Final report: HyProvide – the LT PEM track

Coordinator (IRD):   Carsten Rømer (1-Apr-2015 to 31-dec-2015)
                        John B. Hansen (1-Apr-2014 to 31-Mar-2015)
                        Per Wittenhoff (1-Nov-2012 to 31-Mar-2014)
                        Steen Yde-Andersen (1-Nov-2011 to 31-Oct-2012)

List of Participants		
Beneficiary no.	Beneficiary Name	Beneficiary short name
1 (coordinator)	IRD A/S	IRD
2	TREFOR Enterprise A/S	TREFOR
3	SEAS-NVE Holding A/S	SEAS-NVE
4	AAU Institut for Energiteknik	AAU
5	Moving Energy	ME
6	1st Mile	1M

Dissemination level		
PU	Public	✖
PP	Restricted to other programme participants (including the EUDP)	
RE	Restricted to a group specified by the consortium (including the EUDP)	
CO	Confidential, only for members of the consortium (including the EUDP)	

Revision	Date	Changed by:	Comments
1.00	23-02-2016	Laila Grahl-Madsen	Report
1.10	10-03-2016	Jacob L. Bonde	Proof reading

Contributors to the Final Report:

IRD: Laila Grahl-Madsen & Carsten Rømer
TREFOR: Henrik Lunde & Martin Vesterbæk
SEAS-NVE: Jens Ole Phil
AAU: Anders C. Olesen & Lajos Török
ME: Klaus Rasmussen
1M: Søren Houmøller

Report submitted to EUDP on the Tuesday, 15 March 2016

SHORT DESCRIPTION OF PROJECT OBJECTIVE AND RESULTS

English abstract:

A Danish micro-electrolyser that is capable of efficiently splitting water into ultrapure hydrogen and oxygen has successfully been developed and tested within the present project. The electrolyser is based on the PEM technology that the IRD has developed for fuel cells and recently optimised for electrolysis. The electrolyser has a capacity of producing 1 Nm^3 of H_2 per hour, directly pressurized to 50 bar without a compressor. A drying system capable of reducing the dew point in a pressurised stage to less than -70ºC was also developed to comply with the dew point requirements for the use in a hydrogen filling station. The electrolysis system is CE certified. A number of prolonged cell test has been performed, the results show a huge potential for long lifetime i.e. one cell has successfully been tested for more than 3-years (30,000 hours), the test is still on-going.

Dansk abstrakt:

Der er i projektperioden udviklet og succesfuld afprøvet en dansk PEM elektrolysator der er i stand til effektivt at spalte vand i ultrarent brint og ilt. Elektrolysatoren bygger på den PEM-teknologi, som IRD har udviklet til brændselsceller og siden 2010 videreudviklet til elektrolyse. Elektrolysatoren har en kapacitet på fremstilling af 1 Nm^3 H_2 i timen og fremstiller direkte tryksat brint (50 bar) uden kompressor. Der er derfor udviklet et tørresystem, der kan tørre brinten i tryksat tilstand til tankstation standard (dugpunkt mindre end -70ºC) således at brinten kan bruges i f.eks en brint tankstation. Selve elektrolysesystemet er CE-certificeret. Sideløbende med systemudviklingen er udført en række langtidstest af elektrolysecellerne i projektet og potentialet er lovende, således er en enkeltcelle succesfuldt afprøvet i mere end 3-år (30.000 hours), og testen forsætter ud over projektperioden.

Fig. 1
The developed and CE-certified LT PEM-electrolyser.

EXECUTIVE SUMMARY

The project objective was to develop and functionally test a complete prototype micro-electrolyser unit based on the LT PEMEC technology. The project was initiated in Q3 2011; the starting point for the present project was the 1 Nm^3/h PEMEC stack, designed and tested within the FCH JU PrimoLyzer project. The work within the present project consist of a number of activities ranging from MEA production maturing, PEMEC stack modelling, PEMEC stack maturing, system development, power electronics development and durability test. Very good results are overall obtained within all fields, the obtained results are well in-line with the international *SoA*, but the very-very ambiguous road map targets with respect to cost and efficiency has not be achieved. The main project results are summarised below.

The pre-HyProvide MEA was manufactured by the labour intensive decal transfer. A stable anode-ink was successfully developed for the existing IRD manufacturing line that enables rapid commercial prototyping and simple transition to high volume manufacturing. The long-term single cell MEA test have proved that these MEAs are more robust than the PEMFC MEAs i.e. one of the *on-going* tests started in the PrimoLyzer project and is still *on-going* (more than 3.5 years of nominal operation). More than 150,000 accumulated single cell test hours are obtained.

The PEMEC stack has a circular-planar, interdigitated flow field. While stationary PEMFC have separated flow fields for reactant transport and coolant, it is possible to operate a PEM electrolysis cell with the anode flow field serving as both. This allows for a simpler system and a thinner design. The modelling have shown that under nominal conditions and below a water stoichiometry of 350, flow and temperature maldistribution is adversely affected by the presence of the gas phase; particularly gas hold-up near outlet channels can cause excessive formation of hotspots. The stack has been matured with respect to production. A stack cost reduction has been obtained and further reduction will be achieved at higher numbers, but the foreseen cost is somewhat higher than the targeted cost.

A tailored efficient converter (from the three-phase grid supplying an electrolyser as load) has been developed. The converter proved 94.3% efficiency at the nominal output current (75 A). A preliminary electromagnetic compatibility (EMC) measurement have shown, that the prototype power supply could be categorized as professional equipment according to standard EN-61000-3-12.

A prototype electrolyser system was design, constructed and tested within the project. One (1) electrolyser was tested in IRDs laboratories and four (4) units at TREFOR. 7,500 accumulated test hours was obtained within the project. The stack proved to be 78% efficient (HHV) within the prototype system, while the full system (excl. dryer) proved to be 64% efficient (HHV). This is well within the international SoA efficiencies for small PEM electrolysers. The electrolyser has been CE-certified. A hydrogen dryer that works at 50 bars H_2-pressure has been developed. The test results proved the dried hydrogen to have a dew point below -70ºC.

It is a challenge to store hydrogen the universe smallest element. Existing storage technologies have been analysed in terms of price, weight, system integrability and legislation. High pressure cylinders' type IV proved to be most flexible, cost-efficient and future proof choice. A type IV cylinder is a storage where the investment cost at a hydrogen pressure at 50-100 bar will be less than 130 DKK/kWh.

The project results have been presented at several exhibitions, at conferences, and in peer reviewed papers.

TABLE OF CONTENT

INTRODUCTION

PROJECT OBJECTIVES

The project objective was to develop and functionally test a complete prototype micro-electrolyser unit based on the LT PEMEC technology that fulfils the ambiguous µPEMEC road-map targets with respect to cost and efficiency (Table 1). The project results were expected to strongly contribute to the targeted commercialisation.

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. The original consortium consisted of IRD (coordinator), TREFOR and SEAS NVE. An expansion of the consortium with Ålborg University (AAU), 1st Mile and Moving Energy was accepted by EUDP in spring 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 technical work was divided into ten (10) WPs (Table 2). The responsible WP-leaders/organisations have compiled the sections on each individual WP in the following. The most recently defined Gantt is shown in Fig. 2. Defined milestones are listed in Table 3 and the list of deliverables in Table 4.

Table 1   Cost and efficiency road map targets defined in 2011.

	2012	2014	2016
Stack			
Cost [DKK] @ X units per year	30,000 @ 100	15,700 @ 500	7,400 @ 2,500
Efficiency [% HHV]	87% [4.1 kWh/Nm^3]	90% [3.9 kWh/Nm^3]	93% [3.8 kWh/Nm^3]
System			
Cost [DKK]	NA	53,000	36,000
Efficiency [% HHV]	80%	83%	90%

Table 2   List of work packages and the respective WP leaders.

WP number and title	WP-leader
WP0: Coordination and management	IRD
WP1: Specification and planning	IRD
WP2: LT-PEMEC MEA development	IRD
WP3: LT-PEMEC cell and stack modelling	AAU
WP4: LT-PEMEC stack development	IRD
WP5: Power supply development	AAU
WP6: Hydrogen storage	ME
WP7: LT-PEMEC system development	IRD
WP8: LT-PEMEC prototype test	TREFOR
WP9: Dissemination and planning R&D & commercialisation	TREFOR
WP10: Business strategy	1M

Fig. 2 The most recent up-dated Project Gantt diagram; the associated deliverables and milestones are listed in Table 3-4.

