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# PROJECT FINAL REPORT

## Publishable summary report

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# Executive summary

The NOVEL project consists of a top class European consortium which is carefully balanced between leading R&D organizations and major industrial actors from five member states and associated countries. 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 NOVEL 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 radiation grafted 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 for use in PEM electrolysers.

An advanced cost break down model has been developed and a cost comparison between a conventional PEM electrolyser stack and a range of stack sizes with the NOVEL design and materials included. The cost break down show that a capital cost of 1500 €/$Nm^3h^{-1}$ is achievable, which is 25% lower than the project objectives. A simple cost analysis of the cost of the hydrogen produced show that a hydrogen cost below 4€/kg is achievable. The main remaining cost drivers for the NOVEL stack design is the anodic current collectors and the membrane electrode assemblies, indicating that there are still need for further research and development for improving the materials use in on the anode of PEM electrolysers.

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

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# 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 NOVEL project is to develop and demonstrate an efficient and durable PEM water electrolyser utilising the new, beyond the state of the art materials developed within the project. The electrolyser will demonstrate a capability to produce hydrogen with an efficiency of at least 70% (LHV) at rated capacity with a stack cost below €2,500/$Nm^3h^{-1}$ and a target lifetime in excess of 40,000 hours (< 15 $\mu Vh^{-1}$ voltage increase at constant load).

The NOVEL project consists of a top class European consortium which is carefully balanced between leading R&D organizations and major industrial actors from five member states and associated countries. 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.

- Electrolyser efficiency greater than 70% (LHV)
- A stack life time of 40 000 h
- A reduction in system costs to € 5,000/$Nm^3$ production capacity

To reach these objectives, NOVEL will develop and demonstrate enhanced 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
- Increase performance, in particular of the membrane electrode assembly (MEA), with reduced platinum group metals (PGM) loadings
- Longer life time of the most crucial PEM components, e.g. the membrane, catalysts and current collectors
- Novel system design for cost-efficient operation at high pressure and improved electrolyser lifetime.
- Development of accelerated stress test protocols for PEM electrolysers for lifetime evaluation and durability investigation of novel components.

The NOVEL project is a continuation of the NEXPEL project (www.nexpel.eu), taking advantage of the successes in the project and continuing the development of the most promising technical solutions as well as capitalizing on the existing, well-functioning, organisational structure of NEXPEL.

### WP1 Durability/Lifetime evaluation of PEM electrolysers

The key objective of this work package is the development of accelerated stress tests (AST) able to isolate and identify degradation mechanisms for the key components in a PEM electrolyser stack and to develop methods for lifetime prediction. The degradation of novel materials will be evaluated and experimental results will be used to develop a lifetime prediction tool with a multi scale model. An important activity in this WP is the detailed investigation of the degradation of NEXPEL stacks under real world operation. Results from this WP will give important feedback to the component development in WP 2, 3 and 4. Several iterations on testing of components under development will verify the progress in lifetime during the project period.

### WP2 Novel materials development

The objective of this work package is to develop new materials for electro-catalysts and novel membranes, including direct fabrication of catalyst layers using electro-spun supports and ALD coatings. The particulate catalyst materials should have high surface area, good stability and suitable structure for making porous catalyst layers. The fibrous catalyst layers must contain stable, high surface area support fibres and be able to be coated with oxide and metal layers via ALD.

For membranes, the aim is to produce films with low crossover, low degradation rates and high conductivity using both PFSA and radiation grafted membranes, such that operation is practical at higher temperatures. 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 mechanical stresses and temperatures (~80 ºC) experienced.

### WP3 Development of low cost MEAs

The key objective in this work package is to create an MEA with better than state of the art performance at significantly reduced cost. The MEA will use PGM-thrifted catalysts and catalyst layer designs and the new membranes from WP02. A further objective is a realistic assessment of the projected durability of the new MEA design using AST methods developed in WP1. There will also be a benchmarking activity using state of the art membranes and catalysts available at partners in the consortium.

### WP4 Bipolar plates and current collectors

The key objective of this work package is the improvement (and hence reduced cost of ownership) or replacement of the expensive titanium material for porous current collectors and bipolar plates. It will combine several coating techniques as well as mechanical and electrochemical evaluation of advanced coatings. Coating strategies for Ti and other construction materials will be evaluated and a selection of solutions will then be tested for further integration in the pilot scale stack. Evaluation of the feasibility for introduction of H2/O2 recombination catalyst on BPP and current collectors will be performed.

### WP5 Stack design and system optimisation

This work package is dedicated to the further improvement of the pilot stack design from the previous NEXPEL project and the assessment of the newly developed materials from work packages WP03 and WP04. The envisaged stack design improvements builds on evaluation in WP01 and is strongly linked with MEA development (WP03) and modified bipolar plates and current collectors (WP04). This will lead to some pilot scale stacks with various improvements in terms of performance and endurance.

Technical assessment of stack development will be supported by economical evaluation. Available cost break down model will be used to prove technical measures for component development in terms of investment costs. To meet required stack costs < 2,500 €/Nm³ H2, cost break down model permits definition of allowable component and manufacturing costs for the electrolyser stack.

The impact of the system running under conditions close to reality on stack degradation must also be studied. System optimisation study will be made to mitigate degradation induced by the system and its peripheral devices. Balance of plant components will be optimised to lower cost and improve system performance and lifetime.

# NOVEL Main Results

## *Durability/Lifetime evaluation of PEM electrolysers*

### Degradation at stack level (stack from NEXPEL)

At the start of the project a PEM electrolyser stack developed as part of the NEXPEL project were tested for long term durability. More than 6 000h of operating time was accumulated at 1 A/cm$^2$ and 35 bar$_g$ and 60°C. The most important results that were found from this experiment are summarized in Figure **1** below.

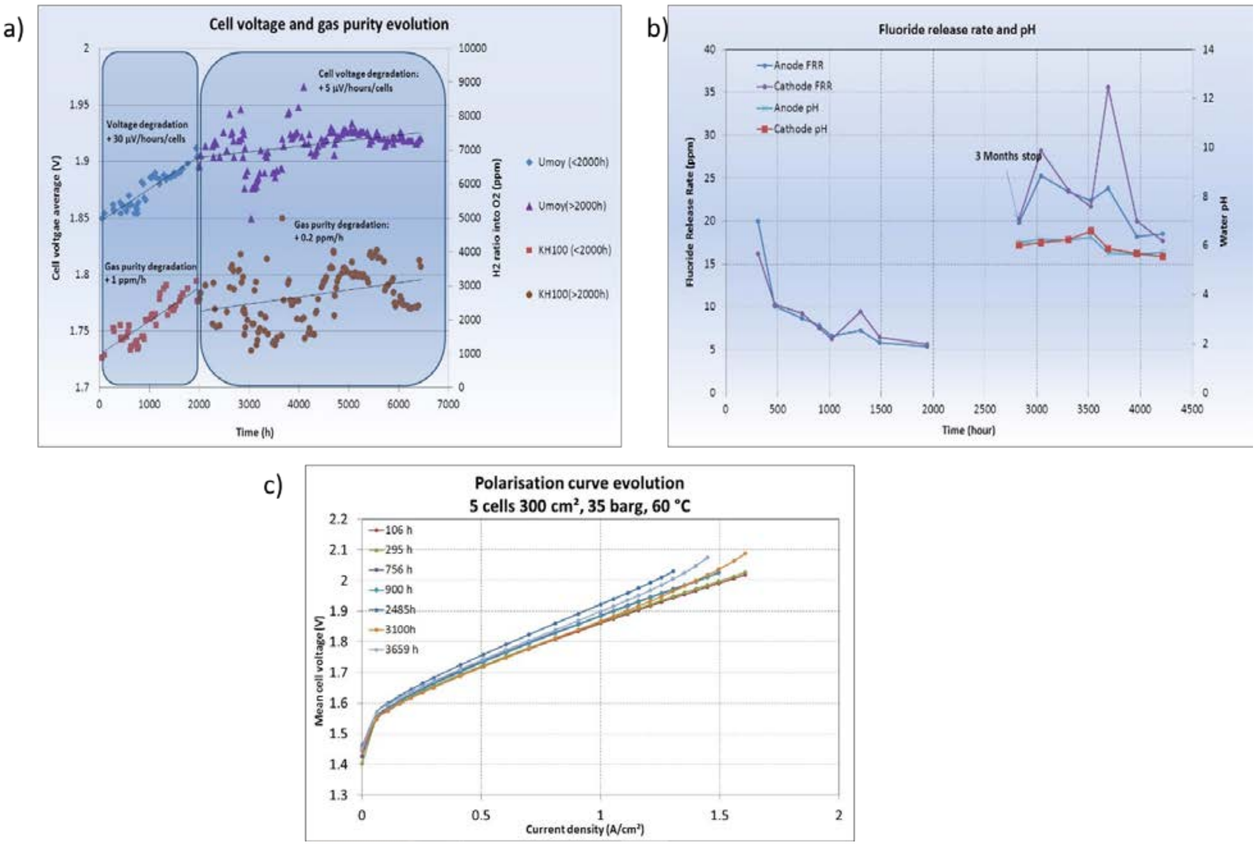

**Figure 1.** Main results of long-term stack test at 1A/cm2 for 6000h at 60°c and 35 bar$_g$

The degradation rate could be split in two regions a fast ageing period below 2 000h and then a smoother region after 2 000h. This trend was observed for the performance decay rate and for the gas purity degradation rate. The main reason for this degradation is assumed to be a change of the surface of the titanium sinters caused by $TiO_2$ growth. Concerning the membrane degradation and fluorine release, we assume that this is due to the leaching out of the weakly bonded side chain parts of the membrane that may detach and lead to high amount of fluoride release.

From these results, the extrapolation of the overall lifetime of the stack was performed. Based to these numbers, we could estimate the stack lifetime to 70 000h with a performance decay rate of 13 μV/h[1]. If the reasoning is applied on the gas purity with a gas purity degradation rate of 0.45 ppm[2] of $H_2$ in $O_2$ per hour. The stack lifetime is evaluated to 42 000h. These numbers highlight that the membrane degradation is the main cause of the stack end of life. In most cases, fluoride release rate which is an indirect consequence of the increase of the water impurity is quite well prevented by a careful monitoring of the water conductivity and exchange of ion exchange resins to keep the conductivity below 0.3 μS/cm (3.3 MΩ.cm).

