PROJECT FINAL REPORT

Publishable summary report

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Name, title and organisation of the scientific representative of the project's coordinator:

Dr Magnus Skinlo Thomassen

Senior Scientist

SINTEF Materials and Chemistry

Tel: +4798243439

Fax: +4773591105

E-mail: magnus.s.thomassen@sintef.no

Project website address: www.nexpel.eu

Executive summary

The NEXPEL project consists of a top class European consortium which is carefully balanced between leading R&D organizations and major industrial actors from 4 member states. The partners are devoted to develop new materials and stack design concepts to increase the efficiency and lifetime of PEM electrolysers and at the same time cutting costs. The three main targets for the NEXPEL project is to demonstrate a capability to produce hydrogen with an efficiency of at least 75% (LHV) at a system cost below €5,000/Nm^3h^{-1} plant capacity and a target lifetime in excess of 40,000 hours.

The project objectives are all related to address the main hurdle for commercialisation of PEM electrolysers for hydrogen production from renewable energy sources, namely high capital costs and limited lifetime under intermittent operation.

The project results have moved the state of the art of PEM electrolysers forward by contributing to both incremental improvements of existing commercial products from the involved industry partners as well as the development of new materials and solutions for stack components and designs

Development of lower cost components have resulted in new hydrocarbon membranes and supported catalysts for the oxygen evolution reaction with the potential to reduce the overall capital cost of an electrolyser by reducing the need for expensive fluorinated membranes and noble metals. These materials show high potential in tests on laboratory scale; however continued efforts are needed before they are commercially exploitable.

A cost break down model has been developed and a cost comparison between a conventional PEM electrolyser stack and the stack designed in NEXPEL show a cost reduction potential of more than 60% at a production volume of 1000 electrolyser stacks with a capacity of 25 Nm^3h^{-1}. The cost study also show that the advanced NEXPEL design can reach the system cost target of €5,000/Nm^3h^{-1} plant capacity at a production volume of 100 stacks. The main cost reduction potential of the NEXPEL stack is the reduction in materials use and production cost of the Titanium bipolar plates.

The unique competence generated within the project is proven indirectly through the establishment of a new FCH-JU project based on several of the NEXPEL partners in which new, major industrial partners have joined. From the European perspective, the project has strengthened European companies and research institutes position for developing both PEM electrolyser stack components, complete stacks and systems for hydrogen production from renewable energy sources by establishing a strong collaborative effort

Table of Contents

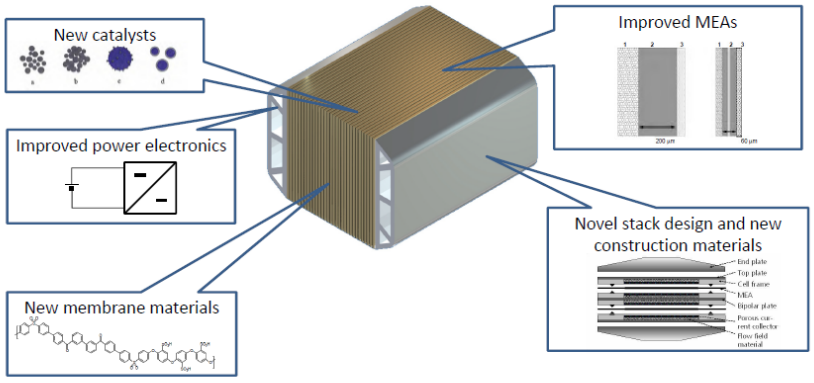
Project context and main objectives **4**
NEXPEL Main Results **7**
Optimised electrolyser system concepts, market requirements and cost assessment 7
Novel membrane materials for PEM electrolysis 12
New binary/ternary catalyst systems 14
Advanced MEA development and manufacture 17
Porous current collectors and materials for bipolar plates 21
Optimised stack design and manufacture 24
Integration and field testing of PEM electrolyser 28
Potential impact **32**
Background 32
Accomplished dissemination activities 32
Planned scientific publications 34
Planned workshops and conferences 34
NEXPEL partners **35**
Coordination contact details, public website and logo **35**

Project context and main objectives

In the context of the increased use of intermittent renewable energy sources, such as wind and solar, PEM electrolysers have great potential to harness these to create H_2 as an energy carrier. Furthermore, as hydrogen powered transport becomes more common, electrolysis of water using electricity from renewable energy will offer carbon-free hydrogen generation for re-fuelling stations. In effect, PEM electrolysers are a technology that will allow local, carbon-free hydrogen generation from renewable energy. PEM electrolysers offer the possibility of low-cost hydrogen and oxygen generation in small, highly efficient units that are particularly suitable for distributed, as well as centralised, operation. PEM electrolysers exhibit excellent dynamic response to power fluctuations, making them ideal for operation with intermittent renewable energy sources (RES) such as wind and solar power. Despite the progress that has been made in PEM technologies in recent years, PEM electrolysers are still facing several challenges to realise commercialisation, including:

- high capital costs related to expensive materials and a high material consumption
- insufficient endurance of its main components
- complex system design and time-consuming production technologies for the components

The main objective of the NEXPEL project, a successful demonstration of an efficient PEM electrolyser integrated with Renewable Energy Sources, supports the overall vision to establish hydrogen as an energy carrier in a large range of applications in the near future.



The NEXPEL project consist of a top class European consortium which is carefully balanced between leading R&D organizations and major industrial actors from 4 member states. The partners are devoted to develop new materials and stack design concepts to increase the efficiency and lifetime of PEM electrolysers and at the same time cutting costs. The three main targets for the NEXPEL project is to achieve

- Electrolyser efficiency greater than 75%
- A stack life time of 40 000 h
- A reduction in system costs to € 5,000/Nm^3 production capacity

To reach these ambitious goals, NEXPEL has developed and demonstrated novel components that are essential for cost-competitive, high-efficiency PEM electrolysis systems through five key concepts:

- lower capital costs of the main stack components; membrane, electrodes and bipolar plates / current collectors
- higher performance, in particular of the membrane electrode assembly (MEA)
- longer life time of the most crucial PEM components, *e.g.* the membrane
- highly efficient advanced power electronics

- Novel stack design for high pressure operation and low assembly costs.

The work in NEXPEL has been divided into 7 RTD and one management work package; WP1 to WP8. There has been a close interaction between different WPs, and all the project partners. The objectives of each WP are described below.

WP1 Optimised electrolyser system concepts, market requirements and cost assessment

The objective of WP1 is to perform a break down analysis of performance, availability and cost from system to component level and a subsequent definition of allowable component and manufacturing costs for key components of the electrolyser stack. Furthermore a system design (flow sheet) for a 100 Nm^3/h hydrogen production plant and a simulation tool for evaluation of system integration with renewable energy sources will be developed. Market evaluations and feedback to required cost and performance targets of materials and design developments in the other WPs are also covered.

WP2 Novel membrane materials for PEM electrolysis

To meet the requirements for membrane materials at higher temperature and system pressure, it is intended in this work package to develop a series of low-cost polyaromatic membranes that possess higher conductivities and lower permeabilities when compared to Nafion 117 as the reference material. The new membranes must have the potential to exhibit lifetimes > 40,000 hours and must possess the mechanical stability to be capable of operating under the pressures (not necessarily under a pressure difference between anode and cathode) and temperatures (> 80 ºC) used.

WP3 New binary/ternary catalyst systems

The objective of this work package is to develop an anode catalyst with improved effectiveness for oxygen evolution in terms of mass activity per gram of noble metal and with an improved stability compared to state-of the-art. The aim is to improve the overall MEA performance by the use of alternative catalyst materials and the use of supports or extenders to reduce the total noble metal loading to below 1 mg cm^{-2} whilst achieving high performance. The use of lower cost metals and novel catalyst structures will be explored as will the utilisation of the cathode electrocatalyst. Long-term stability of the catalysts will also be evaluated.

WP4 Advanced MEA development and manufacture

The key objective in this package is to create a membrane electrode assembly (MEA) with better than state-of-the-art performance and meeting performance requirements defined in WP 01. The aim is to combine the improved membranes and catalysts from WPs 02 and 03, into advanced MEAs using scalable fabrication methods to deposit the catalyst layers and to fabricate the MEA to evaluate the potential for cost reductions to meet the cost targets defined in WP 01.

WP5 Porous current collectors and materials for bipolar plates

The main goal of this work package is the improvement or replacement of the titanium expensive material for porous current collectors and bipolar plates. It will combine experimental evaluation of alternative materials and modelling to select the most promising solution. Coating strategies for Ti and other construction materials will be evaluated.

WP6 Optimised stack design and manufacture

The goal of this WP is to develop a PEM electrolyser stack design adapted to high-pressure operation. The design activity is strongly linked to the component development in WP 04 and WP 05 and the output of WP 01 in terms of an optimised system and stack design. Thickness of current

collectors, flow channel design, heat management, low-cost end plates and compression system will be considered. Finally, pilot scale stacks for field tests will be constructed.

WP7 Integration and field testing of PEM electrolyser

In this WP field tests will be performed for the prototype stacks with focus on the integration of PEM electrolysers with RES systems (wind and solar). For the field test a highly efficient DC/DC converter optimised for RES operation will be developed. Hardware evaluation will be assisted and verified by simulation and analysis of optimal working conditions using the simulation tools developed in WP 01.

NEXPEL Main Results

Optimised electrolyser system concepts, market requirements and cost assessment

In WP1 we have identified market opportunities for PEM water electrolysis, defined costs and performance targets for the stack and studied the safety and environmental issues associated with such systems.

The market analysis (Deliverable 1.5) was performed in two instalments, once in the beginning of the project, where four applications for PEM electrolysis were investigated; Wind farm load levelling, power management of a photovoltaic farm, electrolysers for green buildings and hydrogen refuelling stations. A collocation of the first three marked segments was performed in order to give a prediction of the overall number of annual sales of PEM electrolysers in three size categories. The results are shown in Figure 1 below.

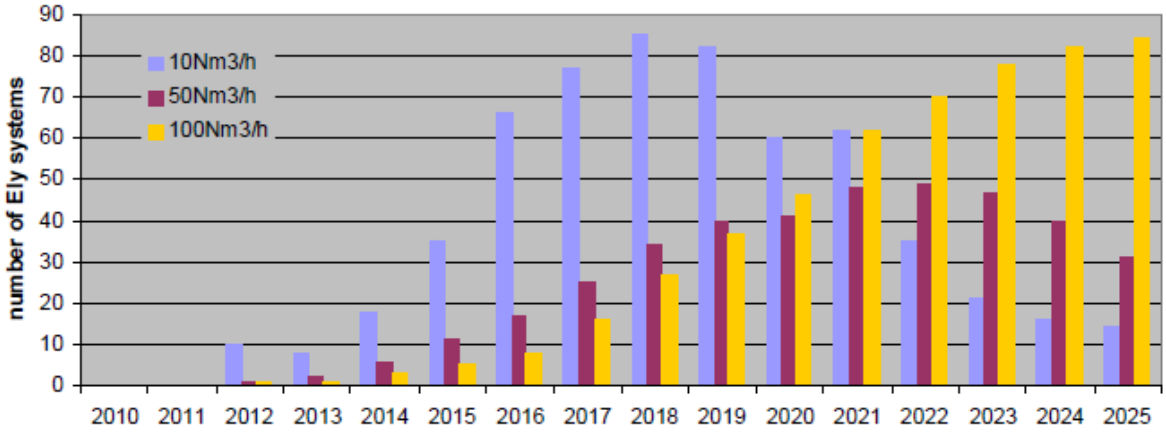


Figure 1: Number of annual sales of PEM electrolysers

The 10 Nm^3/h electrolyser size is expected to be a transition market to higher power, following the trend of the RE sources. The first figures for 50 and 100 Nm^3/h are obviously corresponding to demonstration systems. The commercial phase is expected to start in 2014 for 50 Nm^3/h and 2016 for 100 Nm^3/h where the total cost of ownership of a PEM electrolyser should not exceed 0.7 k€/ Nm^3 year.

In the second instalment of the market analysis, the focus was on hydrogen refuelling stations and a comparison of alkaline and PEM technologies were performed. The study found that a realistic market for hydrogen produced from water electrolysis would be in the range of 40 – 60 million kg H_2 in 2020, growing to between 500 and 2700 million kg in 2050. The study emphasizes that PEM electrolysis is more adapted to small compact hydrogen production facilities with variable powers (for example resulting from renewables), with a limit close to 100 Nm^3/h in a mid-term future and close to 1000 Nm^3/h in a longer term future, whereas alkaline is more adapted to large installations up to 10 000 Nm^3/h at the end with low footprint constraints and stable power.

Right now alkaline technologies have longer experience, larger plant installed and can claim lower hydrogen cost. But on the first hand, both PEM and alkaline technologies are highly dependent on electricity cost which is the most important factor on hydrogen cost. On the second hand, it seems

that PEM technology should reach the same capital cost as alkaline if the stack size increases inducing a system cost reduction.

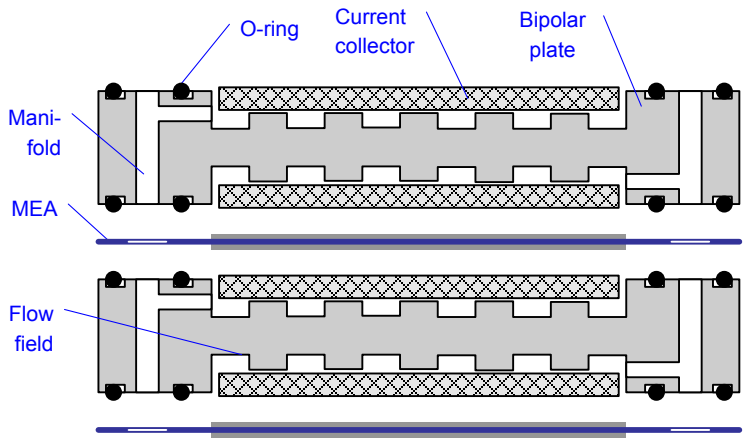
A performance and cost break down study was performed in which a cost model of the components of the PEM electrolyser was developed. With the help of the cost break down model, critical components could be identified and a performance analysis for key components (MEAs, BPPs, etc.) were performed.