Projektets arbejdspakker:	Måned	2011				2012					2013					2014		2015
	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										

WP 0:Coordination and management
- Task 0.1: Steering committee
- Task 0.2: Project coordination and agreement
- Task 0.3: Project contact point and facilitate meeting
- Task 0.4: Project administration
- Task 0.5: Project reporting

WP 1: Specification and planning
- Task 1.1: LT PEMEC specification and planning
- Task 1.2: Smart Grid interface specification

WP2: LT-PEMEC MEA development
- Task 2.1: Electrode R&D
- Task 2.2: MEA R&D
- Task 2.3: MEA manufacture
- Task 2.4: Single-cell test

WP3: LT-PEMEC Cell and stack modelling
- Task 3.1: Cell and stack fluid dynamcs modelling
- Task 3.2: Cell and stack thermo dynamics modelling
- Task 3.3: Cell and stack model revision

WP4: LT-PEMEC Stack development
- Task 4.1: Stack design
- Task 4.2: Stack construction and test

WP5: Power supply development
- Task5.1: Grid connected power supply
- Task5.2: Photovoltaic supplied power supply

WP6: Hydrogen storage
- Task6.1: Hydrogen storage
- Task6.2: Hydrogen storage capacity for residential use

WP7: LT-PEMEC system development
- Task 7.1: Safety and regulations
- Task 7.2: Water treatment
- Task 7.3: Other BoP components
- Task 7.4: Control unit
- Task 7.5: System integration
- Task 7.6: Manufacturing and cost evaluation

WP78 LT-PEMEC prototype test
- Task 8.1: Test plans and success criteria
- Task 8.2: Laboratory test
- Task 8.3: Test evaluation

WP9: Dissemination and planning R&D & commercialisation
- Task 9.1: Dissemination of project results
- Task 9.2: Economic and environmental analyses
- Task 9.3: Smart Grid solutions
- Task 9.4: Securing patents and planning commercialisation
- Task 9.5: Detailed planning and securing HyProvide Phase 2

WP10: Business strategy
- Task 10.1: Definition of unique value proposition and strategic intent
- Task 10.2: Business strategy
- Task 10.3: Business strategy review

Major Milestones
- M1: All specifications and planning done
- M2. Business Plan review
- M3: Midterm evaluation of system R&D
- M4: System prototype developed
- M5: System prototype constructed and testing initiated

Table 3   List of Milestones. All milestones are completed except M9.1 (cf. section 'Perspective and Utilization of project results', *ibid*).

No.	Name	Verification
M0.2	SC meetings (kick-off, half year & at end)	Meeting notes
M0.2	Project agreement signed	Signed agreement
M0.3	EUDP grant acceptance forms	Submitted form
M0.4	Annual reports	Reports
M0.5	End Project & Financial reports	Reports
M1.1	All specifications & planning conducted	Data sheets
M2.1	LT-PEMEC test MEA ready	Test stack
M3.1	LT-PEMEC cell and stack, two phase modelling completed	Test stack
M4.1	LT-PEMEC test stack ready	Test stack
M5.1	Grid connected power supply constructed and tested	Power supply
M5.2	PV connected power supply constructed and tested	Power supply
M6.1	Hydrogen storage ready for integration	Storage
M7.1	Laboratory test LT-PEMEC system ready	Test system
M8.1	Laboratory test conducted & evaluated	Report
M9.1	HyProvide Phase 2 plan	Other
M10.1	Decision gate: Enter commercial production	Gate decision

Table 4   List of deliverables. All deliverables are completed except D9.4; D10.4 & D10.5 (cf. section 'Perspective and Utilization of project results', *ibid*).

No.	Name	Nature
D0.1	Project Agreement between participants	Other
D0.2	EUDP grant acceptance form & project info form	Other
D0.3	Quarterly grant payment request	Other
D0.4	1st Annual report	Report
D0.5	2nd Annual report	Report
D0.6	3nd Annual report	Report
D0.7	Project end report	Report
D0.8	Project end financial report	Report
D0.9	Project end form	Other
D1.1	LT-PEM Specification	Data sheet
D1.2	Smart Grid interface specification	Data sheet
D2.1	LT-PEMEC MEA for prototype	MEA samples
D3.1	LT-PEMEC cell, two phase flow modelling	Other
D3.2	LT-PEMEC stack, two phase flow modelling	Other
D3.3	LT-PEMEC stack thermodynamic modelling	Other
D3.4	LT-PEMEC stack model revision	Other
D4.1	LT-PEMEC stack	Test-stack

No.	Name	Nature
D5.1	Topology study and specifications for grid connected power supply	Report
D5.2	Grid connected power supply	Report/Power supply
D5.3	Topology study and specifications for PV connected power supply	Report
D5.4	PV connected power supply	Report/Power supply
D6.1	Hydrogen storage technologies for residential use	Report
D6.2	Hydrogen storage capacity for residential use	Report
D7.1	Safety & regulations analysis	Report
D7.2	Balance of Plant components	Test components
D7.3	Secondary system components	Test components
D7.4	System integration	Test system
D7.5	Manufacturing & cost evaluation	Other
D8.1	Test plan & success criteria	Plan document
D8.2	Laboratory test	Other
D8.3	Test evaluation	Report
D9.2	Smart Grid solutions	Other
D9.3	Patent securing initiated & commercialisation planned	Other[1]
D9.4	HyProvide Phase 2 planned & secured	Cancelled[2]
D9.6	Dissemination of project results	Other
D10.1	Business plan	Business plan
D10.2	Market analysis including value drivers	Report
D10.3	Business plan	Business plan
D10.4	Go-to-market execution plan	Cancelled
D10.5	Go-to-market execution plan review	Cancelled

STATE-OF-THE-ART

A PEMEC cell is built up around a proton exchange membrane that is in direct contact with two gas diffusion electrodes, which generate hydrogen and oxygen, respectively. In principle, the PEMEC resembles the PEM fuel cell (PEMFC) and significant parts of the technical advances of the past few years within PEMFCs can be used for PEMEC plants. The area in which the PEMEC distinguishes itself most clearly from the PEMFC is the choice of materials for the oxygen electrode.

PEMEC presents several advantages over traditional alkaline liquid electrolyte water electrolysis including higher performance and energy efficiency, higher operating pressures; this results in a larger hydrogen production rate and more compact design cf. Carmo et al (2013)[i] & Arico et al (2013).[iv] PEM electrolysers can operate at much higher current densities compared to other technologies, which reduces the capital costs and the overall cost of electrolysis. Ohmic losses limit the maximum achievable current densities, with a thin membrane capable of providing good proton

---

[1] US Patent and Trademark Office received a patent application (no. 20160002798 for US Patent) that was published on 7-01-2016, by IRD Fuel Cells A/S, titled as "Composite Flow Plate for Electrolytic Cell " for the registration of patent.

[2] This deliverable is cancelled due to the new business strategy of IRD A/S c.f. section "Perspective and Utilization of project results", *ibid*.
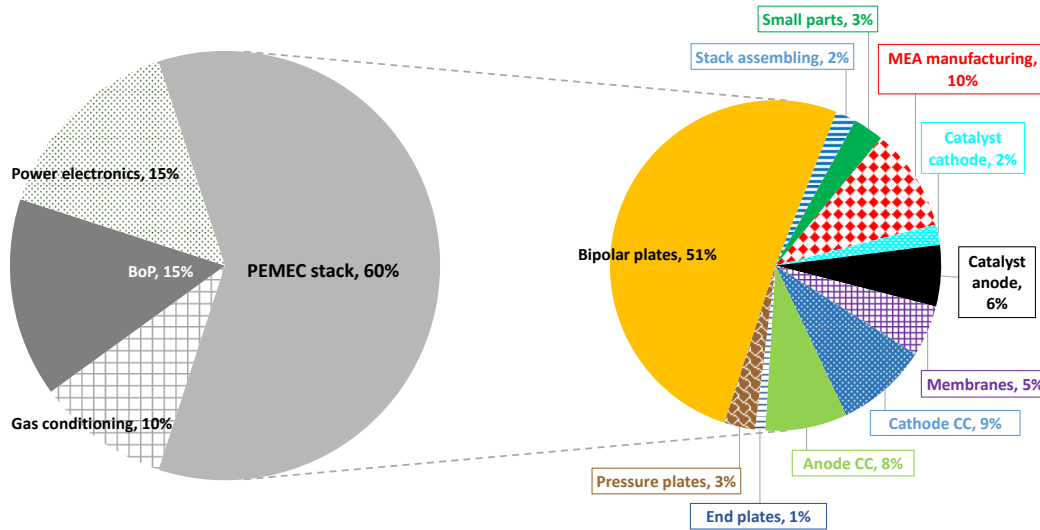
Fig. 3
Cost break down of the *SoA* PEM electrolyser.[iv]

conductivity high current densities can be achieved. The solid polymer membrane allows for a thinner distance between the electrodes than the alkaline electrolysers. The low gas crossover rate of the polymer electrolyte membrane (yielding hydrogen with high purity), allows for the PEM electrolyser to safely work under a wide range of power inputs (both a technical and economic benefit). This is due to the fact that the proton transport across the membrane responds quickly to the power input. A solid electrolyte allows for a compact system design in which high operational pressures (equal or differential across the electrolyte) are achievable.

The *SoA* PEM electrolyser typically operates at low temperature (60-70ºC) and the active catalysts are therefore based on platinum group metals-PGM e.g. Pt, Ir and Ru. Furthermore, the corrosive acidic regime provided by PEM requires the use of distinct expensive materials such as noble catalysts (platinum group metals-PGM e.g. Pt, Ir and Ru), titanium based current collectors, and separator plates. This results in a very high stack cost (Fig.3).

PEM electrolysers are commercially available on small scale (cf. Fig. 4), and large-scale e.g. larger prototype systems are presently being demonstrated worldwide ($\approx$240 Nm^3/h) by 2014.[ii]

The present project rest on the results of the terminated FCH JU project; PrimoLyzer[iii], where PEMEC MEAs was developed and a 1 Nm^3/h PEMEC stack designed and tested.
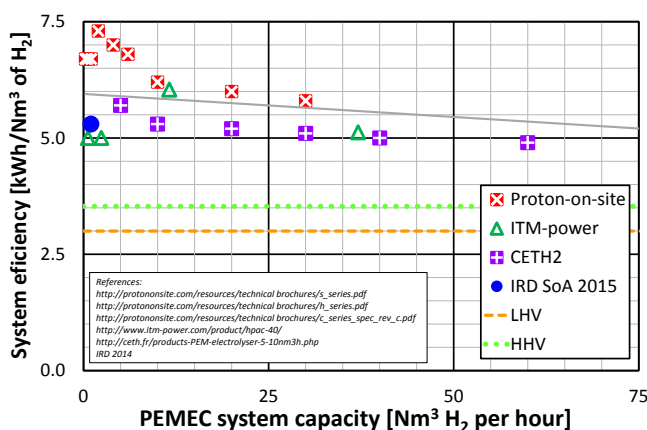
Fig. 4
SoA efficiencies for commercial available µPEMEC systems and the system developed within the present project.