Based on the tests performed above, AST protocols were developed to evaluate how those protocols may lead to the end of life state of the stack components in a shorter period of time. To this end, in the deliverable D1.4 “Accelerated Stress Test (AST) protocols for lifetime prediction of PEM eletctrolyzers” several AST were tested and AST-2 (0.3 A/cm$^2$ for 60 min and 3 A/cm$^2$ for 15 min at 90°C and 1 bar$_g$) was recommended as the most degrading protocol.

Bibliographical survey on degradation mechanisms in PEM WE.

A literature review of observed degradation mechanisms for components in PEM water electrolyseres were performed. Degradation mechanisms in PEM water electrolyzer are difficult to identify. As well as on PEM fuel cell, there is not a unique cause of degradation and mechanisms are usually coupled. The main difference with PEMFC is that in PEM water electrolysis, degradation mechanisms occurs very slowly with a typical characteristic time of thousands of hours, compared to hundreds of hours in PEMFC. In this report we propose different testing protocols that will be used as accelerated stress tests for PEMWE components used in the NOVEL project. These AST protocols are proposed on the basis of the partners’ expertise and review of the literature. They were discussed for each component and specific ageing tests were decided to evaluate their evolution during ageing. Results of these AST protocols will also be used to estimate or predict the durability of the electrochemical components in real operation conditions.

From the litterature review the following overview of degradation mechanisms for membranes, catalysts and bipolar plates were assembled:

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[1] This is weighted average (30 μV/h x 2000 h + 5 μV/h x 4000 h) / 6 000 = 13,3 μV/h

[2] This is weighted average (1 ppm/h x 2000 h + 0.2 ppm/h x 4000 h) / 6 000 = 0,45 ppm/h

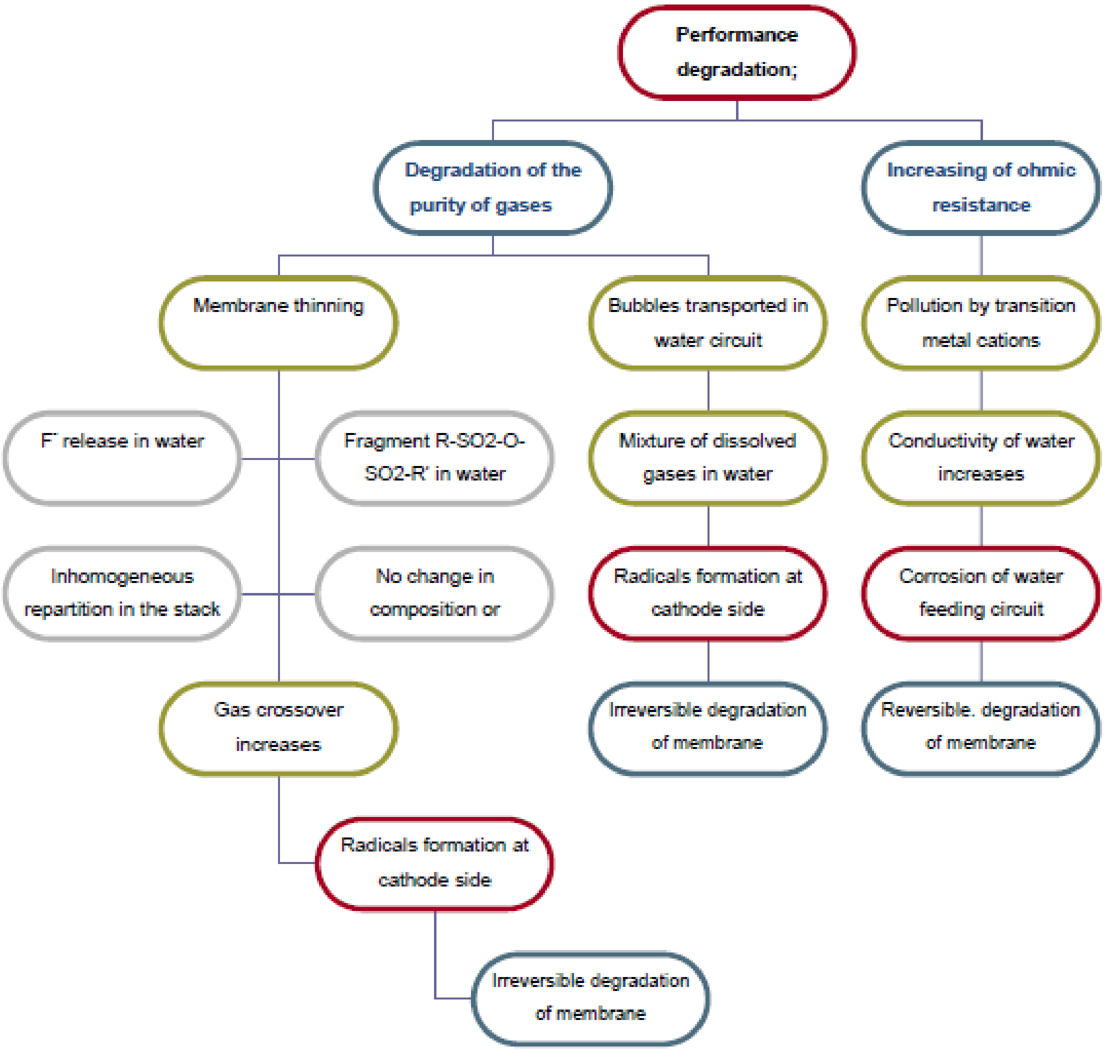


**Figure 2: Membrane degradation mechanisms overview**

**Figure 3: Catalyst degradation mechanisms overview**

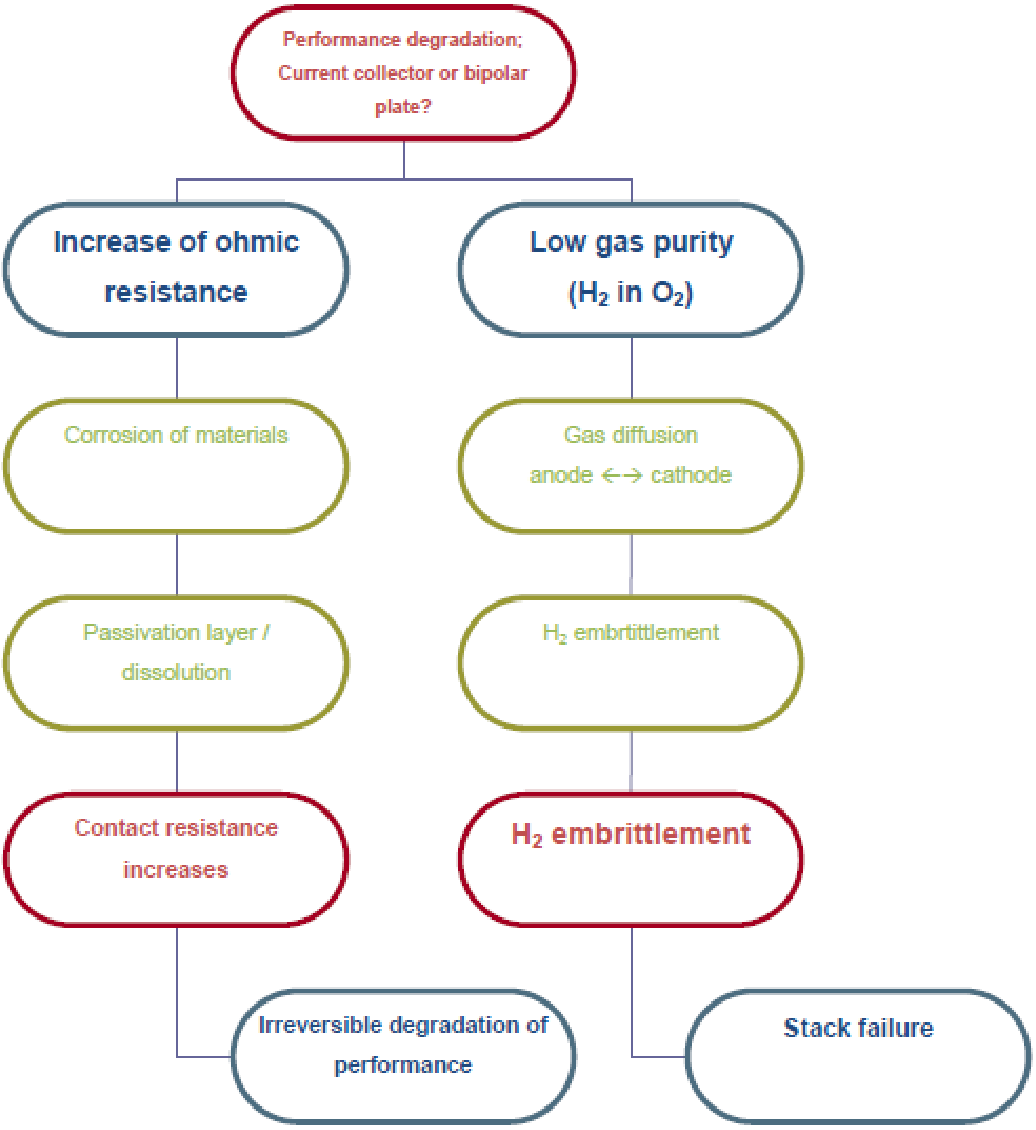
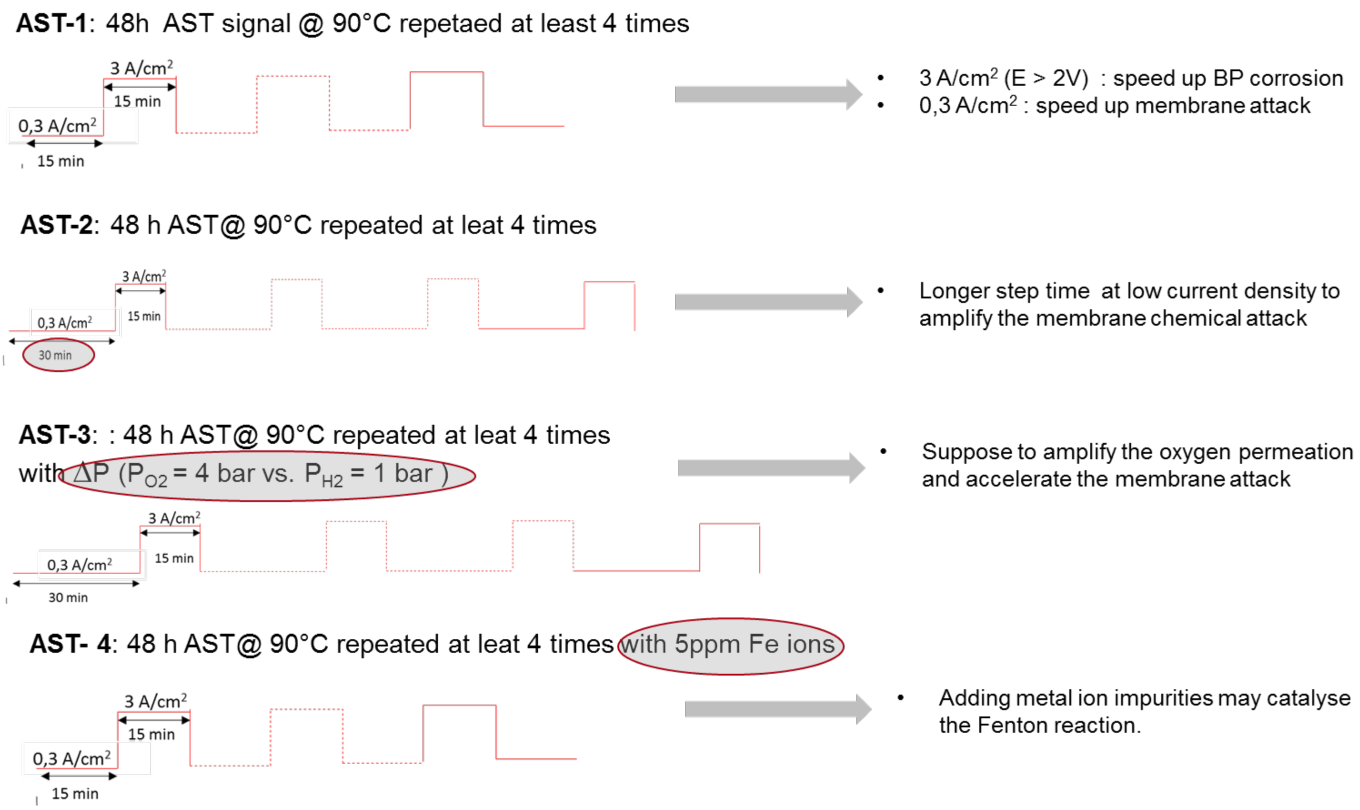