For a reasonable system configuration, stacks with 10 and 25 Nm³/h are regarded. To conclude on design parameters state-of-the-art specifications for the catalyst, MEA and operating conditions are taken for this initial point of the cost break down. All preliminary specifications are taken from experimental data and experience in MEA and stack development at the partners. They are summarised in Table 1. The maximum operating pressure and temperature are 30 bar and 80 °C, respectively. Taking into account operating conditions as 1 A/cm², the stacks consist of 75/94 cells with active areas of 300/600 cm² per cell.

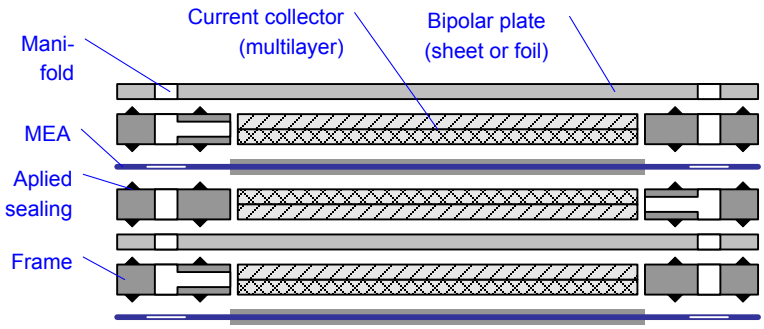
Table 1: Stack specifications as used for the cost break down

	Specifications
Hydrogen production rate per stack	10/25 Nm³/h
Active cell area	300/600 cm²
Number of cells per stack	75/94
Maximum operating pressure	30 bar
Maximum operating temperature	80 °C
Nominal cell voltage	1.8 V
Nominal current density	1 A/cm²

Within the cost break down model, two different cell/stack designs are taken into account. The main features are depicted in Figure 2.



a)



b)

Figure 2 Comparison of the two cell/stack designs considered in this report; a) conventional design with milled BiP made from Ti and b) advanced design with Ti sheets without milled structures

The cost breakdown focussed on the circular cell design, with titanium felt and carbon paper as current collectors as well as a catalyst loading of 2 mg/cm² at the anode (IrO_2) and 1 mg/cm² at the cathode (40 *wt.*% Pt/C). To analyse possible cost reductions, four different scenarios are evaluated by varying the produced number of stacks (10, 100, 1,000 and 10,000 produced stacks)

The conventional design deals with already constructed and characterised electrolyser stacks. Bipolar plates of the conventional design are produced with flow fields by milling which requires high effort and costs. The plates are made from titanium to meet the high corrosion and conductivity requirements. The bipolar plate with its flow field forms the compartment of the half cell. Sealing is done by O-rings. The MEA itself is produced similar to the case of the advanced stack design through manufacturing instead of automation.

Figure 3 shows stack prices in total. To calculate the specific costs in €/(Nm³/h), the value has to be divided by 10.

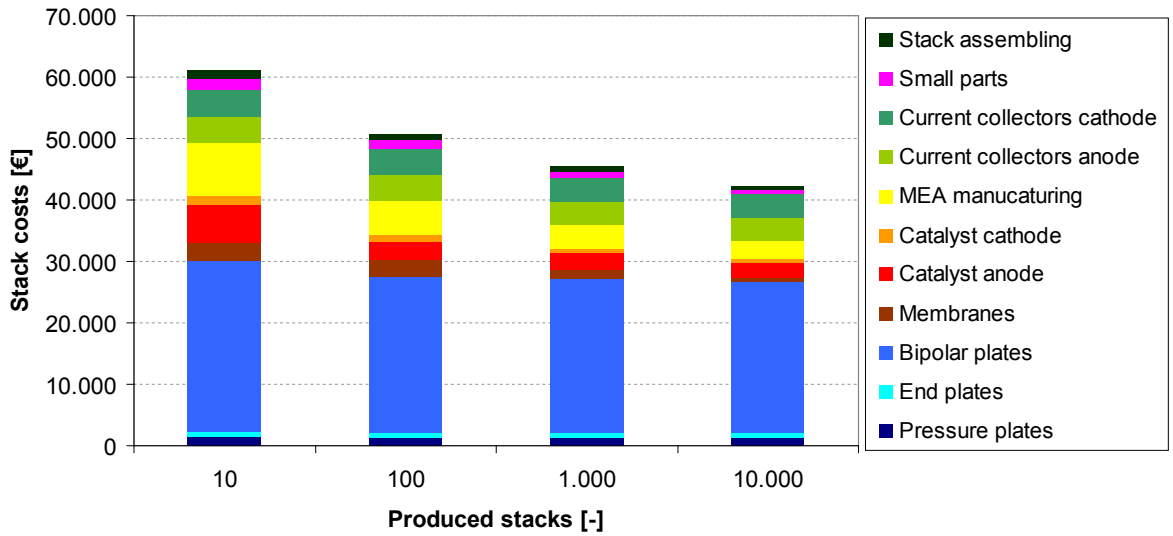


Figure 3 Cost break down for circular conventional designed 10 Nm³/h stack with titanium felt and carbon paper as current collectors

About 50 % the costs of a stack are dominated by the share to manufacture the BPP. The remaining costs are generated mainly by the MEA and Current Collectors. A tenfold increase in production (100 stacks) decreases the total stack costs by 10,000 € whereas the share of the bipolar plates increases consistently. This effect is given by practically constant costs for BPP milling. Materials

and manufacturing of the MEA has a decreasing share on the stack for higher quantities of produced stacks.

With this cost break down for a 10 Nm³/h stack in conventional design, it can be concluded that only with large production numbers can a cost reduction to approx. 40,000 € for one stack (4,000 €/(Nm³/h) be achieved.

The comparison of a stack with 10 Nm³/h (cell area: 300 cm²) and 25 Nm³/h (cell area: 600 cm²) reveals some differences, see Figure 4 (specific costs for the 25 Nm³/h stack in €/(Nm³/h) can be calculated by dividing the total costs with factor 25). Specific costs of 4,000 €/(Nm³/h) are already obtained for a small series of 100 produced stacks. The impact of the BPP is significantly higher compared to the cost break down of the 10 Nm³/h stack.

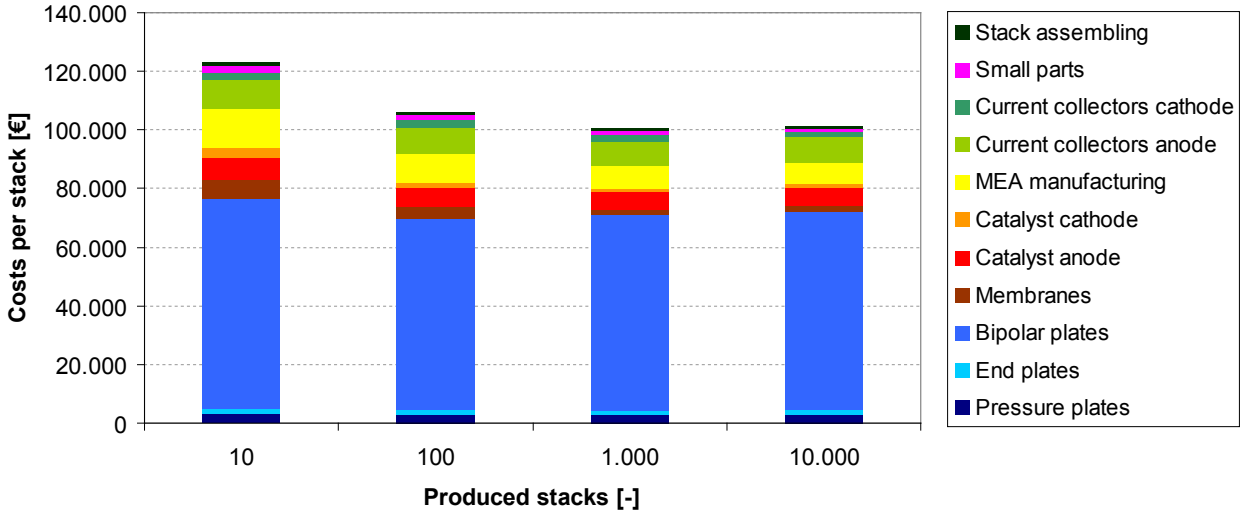


Figure 4: Cost break down for conventional 25 Nm³/h stack in circular design with titanium felt and carbon paper as current collectors

However, the cost break down for both stack sizes clearly shows the challenge with the conventional design to match specific costs as low as 4,000 €/(Nm³/h). To meet the cost target of 2,500 €/(Nm³/h), the stack design has to be more cost efficient.

The advanced design deals with thin (around 2 mm) titanium plates without any milled flow field structures. Current collectors are embedded in frames made from hard thermoplastics by injection moulding. All in all, this design should lower the total costs as less titanium is used and machining of this metal is avoided. Instead of O-rings, kamprofiles or directly dispensed silicone sealing are used for sealing the half-cells of the stack. Components and materials for MEA, Current Collectors and others are equal to the conventional design. However thicker Current Collectors are necessary to provide a similar performance for the water flow and gas removal as it is the case for BPPs with a flow field structure.

As before, the cost break down for the advanced stack design is generated for stacks with a hydrogen production rate of 10 Nm³/h and 25 Nm³/h respectively. Apparently, the large share of bipolar plates in the conventional stack design is reduced notably to an almost negligible share for the advanced stack design. With the advanced design, the largest share is given by the materials and production of the MEA, followed by the current collectors.

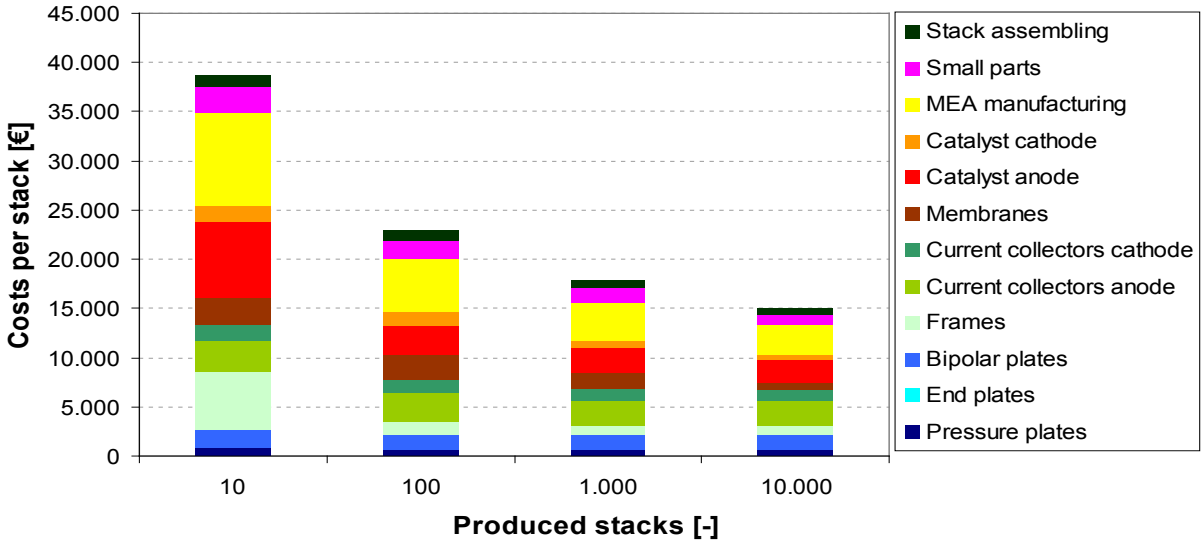


Figure 5: Cost break down for a 10 Nm³/h stack in circular advanced design with titanium felt and carbon paper as current collectors.

Due to the high tool costs, the injection moulded frames have a comparable high share on the total stack costs if only a small number of stacks are produced. With higher quantities, costs for the frames are minimised directly. Total costs for current collectors remain nearly the same for the different quantities of produced stacks as only little price information are available for the required large quantities of current collectors. Catalysts and membrane costs decrease considerably due to the higher ordered quantities. All in all, clearly lower specific stacks costs can be realised with the advanced design in comparison to the conventional design. If 100 stacks are produced, the stack costs would already be lower than target costs of 2,500 €/(Nm³/h). With a series of 1,000 and 10,000 produced stacks specific costs could be lowered to 1,800 and 1,500 €/(Nm³/h), respectively.

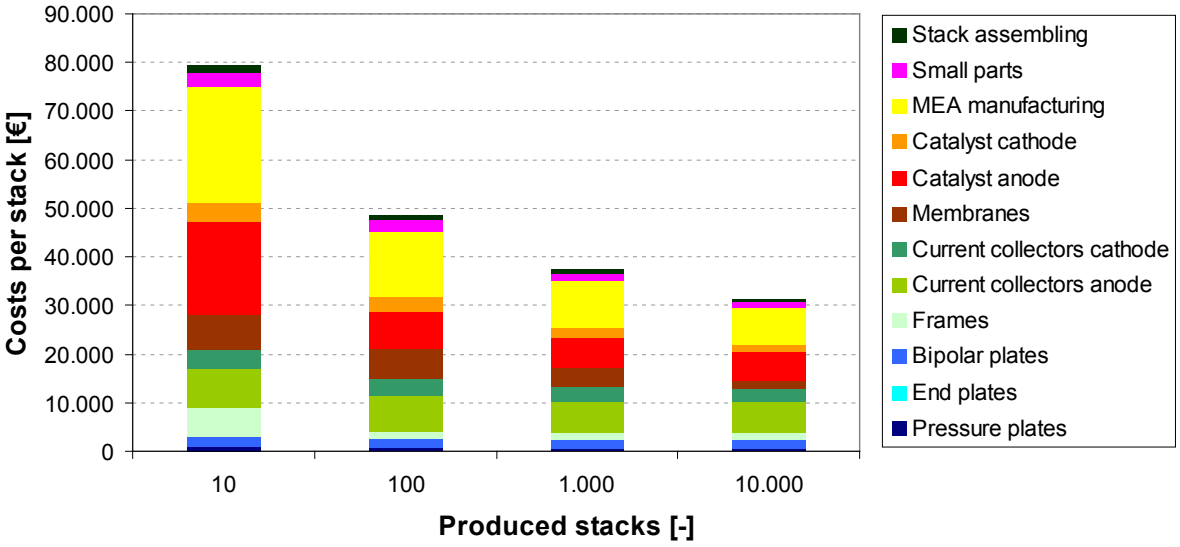


Figure 6: Cost break down for a 25 Nm³/h stack in circular advanced design with titanium felt and carbon paper as current collectors.