9

PROJECT RESULTS

WP1: SPECIFICATION AND PLANNING

The size of the hydrogen-production capacity, quality, and storage has been analysed based on present and estimated future power prices. The work has been done with great support from Energinet.dk and special adviser Lars Yde. The conclusion was that this technology requires low-cost renewable electricity and/or a combination of higher natural gas & carbon prices and perhaps public support or new legislation to be cost competitive with the existing/competing technologies.

WP2: LT-PEMEC MEA DEVELOPMENT

The objective of WP2 was to optimise the MEA manufacturing process, incorporate novel materials and components that facilitates the target performance of 1.6 V @ 1.0 A/cm^2 at 30 bars and a stack cost of 15,700 DKK/Nm^3h H_2 in 2014. The MEA manufacturing routes was at project start based on the labour heavy decal method that could not utilise the manufacturing line at IRD. More than a 100 MEAs have been manufactured for process optimisation and reproducibility. Most MEAs were tested for BoL performance and selected cells also for durability and lifetime (Table 5). One type of MEA proved closed in performance to the targeted performance (MEA AE2R, Table 5). However, this MEA was assembled with the relatively thin membrane Nafion 115 that do allow a too high hydrogen crossover for safe operation at 1 A/cm^2. The realisation of this safety issue instigated IRD to continue the work with the 50% thicker membrane, Nafion 117. This shift caused some performance loss due to higher resistance and some of the best results with this membrane is shown in Fig. 5. A stable anode-ink was successfully developed for the existing IRD manufacturing line utilising a novel anode catalyst.[3] MEA AD2S (Table 5) is one example of a MEA manufactured on IRDs process line aimed for high volume production.

MEA AEK3
BoL (05.09.2013)

$y = 0.2511x + 1.4703$
$R^2 = 0.9898$
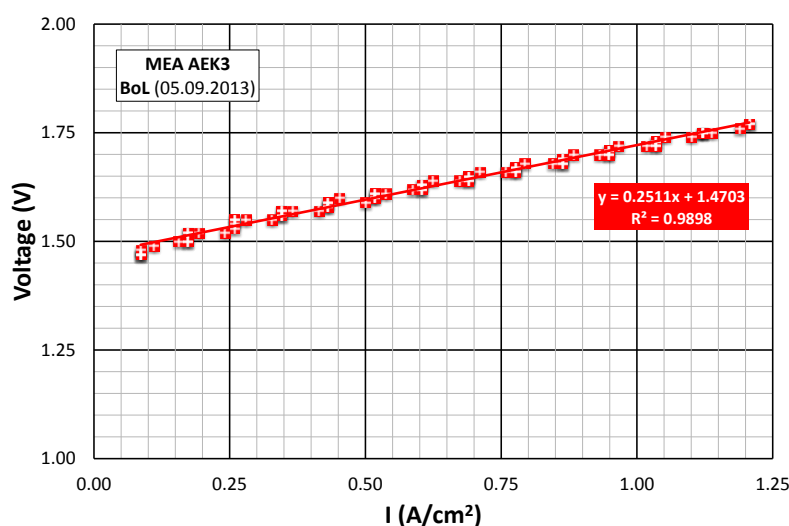
Fig. 5
BoL single cell performance at ambient pressure and 70ºC. The performance at 1 A/cm^2 is 1.72 V.

---

[3] This work was done as a joint effort between the existing and the on-going DSF project e-Store

Table 5   List and main results of long-term tested single cells.

MEA S/N	IrO₂ mg/cm²	Membrane type	Pt/C mg/cm²	Hours @ 1 A/cm²	Degrad. µV/h	BoL voltage @ 1 A/cm²	S/S
MEA211111_6	0.61	Experimental	0.62	14,418	3.6	1.87	-
AIHS	2.49	Experimental	0.63	5,296	-3.3	1.87	127
AIGR	0.33	Experimental	0.52	735	110.8	1.83	37
AIJ5	2.46	Experimental	0.63	582	146.7	1.83	36
AHEP	0.57	Experimental	0.52	4,989	109.0	1.75	172
AHRT	0.35	Nafion 115	0.51	3,332	3.8	1.80	158
AHRU	0.35	Nafion 115	0.51	4,359	5.7	1.80	180
AIMZ	0.35	Nafion 115	0.51	1,724	30.0	1.70	50
AH6N	0.31	Nafion 115	0.50	4,063	59.3	1.76	119
MEA211111_7	0.61	Nafion 115	0.63	30,947	1.6	1.78	-
AE2R	0.29	Nafion 115	0.53	10,428	20.3	1.64	364
AEZR	0.22	Nafion 117	0.53	9,687	0.8	1.81	345
AH5N	0.45	Nafion 117	0.49	4,278	25.3	1.76	129
AFDZ	0.32	Nafion 117	0.51	11,045	8.2	1.80	357
AFLB	0.30	Nafion 117	0.51	10,562	8.9	1.79	323
AFGX	0.33	Nafion 117	0.51	10,525	9.6	1.74	360
AELB	0.32	Nafion 117	0.49	11,925	9.0	1.79	356
AH5O	0.45	Nafion 117	0.49	4,535	22.2	1.80	135
AH6A	2.55	Nafion 117	0.50	3,548	22.7	1.82	94
AH4L	0.31	Nafion 117	0.50	4,186	32.7	1.75	105
AGOA	0.15	Nafion 117	0.53	1,168	45.8	1.93	34
AGOC	0.64	Nafion 117	0.53	1,265	-34.8	2.03	36
			Total	153,597			

The long-term test of the electrolysis MEAs have proved that they are more robust than the PEMFC MEAs i.e. one of the on-going tests started in the PrimoLyzer project and is still *on-going* (more than 3.5 years of nominal operation, Table 5 & Fig. 6). The state of the membrane in all the long-term single cell test are monitored regularly by measuring the F-ion release and the amount of water that has crossed-over to the cathode, an example of the data is shown in Fig. 7.

The degradational pattern of the single cell is rather characteristic, as all cells shown an initial high degradation that decreases after 2-6,000 operational hours. This pattern probably reflects different dominant degradation mechanisms i.e. an initial high Pt-particle growth. An academic definition of EoL is defined as 10% voltage loss in fuel cells. This definition does not fit well in PEM-electrolysis (10% voltage gain!), because severe corrosion of the MEA and stack elements will occur above a cell voltage of 2 V. The long-term tested MEAs possesses a potential for long life-time if an EoL definition of 2 V is accepted (Fig. 8).
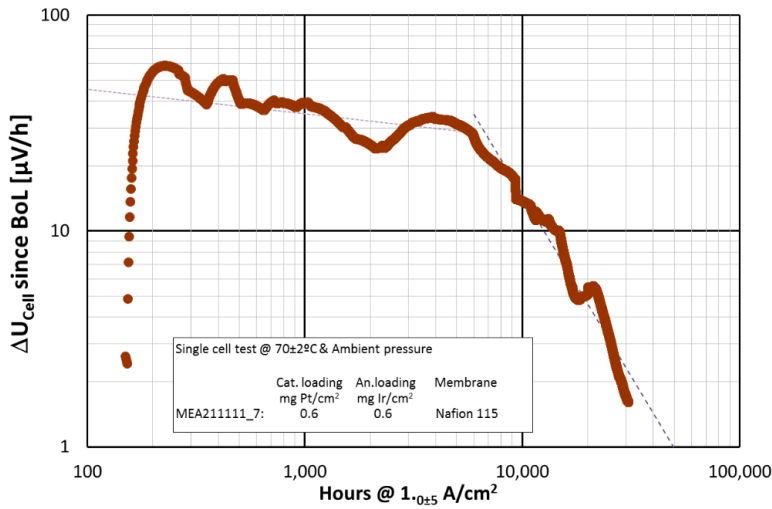
Fig. 6
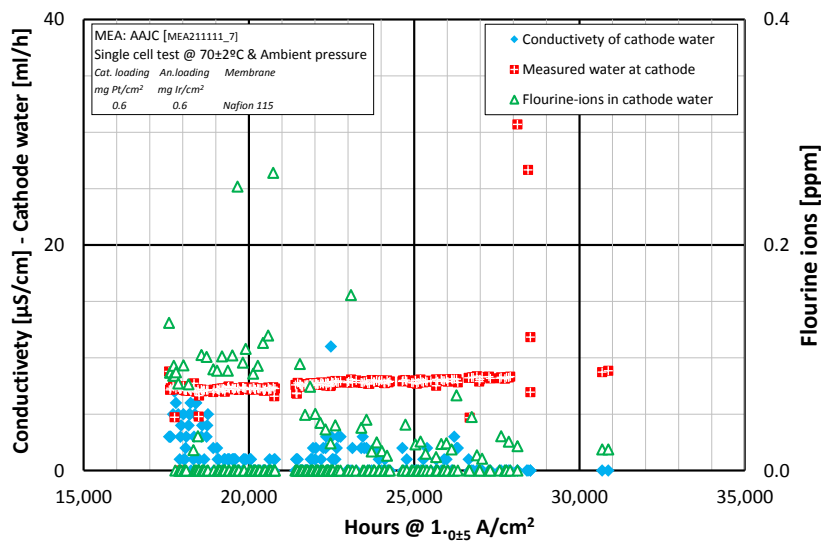Development of the degradation during test of MEA211111_7.