**Figure 4: Bipolar plate and current collector degradation mechanism overview.**

Degradation from AST at single cell scale.

Based on the evaluation of the stack degradation and the review of degradation mechanisms for PEM components and component ASTs, a set of AST protocols for single cells were developed and evaluated. The design of the protocols are based on the attempt to magnify two main degradations that occur on the Polymer Exchange Membrane Water Electrolysis (PEMWE) system, say: the membrane thinning and the increase of the electrical resistance. Beside those phenomena the active layers (anode and cathode) may also be altered.

The stress signals are based on step signals with a low current value in order to age the membrane and a high current value to oxidize the anode current collectors. The AST are performed at high temperature 90°C to be more aggressive on the different ageing mechanism. A test with pressure differential (PO2 > PH2 ) and polluted feeding water were performed. A schematic representation of the AST protocols developed are given in Figure 5.


**AST-1**: 48h AST signal @ 90°C repetaed at least 4 times

- 3 A/cm² (E > 2V) : speed up BP corrosion
- 0,3 A/cm² : speed up membrane attack

**AST-2**: 48 h AST@ 90°C repeated at leat 4 times

- Longer step time at low current density to amplify the membrane chemical attack

**AST-3**: : 48 h AST@ 90°C repeated at leat 4 times with ΔP ($P_{O2}$ = 4 bar vs. $P_{H2}$ = 1 bar )

- Suppose to amplify the oxygen permeation and accelerate the membrane attack

**AST- 4**: 48 h AST@ 90°C repeated at leat 4 times with 5ppm Fe ions

- Adding metal ion impurities may catalyse the Fenton reaction.

**Figure 5: AST protocols for PEM water electrolyser single cells.**

Using CCM MEAs comprising roughly 2 mg cm$^{-2}$ IrO2 and 1 mg cm$^{-2}$ Pt black over a membrane N115, we performed 4 different AST protocols labelled (AST-1, AST-2, AST-3 and AST-4). All the AST are characterized by square-wave signal with a low current density value of 0.3 A.cm-2 and a high current density of 3 Acm$^{-2}$. These values were chosen in order to stress mainly the membrane at low current density (low voltage) and stress the electrical contact resistance at high current density (high voltage). The AST differ one from the other by the following parameter by the duty cycle (50% at low current density for AST-1 and AST-4, 80% at low current density for the AST-2 and AST-3). In addition, special parameter was changed such as the pressure differential and 5 ppm of Fe in the feeding water for AST-3 and AST-4 respectively. To better understand the effects of the AST, we based the characterization of electrochemical measurements (polarization curves, ECSA, G-EIS) and also on ex-situ measurements (contact resistance, SEM images and fluoride release concentration). At the end of this study we found the following conclusions:

- The electrocatalytic activities are not impacted by the AST. The charge transfer resistances were not changed and the performance slope decay at low current density is much lower than at high current density.
- Despite some changes on the ECSA, these phenomena did not influenced the kinetic part of the polarization curve.
- Consistently with the polarization curves, the performance slope decay at high current is more important than at low current (125, 625 and 1020 mV.h-1 at 200, 1 000 and 2 000 mA cm$^{-2}$ respectively for the AST-1). This tendency is also supported by the increase of the HFR during the AST. Therefore the main effect of the AST is to degrade the ohm contribution of the cell (ionic and/or electronic percolation). However, a contradictory result was found comparing the potential slope that showed AST-3 as the most impacting protocol was AST-3 with 1380 mV/h at 2 Acm$^{-2}$ and the HFR slope during the AST that showed AST-1 as the most aggressive protocol.

- Comparing the SEM images after the AST, it was found that the AST-1 mainly degraded the electrode (it has shown many cracks on the anode and cathode layer) while the AST-2 and AST- 3 have aged the membrane which is became thinner (thinning rate about 50 nm/h from CEA observations). The cracks on the AST-1 may explain the poor interfacial contact resistance that was found during the G-EIS measurement.
- The higher thinning rate of the AST-2 is supported by the fluoride concentration measurement. We also found accordingly to what was reported from long-term stack durability test, after a period of time the fluoride content remain low and constant. This threshold is reduced from 1000h to 400h with the AST.

Based on these results we may recommend the AST-2 as the best ageing protocol among those were tested because it is able to both stress the membrane (50 nm.h-1) and ohm resistance (1.5 mWcm$^2$h$^{-1}$ for the contact resistance and 0.4 mWcm$^2$h$^{-1}$ for the HFR) as well.

## Modelling lifetime based on membrane degradation

Degradation mechanisms in water electrolysers are difficult to identify. In this work we have focused mainly on membrane degradation and study the impact of different operating conditions (current density and temperature) using both experimental and modelling means. Single-cell degradation tests are performed to study the impact of temperature and current density on membrane degradation. The chemical degradation is characterized by regularly collecting the effluent water of the cell at the anode and at the cathode sides and by measuring the fluoride release rate in the samples. Electrochemical characterization tests are also performed regularly to follow the performance evolution of the cell. A 1D polymer electrolyte membrane water electrolyser (PEMWE) performance model that incorporates chemical degradation of the membrane has been developed. In the 1D performance model, electronic and ionic transports through the different cell components are considered together with the electrochemical behaviour of the anodic and cathodic catalyst layers. The membrane degradation model describes the oxygen cross-over from the anode side to the cathode side, the formation of hydrogen peroxide at the cathode side together with the subsequent formation of radicals via Fenton reactions involving metal-ion impurities and the membrane degradation. The single-cell degradation tests confirm that most of the membrane degradation occurs at the cathode side and show the strong influence of the temperature and current density on the degradation rate. The influence of these two operating conditions on PEMWE membrane degradation is well captured by the model. Based on these results, the model is used to study the time evolution of the membrane thickness and to study the impact of both temperature and current density on the life-time of the electrolyser

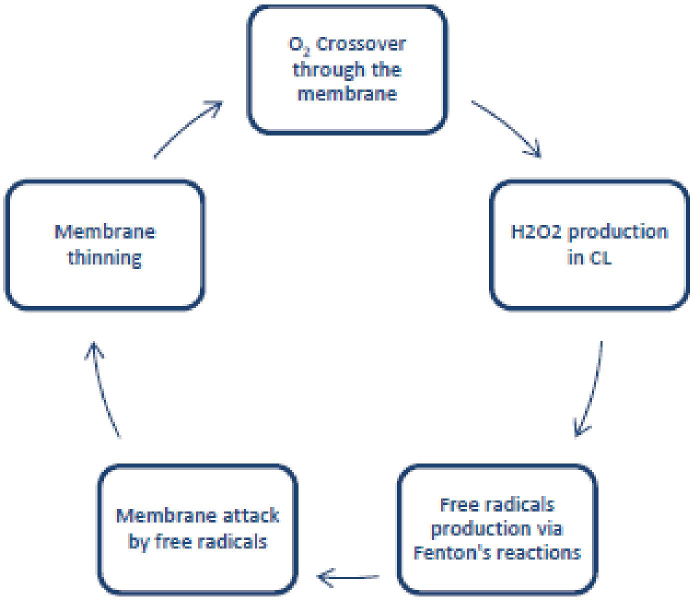


**Figure 6: Chemical membrane degradation scenario**

## *Novel materials development*

### Catalyst development and characterization

The main objective for this activity has been to develop new catalyst materials for the hydrogen and oxygen evolution reaction in PEM electrolysers with the potential for reduced use of noble metals such as Pt and Ir.
For the hydrogen evolution reaction, the aim was to demonstrate catalysts for PEM electrolysers that have higher mass activity, in terms of A/mgPt, than Platinum black for the HER that takes place on the electrolyser cathode. In many electrochemical applications, a simple way to improve the mass activity of Pt is to disperse it on a high surface area carbon support such that the surface area to volume ratio of the Pt is increased and the chance of sintering is reduced, compared to Pt black, by avoiding Pt-Pt contacts. The main concern with this approach for the hydrogen electrode of the PEM electrolyser is the possibility of generating hydrogen peroxide on the carbon, as a result of the reaction between hydrogen generated on the cathode and oxygen that crosses over from the anode, through the membrane. Similar conditions at the anode of PEM fuel cells have been shown to generate hydrogen peroxide, which can decompose at impurities within the membrane leading to radicals that attack the membrane. To address these questions, a range of Pt/C Pd/C and Pt black catalysts were synthesized at JMFC and supplied to SINTEF for electrochemical evaluation, because SINTEF had suitable test capability and experience in rotating ring disk electrode (RRDE) testing. At SINTEF, an evaluation of the formation of hydrogen peroxide on the catalysts was performed, together with a measure of the HER mass activity. The evaluation was performed by applying an experimental approach designed to quantify the amount of hydrogen peroxide generated in the H2-evolution region
From the applied experimental approach developed, several catalyst samples consisting of both supported and unsupported noble metal catalysts were analysed and one sample was found to have almost one order of magnitude higher mass activity as well as a significantly reduced peroxide production than state of the art catalysts.