Analysing the 25 Nm³/h stack, specific costs per Nm³/h can be lowered again. Specific costs < 2,000 €/(Nm³/h) are feasible for a medium series of 100 stacks. Similar to the smaller 10 Nm³/h stack main cost driver are catalysts, membranes and MEA manufacturing.

Novel membrane materials for PEM electrolysis

An investigation into a series of polyaromatic membrane materials has been completed. Both components of the polymer, hydrophilic and hydrophobic, have been considered resulting in the most effective monomers being selected. Scale up of the synthesis of the hydrophobic monomer has been achieved and a commercially available hydrophilic monomer used. Polymerisation has been achieved on a large scale (~10 g) and to a high molecular weight (Mn ~100,000). The polymer showed good thermo-mechanical properties with a glass transition temperature 195-197 °C prospectively allowing for higher temperature operating conditions. The high molecular weight enabled conversion to the ionomer. This has been successfully completed with the use of sulfuric acid facilitating the introduction of sulfonic acid groups to enable proton transport through the material. The ionomer is soluble in suitable organic solvents such as *N*-methyl-2-pyrrolidone and has been cast from a 15 % solution to produce a membrane of desired thickness 60-100 µm.

The novel ionomer material was synthesized in several batches to provide a homogenous material, with 185 g being provided by UoR for membrane and MEA fabrication. The selected ionomer membrane was at 205 mm width, 5.5 m length with a thickness of 40-50 µm from DMAc by FumaTech.

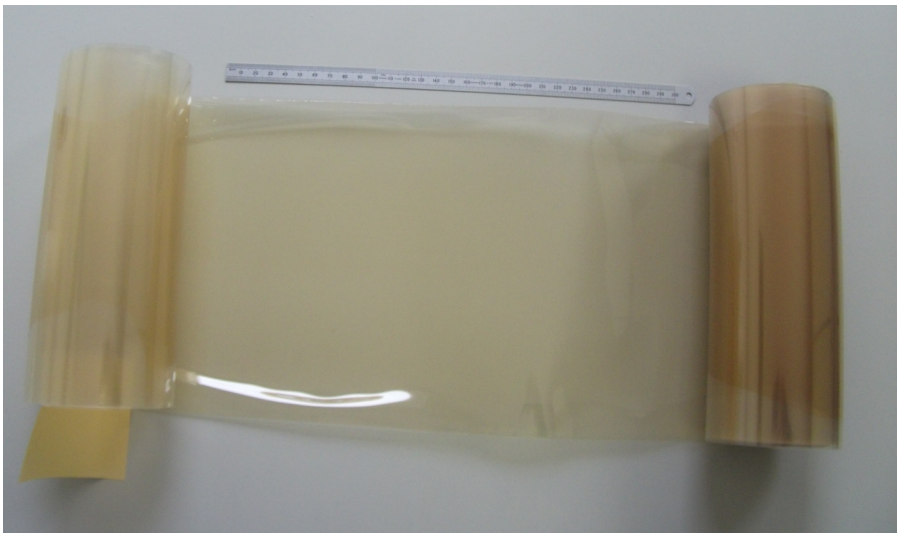


Figure 7: Picture of cast UoR membrane

Figure 8 shows the variation of proton conductivity of UoR ionomer (gold and green) with temperature at different humidity levels, reaching 94 mS cm^{-1} at 90 °C, and of Nafion® 117 under the same conditions (brick and blue), reaching 173 mS cm^{-1} at 90 °C.

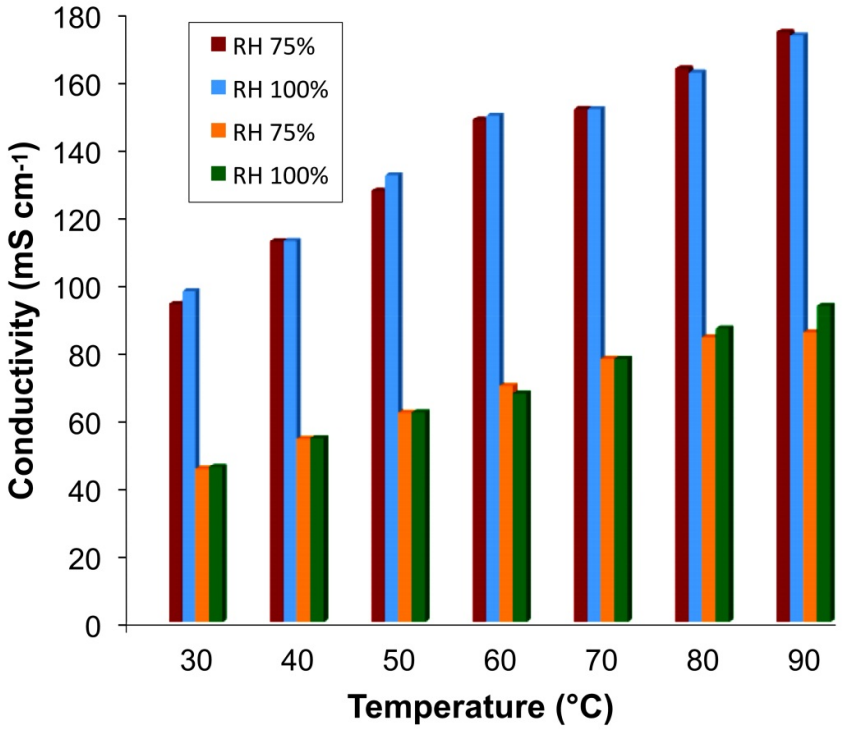


Figure 8: In plane conductivity of NEXPEL membrane (gold and green) and Nafion117 (blue and brick) at different temperatures and relative humidities.

New binary/ternary catalyst systems

A series of new electrocatalysts for the oxygen evolution reaction has been developed in the project. The catalysts are based on Ir nanoparticles supported on a conductive oxide (Sb doped SnO_2). Through a modification of the polyol method, 2 nm sized Ir particles were successfully deposited on the ATO support (see Figure 9) and the process was up-scaled to a batch size of 30g in order to supply sufficient catalyst to MEA manufacture.

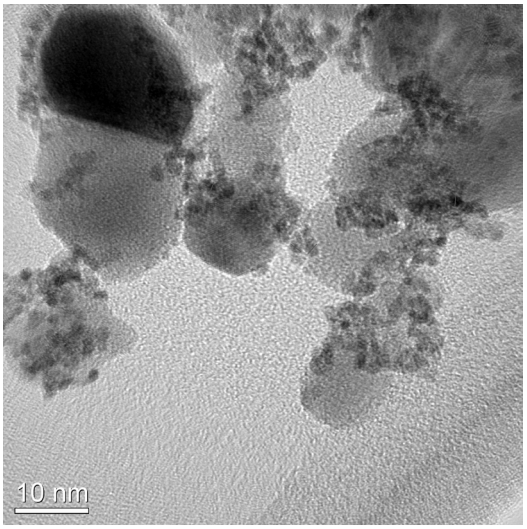


Figure 9: TEM micgrograph showing 2nm Ir particles deposited on ATO support.

Ex situ electrochemical characterisation showed that the catalyst had significant pseudocapacitance in the complete voltage window investigated, indicating that the Ir nanoparticles readily oxidise to IrO_2 and that more than 90% of the total Ir mass is electrochemically active in the intercalation of protons, see Figure 10.

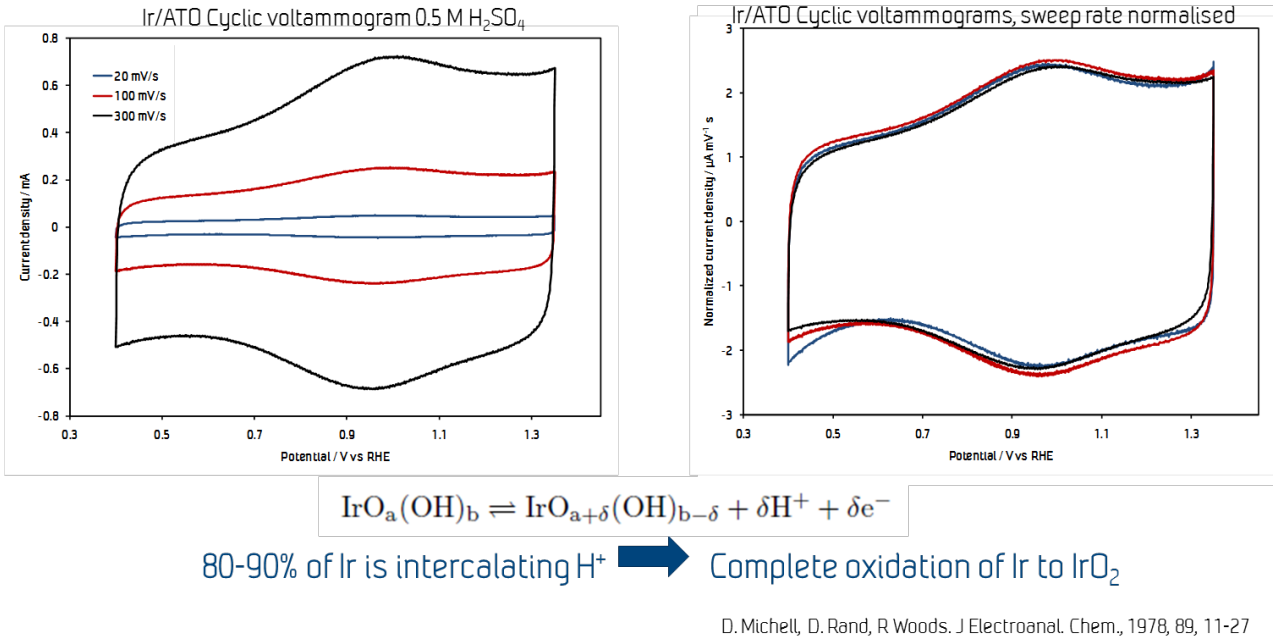


Figure 10: Cyclic voltammograms of Ir/ATO catalysts in 0.5M H2SO4 showing pseudocapacitive behaviour

Ex situ polarisation curves of 20 *wt.%* Ir/ATO has been compared to state of the art Ir black and IrO_2 catalysts and the results show that the NEXPEL catalyst show more than 200% higher mass activity than the state of the art catalysts, see

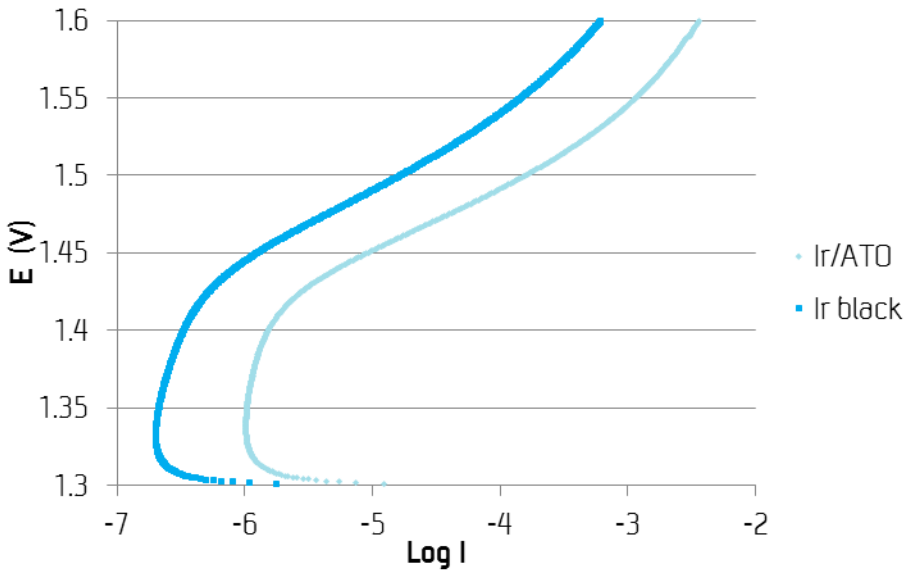


Figure 11: Polarisation curves of Ir black and 20wt% Ir/ATO in 0.5 M H_2SO_4. The mass of Iridium is equal in the two experiments.

Investigations of the catalyst activity in PEM electrolysers were also performed. Initially, varying amounts of catalyst was deposited on Nafion 115 membranes and tested for short term performance. Catalyst loadings between 0.2 and 1.0 mg Ir/cm^2 were investigated. Figure 12 shows a cross section of one of the MEAs.