Fig. 7
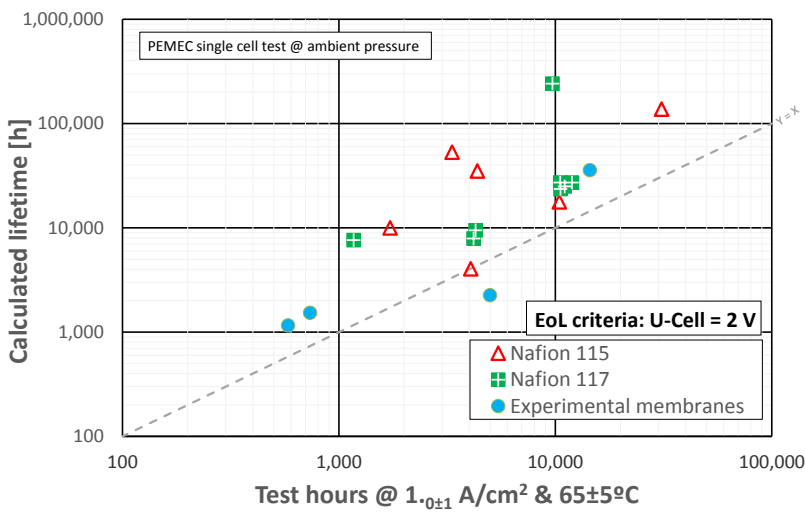Fluorine release, water conductivity and cathode water crossover (NB 7.5 ml/h corresponds to ≈2.6 ml/cm² MEA/h).

Fig. 8
Hours to EoL based on the measured degradation rate. The used EoL criteria is when the cell has reached a voltage of 2.0 V.

WP3: LT-PEMEC Cell and Stack Modelling

The overall objective of WP3 was to develop mathematical models that could contribute to a better understanding of two-phase flow phenomena found on a cell and stack level, as well as the overall thermodynamic behaviour. Moreover, the goal was to apply this improved understanding to optimize the existing cell and stack design.

On a cell level, the research efforts of WP3 have led to the publication of two articles; one in the International Journal of Hydrogen Energy and another in the ECS Transactions (cf. section 'Dissemination and Education', *ibid*).

Meanwhile, due to a combination of unforeseen challenges during the course of the project and a desire from IRD to focus on cell level, only preliminary studies on stack level could be conducted within the time frame of this project. Consequently, the results of that work have therefore not been included in this summary report.

THE NUMERICAL STUDY OF THE GAS-LIQUID, TWO-PHASE FLOW

The aim of this research effort was to establish the extent of flow and temperature maldistribution associated with the use of a circular-planar, interdigitated anode flow field. A figure of the studied interdigitated flow field developed by IRD A/S is shown in Fig. 9. When examining the flow field, it should be noticed how non-straight channels have been applied. The bending of the channels counteracts the appearance of a parabolic velocity distribution under the land area in the channel length direction, which else would be seen for straight interdigitated channels. Other features included wide land areas relative to the channel width. These are necessary due to the large compression force that is exerted by the cathode onto anode, when operating the PEM electrolysis cell asymmetrically pressurized.

To investigate maldistribution phenomena, computational fluid dynamics (CFD) models were developed in the modelling framework of ANSYS CFX. By developing one CFD model that accounts for gas-liquid, two-phase flow and another that only accounts for single-phase liquid flow, the separated effects of two-phase flow and geometry on maldistribution could be identified. In order to further evaluate the impact of a mass flow maldistribution on the local temperature distribution, energy transport was taken into account in both cases. Furthermore, since the liquid water serves as both fuel and coolant supply in the design by IRD A/S, high mass flow rates causes turbulent transport phenomena that likewise need to be taken into consideration.

By studying the circular-planar, interdigitated flow field under nominal operation conditions, it was found that the flow field suffers from a flow and temperature maldistribution; particularly when examining the channel mass flow normalized by channel length, as shown in Fig. 10. Here it becomes apparent that a rather non-uniform distribution of liquid water occurs across the active surface area. In fact, this maldistribution leads to the formation of hotspots and areas of large gas hold up. Interestingly, Fig. 10 further reveals that the maldistribution primarily arises due to the geometry and not the two-phase flow under nominal conditions. Nonetheless, when changing the water stoichiometry, or equivalently the water flow rate, the importance of the two-phase flow changes. The lower the water stoichiometry, the more severe the impact of the two-phase flow becomes on the maldistribution and particularly the formation of hotspots.
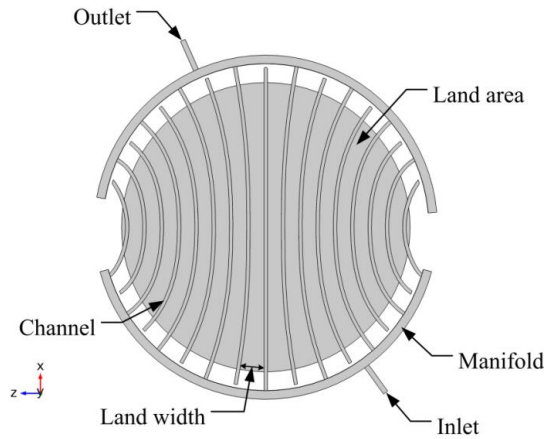
Fig. 9
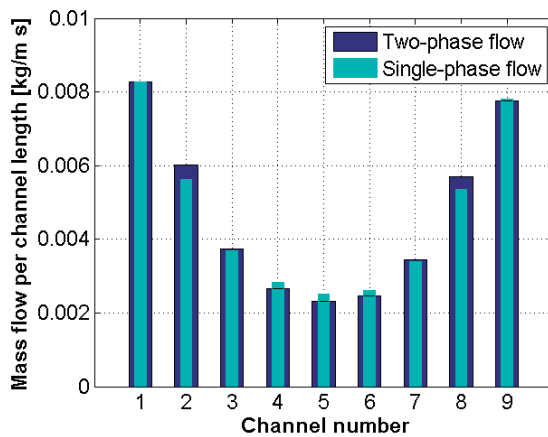Three dimensional fluid domain of a PEM electrolysis cell.

Fig. 10
Bar plot of the mass flow maldistribution between channels for single and two-phase flow model under nominal operation conditions.

In order to improve the flow distribution and circumvent the formation of hotspots, it was found that by approaching equal in-plane cross section land area sizes, a more uniform distribution can be obtained. Moreover, to further reduce the formation of hotspots, it was concluded that bending of the longest channels should be reduced.

THE EFFECT OF CATHODE PRESSURE ON THE PREDICTED PERFORMANCE

The overall aim of this research effort was to investigate the consequences of operating a PEM electrolysis cell asymmetrically pressurized. In particular, focus was on establishing the impact of the physio-chemical changes in the perfluorinated sulfonic acid (PFSA) membrane associated with membrane compression and its influence on the electrochemical behaviour of the cell. To be able to do this, a two-dimensional, mathematical model that included two-phase flow as well as multicomponent, energy and charge transport was developed. Furthermore, detailed thermodynamics, reaction kinetics as well as mechanical compression of the anode GDL was included to ensure that all significant phenomena that depend on cathode pressure were included. For this investigation, the PEM electrolysis model was developed in MATLAB and COMSOL Multiphysics.

A schematic overview of the applied membrane electrode assembly (MEA) domain is shown in Fig. 11. For both the anode and cathode, a micro-porous layer (MPL) and GDL was applied. For the cathode a conventional SGL carbon fibre paper incl. MPL was assumed, while for the anode titanium felt with coated iridium MPL on top was used.
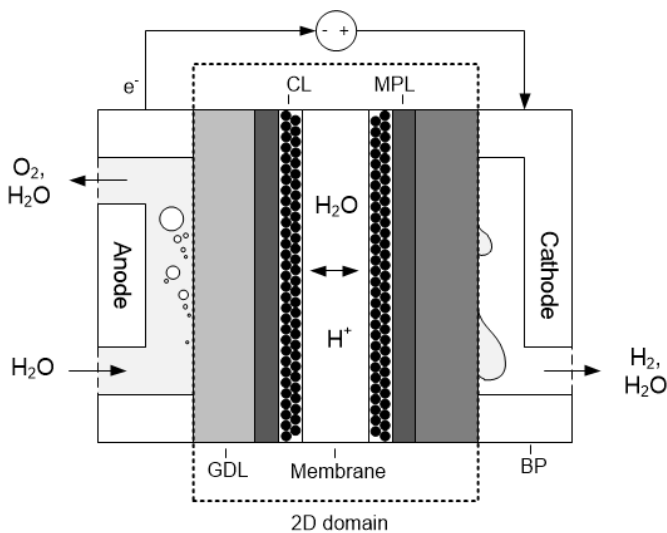
Fig. 11
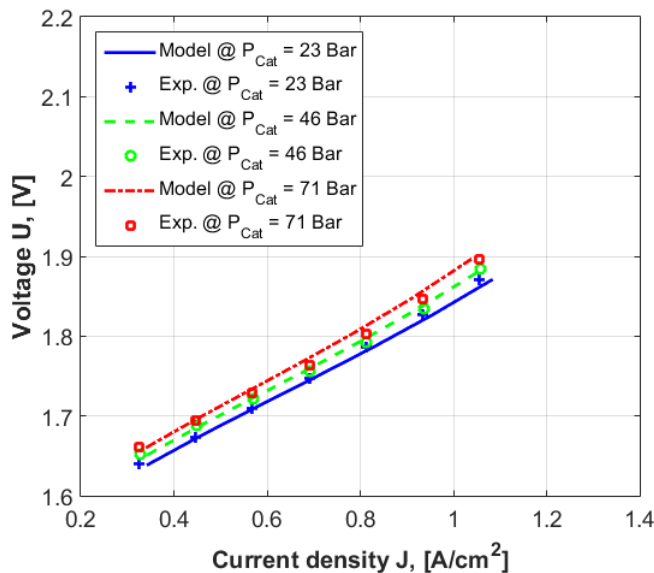Two-dimensional, schematic overview of a PEM electrolysis cell.

