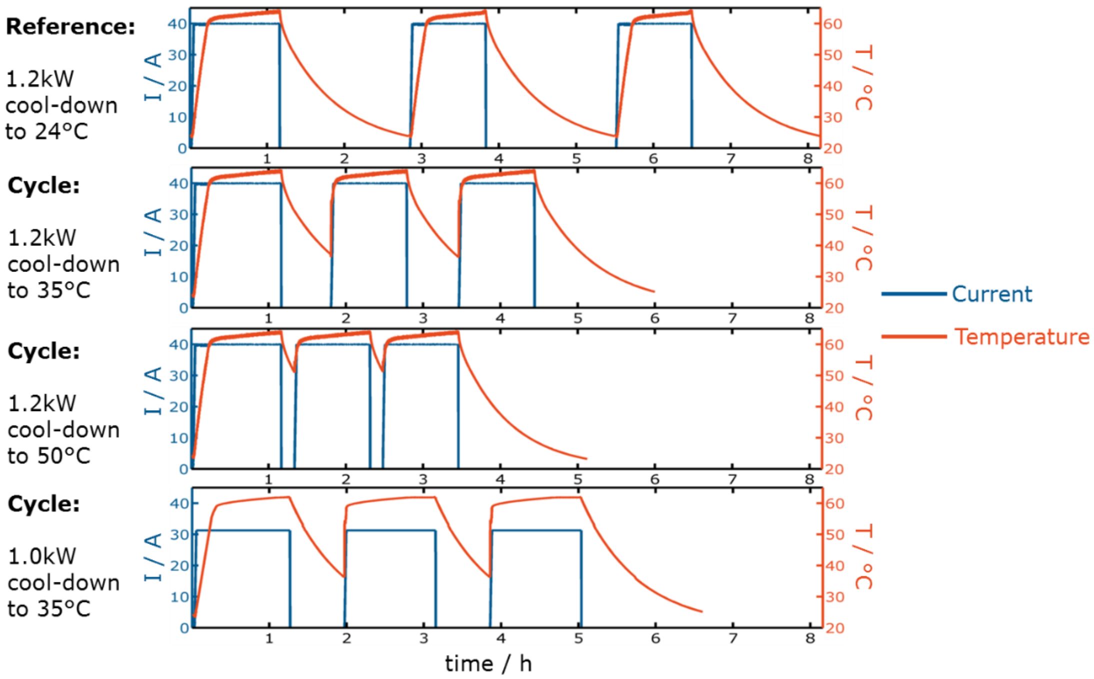


Fig. 17 Visual comparison of the different cycles.