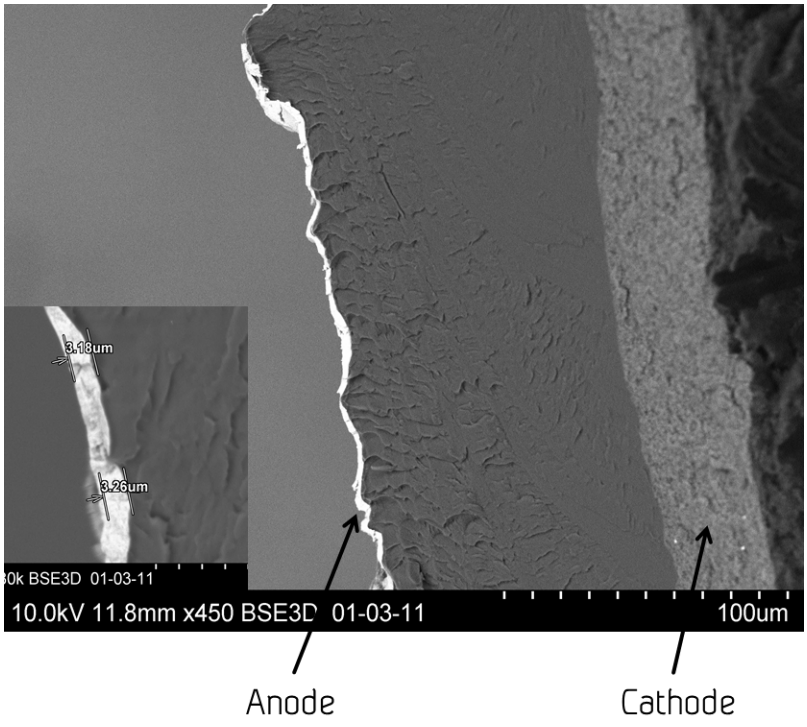


Figure 12: SEM cross section of electrolyser MEA with 20wt% Ir/ATO on the anode and 20wt% Pt/C on the cathode.

The MEA with 0.8 mg Ir/cm2 demonstrated the highest activity of the produced MEAs, giving a current of 1 Acm^{-2} at 1.65V and 80 °C (Figure 13).

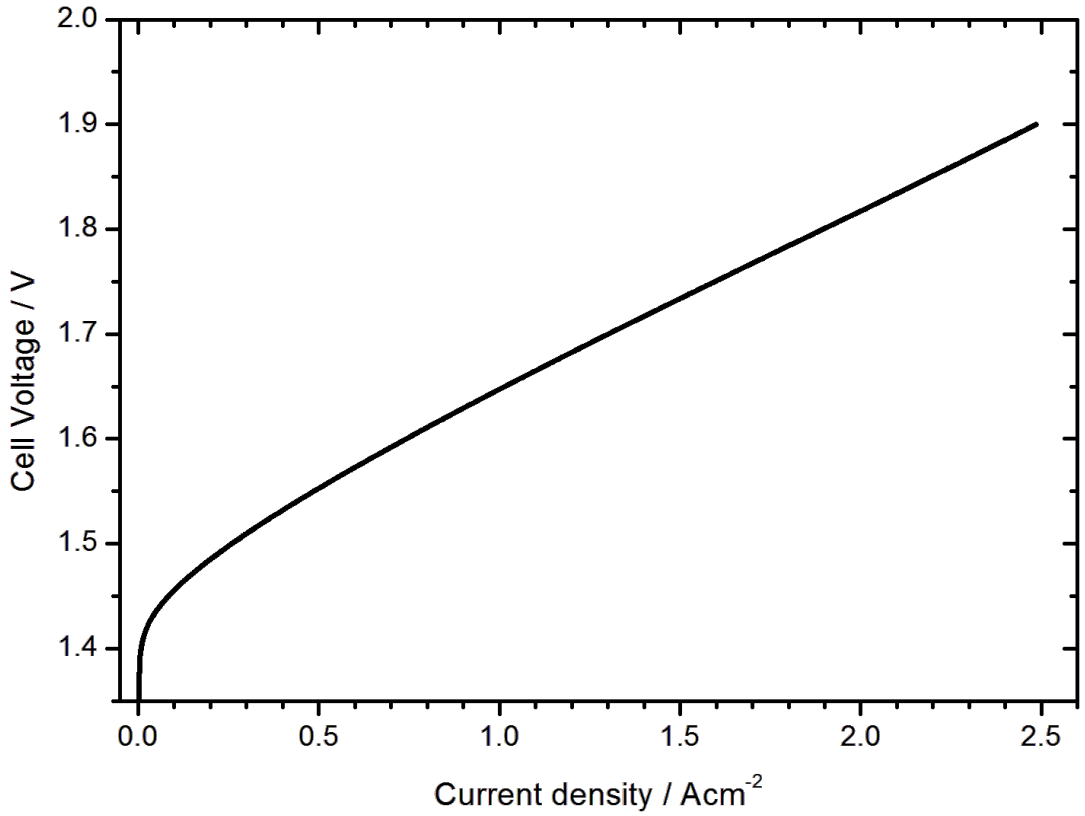


Figure 13: polarization curve obtained on single cell test, 80°C and atmospheric pressure with MEA loaded at 0.8 mg Ir/cm^2 with 20wt% Ir/ATO on the anode and 20wt% Pt/C on the cathode.

The developed catalysts thus show potential for improved mass activity in PEM electrolysers with significant reduction in the use of noble metals and it can currently be produced in a scale of 30 g/batch, sufficient for a stack with a capacity of 15-20 Nm^3/h.

Advanced MEA development and manufacture

Fumatech has supplied three different kinds of standard-type CCM to the partners. All partners involved in the project received the number of CCM according to the requests in appropriate size and they completed the testing according to their own testing protocol.

First type of Fumatech's CCM, coded as fumea®EF-10, is based on reinforced membrane of the thickness 180 micron. This type of membrane shows typically high conductivity so the CCM offers good performance, with the pressure limit for operation of about 10 bar. The highest current density levelling around 1.9 A/cm^2 at potential 2 V has been achieved on the testing station of ISE at 80°C (see Figure 14).

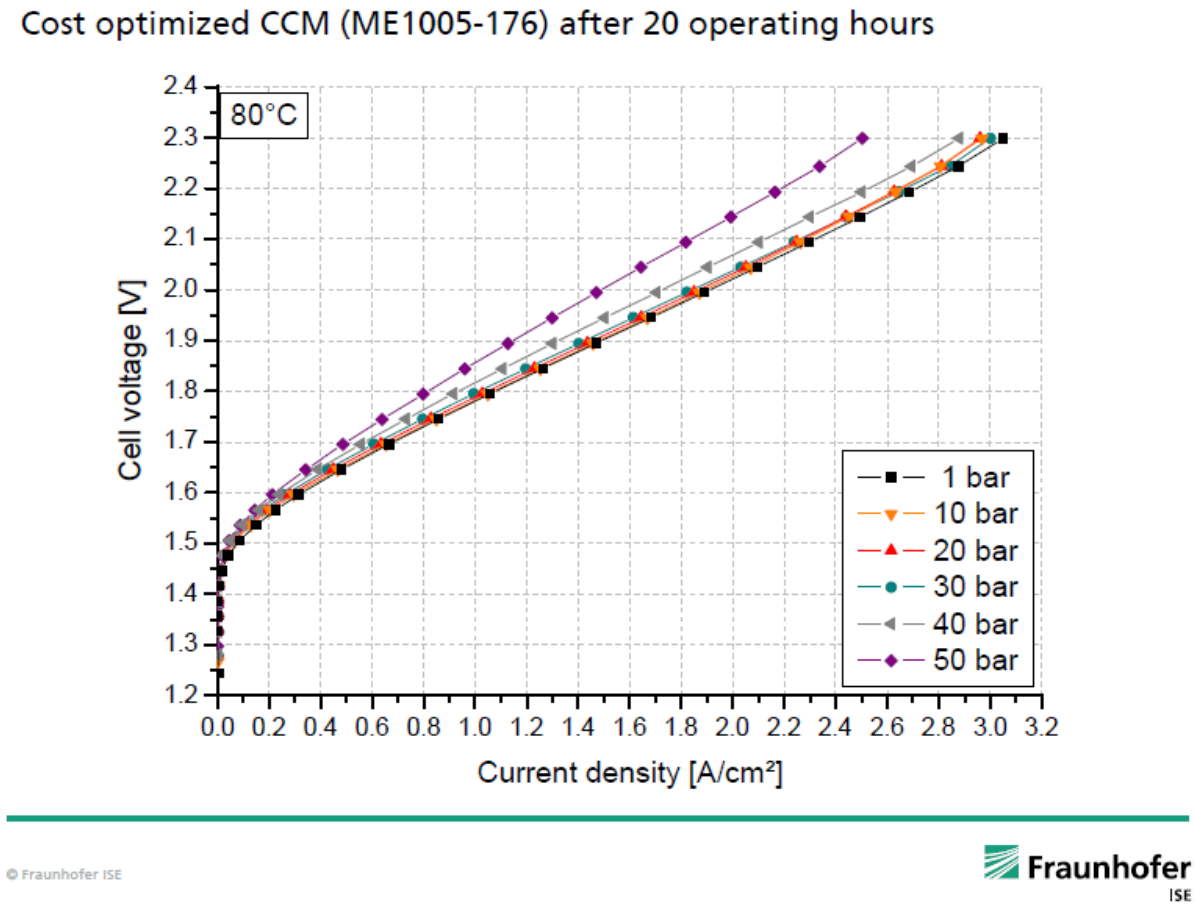


Figure 14: ***EF-10 type of CCM***

The second type CCM coded as fumea®EF-30 is also based on a reinforced membrane. The thickness of the membrane is 250 micron. This type of CCM is capable to withstand the pressures up to 30 bar. At atmospheric pressure the concentration of H_2 in O_2 produced at the anodic side was well below 100 ppm. At 20 bar the concentration of Hydrogen in the anode side rose to about 1-1.3 %. The performance of fumea EF-30 at ISE was a bit lower when compared to fumea®EF-10 (Figure 15).

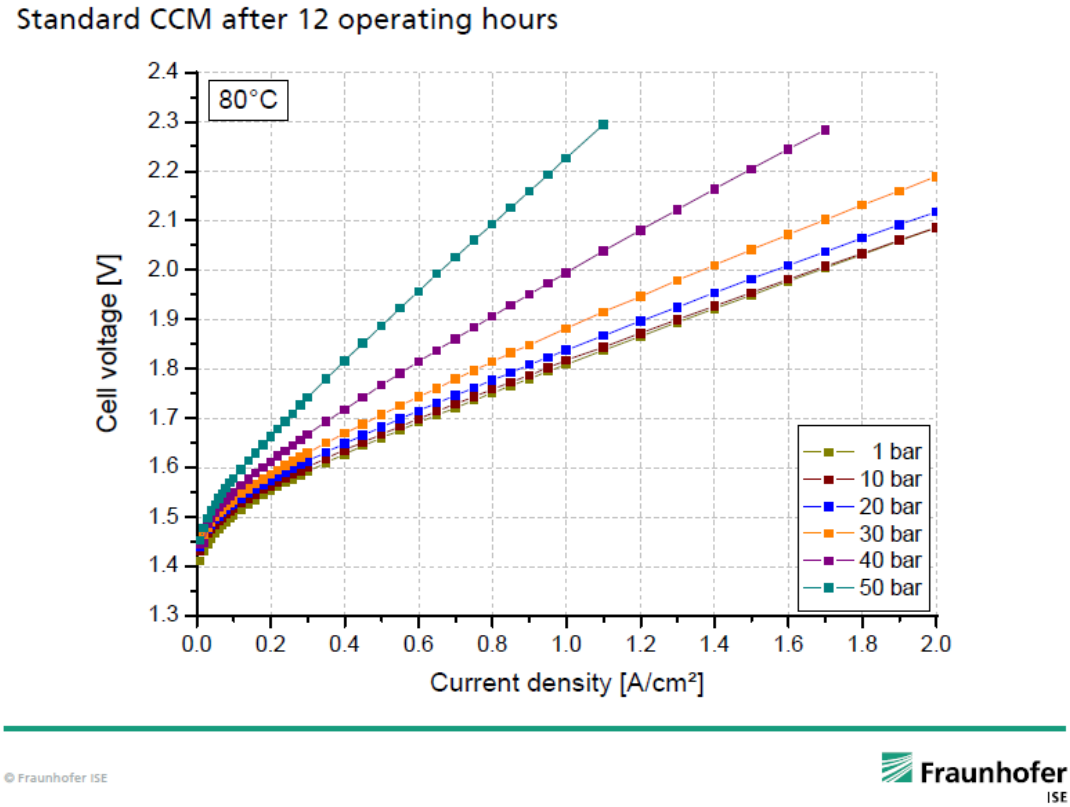


Figure 15: ***EF-30 type of CCM***

The third type of CCM coded as fumea@EF-40 is based on reinforced membrane of thickness 240 micron, but made with a different type of polymer and reinforcement film compared to EF-30. Due to the different production technology, treatment and coating steps, the membrane is easier to be sealed. It offers the same performance as EF-30, but higher grade of gas purity is achieved and the CCM can be operated up to 40 bar. As measured at CEA and Helion, the concentration of H_2 in O_2 was between 0.2-0.7 % at 20 bar. In addition, the CCM shows reduced loss of performance with increased pressure compared to other types of membranes. Also in this case, the data from CEA and Helion fully comply with figures obtained at ISE.