Fig. 12
Polarization curves as function of cathode pressure.

To ensure validity of the devised model, a comprehensive parameter variation was conducted by variating the operating temperature and cathode pressure. For both parameters, the predicted cell behaviour was in good agreement with the experimental measurements obtained by IRD A/S. In Fig. 12, the predicted dependence on cathode pressure is shown. Over the entire range of current density and for all three data set of cathode pressures, the changes in voltage are captured.

For comparison, the influence of ignoring the membrane compression model and hence the accurate description of water uptake and proton conduction was investigated. This study showed that a significant under prediction occurred. The validated model was then further used to examine the impact of the specific surface area of the ionomer in the catalyst layer. The conducted simulation showed that an improved operation could be achieved at high current density operation by increasing the surface area. On the other hand, the results likewise underlined the sensitivity of the model towards water uptake kinetics in conjunction with the PFSA membrane model.
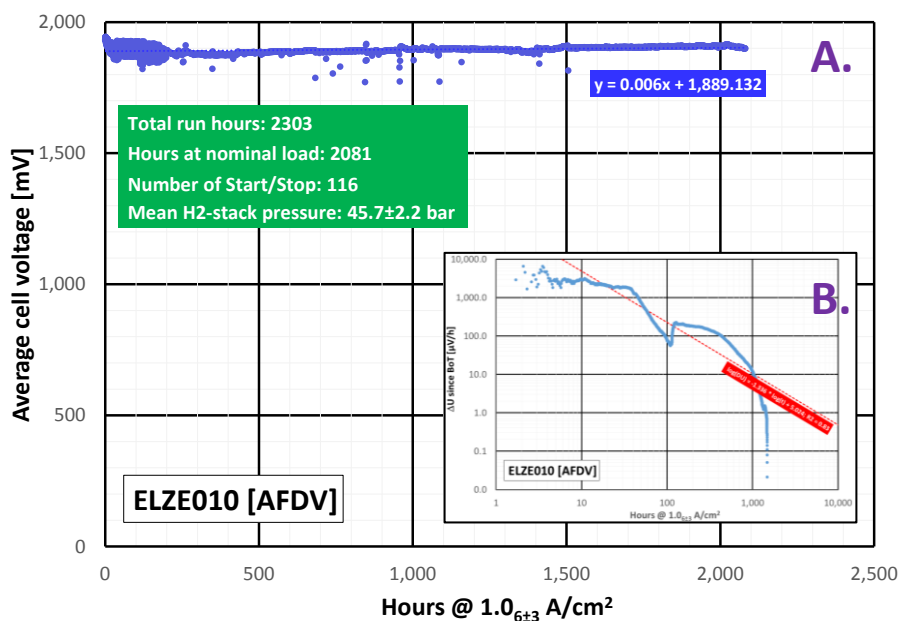
Fig. 13
An example of test results of a full size 'HyProvide' 33-cell stack. A) Average cell voltage & B) Average cell degradation.

Table 6   Obtained and estimated stack cost reduction.

	2011 by the piece production	2014 Estimated cost of 2011 cost (+100 units)
Stack elements excl. MEA	47%	28%
MEAs	41%	20%
Labour	12%	7%
Total	100%	55%

WP4: LT-PEMEC STACK DEVELOPMENT

The basic stack design concept from the terminated PrimoLyzer project has not been changed. The PrimoLyzer stack was designed to 100 bars of direct hydrogen production. However, longer-term tests proved not only that several design and technical adjustments were necessary, but also that no visible corrosion occurred at the anode graphite-composite bipolar plate in the present design.

The stack has been designed with relatively cheap components avoiding expensive precious metal coatings. All stack tests have been performed within the developed system (WP7, *ibid*). This has saved a lot of investment in expensive test stands, but has also some draw backs as several novel tings are tested simultaneously. One example is the enhanced content of Fe-ions in the cathode water, which probably originate from the attempt to recirculate both the anode and the cathode water to minimize the supply of DI water to the system. Fe-ions are known to facilitate the Fenton-reaction that decomposes the PFSA-membrane. An example of a longer term stack test is shown in Fig. 13.

Another important issue within this WP has been to production mature the stack although the stack not yet is ready for mass production. A stack cost reduction is obtained within the system (Table 6), but the foreseen cost is almost double of the targeted cost.
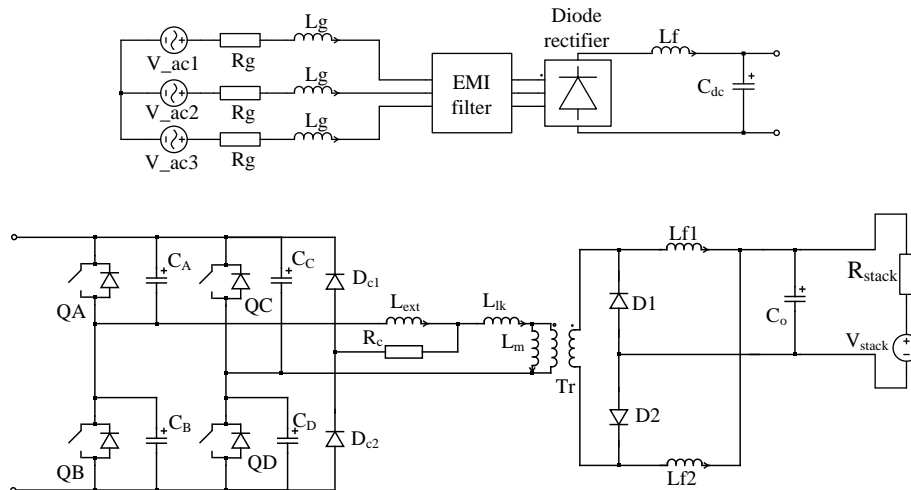
Fig. 14
Three-phase grid connected power supply for electrolyser application.

WP5: POWER SUPPLY DEVELOPMENT

Power from renewable sources like windmills or solar cells is fluctuating a lot over time. Storing energy when there is an excess power and using this power when the grid is missing power would be an attractive solution to balance the grid and get full advantage of the fossil free power. Using a micro power plant, based on hydrogen as storage media, is a promising solution for regulating the grid. The work in WP5, which is part of a larger project such as a micro power plant including an electrolyser for hydrogen production and a Micro Combined Heat and Power (µCHP) for power production from hydrogen, consists of the development of a power supply for the electrolyser in discussion.

Different power supply topologies were proposed for electrolyser applications. Most commonly used converters for low voltage and high current applications are the phase-shifted full bridge converters. The initial used solution for the electrolyser: paralleling two single phase commercial power supplies to reach the required power level. The efficiency of these power supplies is around >89% each at full load and >90% at light load (datasheet values). One goal of the presented work was to design and build a single unit prototype power supply. This should meet the required power level, should supply with high efficiency the required current from the three-phase grid to the PEM electrolyser increasing also the overall system efficiency. The target efficiency should be higher than the efficiency of the power supplies currently available on the market

DESCRIPTION OF THE POWER SUPPLY FOR THE ELECTROLYSER SYSTEM

The power supply consists of two main parts. On the input part there is a grid connected AC-DC converter that consist of an Electromagnetic Interference (EMI) filter, a rectifier and an LC filter on the DC side of the rectifier, as it is shown in Fig. 14. The role of this converter is to converter the 400 V_{ac} line to line voltage to 564 V_{dc}. Besides, the EMI filter a 1.4 mH three-phase line choke is placed between the grid and EMI filter to reduce the inrush current and improve the line current THD (Total Harmonic Distortion) and PWHD (Partial Weighted Harmonic Distortion). Another way to limit the inrush current is to reduce the DC-link capacitor (C_{dc}=3 µF). Such way a small DC-link system is obtained which is characterized by a 300 Hz ripple in the DC link voltage. In Fig. 14 *Rg* represents the grid resistance, *Lg* the grid inductance, *Lf* the DC-link filter inductor to reduce high frequency noises

Table 7 Specifications for the electrolyser power converter

Input voltage	V_{ac}	400 V$_{RMS}$
Output current	I_o	0-90 A
Switching frequency	F_{sw}	20 kHz
Target Efficiency	η	95%

and C_{dc} is the small DC-link capacitor (<10 µF). The output of the AC-DC converter is connected to a phase-shifted full bridge converter.

A current doubler rectifier circuit is connected to the secondary side of the PSFB transformer to reduce the current rating of the secondary winding and to increase the circuit efficiency for high output current (Fig. 14). The switches used for the full bridge (Q_A-Q_D) are 80 mΩ SIC MOSFETs from Cree (two in parallel for each switch to reduce the conduction losses). The design specifications for the power supply are listed in Table 7.

RESULTS AND DISCUSSION

The power supply was developed in a university laboratory. The two parts of the converter were stacked one on the top of the other (Fig. 15). Firstly the power supply was tested in the laboratory, using a simple resistive load. The electrolyser was placed at our partner company. The power supply was taken to company and tested together with the electrolyser (Fig. 16).