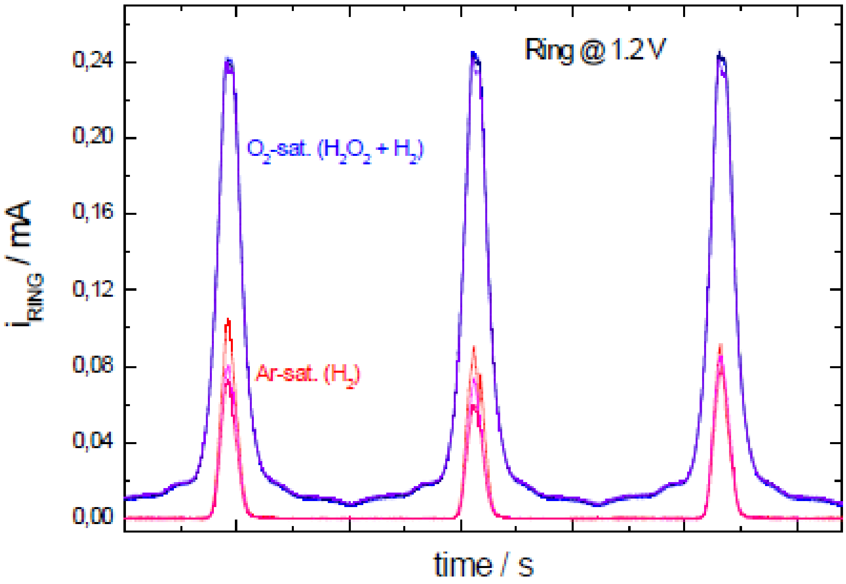
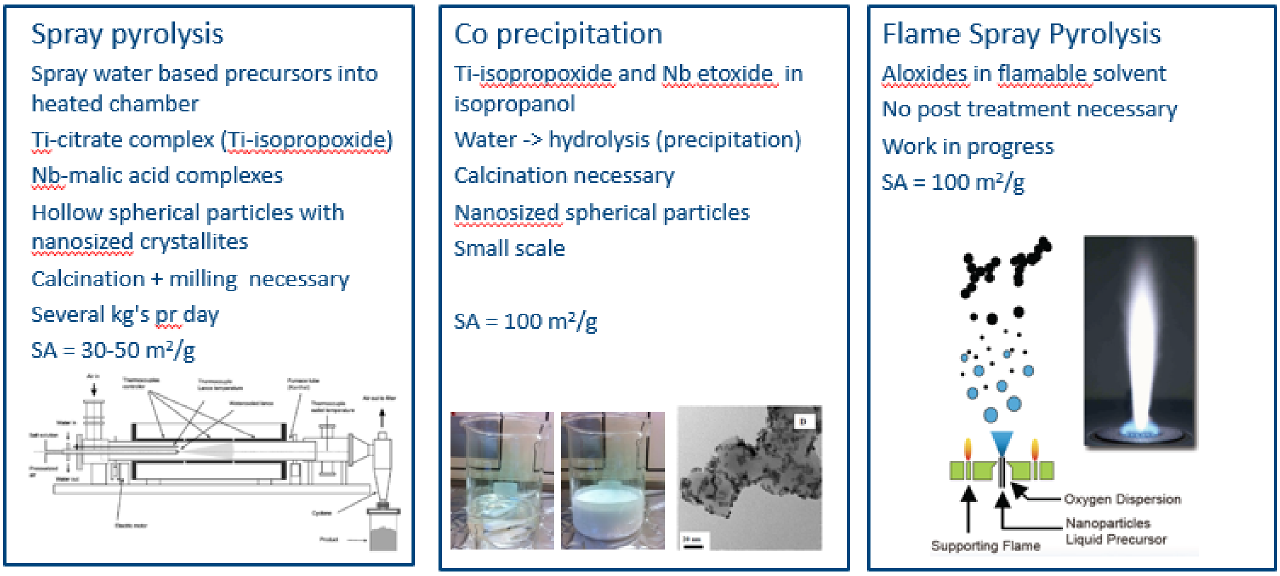


**Figure 7: Example of response to peroxide production under oxygen atmosphere for cathode catalysts.**

For OER catalysts in PEM water electrolysis there are only a few selected materials that can withstand the environments during operation, both as support materials for the electrocatalysts and as electrocatalysts. Due to the high electrochemical potentials and $O_2$ partial pressure on the anode, the materials will be oxidized during operation, thus the range of suitable materials tends to be limited to oxides. The challenge in using an oxide support material is to achieve sufficient conductivity and sufficient surface area with oxide materials that can tolerate acidic environments. Based on this we have limited the work on supports to $TiO_2$ based materials and new, mixed oxides as catalysts described below.

Ir based catalysts have been deposited onto support materials based doped on $TiO_2$ and $SnO_2$. The catalysts show good anchoring to the support materials, Even though the conductivity of the support based on doped $TiO_2$ is much lower than ATO support, the conductivity of the support with catalyst is in the same range, demonstrating that the conductivity of the support is not as critical as previously assumed. However, the performance of the catalysts using $TiO_2$ support in an electrolyzer is lower than using ATO due to higher resistance and high frequency behaviour.

The support materials based on $TiO_2$ have been synthesized by different methods to evaluate the overall properties as support materials. The materials have been synthesized by spray pyrolysis, co-precipitation method, flame spray pyrolysis and template assisted synthesis. $TiO_2$ has been doped with Nb and Ta in various amounts and heat treated at different temperatures and atmospheres to enhance the electrical conductivity, whilst keeping the surface area as high as possible.



**Spray pyrolysis**

Spray water based precursors into heated chamber

Ti-citrate complex (Ti-isopropoxide)

Nb-malic acid complexes

Hollow spherical particles with nanosized crystallites

Calcination + milling necessary

Several kg's pr day

SA = 30-50 m²/g

**Co precipitation**

Ti-isopropoxide and Nb etoxide in isopropanol

Water -> hydrolysis (precipitation)

Calcination necessary

Nanosized spherical particles

Small scale

SA = 100 m²/g

**Flame Spray Pyrolysis**

Aloxides in flamable solvent

No post treatment necessary

Work in progress

SA = 100 m²/g

**Figure 8: Synthesis methods used for conductive catalyst supports in the NOVEL project.**

Ir has been deposited on the supports using the polyol method for electrochemical characterization of the combined support and electro-catalyst materials. In addition, a range of catalysts with varying levels of Ru have been prepared and evaluated for activity and stability.

Figure 9 shows a TEM image of $TiO_2$ doped with 10% of Nb with an Ir electrocatalyst added using the polyol method. As can be seen from the micrograph, the Ir particles are well dispersed on the surface of the support. The overall loading of Ir on the support was characterized using energy dispersive spectroscopy during electron imaging of the samples. The Ir loading versus target loading was dependent on the available surface area. Higher surface areas resulted in loading similar to the targeted loading, while lower surface areas resulted in significantly decreased loadings compared to the target loading

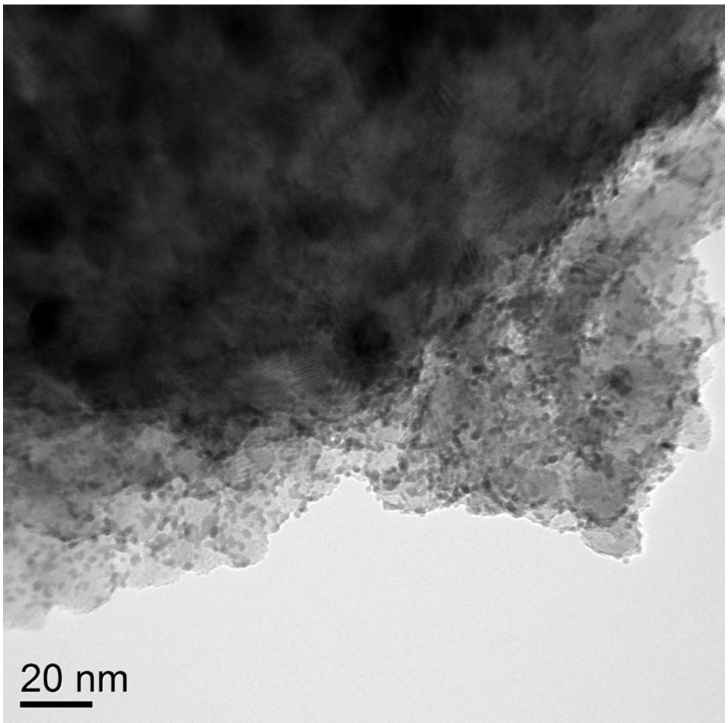


**Figure 9: TEM image of Ir deposited on TiO2 doped with 10% Nb**

Figure 10 shows the mass-normalised oxygen evolution activity of two supported Ir electrocatalysts based on Nb doped TiO2 and Sb doped SnO2 as well as the activity of an unsupported Ir black electrocatalyst. The measurements have been performed using a RDE electrode in 0.5 M H2SO4 at room temperature. It can clearly be seen that the two supported catalysts have approximately a threefold higher mass activity than the unsupported Ir.