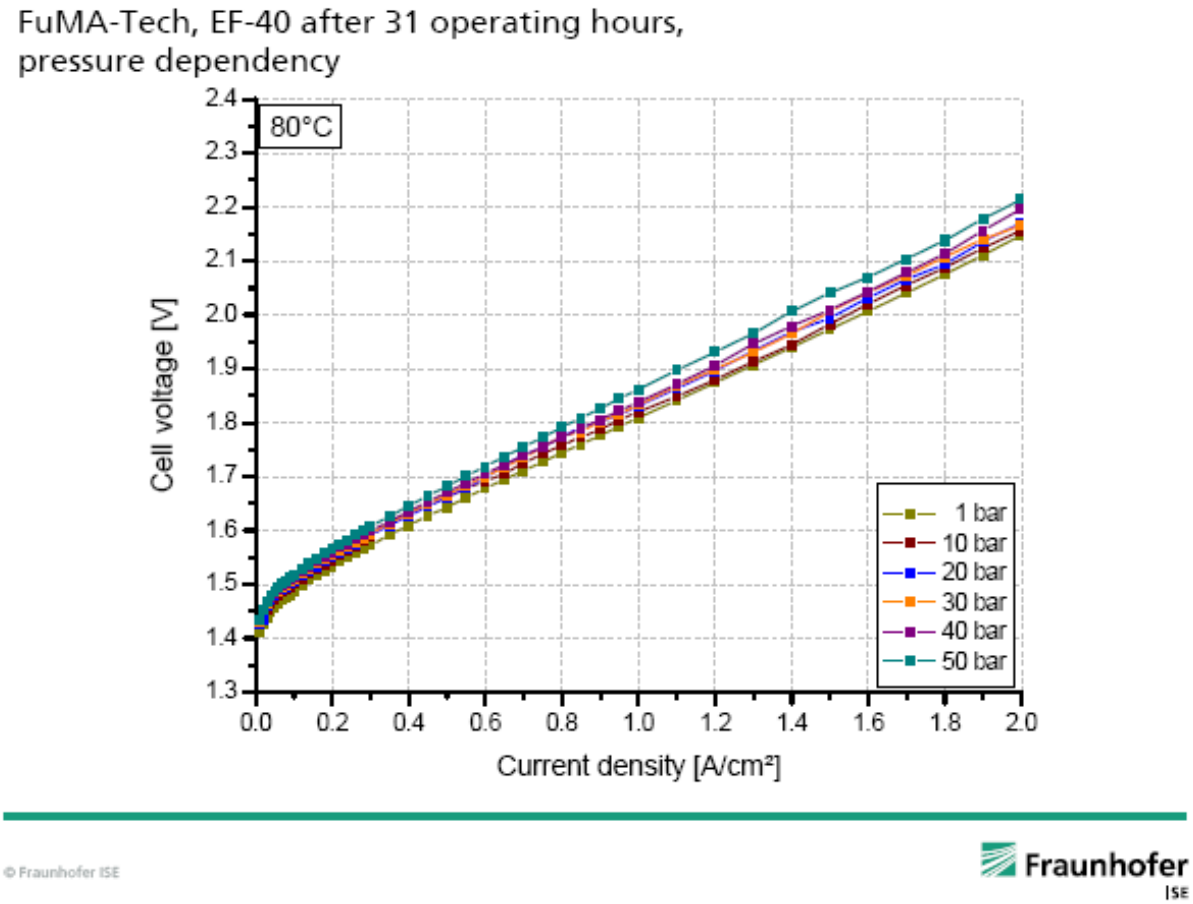


Figure 16 EF-40 type of CCM

Production of CCMs based on Ir/ATO

CCMs based on 20 *wt.*% Ir/ATO and Fumatech EF-40 membranes were manufactured by both CEA and Fumatech. The catalyst loading was chosen to be 0.8 mg Ir/cm^2, significantly lower than "state of the art" CCMs and also lower than the standard EF-40 CCM. Figure 17 shows the results from CCMs made at CEA compared to a reference standard EF-40 CCM. Even with significantly lower catalyst loading, the performance of the Ir/ATO CCM is comparable with the reference. A somewhat higher ohmic resistance is observed with the Ir/ATO, most probably originating from the lower conductivity of this catalyst.

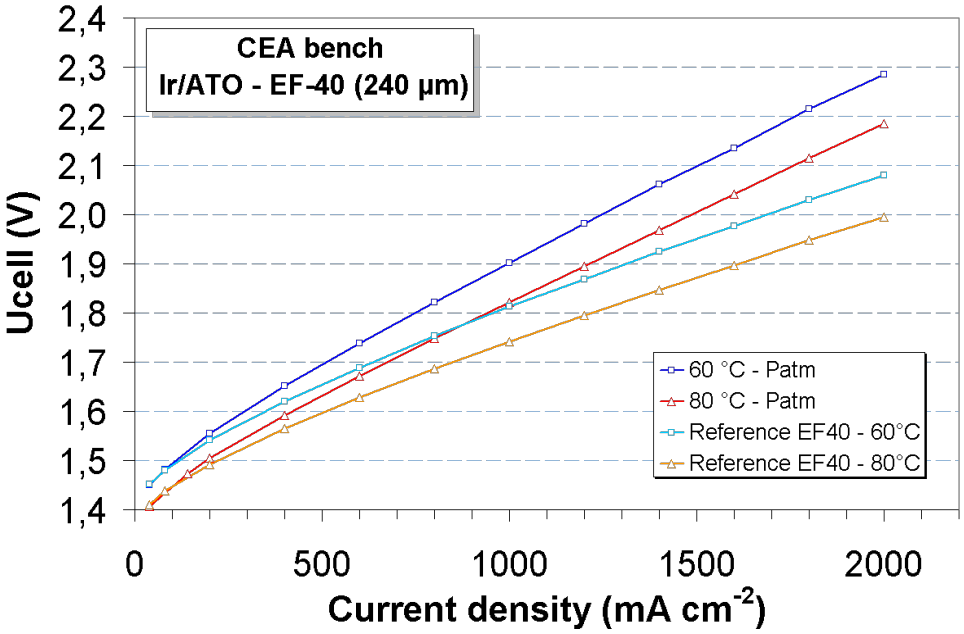


Figure 17: Comparison of standard EF-40 CCM and EF-40 coated with Ir/ATO.

A 500h stability test was also performed at Fumatech where a Ir/ATO CCM was tested at 70 °C and a current density of 500 $mAcm^{-2}$, see Figure 18. After an initial break in period of 200 h, stable operation was achieved with an average degradation rate of ~5 μVh^{-1}.

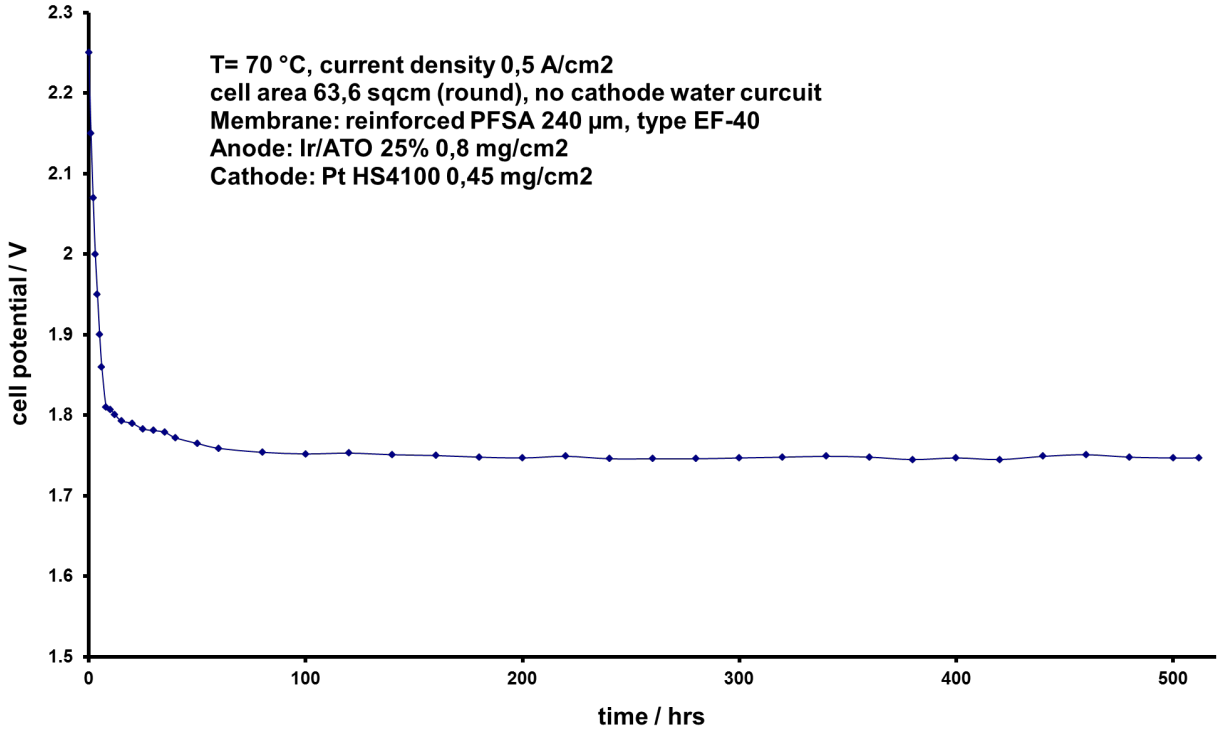


Figure 18: Long term stability test of Ir/ATO catalyst on EF-40 membrane

Porous current collectors and materials for bipolar plates

The main goal of this activity was to improve or to replace the expensive titanium components used as porous current collectors and bipolar plates to reduce the effective cost of PEM water electrolysers.

During the first part of the project, a wide bibliographic review to define suitable materials or coating strategies for the titanium replacement was performed. A benchmark of possible solutions started in the middle of the first year, consisting of an evaluation of the corrosion resistance and electrical contact resistance of the most promising materials used for the bipolar plates. Several titanium grades and coated stainless steel samples have been evaluated by corrosion tests in conditions representative of PEMWE operation for hundreds of hours.

The results show that stainless steels and hastealloys were not sufficiently resistant to corrosion in PEMWE water electrolyte at a potential of 2 V *vs.* RHE. One solution was to protect stainless steel with a thin layer of a refractory metal. Electrodeposition of a tantalum layer lead to an important reduction of the corrosion rate of the sample but the coating probably did not fully cover the metal and corrosion still occured. More efficient coatings have to be developed but coating process and material costs increase significantly the price of a bipolar plate.

Several titanium grades have been compared, see Figure 19. No major differences were observed on the different grades and thus, due to lower materials cost, we presently recommend using the unalloyed titanium grade 2 as bipolar plate material.

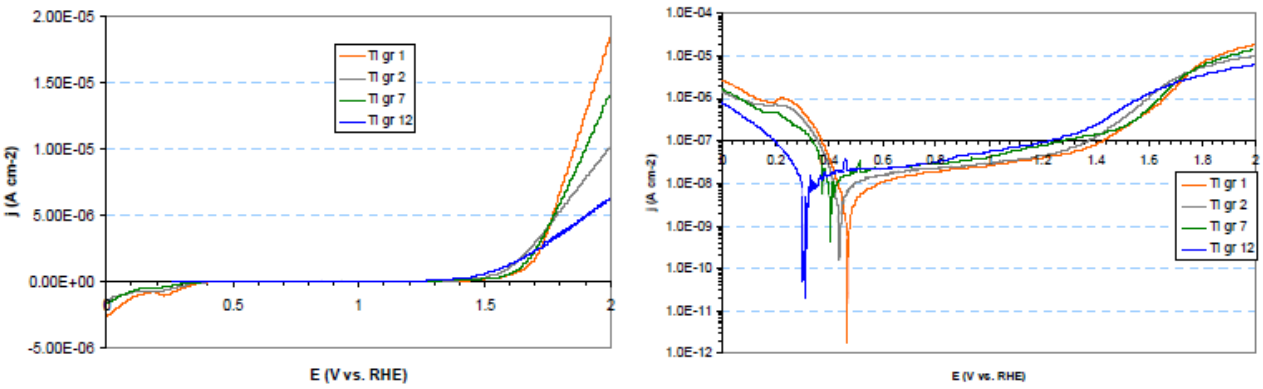


Figure 19: polarisation curves obtained on titanium grades 1, 2, 7 and 12. Current density vs. applied potential,linear plot (left) and log(j) plot (right)

The cost break down study performed in WP1 show that there is a relatively small cost reduction with increasing quantity. Consequently, to reach the cost objective of 5 k€ per Nm^3 h^{-1} on a system level, an alternative to the state of the art sintered titanium discs must be found.

In this project, a series of solutions for current collectors have been evaluated using several different tests such as compression and contact resistance measurements where the contact resistance was measured between the current collector and two titanium plates. Experiments were conducted while recording the thickness of the samples the electric resistance vs. mechanical pressure applied from 0 to 4 MPa at a constant compression speed of 0.2 kN min^{-1}. Furthermore, the solutions to replace

anodic and cathodic current collectors were tested in real conditions of operation in PEMWE single cell. Bipolar plates with and without machined channels were made to fit with the different samples. During the tests, electrical efficiency of the cell was evaluated by polarization curves and compared with state of the art solutions.

To replace titanium sintered disc as current distributor, stacks of different titanium components were realised to obtain a porosity gradient. No influence of welding was observed, but components were welded to have a distributor of a total thickness around 1 millimeter.

Several prototypes were produced and evaluated.

a. Distributor n°1
   This stack is composed of two titanium expanded grids of 150 µm and one foil of woven titanium (600 µm). The global measured thickness is around 900 µm.

Figure 20: Composition of the current distributor n°1.

b. Distributor n°2
   This distributor is composed of cheaper components (only expanded grids). Three titanium grids of small apertures are placed near the electrocatalytic layer to ensure electronic contact and two grids with bigger apertures are placed on the bipolar plate side. The total thickness is around 950 µm.

Figure 21: Composition of the current distributor n°2.

c. Distributor n°3
   This component was realised to enhance electronic contact between the distributor and the bipolar plate. Indeed, a grid of small apertures was placed on each side of the component. The thickness of this component is around 1050 µm.

Evolution of measured ohmic resistance with the cell clamping is presented in Figure 22 for the grids stacks n°1 and 2 and for the titanium sintered disc and the titanium fibres. The surface area is 25 cm². The clamping torque of cells in water electrolysis tests is generally 8 Nm which corresponds to of a pressure of around 1 MPa.