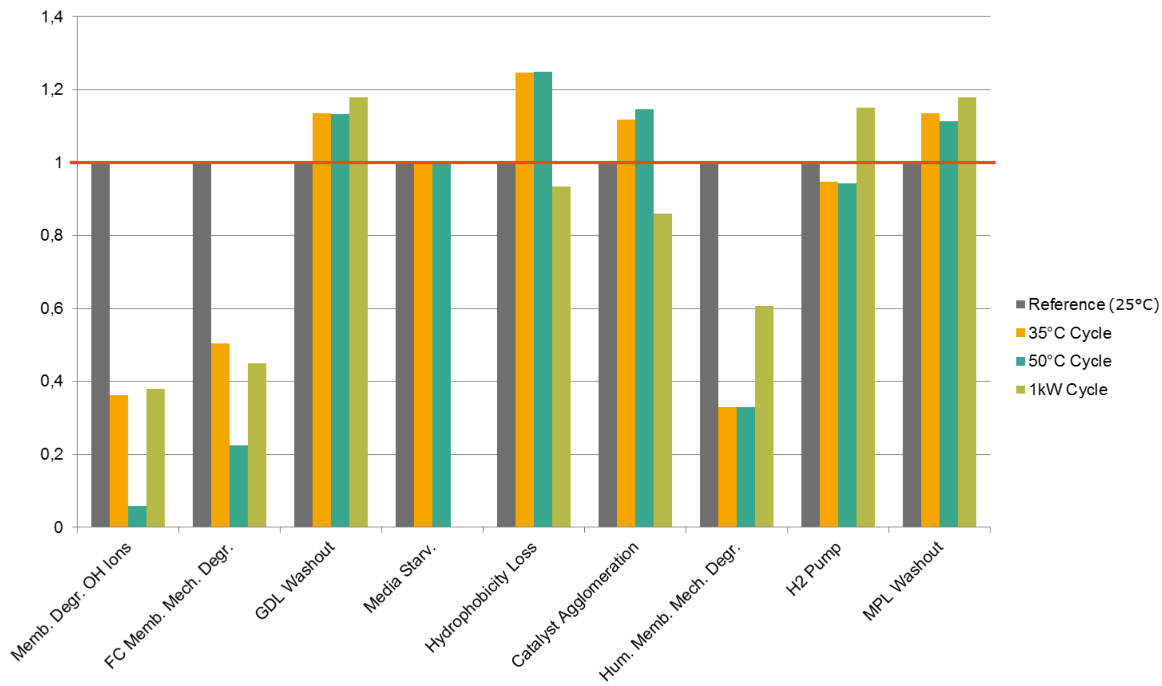


Fig. 18 Acceleration factors (AF) for the different failure modes. AF = 1 means "equal" damage in test cycle compared to reference cycle, whereas AF<1 / AF>1 means that the test cycle causes less/more damage than reference cycle.

damage model. The damage is caused by the gradual removal of the hydrophobic coating by the gas streams, an irreversible process. Thus, the water transport is impeded and the carbon structure is less protected from corrosion. The damage is a function of the mean gas flow and the cumulative operating time[10] and is highly dependent on the operating temperature[11]:

$$DI \sim \text{flow} * \sqrt{T} * e^{-\frac{a^*}{T}}$$

In order to perform a 1,000 cycles test analysis, several test cycles were generated to simulate different shutdown and start-up periods and thus vary temperature and humidity parameters. They were built upon the measurement data of the reference cycle and were extrapolated for the regions differing from the reference cycle. Additionally, a test cycle with reduced rated power was generated to investigate the impact of this parameter on the accelerations factors too (Table 4 & Fig. 17). For each cycle, the accumulative damage for each failure mode was calculated and compared to the reference cycle, resulting in an acceleration factor for each failure mode (Fig. 18).

Some failure modes showed less accumulative damage in the test cycles compared to the reference cycle, especially fuel cell and humidifier membrane degradation due to swelling. This can be explained by the lower fluctuations of the humidity and less condensation since the cool-down temperature (the temperature the system is allowed to cool down after one cycle) is higher than in the reference cycle. In general, both models indicate, that most of the damage is done during start-up and shutdown. On the other hand, some failure modes are affected by the cool-down temperature, namely GDL & MPL Washout, Hydrophobicity loss and catalyst agglomeration.

The simulation shows that running the system at lower power (e.g. 1 kW instead of 1.2 kW rated power) but for a longer time (to dissipate the same amount of electrical energy) may reduce the damage for most failure modes. Of course, this operating strategy will be disadvantageous for certain failure modes, which are primarily affected by "pure" operating time (e.g. hydrogen pump).

[10] Wood et al.: Durability Aspects of Gas-Diffusion and Microporous Layers in Büchi: Polymer Electrolyte Fuel Cell Durability, Springer (2009)

[11] El-kharouf and Pollet: Gas Diffusion Media and their Degradation in Garche: Polymer Electrolyte Fuel Cell Degradation, Academic Press (2012)

DISSEMINATION AND EDUCATION

The project results have been presented at numerous events as a joint effort between the present and related projects, as listed below:

CONFERENCES, SYMPOSIUMS, WORKSHOPS ETC.:

1. Jacob L. Bonde (2012): Hydrogen based PEM. Oral presentation at the HyFC 'summer' school at AAU, week 46, 2012
2. Laila Grahl-Madsen (2012) gave a presentation on 'Status og planer for PEM- og Metanol teknologien' at the 'IDA Energy meeting on Fuel Cells' on the 7th of February 2012
3. Laila Grahl-Madsen (2013): Real-life experience obtained in Vestenskov during field test with hydrogen fuelled LT PEM µCHPs. Oral presentation at the PEMFC Degradation workshop, Sintef Oslo on the 3rd – 4th of April, 2013
4. Laila Grahl-Madsen: Field experience with a Hydrogen fuelled µCHP. Keynote speaker on the 5th International Conference on Fundamentals & Development of Fuel Cells, Karlsruhe, Germany on the 16th to 18th of April, 2013
5. Laila Grahl-Madsen (2013): µCHP. Oral presentation at the HyFC Academy Ph.D. Workshop on Hydrogen and Fuel cells, DTU on June 24th 2013
6. Laila Grahl-Madsen (2013): FCs at IRD. An oral presentation made at the work-shop 'Klima og Energi', arranged by 'Svendborg municipality' for science teachers at HTX, STX & technical college on the 9th of september, 2013 @ Svendborg
7. Laila Grahl-Madsen (2013): Tekniske erfaringer med mikrokraftvarme. An oral presentation made at the workshop 'Temadag om mikrokraftvarme', arranged by 'Dansk Energi' on the 27th of May 2013 @ TREFOR
8. Laila Grahl-Madsen (2014): Brændselsceller**,** Erfaringer fra brintlandsbyen Vesterskov på Lolland. Oral presentation on the seminar on the future of energy, 20-mar-2014 arranged by 'Dansk Fjernvarme'
9. Laila Grahl-Madsen (2014): Demonstration af H2 LT-PEM i Vestenskov. Oral presentation on the concluding conference on Danish micro-CHP demonstration and field test. September 23rd 2014 at Bella Sky Comwell, Copenhagen http://www.dmkv.dk/downloads/Afslutningskonference/DMKV_konferenceprogram_140923.pdf
10. Lars Jacobsen (IRD) participated in the networking day 'EU Prospects Fuel Cell CHP' on the 27th of November 2012 held at Park Plaza Amsterdam Airport
11. Madeleine Odgaard (2012) presented the IRD µCHP results and initiatives at the symposium in Grenoble 26th – 27th of September 2012 [International workshop on characterization and quantification of MEA degradation processes]
12. Madeleine Odgaard (2013): Nano-materials in Commercial PEM Fuel Cell Applications. An oral presentation made at the seminar at NREL (National Renewable Energy Laboratory) Golden, Colorado, October 7, 2013
13. Martin Vesterbæk (2013): Mikrokraftvarme og smartgrid. An oral presentation made at the workshop 'Temadag om mikrokraftvarme', arranged by 'Dansk Energi' on the 27th of May 2013 @ TREFOR
14. Mikkel Juul Larsen (2013): IRD Fuel Cells A/S - providing sustainable power and heat in Denmark and be-yond. Oral presentation at the Danish Korean PEM Fuel Cell Workshop, November 18-19, 2013, KIST, Seoul

15. Steen Yde-Andersen (2014): Development and demonstration of PEM FC based µCHP units in the hydrogen village Vestenskov on Lolland in Denmark. Oral presentation at the workshop on “Progress in PEMFC Stack Testing Procedures” organised by Next Energy on 28th – 29th of January 2014
16. Theiss Stenstrøm shortly presented the IRD µCHP initiatives at the 7th Annual Delta-ee ‘Micro-CHP in Europe’ Summit 13-14 June (2012) in Windsor, London

ARTICLES IN MAGAZINES (joint publications with the Danish µCHP demonstration project):

1. Mikrokraftvarme på brint i Vestenskov, Gasteknik 5/2014,
2. Micro-CHP - A tool for increased market access, Cogeneration and On-Site Power Production, May-June 2014
3. Mikrokraftvarme i praksis, Gasteknik 6/2013
4. Mikrokraftvarme er succes – nu skal prisen ned, FiB 44, april 2013
5. Test af mikrokraftvarme i stor skala i private hjem, Gasteknik 3/2013

EXHIBITIONS:

1. The gamma up-date µCHP was together with the ‘HyProvide’ PEMEC presented at ‘The Festival of Research’ in Odense on the 24th to the 26 th of April, 2014
2. The gamma up-date µCHP was together with the ‘HyProvide’ PEMEC presented by L. Grahl-Madsen and Madeleine Odgaard at the ‘Confederation of Danish Industry’ exhibition on Bornholm medio June, 2014
3. The gamma up-date µCHP was together with the ‘HyProvide’ PEMEC presented at the opening ceremony at the Green Tech House in Vejle on the 24th of June, 2014
4. Several visitors to the TREFOR showroom cf. Fig. 9
5. The developed µCHP was exhibited at H2interaction in Vestenskov for several years. This exhibition was visited by several national and international delegations

EDUCATION:

1. Two (2) engineer trainees has worked at TREFOR in the autumn 2012 with straighten out the advantages and disadvantages of $\mu CHP_{FC/EC}$ based on a reel-life situation in TREFOR distribution grid. Both students were granted 10 for their trainee-report that also served as their thesis. The two students developed a very useful tool for design of heat-demand in a single-family house.
2. One (1) engineer trainees has worked for 5-month at IRD in the autumn 2013 with extended µCHP tests.