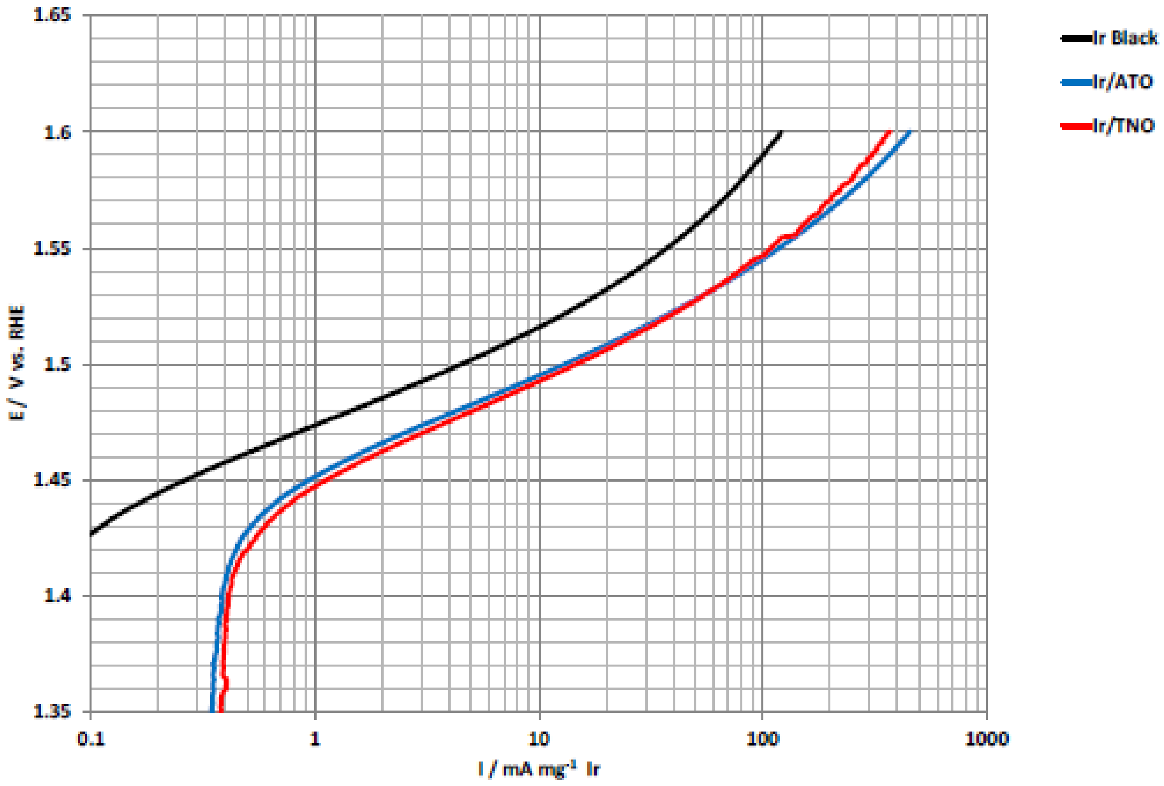


**Figure 10: Anodic polarisation curves of a set of Ir catalysts in 0.5 M H2SO4 at 25°C using a RDE electrode**

A number of new unsupported oxygen evolution catalysts based on iridium oxide have also been produced and tested for activity and stability. Whilst it has been possible to form different oxides and mixed metal oxides, which show better activity or stability than the commercially available iridium oxide black selected earlier in the project for the CCMs for stack testing, it has not been possible to demonstrate both in the same catalyst during this project.

The properties of the electrolyte membrane in the water electrolyzer have a substantial impact on the achievable current density and efficiency of hydrogen production. The ohmic losses associated with the membrane are the dominant losses at high current density, say above 2 A/cm$^2$. The key membrane properties for electrolysis application that were addressed in this project are ohmic resistance, $H_2$ crossover, mechanical robustness and chemical stability.

Radiation grafted membranes have been shown to be a promising alternative to Nafion® type membranes. They have the potential to be of much lower cost than perfluorinated membranes, which are currently widely used. In NOVEL it was shown that radiation grafted membranes with carefully chosen monomer combinations can show significant advantages over Nafion® type membranes in terms of these properties. *Ex situ* stability tests in hot water was used to down-select candidate membranes for tests in the electrolysis cells

Electrospinning has shown to be able to produce highly porous webs with a wide range of properties suitable for reinforcing conventional PFSA membranes. The best performing of these has shown improved mechanical properties combined with high proton conductivity and low hydrogen crossover and so should be a good candidate for future PEM electrolysis membranes.

For the quantitative assessment of membrane properties and to characterise the suitability of the various membrane types for application in the water electrolysis cell, a figure of merit M is introduced, taking into consideration ohmic resistance, H2 permeation and mechanical robustness:

$$M = \frac{W}{R_{\Omega} \cdot i_x}$$

Where W is the fracture toughness of the membrane (in MPa or J/cm3), RΩ is the areal resistance of the membrane (in Ω·cm2) and ix is the H2 crossover current density (in mA/cm2). The figure of merit M therefore has the unit MPa/V or C/L. For the series of Nafion membranes, M = 0.26 (± 0.08) ·MPa/V. The aim for the development of alternative membranes is, in addition to reducing cost, to improve this figure of merit in comparison to Nafion®. In Figure 11, the characteristics of the membranes developed in the framework of the NOVEL project are shown.

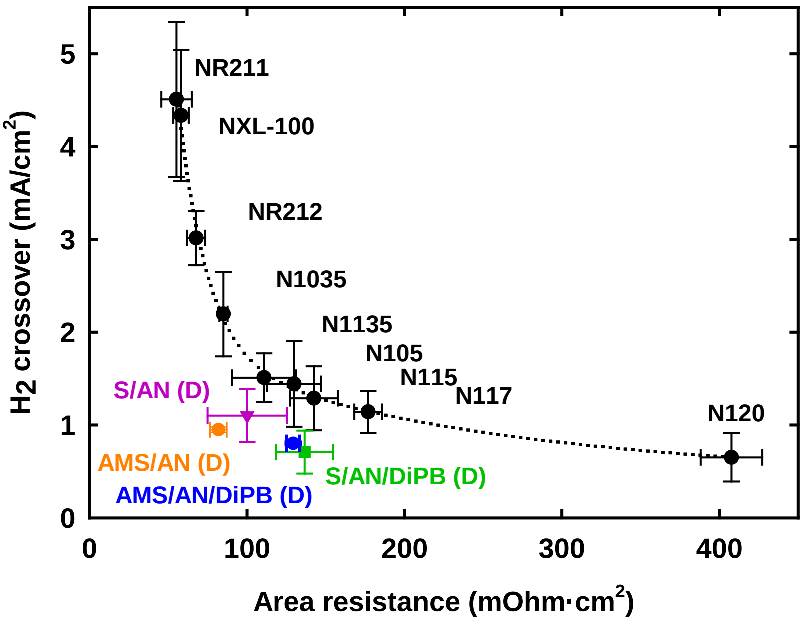


**Figure 11: Figure of merit for Nafion and ETFE membranes tested in NOVEL.**

## *Advanced MEA development and manufacture*

The membrane in an electrolyser Membrane Electrode Assembly (MEA) has a significant influence on the performance, durability and cost of the assembly. In an attempt to reduce the cost and improve the performance, radiation grafted membranes have been produced by the Paul Scherrer Institute (PSI). Samples based on a range of different base films, with or without a cross linker, have been produced and the properties characterized ex-situ. The membranes have an improved combination of conductivity, crossover and mechanical properties (stability) compared to state of the art Nafion membranes. These improvements were captured in a figure of merit, as defined in Figure 11.

Catalyst layers were by Johnson Matthey deposited directly on to the radiation grafted membrane according to a process developed in the project and the coated MEAs were sent to SINTEF to test in single cell electrolyser hardware of 5 x 5 cm active area.

Polarisation curves were measured for the samples using GKN Ti sinters, which had been through a cleaning process prior to use. On initial testing of the MEAs containing radiation-grafted membranes, it was not possible to reach current densities of 1 Acm-2 for any of the samples. As such, the typical conditioning protocol could not be followed. As can be seen in Figure 12, however, at low current densities a number of the samples are matching the commercial Solvicore MEA performance, which uses a perfluoro-sulphonic acid (PFSA) ionomer membrane. The best performing sample has equivalent or better performance up to 0.5 Acm-2 with a membrane showing a higher figure of merit than Nafion/PFSA membranes. It can also be seen that the curves do not follow the behaviour expected from the combination of Butler-Volmer kinetics and uncompensated resistance that was demonstrated by the Solvicore MEA.