The communication between the power supply and the electrolyser system was ensured by a 0-10 V external reference signal sent by the electrolyser control unit to the power supply. This signal was the reference signal for the output current (0-10 V corresponding to 0-100 A). The ramping of the current inside the power supply was set to 1 s from 0-100 A to avoid sudden current steps due to reference changes. The ramp-up of the electrolyser current needs even longer time so the control algorithm could easily adapt to the reference changes.

As the measurement result show, the validation of the power supply model and control algorithm has been obtained. The measured converter efficiency (from the three-phase grid to the electrolyser), working together with the electrolyser was 94.3% at nominal output current (75 A load current). As it is shown the efficiency of the convert is higher than 90% even at light loads (>1 kW). The efficiency might be higher if the PSFB converter would not get out of ZVS mode from time to time due to the 300 Hz DC-link voltage ripple and such the switching losses on the transistors have increased. The output current and voltage characteristics of the prototype power supply are presented on Fig. 17.

The THD of the line current was around 34% but the PWHD could be kept under 45%. The general standard for low voltage high current power supply is the EN-61204. This refers also to the general harmonic standard EN-61000-3-2. The designed power supply does not match these criteria but due to the PWHD values there was a possibility to classify the converter as professional equipment meeting the values stated in EN-61000-3-12.

The obtained hydrogen amount was according to the expectations (Fig. 18), 1 Nm^3/h H$_2$ could be produced using the new power supply even though the output current ripple contained a 300 Hz ripple due to the small DC-link capacitor.
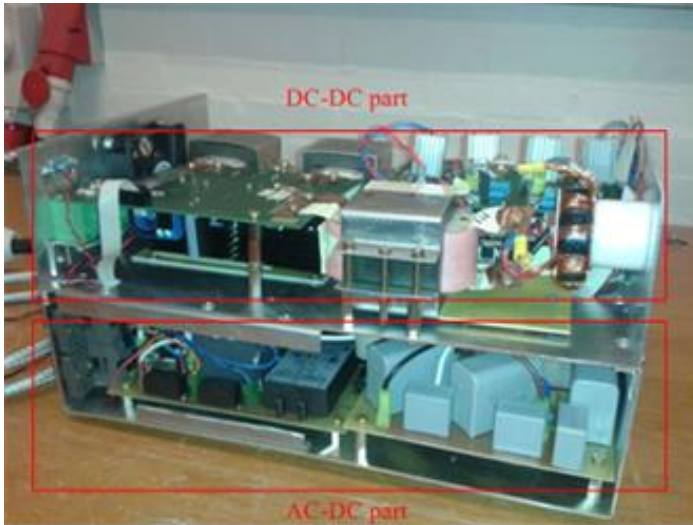
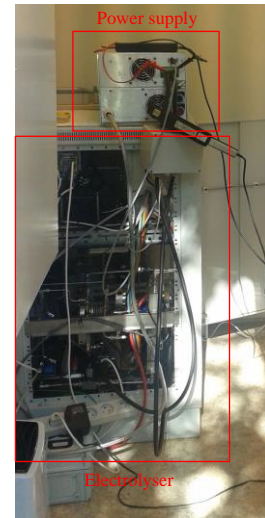Fig. 15 Three phase electrolyser power supply: AC-DC part (bottom) and DC-DC part (top).

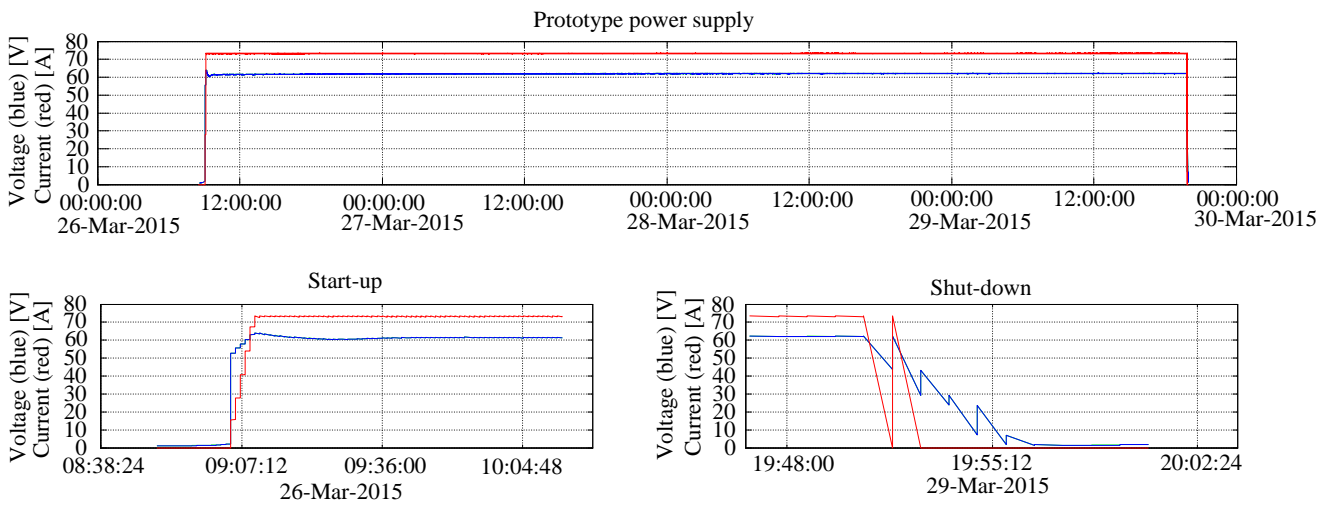Fig. 16 Electrolyser with the power supply.

Fig. 17 The measured output current and voltage waveforms of the electrolyser stack using the prototype power supply.
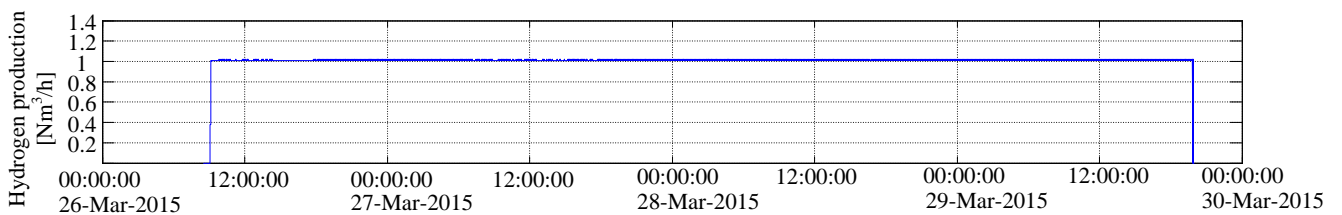

Fig. 18 The hydrogen production of the electrolyser with the prototype power supply.

The goal of the work presented in this paper was to increase the efficiency of an electrolyser for household hydrogen production and storage system. For this purpose a high efficiency three-phase grid-connected prototype power supply was designed and built to control the input current of the electrolyser and communicate with H_2 production system for better overall system performance.

As the measurement result show, the validation of the power supply model and control algorithm has been obtained. The measured converter efficiency (from the three-phase grid supplying an electrolyser as load) was 94.3% at nominal output current (75 A). As it is shown the efficiency of the convert is higher than 90% even at light loads (>1 kW). The efficiency might have been higher if the PSFB-CD converter would not get out of zero voltage switching (ZSV) mode from time to time due to the 300 Hz DC-link voltage ripple. In such conditions the switching losses in the transistors are increased. As preliminary electromagnetic compatibility (EMC) measurements have shown, the prototype power supply could be categorized as professional equipment according to standard EN-61000-3-12.

As future work the realization of a complete renewable energy generation system could be mentioned using hydrogen as long term storage, where grid and Photo Voltaic (PV) power could be used for hydrogen generation. Now only the gird connected power supply was designed and built. Further on a PV array connected power supply should be built and tested. This part of the project was already started but ended in the design phase. Also the grid connected power supply should be replaced with an active rectifier to allow the bidirectional power transfer from grid to electrolyser or electrical power from PV or μCHP into the grid.

WP 6: HYDROGEN STORAGE

The Danish project "HyProvide - hydrogen produced by electrolysis" has the objective to develop an electrolysis system as part of a micro Combine Heat and Power [μCHP] unit that can be installed at residential homes. The electrolyser produces hydrogen by utilizing power from renewable energy produced by wind turbines or solar panels. The produced hydrogen will be stored and can later be used as fuel for a fuel cell when there is shortage of renewable energy or when there is a need of power in the low voltage grid.

The electrolyser from IRD are develop to instant high press production of hydrogen (electro chemical) at 50 bar. This project will explore and analyse current technology solutions and regulation on how to store hydrogen at residential homes.

It has always been a challenge to store hydrogen the universe smallest element. 1 litre of gas weighs about 90 mg and is 13 times lighter than the air we breathe. There are today generally three methods on how to store hydrogen.

- Compression - storage of gas at high pressure
- Cooling - storage in liquid form at a low temperature (-253°C is the boiling point of the hydrogen)
- Solid form - storage of hydrogen by binding (adsorption / absorption) of hydrogen into another material.

The project analyses all storage technologies in terms of price, weight, system integrability and legislation. The result of the analysis is also weighted in a qualification matrix that clearly present that high press cylinders' type IV are the most flexible, cost-efficient and future proof choice. This type of cylinder has very low weight and design options that can be adapted to the need of a future μCHP plant.

A type IV cylinder is a storage where the investment cost at a hydrogen pressure at 50-100 bar will be less than 130 DKK/kWh. In the case where there is a need of a storage capacity of 60 kWh, the cylinder price will be approximately 7,800 DKK.