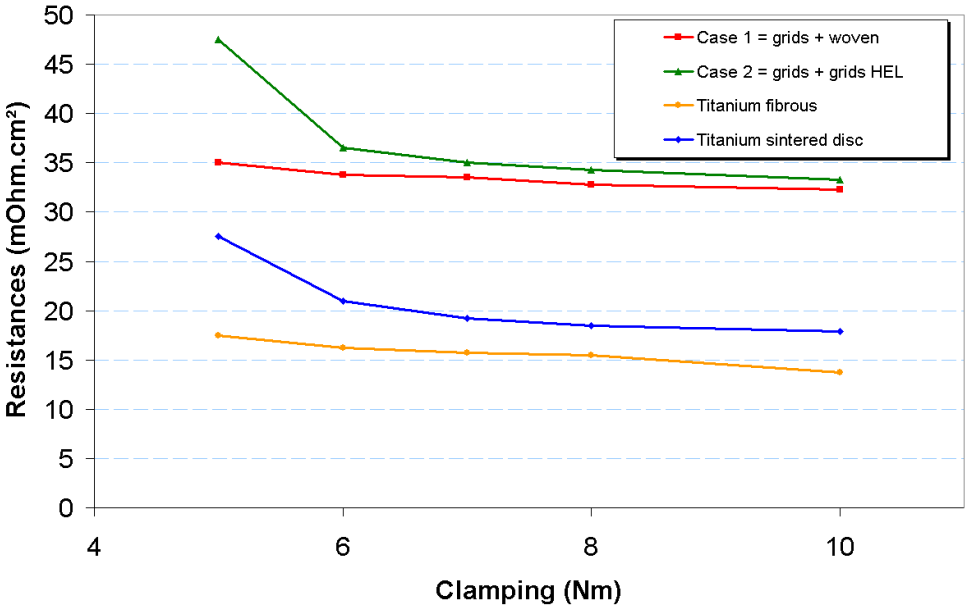


Figure 22: Ohmic resistances vs. cell clamping for different current distributors

All the current collectors composed of titanium grids were tested in single cell with bipolar plates without channels (red). Comparisons were realised with a "reference configuration" composed of a titanium sintered disc and bipolar plates with channels as presented in Figure 23 (blue). The cathodic diffusion layer was a carbon component of the thickness 250 µm.

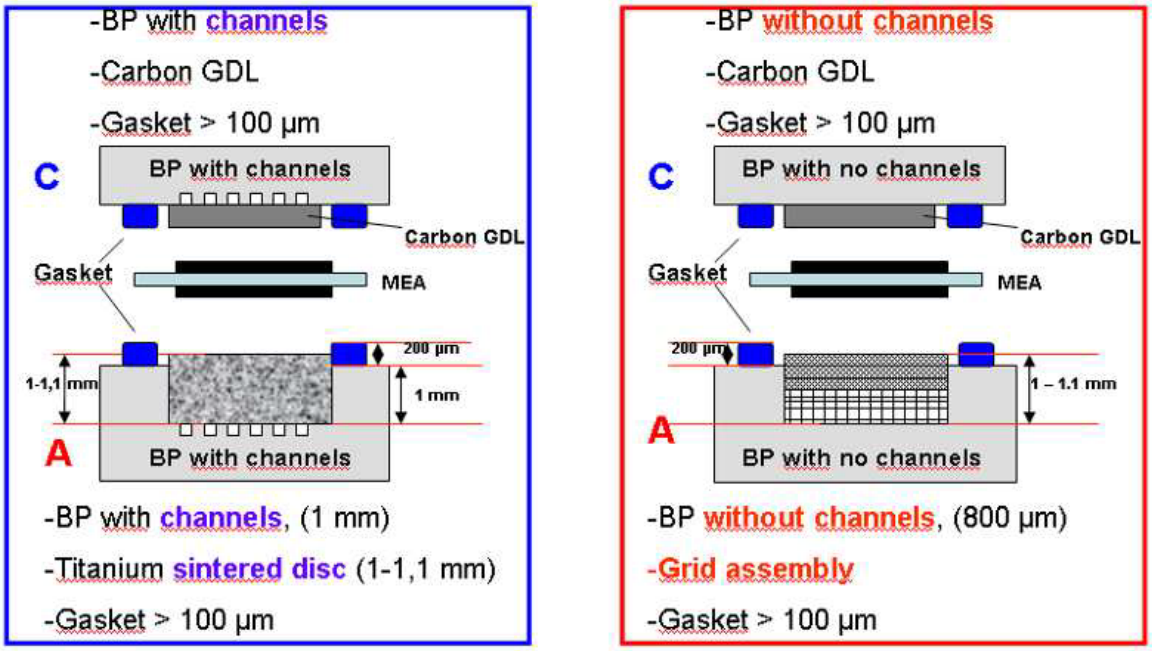


Figure 23: Cells configurations studied

Polarization curves of the reference and the distributor n°2 are presented in Figure 24 below. No significant differences between configurations were observed, only a slightly better performance is observed for the reference at high current densities. Moreover, results under pressure show that a configuration without channels and with grid components can be used under pressure. The same observations were seen with distributor n°1.

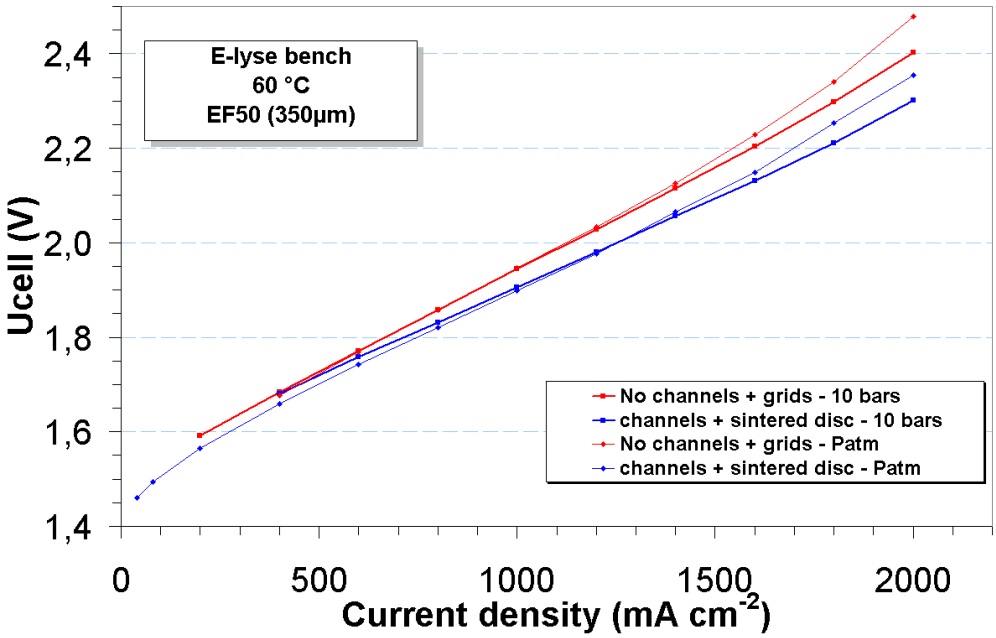


Figure 24: Reference vs. distributor n°2 / EF-50 / (60 °C, Patm and 10 bars)

From the above evaluations several generations of current collectors were developed within the project, ranging from 25 cm^2 samples to the final 20 pieces of 150 cm^2 samples delivered for integration in the final two demonstration stacks. Figure 25 shows a timeline of the development of the current collectors.

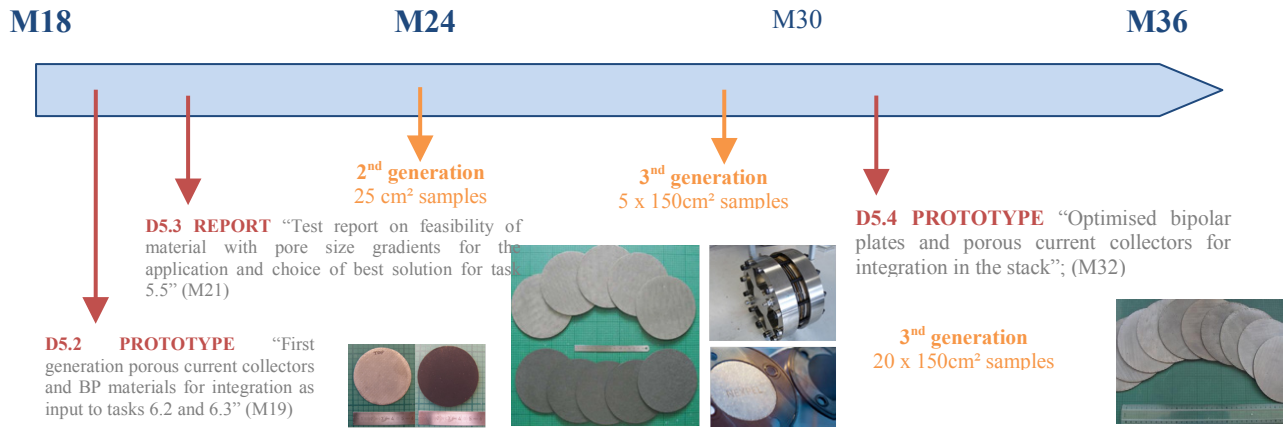


Figure 25: Timeline of the WP5 deliverables and prototypes developments

Optimised stack design and manufacture

The basic concept for the NEXPEL stack design was a simple design in which the number of parts is significantly reduced compared to conventional designs. Furthermore, cost reduction will be achieved by avoiding machining parts, especially machined flow fields on bipolar plates.

The project is targeting an electrolysis system with a hydrogen production capacity of 100 Nm^3/h. However, the project is focusing on technology improvements with stack demonstration of 1-2 kW. Therefore, it was agreed upon, that the prototype stacks will have an active area of 150 cm^2 with 10 cells. Applied silicone was identified as the preferred sealing concept for high pressure application. Due to its high mechanical strength (over 200 GPa E-modulus), high availability, low cost and feasibility in machining, the thermoplastic PPSU (Polyphenylene Sulfone) was chosen as material for the frame. Figure 26 gives a comparison of the main differences between a conventional stack design with machined bipolar plates and the NEXPEL design.

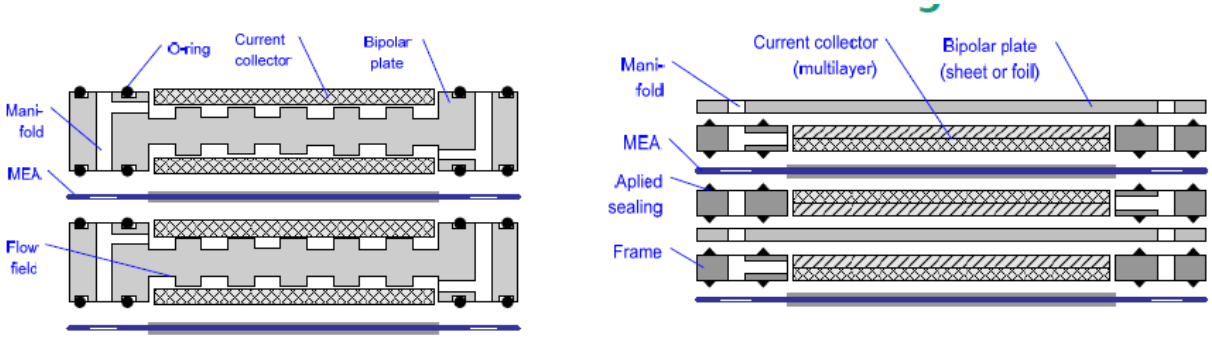


Figure 26: Comparison of conventional (left) and NEXPEL (right) stack design

Parts for the modified design were constructed and a two cell stack was assembled to test the sealing concept. Gas tightness test was performed using nitrogen gas, and the stack was completely gas and water tight up to 35 bar, proving the success of the applied silicone sealing concept.

The end plate is one of the main components of a PEM electrolyser. Conventionally, stack components are assembled between two end plates, which serve as a supporting structure for the unit cells. Consequently, the end plate bear the entire mechanical load applied on the stack through clamping bolts and, provide passage for reactant water and product gasses in and out of the stack respectively. The major role of the end plate though, is to provide a uniform and optimal pressure distribution between various components of the stack. Through the distribution of pressure between sealing rings and relevant stack components (external stack), water and gas tightness of the stack is achieved. While, by the distribution of contact pressure between the bipolar plates and current collectors, as well as between the current collectors and the MEA (internal stack), contact resistance between them can be reduced, and consequently improved performance and efficiency of the electrolyser stack.

One of the key parameters in end plate design is its thickness. In order to select the optimum thickness, end plates with different thicknesses and structures have been analysed. The FEA method has been used to choose the endplate thickness, based on the minimum endplate deflection (deformation) and minimum total von Mises stress at the maximum operational clamping pressure through the bolts. The effects of maximum clamping pressure on the structural deformation of two different design structures, planar and ribbed, have been investigated for different plate thicknesses, and the design with the least deformation has been chosen. Both design concepts are from the same material, steel, with an E-modulus value of 200 GPa. The overall goal was to optimise the plate thickness in order to achieve the least deflection possible, while reducing the total bulkiness of the endplate. Figure 27 show the results from the FEA study on the deformation of a 50mm thick endplate with the two selected designs.

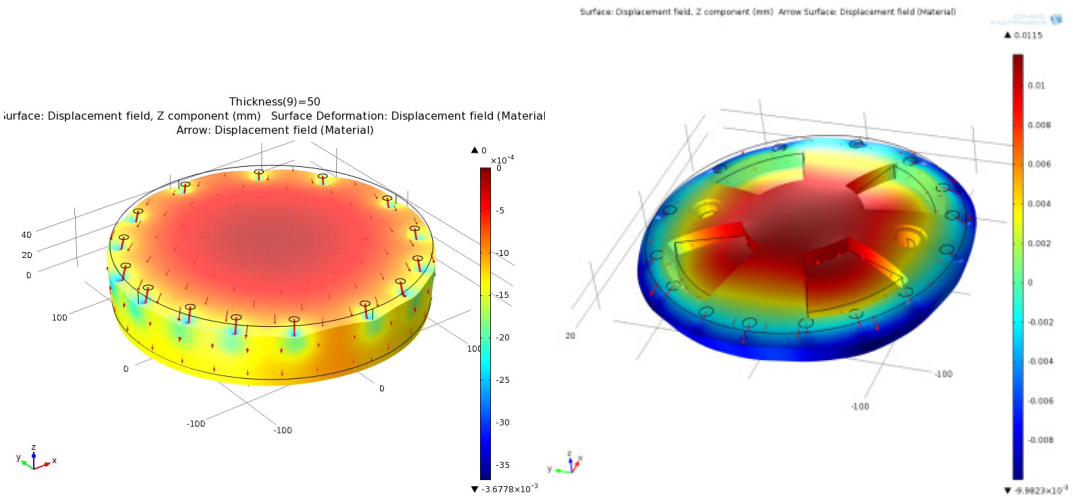


Figure 27: Surface plots showing maximum deformation of a 50 mm planar (left) and ribbed (right) endplate under 30 MPa clamping load.