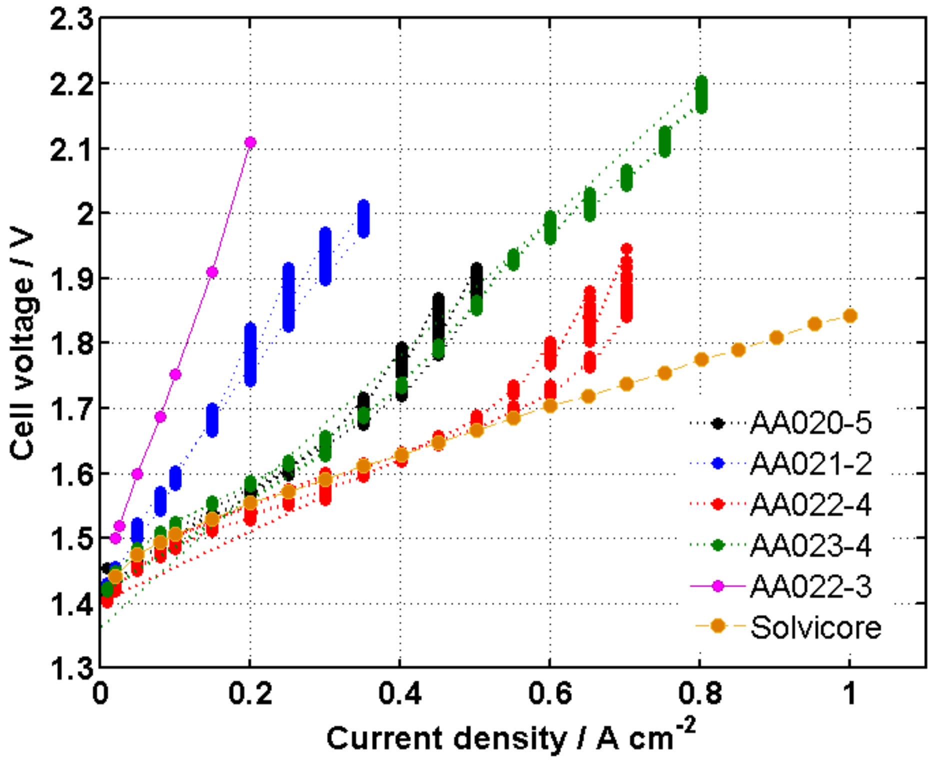


Figure 12: Polarisation curves for different MEAs produced using radiation grafted membranes. All testing was carried out at 80 °C with 500 ml min-1 of Milli-Q grade water on anode and cathode sides.

Following a final material down-selection exercise half way in the project, work has taken place to optimize the CCM configuration to maintain high performance whilst reducing costs through optimization of the membrane and anode catalyst layer in an attempt to achieve both the precious metal loading and performance targets set in the project.
The preferred membrane was found to be a modification of existing perfluorosulphonic acid (PFSA) membranes designed for automotive fuel cell applications. A stack of these membranes with additional recombination catalysts showed lower hydrogen crossover and higher conductivity than state of the art materials.

MEAs were produced via a route suitable for pilot / small production scale and have in single cells shown a beginning of life performance that is in line with the project performance targets, as shown in Figure 13

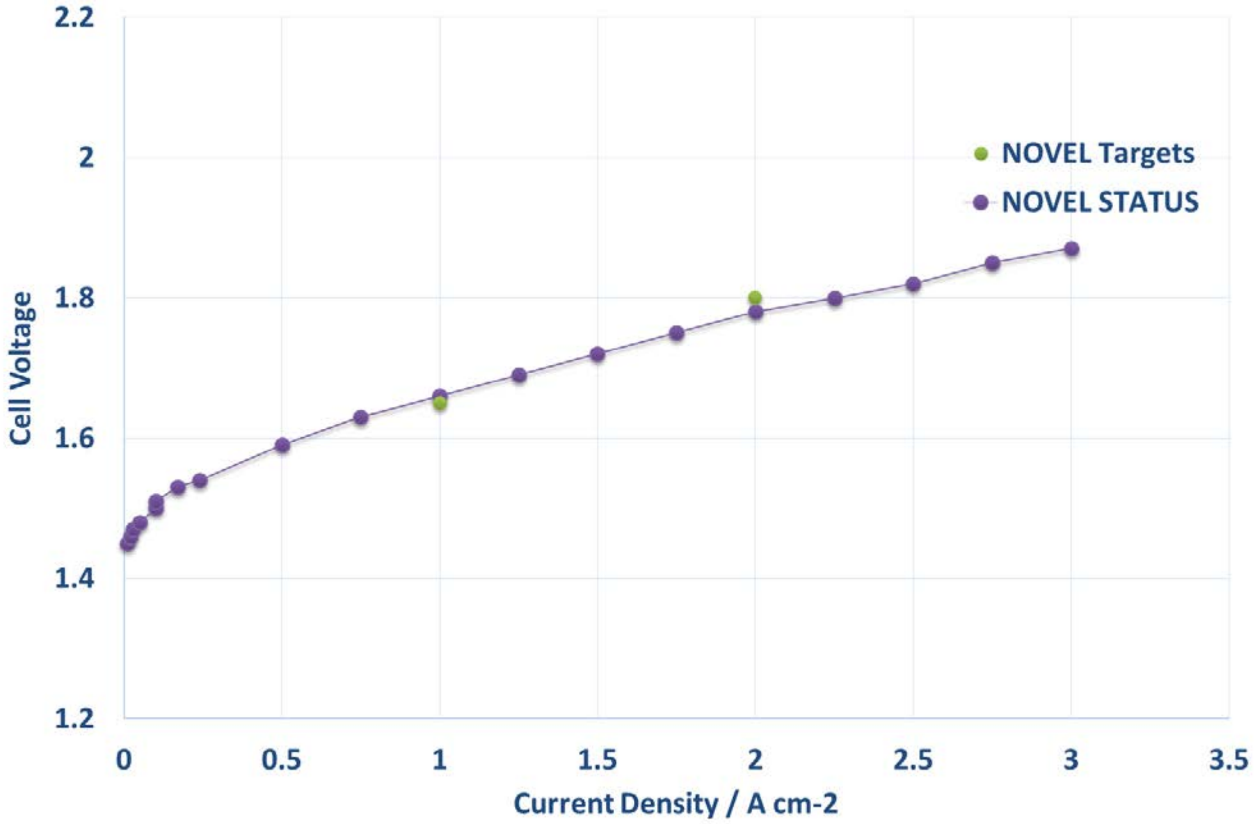


**Figure 13: Performance of final NOVEL MEA tested in laboratory single cell and compared with NOVEL performance targets.**

## *Porous current collectors and materials for bipolar plates*

The objective of this activity is the improvement or replacement of the expensive titanium material and/or noble metal coatings used for porous current collectors and bipolar plates by coatings, which suppress the formation of high contact resistances based on lower cost materials.

Coating strategies were developed and candidate materials for bipolar plates and current collectors were selected. For this, a review of state of the art for thin film coatings on electrolysers, leading to an agreed prioritized list of candidate coatings for evaluation was given, and benefits and drawbacks for different coatings methods available were described, including possibilities for integration of coatings for catalytic recombination to increase gas purity.

Closed field unbalanced magnetron sputter ion plating (CFUBMSIP) technology has been used by TeerR Coatings Limited (TCL) as a primary procedure for the development of NOVEL coatings for bipolar plates and current collectors. For comparison, HIgh Power Impulse Magnetron Sputtering (HIPIMS) and linear ion source (LIS) technologies are also being investigated. HIPIMS power supplies (with a compatible substrate bias supply) and a linear ion source (with an associated high voltage power supply) have been integrated into TCL’s deposition systems. At Fraunhofer ISE, balanced magnetron sputtering was applied as it is used in large area coating processes.

Corrosion and interfacial contact resistance (ICR) testing facilities have been set-up and applied.

Given that the electrochemical conditions on cathode sides during electrolysis are different from those on anode sides, different coatings have been applied on each side rather than effectively over-specifying the coatings on cathode sides by using the same coating on the anode and cathode. Metallic coatings have been chosen as the primary approach for the anodic coating developments.

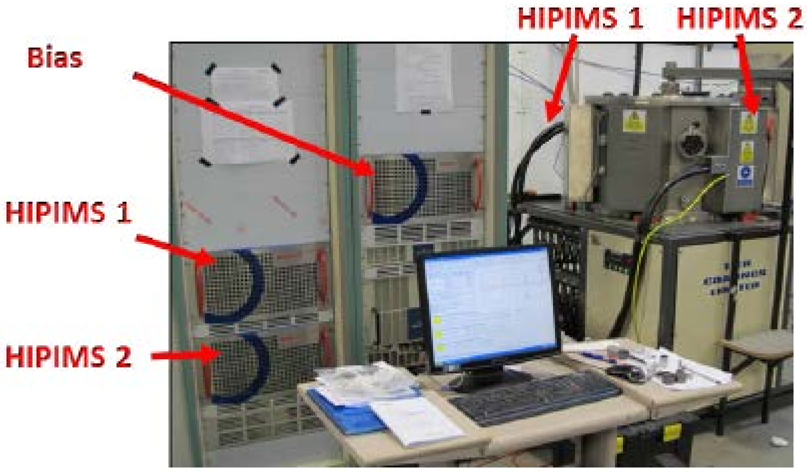


**Figure 14: One bias and two HIPIMS power supplies integrated in TCL’s coating system**

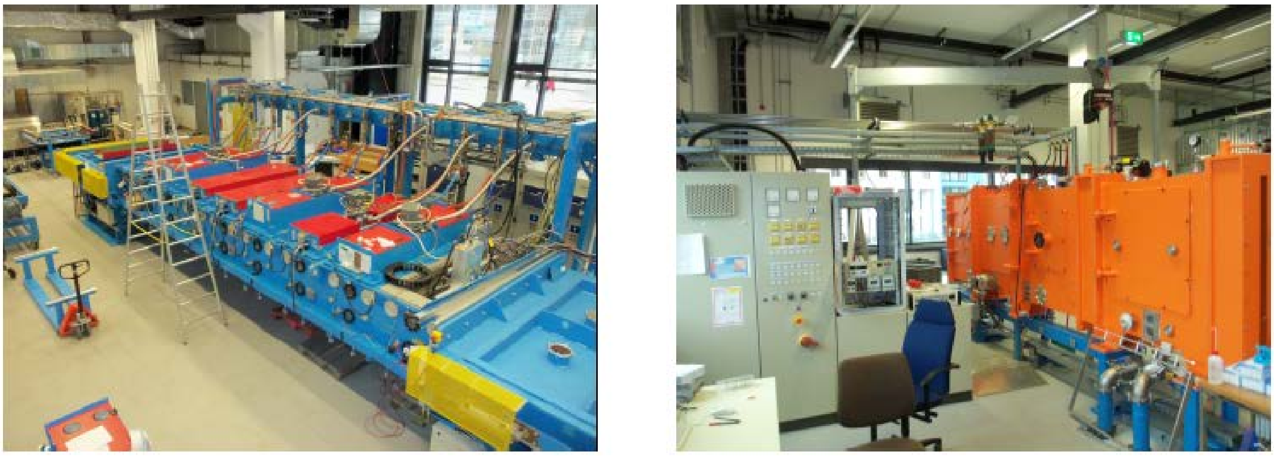


**Figure 15: Magnetron Sputter Coaters at Fraunhofer ISE**

The coatings developed in the project have been tested with respect to their contact resistance and stability against corrosion in ex-situ setups. Physical and electrochemical methods of evaluation have been developed. The focus was on utilizing a a fortified stress test, which allows comparing a set of coated bipolar plates with respect to their corrosion stability. Here, an accelerated stress test protocol has been developed for an ex situ testing of the corrosion stability of coated bipolar plates. It was applied on a set of coatings. Coatings have also been tested for their adhesion to the substrate material. The most promising coatings show after being exposed to the *ex-situ* AST test a significantly lower contact resistance than uncoated Ti bipolar plates, as shown in Figure 16.