PERSPECTIVE AND UTILIZATION OF PROJECT RESULTS

Residential µCHP shipments have on an international level continued to grow in 2014 over 2013, mainly due to Japan's Ene-Farm programme, but even with subsidies these µCHP units rarely provide a positive return to customers, not even over ten years[12]. This conclusion is supported by a yet unpublished calculation done by the Danish Energy Association in the EUDP-project 'Analysis for Commercialization of Hydrogen Technologies'. The Danish Energy Association has also evaluated the Danish socio-economic aspects and conclude that neither the NG-fuelled nor hydrogen-fuelled µCHPs are beneficial from a Danish socio-economic aspect.

The Japanese manufacturers have benefited from the economies of scale provided by the ramp-up of production created through heavy subsidies from government and gas companies (66% of customer price), but these are not even sufficient to deliver fully competitive systems. They continue to reduce cost through better design and engineering, cheaper and better components and materials – and to seek additional markets through partnerships, such as in Europe. The success of the Japanese µCHP experience and technology, and the Japanese manufacturers' desire for bigger markets, has been translated into joint ventures with European partners. Toshiba is working with Baxi, Panasonic with Viessmann, and Aisin with Bosch. Furthermore, Ceres Power reports partnering with Korean business Navien and two (2) unnamed Japanese OEMs with its SOFC technology; these are in addition to the long running relationship with British Gas.

The deployment of fuel cell µCHP in Europe has been muted in comparison to Japan. Several national and European projects have begun demonstration and commercial pre-deployment, but with considerably smaller subsidies available. However, the results of the recent Japanese-European partnerships are that the European market is/will-be dominated by Japanese stack and system technology. It is, in the light of the international development, and the lack of support for further deployment in Denmark not surprising that IRD have failed to find a valid business (ramp up) model for their hydrogen-fuelled µCHP. However, the results of the present project have important spin-offs, as summarised below:

- The extensive *on-going* test program has supported IRDs component business that comprises MEAs and bipolar plates. This business area is steadily growing with around 10% per year at IRD
- The knowledge on hydrogen fuelled LT PEMFC systems will be exploited as a consultancy (application, lifetime, BoP know how) as enabling measure for creation of long-term relations with option for component customers and system integrators
- The µCHP exploitation plans are closely related to the business-opportunities of the hydrogen technologies. The present Danish laws and regulations don't favour implementation of a hydrogen society although hydrogen is identified to play an important role in the Danish road towards a secure fully RES-system in 2050. Possible business opportunities are explored as a joint effort between the present project and other related projects and initiatives where IRD actively participate e.g. the 'FCH JU commercialization study'; the EUDP-project 'Analysis for Commercialization of Hydrogen Technologies'.

[12] http://www.fuelcells.org/pdfs/TheFuelCellIndustryReview2014.pdf

The conclusion of all commercialisation efforts is that the µCHP cannot become attractive on the commercial market in the near future. IRD has therefore decide that the hydrogen-fuelled µCHP for the time being will not be explored beyond the present project. However, the project has resulted in significant knowledge for IRD and has strongly contributed to support other business areas, as explained above. The gained experience may, at a later stage be utilised to design and construct another sized CHP.

ACRONYMS AND ABBREVIATIONS

AST	Accelerated Stress Test
BoL	Beginning-of-Life
BoP	Balance-of-Plant
BoT	Beginning-of-Test
CHP	Combined Heat and Power
µCHP	Micro Combined Heat and Power (0-5 kW)
DMFC	Direct Methanol Fuel Cell
EoL	End-of-Life
EoT	End-of-Test
FC	Fuel Cell
GDL	Gas Diffusion Layer
LHV	Lower Heating Value
LT	Low Temperature
MEA	Membrane Electrode Assemblies
MPL	Micro-Porous Layers
MS	MileStone e.g. MS1.2 meaning milestone no.2 in WP1
NG	Natural Gas
OCV	Open Cell Voltage
PEM	Proton Exchangeable Membrane
QA	Quality Assurance
RE	Renewable Energy
RH	Relative Humidity
RT	Room Temperature
S/S	Start/Stop
SOFC	Solid Oxide Fuel Cell
THDA	Total Harmonic Distortion Analysis
WP	Work Package