Based on the results of the FEA model, an endplate with optimal thickness (50 mm) and with the ribbed structure has been constructed from stainless steel with E-modulus value of 200 GPa, see Figure 28.

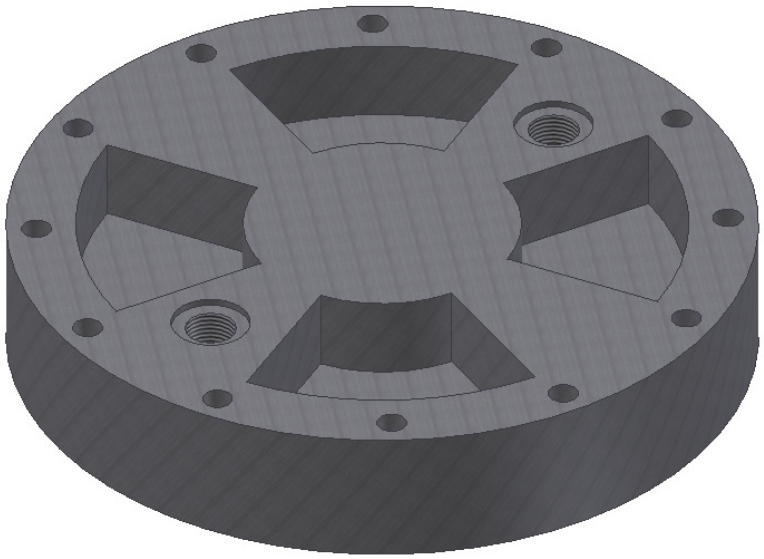


Figure 28: Final NEXPEL end plate design.

Summary of stack design

The prototype stacks consists of 10 cells in total, with active area of 150 cm² per cell. To reduce cost of stack, the bipolar plate is made only from a thin sheet of Titanium, without machined of flow channels. The cell frames are made from injection moulded Polyphenylene Sulfone (PPSU) and, they have as function, to serve as support for the sealing rings and to conduct fluids into and out of the active area. Applied silicone sealant was used as the sealing preference for high pressure operation. The anode current collector consist of expanded titanium grade 2 meshes, stacked together to form a porosity gradient, with the biggest mesh size on the bipolar plate side, while at the interface with the MEA, fine micro-pore layers were introduced on the current collector. The titanium meshes were stacked together by point-wise laser welding. To address the concerns of

hydrogen embrittlement on the cathode side, carbon-based material such as those used in fuel cell application, was selected as choice of current collector on the cathode side. This was chosen to be compressible enough to compensate for some of the tolerances in the manufacturing of other stack components. Figure 29 below shows the NEXPEL stack design concept in 3-D.

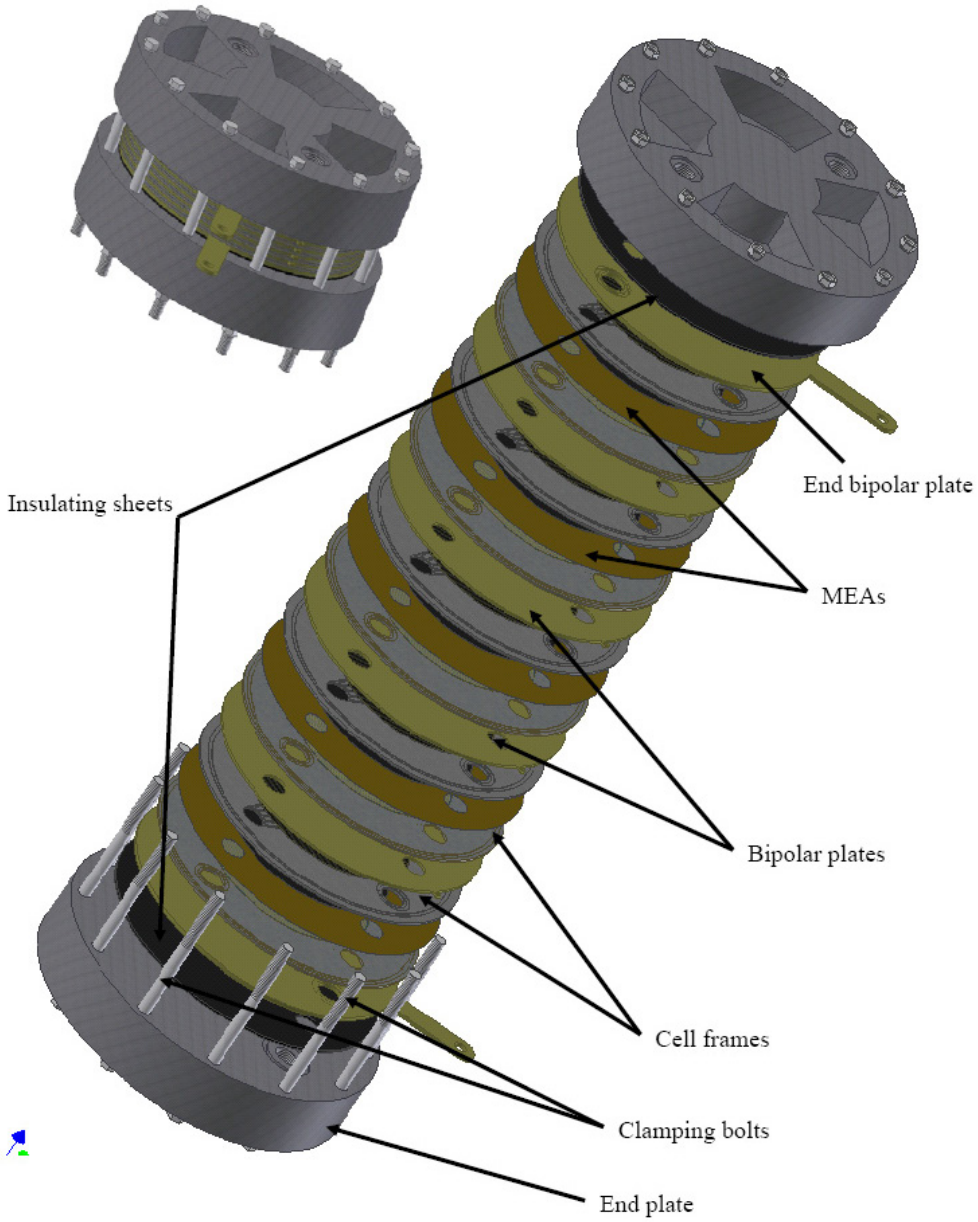


Figure 29: NEXPEL stack in 3D

Development of DC/DC converter

WP 7 was dedicated to field testing of the NEXPEL electrolyser. In order to achieve efficient operation, a new DC/DC converter was designed and constructed especially for this electrolyser. Requirements and goals for the converter within this project were: efficiency of at least 97 %, cheap design based on PCB, control of power, current and voltage for a safe operation, suitability for operation at high efficiency at different voltage levels.

After the successful assembling of the converter, the efficiency of the converter was analysed over the whole output power range. The results are shown in Figure 30. At 25 V output voltage the

efficiency is over the bigger part above 97 % (maximum 97.45 %). Only at small loads is it below 97, due to self-consumption of the converter. The relatively flat curve can be achieved with the paralleling of multiple strings (12 at full load) which compensates the ohmic losses at higher load currents.

At 10 V output voltage the maximum efficiency is at 95.2 %. The maximum is only reached at output currents above 100 A. At lower output voltage the influence of the auxiliary supply of the converter is higher when considering the same currents. This is because of the lower resulting output power when comparing efficiencies with the same output voltage.

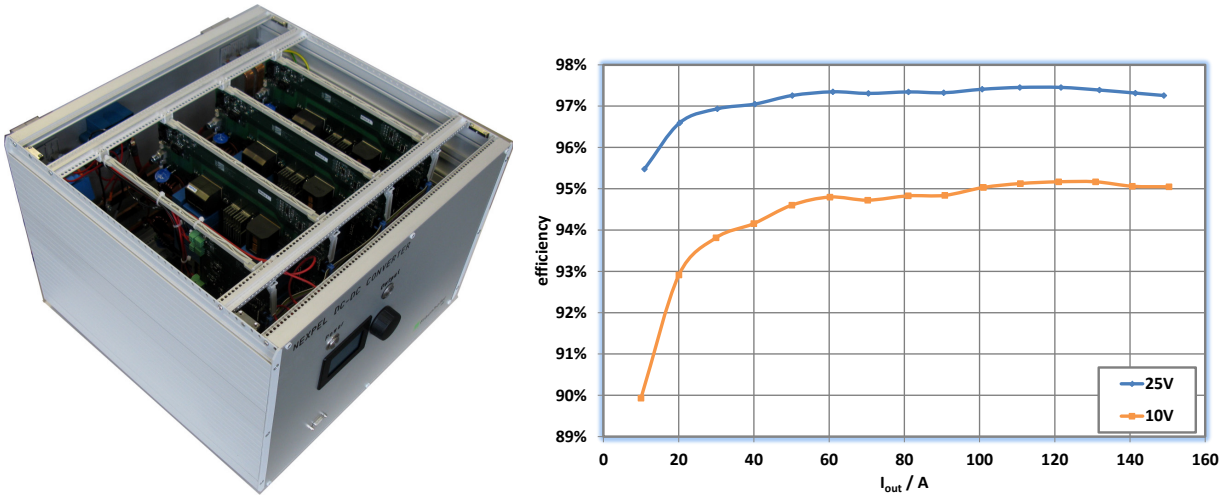


Figure 30: Picture of DC/DC converter and performance data.

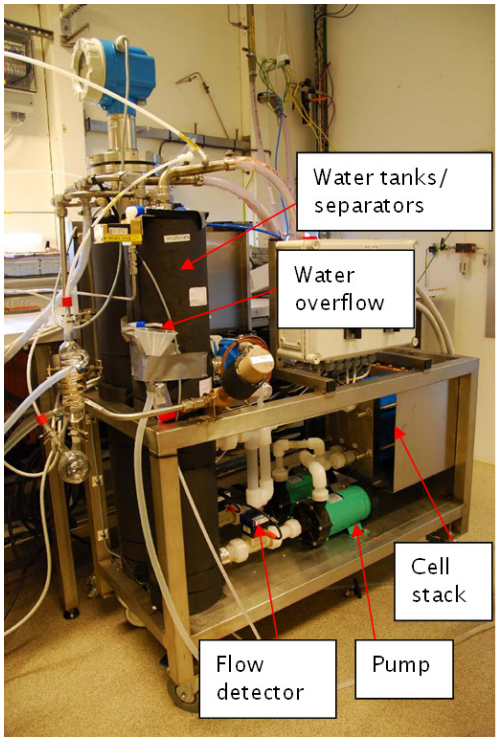
The DC/DC converter can be controlled by the user via the panel (display + buttons) or via the RS232 interface and a computer. The user can choose between current and voltage control mode. In both modes the limits (current and voltage) can be chosen in the specified range. The master controller submits the set point values to each power module depending on the load. It adapts the number of modules to the load. Then again each module will adapt the number of strings to the demanded load current in order to achieve maximum efficiency. The control algorithm was tested and verified by simulations and then translated into C-Code for the implementation on the µC.

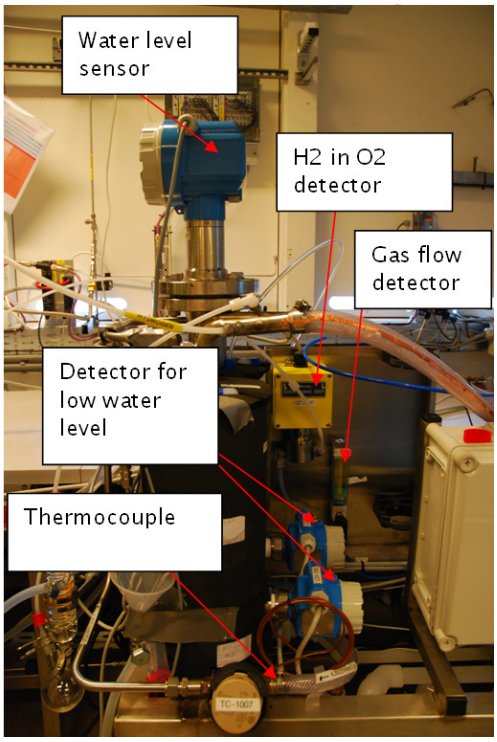
Integration and field testing of PEM electrolyser

Two NEXPEL stacks have been tested for overall performance and to study the feasibility of coupling the stacks to renewable energy sources. The first stack, using the reference EF-40 CCMs produced by Fumatech, has been field tested in Statoil's Energy Park at Herøya, Porsgrunn, Norway. This energy park consists of two 6 kW wind turbines and two 2.1kW solar panels. The park is equipped with a 70 kWh lead acid battery storage system. It can operate as a standalone unit or be connected to the main grid for export. The facility can be used for testing the combination of renewable power sources with water electrolysis. Other applications include testing of control systems for wind power production as well as testing of components for energy conversion and energy storage systems. The park is located by the hydrogen filling station at Herøya. A picture of the Energy Park is shown in Figure 31 below.

Figure 31: The Energy Park at Herøya. The laboratory is located in the garage to the left.

To facilitate the test, a lab was integrated on site with a custom fume hood and water purification system. The fume hood housed an electrolyser skid which could easily be modified to suit the NEXPEL stack. See pictures in Figure 32 below.