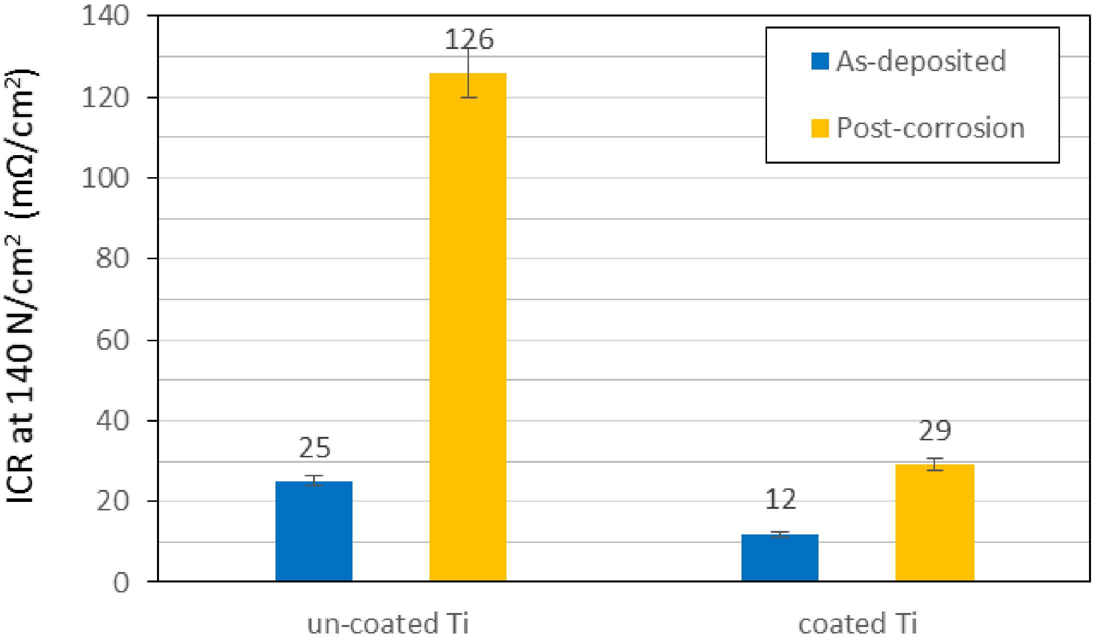


**Figure 16: Comparison of contact resistance of an uncoated Ti and coated Ti before and after AST corrosion test.**

Coated bipolar plates and porous current collectors have been produced on stack scale for integration in prototype stacks at Fraunhofer and ArevaH2Gen. The coatings have been applied to various parts of the stack to produce a rainbow stack where the effect of coating on each part can be extracted. See the figure below for one example of this strategy.

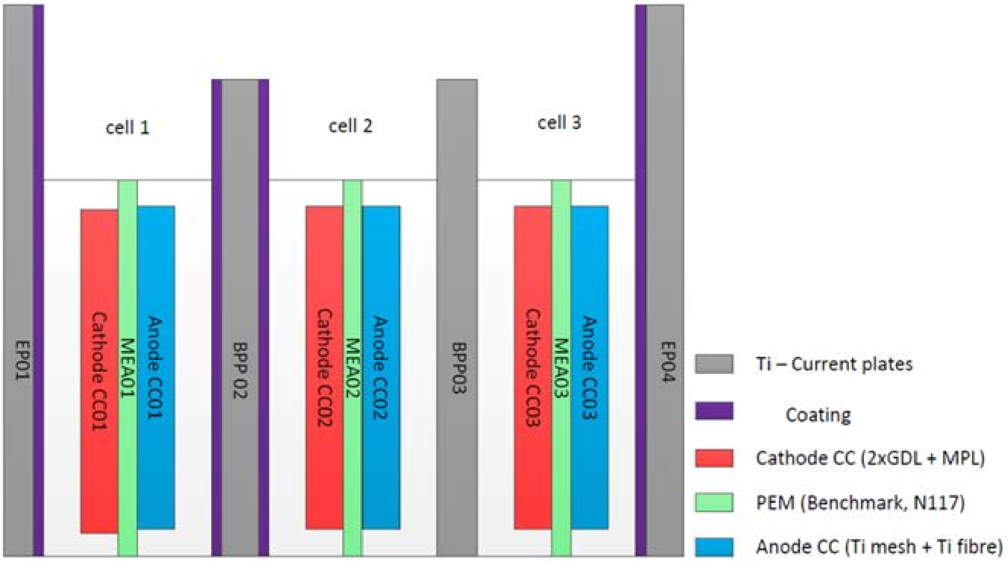
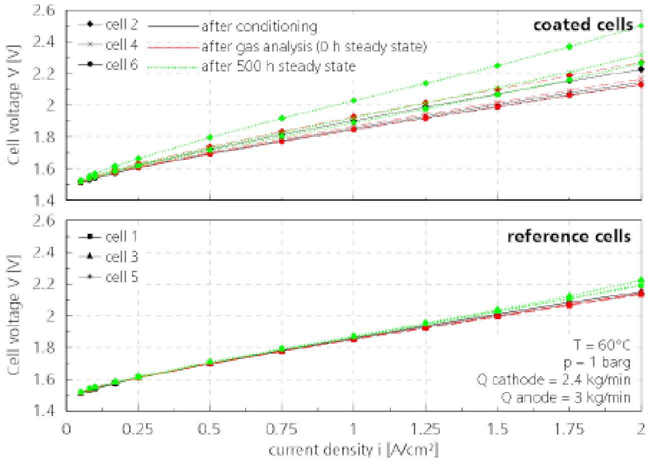


**Figure 17: Composition of coatings in rainbow stack at ArevaH2Gen.**

Several rainbow stacks were assembled and tested during the final part of the project, but no clear effect of the applied coatings could be determined from these tests as the variation of performance between cells were too high for any statistically significant difference between coated and uncoated cells could be observed.

A single cell study of the coatings were also performed by Fraunhofer ISE, showing that the coated cells have a slightly better performance and the uncoated reference cells during the first 500h of operation.

- Uncoated cells show low increase of cell voltages over 500 h (see steady state)
- Coated cells show different increase of voltage



| 1 A/cm², 60°C, 1 barg | 0 h steady state | 500 h steady state |
|---|---|---|
| coated | 1.880 V ( $\eta_V$ = 79 % HHV) | 1.946 V ( $\eta_V$ = 79 % HHV) |
| uncoated | 1.851 V ( $\eta_V$ = 80 % HHV) | 1.868 V ( $\eta_V$ = 79 % HHV) |

## *Optimised stack design and manufacture*

This activity has been dedicated to the further improvement of the pilot stack design from the previous NEXPEL project and the assessment of the newly developed materials and component solutions in the project. During the project, 6 stacks were assembled by the project partner Fraunhofer ISE. An overview of all stacks, with information to the materials, the time in steady-state operation and a central statement is given in Table 1.

**Table 1: Information on tested stacks during the Novel Project. The table contains information on cell number, used materials and time in steady-state operation**

| Stack No | No. of cells | Project partner | Materials used | Time in steady-state operation [h] |
|---|---|---|---|---|
| **1** | 5 | Fraunhofer ISE | Nafion 117 based benchmark MEA; No coating | 1250 |
| **2** | 3 | Fraunhofer ISE | Stacked MEA (by projectpartner JM) with recomb. Layer; partially coated (by proejctpartner TEER-Coating) | 380 |
| **3** | 3 | Fraunhofer ISE | Stacked MEA (by projectpartner JM) with recomb. Layer; partially coated (by proejctpartner TEER-Coating) | 0 |
| **4** |  | Fraunhofer ISE | Nafion 117 based benchmark MEA; partially coated (by proejctpartner TEER-Coating) | 1314 |
| **5** | 6 | Fraunhofer ISE (demonstrator stack) | Stacked MEA (by projectpartner JM) with recomb. Layer and reduced Ir loading of anodic catalyst | 1125 |
| **6** | 6 | Fraunhofer ISE (reference stack) | Nafion 117 based benchmark MEA (improved catalyst layer); partially coated (internal coating) | 1960 |

The large number of stacks was a necessity for evaluating material variations during the project period. The concept was developed to have cost efficient stack design by using materials that can be produced by industrial proved high throughput processes. Also, a big learning procedure concerning stack assembly was necessary to improve reproducibility in stack testing. Therefore, a significant learning process was passed for the involved project partners during these stack tests.

The most important improvements concerning stack testing and long term characterization of electrolysis stacks that were realized within this project are:

1. In situ and ex situ test procedures for long term measurements + characterization methods The in situ procedure that was developed within Novel based on previous long term stack tests at Fraunhofer ISE. The procedure was adapted and refined to the new developed test bench (also developed within Novel) and the stack platform. The ex situ methods were extended to see degradation effects. For example, SEM cross section analysis for measuring

membrane degradation, interfacial contact resistance (ICR) and reflectance measurement to measure BPP and PTL degradation, were newly applied.

2. Preparation of the stack materials and assembling procedure
   The preparation procedure could be improved by higher precision of the stack components (mainly the BPP), the change in pretreatment of these and the change from the initial way of using the tightening torque to measuring the distance between the BPP. All these changes leaded to more homogeneous clamping pressure on the active area and therefore to lower variation between each cell.

3. Structure of the porous transport layers (PTL) on anodic and cathodic side
   As PTL on anodic side, a commercial dual layer concept consisting of a highly porous Ti mesh and an overlaying Ti fibre sinter was used to achieve high hydraulic permeability and homogeneous clamping pressure on the active area, mostly eliminating fluidic bypasses.