Still, two development opportunities can influence the price downwards:

- To develop an electrolyser that can produce hydrogen at 200 bar. This development will secure full utilization of current pressure limits of type IV cylinders in today's market.
- Though partnership with type IV cylinders' manufactures develop a cylinder that fits pressure conditions and storage capacity of tomorrows μCHP units

The main component costs are the cylinder and the valve costs, which will be less than 10,000 DKK. Having main component cost prices in mind, it seems as there are room of economy to unit assembly costs and a reasonable sales margin. IRD earlier estimated the hydrogen storage sales prices to 20,000 DKK.

Today's legislation is very unclear when referring to local storage of hydrogen at residential homes that in the future. Homes that in the future can become energy producers based on own hydrogen production and storage of hydrogen.

Hydrogen will in the future not only be a local energy storage gas, the gas (hydrogen) will also become energy carrier that can supply cars with renewable energy. Therefore, authorities and technology producers has to focus more on how to set up procedures and legislation that can allow residential homes to produce, store and consume hydrogen.

The test projects that IRD in collaboration with TREFOR is going to install at residential homes will contribute to better understanding and dialogue between equipment suppliers, utility companies and authorities.

This work package has detected following areas that need to be analysed further in order to develop a regulation on how to handle hydrogen in residential homes:

- What impact has hydrogens volatility on safety? - Hydrogen is 13 times lighter than atmospheric air. Propane, which is very detailed described in today's regulation, is 1.5 times heavier than air - How are safety distances influenced by the hydrogens volatility?
- If hydrogen is produced locally (private consumers), who is the real gas supplier and therefore according to today's regulation responsible for the hydrogen storage?
- If hydrogen storage only act as an energy storage for local use of hydrogen, which means that there will be no hydrogen transfer to and from external sources, will this process actually be seen as a gas production?

In the Danish regulation "Bekendtgørelsen for tekniske forskrifter for gasser " there is a separate section referring to LPG this section is also categorizing the LPG as the third "gas family" respecting the LPG physical characteristics. The Danish Emergency Management Agency, as part of the current

regulation, need to focus more on Hydrogen and an idea could be to create a new gas family related to hydrogen.

A more accurate description of hydrogens physical characteristics including detailed safety regulation on how to store hydrogen could support the development of Denmark as a low carbon community.

The world needs technical solutions that can store renewable energy. This analysis present that it is already technologically possible to store hydrogen efficiently, but the energy industry needs transparent legislation that support the utilization of hydrogen as a storage gas for renewable energy.

The last part of work package 6 also analyse the future need for hydrogen storage capacity however due to large complexity there are no indication of the most optimal hydrogen storage size. However, drivers that influent future sizing of hydrogen storage are analysed in the work package and drivers are:

1. Future spot prices on electricity
2. Future prices on regulating power services
3. Future power load in low voltage grid
4. Future power production in low voltage grids (solar panels, mikro-wind turbines)
5. How much heat can be supply to existing houses?
6. How does locale power storage benefit local utilities companies?
7. What is the benefit to the total power market if energy can be store and produced on demand?

Individual hydrogen storage based on high-pressure cylinders is available. Cylinders/vessels up to 350 litres having a maximum operating pressure of 200 bar can storage up to 200 kWh. It is today possible to build a hydrogen storage at the cost of 125 DKK/kWh. Hydrogen storage is today in favour of battery storage where Li-Ion battery prices according to Wikipedia retail around 500 $/kWh (2012 figures)

To utilize the potential of today's hydrogen storage, future development of electrolysers at IRD has to target 200 bars as operating pressure. At the same time liaison with governmental authorities is off great importance in order to succeed with a regulation that can support the establishment of hydrogen storage facilities at residential homes.

WP7: LT-PEMEC System Development

A prototype system was first functionality tested as a spread-out version. Key BoP was ex-situ tested. The main focus in the design has been safety and functionality, cost and efficiency was considered secondary. The constructed µPEM electrolysator is shown in Fig. 19. The electrolysator was tested with respect to the following standards and directives:

- Machinery Directive (2006/42/EC) / Low Voltage Directive (2006/95/EC) Based upon:
  - EN 60204-1 "Safety of machinery – Electrical equipment of machines".
  - ISO 22734-1 "Hydrogen generators using water electrolysis process – Part 1: Industrial and commercial applications".
- Electromagnetic Compatibility Directive EMC-D (2004/108/EC) Based upon:
  - EN 61000-6-1 "Electromagnetic compatibility - Part 6-1: Generic standards - Immunity for residential, commercial and light industrial environments".

Fig. 19 Picture of the developed µPEM electrolyser. The circular PEMEC stack is shown just below the centre of the system.

Nominal output:

$H_{2(g)}$ capacity	1.0 Nm^3/h
$H_{2(g)}$ pressure	50 bar
$H_{2(g)}$ purity	>99.995%
$H_{2(g)}$ humidity	100% RH
$O_{2(g)}$	0.5 Nm^3/h
Heat power @ RT	1,300 W

Nominal input:

Power	5.5 kW$_{AC}$
Voltage	3x400 V
Net water consumption	1 l/h
Water quality	<2 µS/cm (ASTM type II)

Enclosure and communication:

Location	Indoor
Communication Interface	Ethernet
Dimensions	600 x 600 x 1010 mm^3
Weight	130 kg

o EN 61000-6-3 "Electromagnetic compatibility - Part 6-3: Generic standards - Emission standard for residential, commercial and light industrial environments".
o EN 61000-3-2 (2006) "Part 3; Section 2: Limits for harmonic currents emissions [equipment input current < 16 A per phase]".
o EN 61000-3-3 (1995) "Part 3; Section 3: Limitation of voltage fluctuations and flicker in low-voltage supply systems for equipment with rated current < 16 A" + A1(2001), A2(2005).

Finally the electrolyser was CE-certified by KIWA Nov-14.

It was during the project period realized that the produced hydrogen had to be dried for safe pressurized storage. A search for commercial available dryer systems was not successful as the available systems was either too big, prohibitive expensive or too ineffective. It was therefore decided to design a tailored drying system. An efficient cheap dryer that reached a hydrogen dew point below -70ºC at 1 atm. (hydrogen refilling station requirement) within the pressurised stage (50 bars) was targeted. A hydrogen dryer consisting of a combination of a liquid drainer section and a zeolite column dryer section has been successfully designed, constructed and successfully tested (Fig. 20). Dew points well below the targeted -70ºC has been obtained.
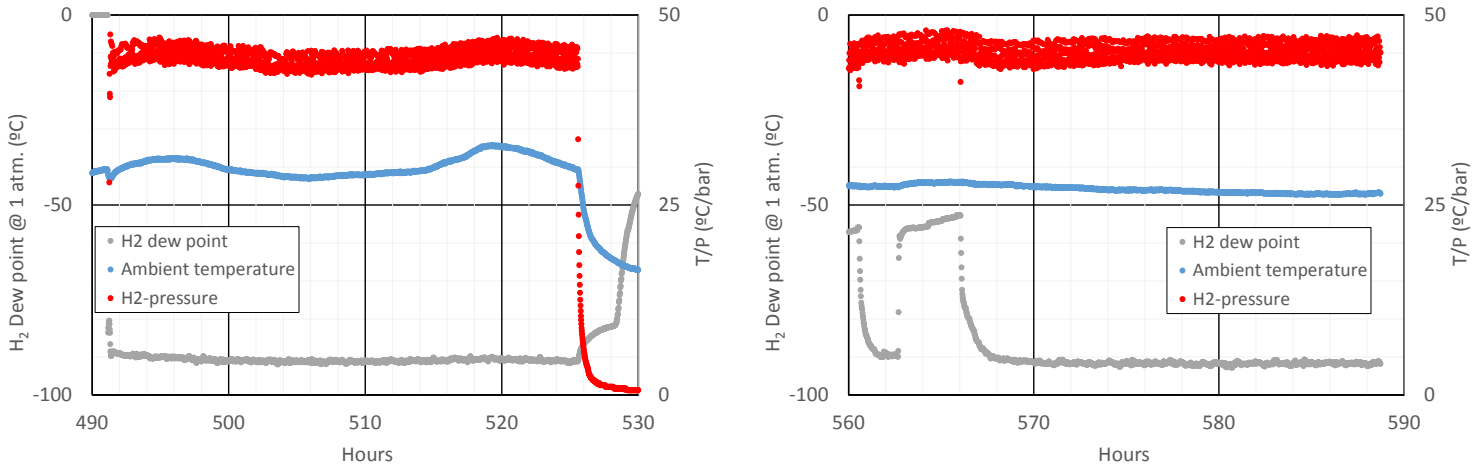
Fig. 20   Two examples of successful test results obtained with the prototype hydrogen dryer.

Fig. 21
The test setup at TREFOR.

WP8: LT-PEMEC PROTOTYPE TEST

Several pre-prototype and one final the PEM electrolyser was tested in IRDs laboratories; four final electrolysers was tested at TREFOR (professional end-user) (Fig. 21). 7,500 accumulated test hours was obtained with the final prototype electrolysers. The hydrogen produced at TREFOR was utilised in the LT PEM based µCHPs developed in the parallel running project 'Competitive µCHP for H2omes'.[4] An example of test results is shown in Fig. 22. The stack proved to be 78% efficient (HHV) within the prototype system, while the full system (excl. dryer) proved to be 64% efficient (HHV). This is unfortunately somewhat lower than the very ambiguous targets outlined in Table 1.