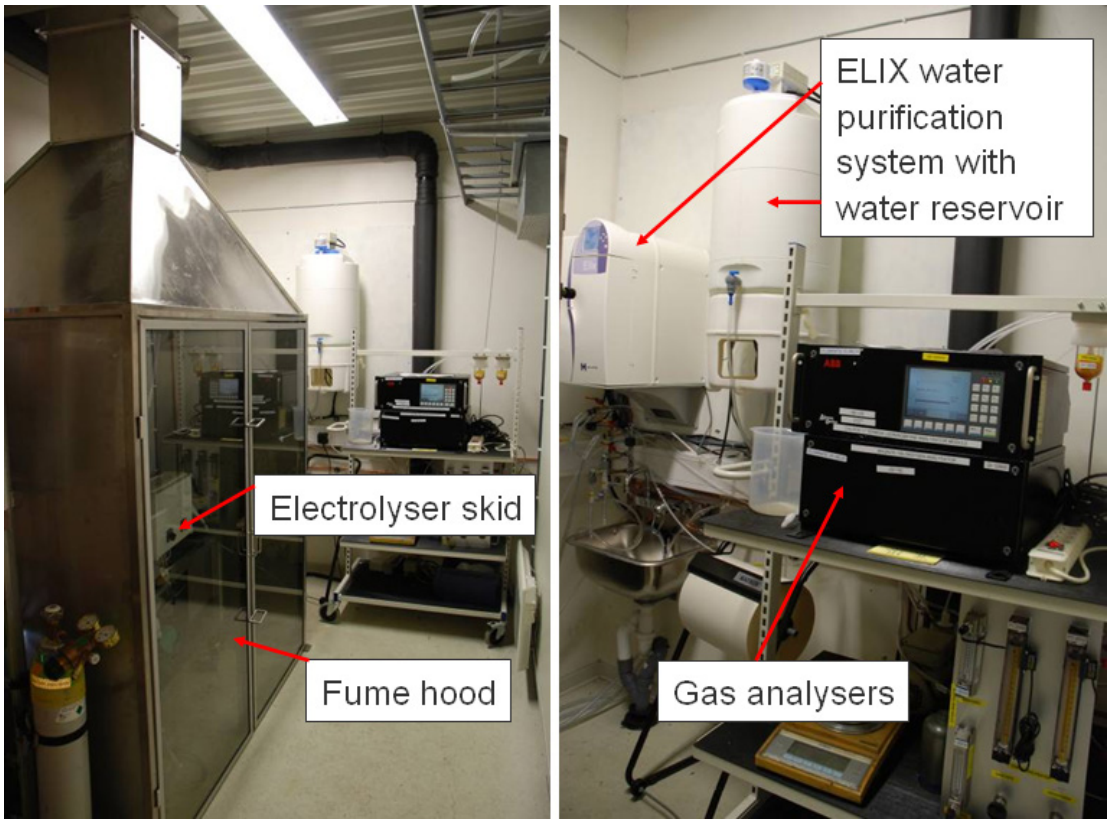


Figure 32: Pictures of laboratory and electrolyser skid.

Due to late delivery of the NEXPEL stack, the field test could only take place during M36, leading to far less testing time than planned for. The test was more of a function test, involving initial characterization and one 72 hour wind profile. A compromise on time resolution for the wind profile had to be made, and hence the medium resolution (10 s) was chosen. Figure 33 shows the overall performance of the 10 cell NEXPEL stack.

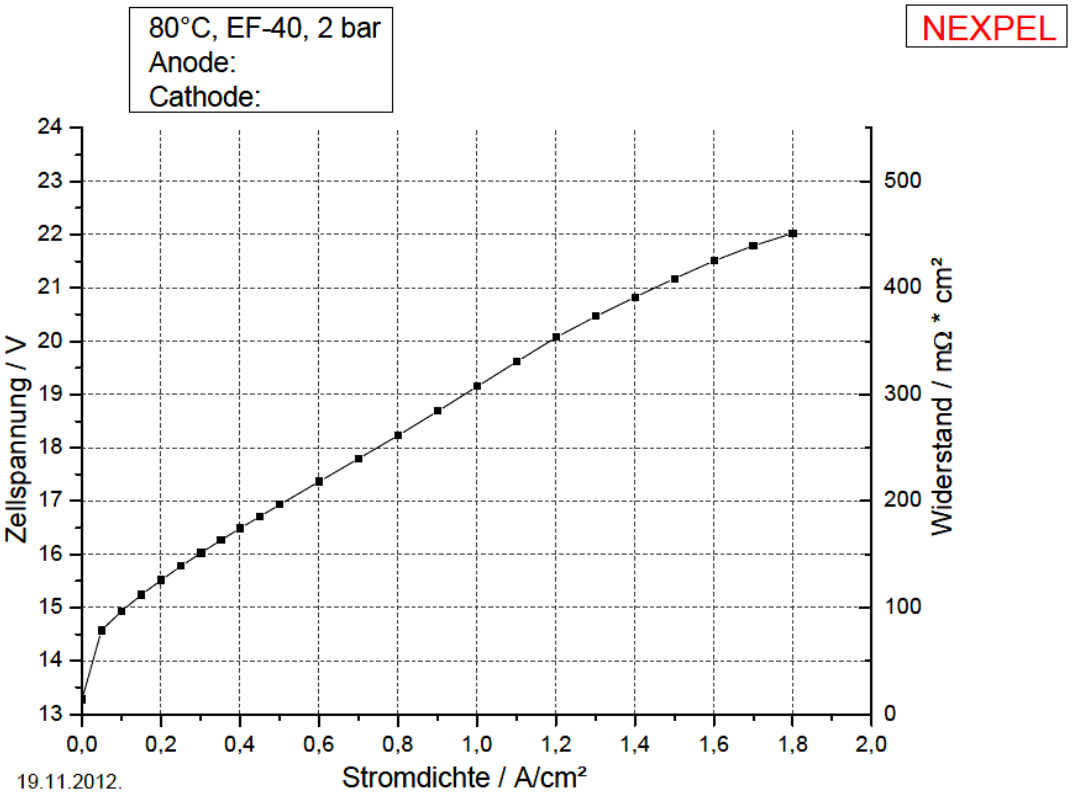


Figure 33: Overall NEXPEL stack performance at 80°C

The second 10 cell stack incorporated the Ir/ATO catalyst developed within the project and has been tested in a stack test stand at Fraunhofer. At the time of the writing of this report, the initial tests results show that the CCMs are exhibiting a large variation in performance, causing the overall performance of this stack to be significantly lower than the stack using the reference EF-40 membranes, see Figure 34. A new batch of CCMs are under production and will be tested in the stack at a later stage and published on the NEXPEL project website.

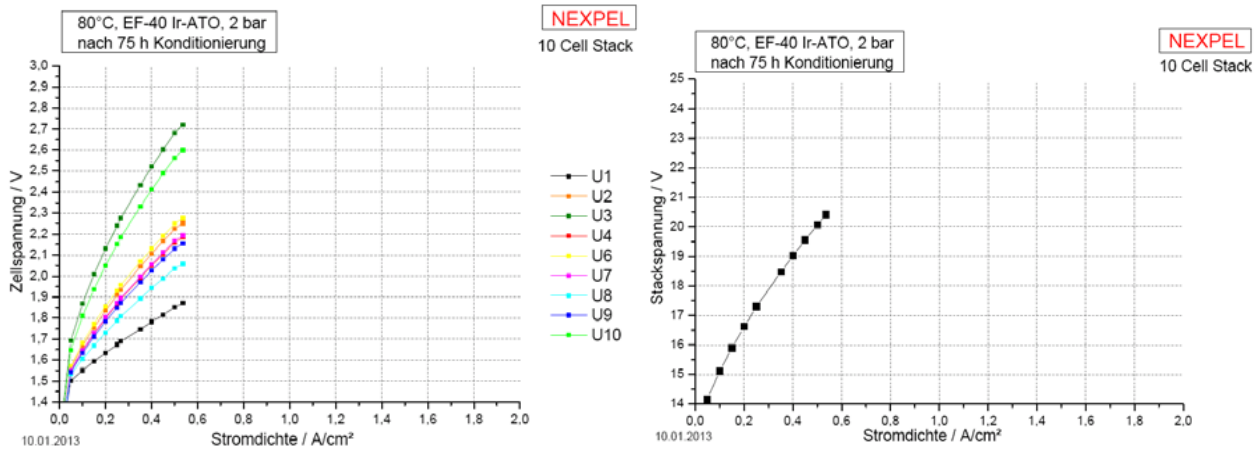


Figure 34: Polarisation curves after 75 hours of conditioning showing single cells performance (left) and overall stack performance (right)

Potential impact

Please provide a description of the potential impact (including the socio-economic impact and the wider societal implications of the project so far) and the main dissemination activities and the exploitation of results. The length of this part cannot exceed 10 pages.

Background

During the NEXPEL project development of new materials and concepts have had high priority. Several of these solutions have been implemented in a demonstrator electrolyser stack which at the end of the project is still being investigated and others are under further development. This again is reflected in the dissemination plan, where a number of scientific papers based upon the results obtained in the project are planned for publication in the coming year.

Accomplished dissemination activities

Significant results from the project have continuously been disseminated to the scientific community through at least 12 oral presentations at major international conferences such as WHEC and ECS meetings as well as seminars and workshops targeted to a wider community of private and public stakeholders.

Printed annual progress reports from the consortium have also been produced and circulated by the consortium at several venues, including WHEC, Fuel Cell Expo and the Hannover trade faire. The project has also published an article in European Energy Innovation, a journal distributed to, amongst others, members of the European parliament and senior commission officials

An international seminar on the role of water electrolysis in the renewable energy sector was organised by the project in collaboration with the FCH-JU project primolyzer with 100 participants from Europe, USA and Asia.

Publication title	Date	Publication type	Venue / Journal name
Advanced Design and Performance of Polymer Electrolyte Membrane Electrolyser Operating at High Pressures	2013.04.17	Oral Presentation	Fundamentals and Development of Fuel Cells 2013, Karlsruhe, Germany
Next Generation PEM Electrolyser for sustainable hydrogen production	2012.06.21	Oral presentation	Let Hydrogen Move You!, Sustainable Energy Week, Brussels, Belgium
Development of Low Cost and Durable PEM Water Electrolysers. Research and Demonstration Activities in the FCH-JU Projects NEXPEL and NOVEL	2012.06.05	Oral presentation	WHEC 2012, Toronto, Canada
A New Highly Efficient PEM Electrolyser without Flow Channels, Operating at High Pressure	2012.06.05	Oral presentation	WHEC 2012, Toronto, Canada
Next Generation PEM Electrolyser for sustainable hydrogen production	2012.05.11	Oral presentation	Water electrolysis and hydrogen as part of the future Renewable Energy System, Copenhagen, Denmark
Advanced bipolar plates without flow channels,	2012.04.17	Oral presentation	Technoport, RERC, Trondheim, Norway

for PEM electrolysers operating at high pressure			
Next Generation PEM Electrolyser for sustainable hydrogen production	2011.10.26	Oral presentation	Hydrogen & Fuel Cells in the Nordic Countries Malmö, Sweden
Supported nanostructured Ir electrocatalysts for oxygen evolution in PEM electrolysers	2011.05.05	Oral presentation	219th ECS meeting, Montreal, Canada
Dynamic control of an electrolyser for voltage quality enhancement	2011.10.05	Oral presentation	The International Conference on Power Systems Transients Delft, The Netherlands

Planned scientific publications

At the end of the project, two peer reviewed publications have been published and/or accepted for publication (see table A below). These are the first of several scientific publications planned from the consortium. In the table below, a summary of six planned publications and their status is presented.

Tentative title	Content	Planned journal	Status
The NEXPEL project	main achievements and significant results	International Journal of Hydrogen Energy	In preparation, 40%.
Low cost stack design for PEM electrolysers	stack design/including performance data	International Journal of Hydrogen Energy	
Stability of supported Ir and IrRu electrocatalysts for oxygen evolution in PEM electrolysers.	catalyst stability/degradation	Journal of the Electrochemical Society	In preparation, 60%
Materials selection and construction of bipolar plates and current collectors for PEM electrolysers	bipolar plates and current collectors		
	post mortem analysis of stack components		Planned, will be published in collaboration with the NOVEL project.
Design of highly efficient DC/DC converter for coupling of water electrolysers to RES.	Paper on DC/DC converter, design, construction and testing		
Advanced Design and Performance of Polymer Electrolyte Membrane Electrolyser Operating at High Pressures	Cost analysis, components development, advanced stack design, performance data	Fuel Cells – From Fundamentals to Systems	Submitted

In addition to the scientific publications above, the a final summary report will be printed as a six page flyer in and distributed via the consortium partners to the scientific community and relevant national and regional stakeholders.

Planned workshops and conferences

The results from the NEXPEL projects will in the coming year be presented at several international scientific conferences and workshops as well as seminars intended for stakeholders outside the scientific community. See a summary in the table below.

Tentative title/content	Planned conference/workshop	Date	Targeted audience
Research and development of new materials and components for PEM electrolysers	IEA-HIA Task on Local Hydrogen Supply for Energy Applications	February 26th, 2013	Technology suppliers and end users
PEM electrolysis for production of hydrogen from renewable energy sources	Norwegian seminar on hydrogen production from wind power,	March 5th, 2013	Scientific community and public officials/stakeholders
Development of nanostructured electrocatalysts for PEM electrolysers and fuel cells	Nordic hydrogen and fuel cell conference 2013.	October 2013	Scientific community and public officials/stakeholders

NEXPEL partners

The NEXPEL project has seven partners:

- CEA LITEN
- Fraunhofer ISE
- FuMA-Tech GmbH
- Helion - Hydrogen Power
- SINTEF
- Statoil ASA
- University of Reading

Coordination contact details, public website and logo

NEXPEL coordinator:
Dr. Magnus Thomassen, Senior Scientist
SINTEF Materials and Chemistry
New Energy Solutions
Sem Sælandsvei 12, NO-7465 Trondheim, Norway
Phone: +47 98243439
e-mail: magnus.s.thomassen@sintef.no

NEXPEL public website: www.nexpel.eu

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