AH2GEN’s NOVEL final pilot stack ready for system qualification

ISE’s NOVEL final pilot stack ready for system qualification

The technical assessment of stack development has been supported by economical evaluations through development of a cost break down model and a study of the overall cost of a PEM electrolyser stack depending on the design and operation condition of the stack.

The stack design used in the cost break down is a square design based on Titanium bipolar plates and injection moulded polymer frames. For anodic and cathodic current collectors, Titanium and carbon is used.

Based on cost data from partners and from external suppliers as well as own experience on stack assembly and qualification, an overall stack cost below the target of 2.5 k€/Nm$^3$ $H_2$ was achieved. A significant cost reduction is also expected by increasing the cell active area from 300 to 1200 cm$^2$, which is caused by more efficient material use and lower labour costs. The main capital cost drivers were identified to be the MEA and anode current collectors, contributing to more than 70% of the overall cost (Figure 18), in which the MEA cost is dominated by the production process and not the catalyst material costs itself.

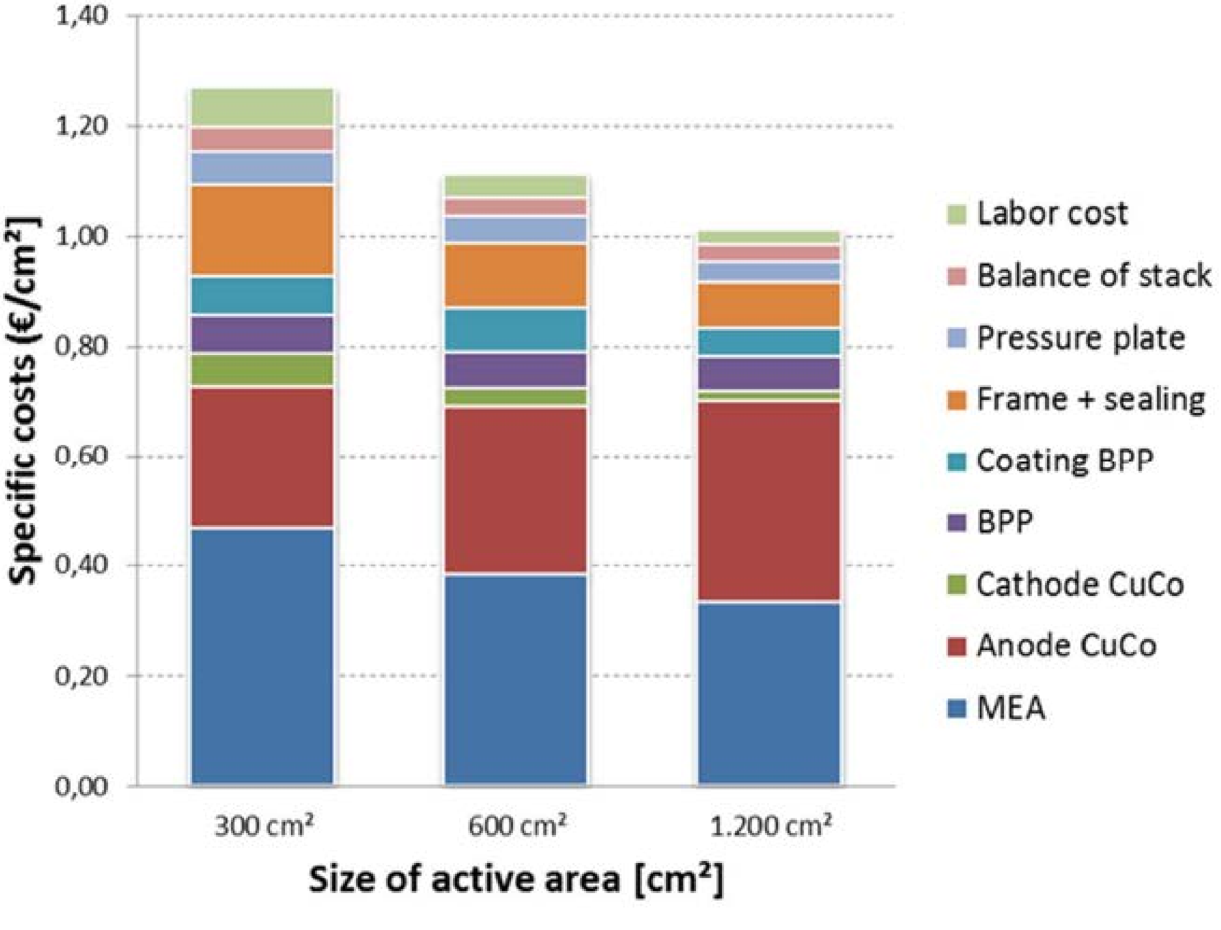


**Figure 18: Cost break down of NOVEL stack.**

# Potential impact

In the NOVEL project, development of new materials and component solutions for realisation of lower cost PEM electrolysers have been in focus. By investigating different approaches to avoiding or minimizing the use of noble metals in the catalytic layers and as coatings for bipolar plates and current collectors, significant cost reduction potentials have been identified. In addition to the reduction of the use noble metals, low cost radiation grafted membranes and MEAs based on laminated automotive fuel cell membranes have been investigated.

Several of these solutions have been implemented in demonstrator electrolyser stacks and others are under further development. This again is reflected in the dissemination plan exploitation an, where a number of scientific papers and patents based upon the results obtained in the project are planned for publication in the coming year.

A wider socio economic impact is expected by implementing and further developing the concepts studied in this project by reducing the capital costs of electrolysers and thereby reducing the cost of producing hydrogen from renewable energy as well as opening up for more use of intermittent energy as the lower capital costs enables less full time hours of use while still ensuring a return of investment. The reduced demand for critical raw materials by noble metal thrifting is also a contribution from this project to securing and reducing the risk of supply of these materials to Europe's economy.

## *Accomplished dissemination activities*

Significant results from the project have continuously been disseminated to the scientific community through at least 18 oral presentations and 7 poster presentations (of which 3 have received best poster awards) at major international conferences such as WHEC and HFCC meetings as well as seminars and workshops targeted to a wider community of private and public stakeholders. Four journal publications and one book chapter have also been published. Details on publication activities are given in the table below.

The consortium has organised two international seminars on degradation and durability of PEM electrolysers. Each with more than 100 participants. Presentations from the seminars, as well as condensed reports on the main findings from these are available on the NOVEL webpage.

## *Planned scientific publications*

In addition to the five publications from the project, two more publications are planned. In the table below, their status is presented.

| Tentative title | Content | Planned journal | Status |
|---|---|---|---|
| **The NOVEL project** | main achievements and significant results | International Journal of Hydrogen Energy | In preparation, 30%. |
| **Proton conducting membranes for water electrolysis with low resistance and high hydrogen barrier properties** | key outcome of research on partially fluorinated membranes | Journal of Materials Science A | In preparation, 70%. |

## *Planned workshops and conferences*

The results from the NOVEL project 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 |
|---|---|---|---|
| **Towards selective test protocols for accelerated in situ degradation of PEM electrolysis cell components** | European PEFC & Electrolyser Forum | 04.-07.06.2017 | Scientific community |
| **Cost Break Down and Cost Reduction Strategies for PEM Water Electrolysis Systems** | European PEFC & Electrolyser Forum | 04.-07.06.2017 | Scientific community |
| **Towards selective test protocols for accelerated in situ degradation of PEM electrolysis cell components** | International Conference on Electrolysis (ICE), Copenhagen, Denmark | 13.-16.06.2017 | Scientific community |

# NOVEL partners

The NOVEL project has eight partners:

| | | |
|---|---|---|
| Stiftelsen SINTEF | Norway | |
| Fraunhofer Gesellschaft zur Förderung der angewandten Forschung e.V. | Germany | Tom Smolinka,<br>tom.smolinka@ise.fraunhofer.de |
| Commissariat A L Energie Atomique Et Aux Energies Alternatives | France | Frederic Fouda Onana,<br>FREDERIC.FOUDA-ONANA@cea.fr |
| ArevaH2GEN | France | Fabien Auprêtre<br>fabien.aupretre@arevah2gen.com |
| Johnson Matthey Fuel Cells Limited | United Kingdom | Jonathan Sharman,<br>Jonathan.sharman@matthey.com |
| Teer Coatings Limited | United Kingdom | Xiaoling Zhang<br>xiaoling.zhang@miba.com |
| Beneq OY | Finland | |
| Paul Scherrer Institute | Switzerland | Lorenz Gubler, lorenz.gubler@psi.ch |

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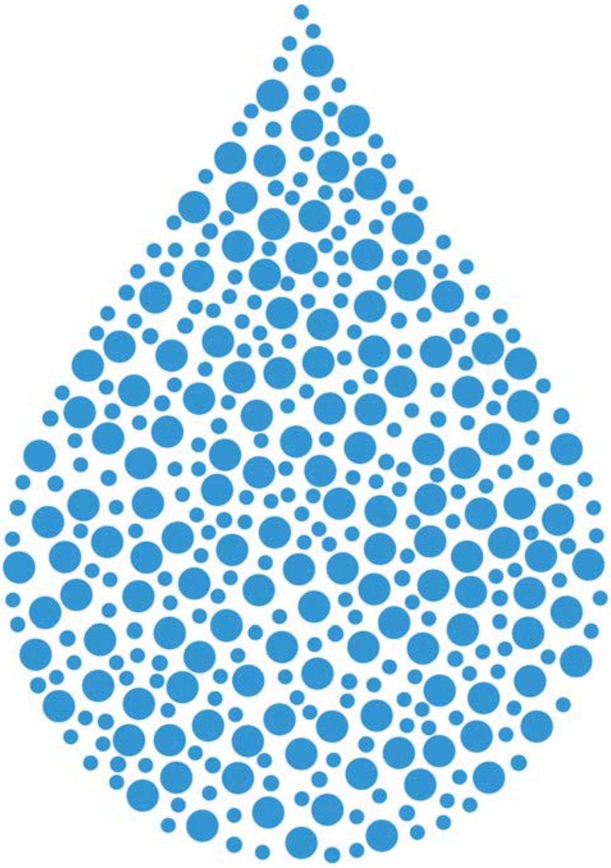

NOVEL