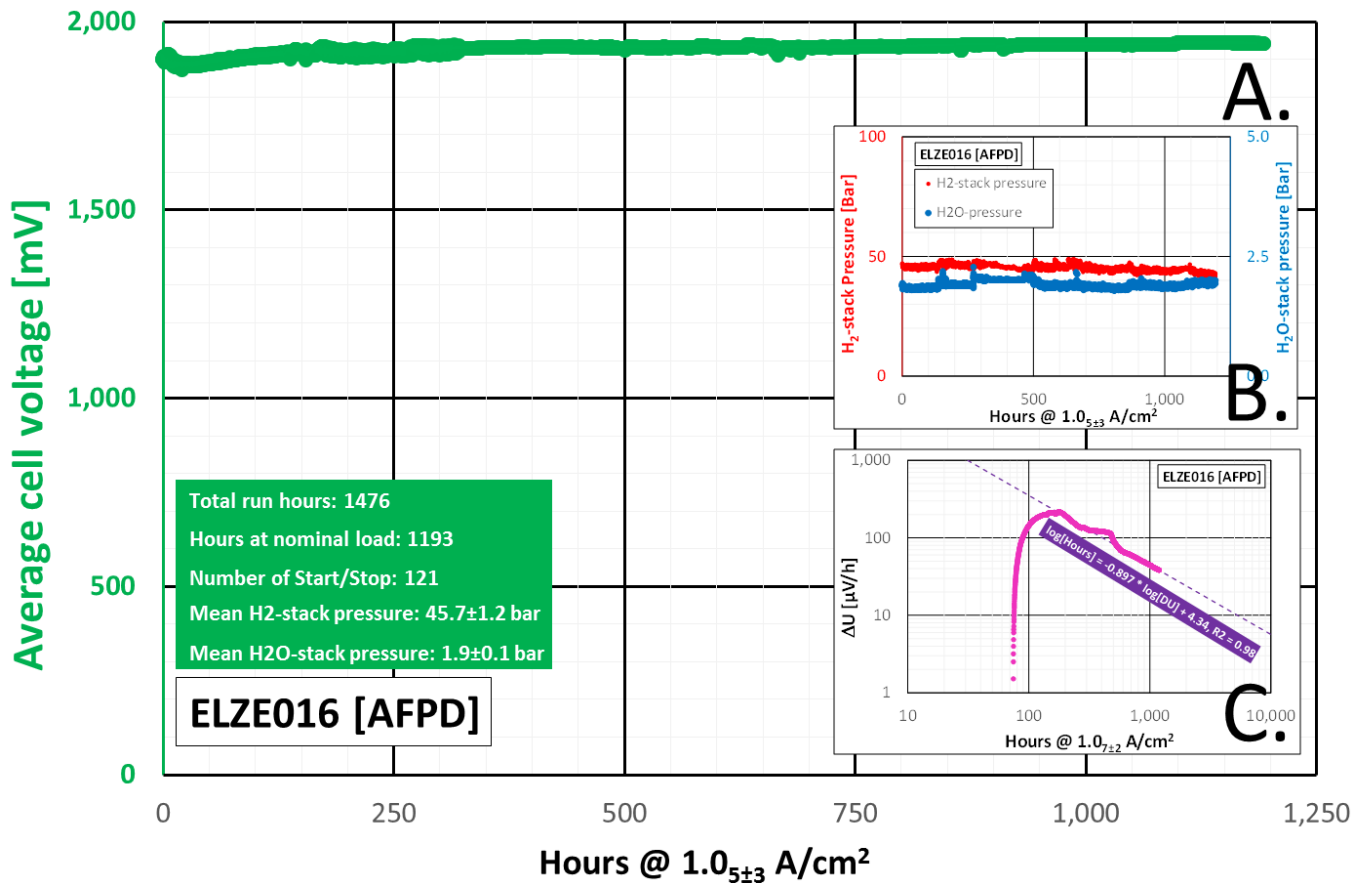[4] EUDP-11-I J.Nº: 64011-0051

Fig. 22   An example of the test results from the prototype μPEM-electrolyser.

WP9: DISSEMINATION AND PLANNING R&D & COMMERCIALISATION

The project dissemination is described in the mandatory section 'Dissemination and Education', *ibid*.

WP10: BUSINESS STRATEGY

The project was defined in 2011, and the partner focus has changed since then. TREFOR acquired the full ownership of IRD in October 2014. Prospectively TREFOR decided that all their 'fuel cell' activities should be handled through IRD. The IRD board decided in October 2015 that IRD solely should focus on PEM components (MEAs & bipolar plates). IRD has therefore decide that the PEM electrolyser for the time being not will be explored beyond the present project. However, the project has resulted in significant knowledge for IRD and has strongly contributed to support the component business areas, as explained above. The gained experience on system level is already exploited in connection with component customers. Furthermore, the HyProvide knowhow may also at a later stage be utilised to design and construct another sized PEM electrolyser.

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.:

Lajos Török, Carsten Karup Nielsen, Stig Munk-Nielsen; Carsten Rømer, Poul Flindt (2015): High efficiency electrolyser power supply for household hydrogen production and storage systems. Proceedings of the 2015 17th European Conference on Power Electronics and Applications (EPE'15 ECCE-Europe). Pp.1-9

ARTICLES IN MAGAZINES:

Anders Christian Olesen, Søren Knudsen Kær & Carsten Rømer (2016): A Numerical Study of the Gas-Liquid, Two-Phase Flow Maldistribution in the Anode of a PEM Water Electrolysis cell. Int. J. Hydrogen Energy. Vol.41, 52-68

Olesen AC, Kær SK. (2015): The Effect of PFSA Membrane Compression on the Predicted Performance of a High Pressure PEM Electrolysis Cell. ECS Trans 2015; 68:99–116 doi:10.1149/06803.0099ecst.

EXHIBITIONS:

1. The 'HyProvide' PEMEC was together with IRDs µCHP 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 'HyProvide' PEMEC was together with IRDs µCHP 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

EDUCATION:

1. Two (2) engineer trainees has worked at TREFOR in the autumn 2012 with straighten out the advantages and disadvantages of µCHP$_{FC/EC}$ 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 single cell MEA tests.

PERSPECTIVE AND UTILIZATION OF PROJECT RESULTS

The large-scale deployment of wind power and solar energy sources will strongly contribute to the implementation of Europe's energy policies objectives, *i.e.* to produce 65% of electricity from renewable energy sources by 2050 and to reduce CO_2 emissions linked to energy production by 50% [iv]. However, wind power and solar energy resources are characterised by intermittent behaviour and their fluctuations affect the stability and reliability of the electrical grid. Consequently, there is a strong need for rapid-response, cost-effective and scalable energy storage systems capable of absorbing the electrical power exceeding the capacity of a transport and distribution line. This will considerably reduce the investments needed to build a new grid infrastructure.

Hydrogen produced from water electrolysis can play a significant role as energy storage medium.[iv,v] Electrolysis can support the electricity grid in terms of power quality, frequency and voltage control, peak shaving, load shifting and demand response. PEM electrolysers are well suited for highly efficient storage of renewable electricity; they have a short start-up time, shorter than traditional alkaline electrolysers and solid oxide electrolysers, and can operate easily at varying current densities. However, the present cost is prohibitive for PEM FCs to make an impact on the TW scale. Further R&D is required to reduce cost particular the stack cost e.g. bipolar plates & loading of precious metals at the oxygen electrode.

The project partners has all gained exploitable results from the project. The most outstanding commercial results are obtained by IRD particular on the MEA and stack level. Several international PEM electrolyser manufactures have qualified the MEA developed within the HyPovide project. This has already resulted in strategic collaboration on further development.

ACRONYMS AND ABBREVIATIONS

BoP   Balance-of-Plant

μCHP   Micro Combined Heat and Power (0-5 kW)

D   Deliverable D1.2 meaning deliverable no.2 in WP1

EMI   Electromagnetic Interference

EoL   End-of-Life

FC   Fuel Cell

GDL   Gas Diffusion Layer

HHV   Higher Heating Value

LHV   Lower Heating Value

LT   Low Temperature

MEA   Membrane Electrode Assemblies

MPL   Micro-Porous Layers

M   MileStone e.g. M1.2 meaning milestone no.2 in WP1

PEM   Proton Exchangeable Membrane

PFSA   PerFluorinated Sulfonic Acid

PSFB   Phase-Shifted Full-Bridge

PWHD   Partial Weighted Harmonic Distortion

RH   Relative Humidity

RT   Room Temperature

S/S   Start/Stop

THD   Total Harmonic Distortion

WP   Work Package

REFERENCES

[i] Marcelo Carmo, David L. Fritz, Jürgen Mergel & Detlef Stolten (2013): A comprehensive review on PEM water electrolysis. International journal of Hydrogen Energy 38(12)4901-34

[ii] 2014 http://www.renewableenergyfocus.com/view/35124/german-wind-park-with-1-mw-hydrogenics-electrolyser-for-power-to-gas-energy-storage/

[iii] http://www.fch.europa.eu/sites/default/files/primolyzer%5B1%5D.pdf

[iv] Bertuccioli, L., Chan, A., Hart D., Lehner F., Madden, B., Standen, E., Development of Water Electrolysis in the European Union. FCH JU, Brussels (2014). http://www.fch-ju.eu/sites/default/files/study%20electrolyser_0-Logos_0.pdf

[v] Genovese, J., et al. Current State-of-the-Art Hydrogen Production Cost Estimate Using Water Electrolysis Independent Review, Published for the U.S. Department of Energy Hydrogen Program. National Renewable Energy Laboratory 1617 Cole Boulevard, Golden, Colorado (2012).