PROJECT FINAL REPORT

Publishable summary report

FCH JU Grant Agreement number: 621233

Project acronym: MEGASTACK

Project title: Stack design for a Megawatt scale PEM electrolyser.

Funding Scheme: FP7-JTI-CP-FCH

Period covered: 01/10/2014 30/09/2017

Name of the scientific representative of the project's co-ordinator[1], Title and Organisation: Dr. Magnus Thomassen STIFTELSEN SINTEF

Tel: +4798243439

Fax:

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

Project website address: www.megastack.eu

[1] Usually the contact person of the coordinator as specified in Art. 8.1. of the grant agreement

Executive summary

The MEGASTACK project consists of a top class European consortium between leading R&D organizations and a major industrial actor from four member states and associated countries. The partners are devoted to developing an electrolyser stack design for MW-sized electrolyser to increase capacity and cutting costs.

The three main targets for the MEGASTACK project is to demonstrate a capability to produce hydrogen with an efficiency of at least 75% (LHV) at a system cost below €5,000/Nm3h-1 plant capacity and a target lifetime of more than 40,000 hours.

The project results have moved the state of the art of PEM electrolysers forward by contributing to a significant step change in capacity and production cost of large scale PEM electrolysers from the involved industry partner as well as improving the fundamental understanding of transport processes and important factors to improve in further development of this technology.

The stack designed and constructed in the MEGASTACK project is now currently being offered on a commercial basis to hydrogen and power-to-X projects around the world and is a clear evidence of the success of the project as well as the FCH-JU programme in bringing new European innovations to the market.

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

Project context and the 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 H2 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 MEGASTACK project is to develop a cost-efficient stack design for MW sized PEM electrolysers and to construct and demonstrate a prototype of this stack. The prototype will demonstrate a capability to produce hydrogen with an efficiency of at least 75% (LHV)1 at a current density of 1.2 Acm^{-2} with a stack cost below €2,500/$Nm3h^{-1}$ and a target lifetime in excess of 40,000 hours (< 15 µVh-1 voltage increase at constant load)

To reach these ambitious objectives, MEGASTACK have developed and demonstrated an enhanced stack design essential for cost-competitive, efficient and dynamic PEM electrolysis systems through the following key concepts:

- The stack design process has had an integrated approach, involving stack manufacturers, component and MEA suppliers as well as PEM electrolyser experts from research institutes.
- Evaluation and adaptation of existing solutions and commercially available components for use in large format stacks and increased ease of stack assembly by the reduction of stack part count
- Advanced multiphase flow modelling coupled with multiphysics models for electrochemical kinetics, heat and momentum transport have been used as detailed design tools for cell and stack components.
- Implementation of quality control measures and supply chain evaluation of all components to reduce costs and minimise technology and manufacturing risks.

The project has been divided into five technical work packages (WPs) with the following main content and objectives:

WP1 Safety, RCS harmonisation, cost and LCA analysis
Determination of size and cost requirements for large scale electrolysers for different markets and corresponding production quantities. Definition of allowable component and manufacturing costs for key components of the stack. Periodic evaluation of required cost and performance targets for stack components and manufacturing. Contribution to harmonization of European RCS for electrolyser technologies and safety evaluation of stack designs.

WP2 Mathematical modelling and model verification
Development and subsequent use of multi-scale and multi-phase models which will serve as engineering tool for stack design and up-scaling. The models were verified and validated using advanced experimental set ups for distributed current mapping and flow visualisation

WP3 Membranes and MEA development
MEA production, procurement and testing for single cells and short stacks. Achieve significant reduction in MEA cost level by reducing production costs and minimize cut-off of expensive materials. Give input to stack design activity in WP4 and modelling activities in WP2.

WP4 Stack design and manufacturing strategy
Development of a large-scale stack design for a PEM electrolyser. Comprehensive testing of cell and stack components and the necessary development of test regimes and performance and durability of single cells. Evaluation of concepts and components, using a multi-criterion (e.g. technical/economical risk, supply chain strength, cost reduction potential) decision matrix.

WP5 Large Scale Stack Prototype and Testing
Short stacks based on the stack design developed in WP4 was constructed and tested. Technical validations of the stack design, test the efficiency and stack performance under real life data cycles and evaluation of stack capability to operate in different applications such as HRS or direct coupling to renewable energy sources.

MEGASTACK Main results

Cost and performance analyses

The amount of renewable energy sources (RES) is expected to constitute a significant portion of the total electric power generation of Europe within the next decades, resulting in a power generating scenario subjected to both seasonal as well as hourly weather variability. It is also expected that significant amount of excess renewable energy (on the order of TWh) will start to emerge in countries across the EU, with surpluses characterised by periods of high power output (GW) far in excess of demand. These periods will alternate with times when RES are only generating at a fraction of their capacity. Therefore, new approaches and tools are required to ensure that this renewable energy is integrated into the power system effectively and have not a negative impact on security and grid stability.

Although not the most efficient option in the PtP sector, the conversion of electricity into hydrogen by water electrolysis is expected to emerge as a viable alternative for energy storage beyond PtP. Produced hydrogen may be injected in the natural gas grid (often referred to as power-to-gas), used as an energy carrier in mobility applications or used as a feedstock in industry, further contributing to the decarbonisation of these sectors. Within the water electrolysis technologies, proton exchange membrane (PEM), alkaline and solid oxide electrolysers are currently the most promising technologies for this application.

In the MEGASTACK project we have provided an updated overview of the market sizes as predicted by several recently published studies and have summarised the current status of PEM water electrolysis technology and what is needed for today's PEM electrolyser technology to achieve its full potential as megawatt (MW) or multi-MW energy storage devices. In the publicly available MEGASTACK deliverable D1.1 we report the water electrolysis market size, state-of-the-art and targeted cost and performance based on recently published techno-economic analysis as well as cost reduction strategies and guidelines based on recently held stakeholder participation in a MEGASTACK workshop.

Life cycle assessment (LCA)

A comparative Life Cycle Assessment (LCA) on a MW sized PEM electrolyser was performed in the project. The LCA was based on the existing stack design of ITM and the cost-efficient stack design developed and demonstrated in the MEGASTACK project. The LCA compares in a life cycle (cradle-to-gate- plus use phase-) perspective the environmental aspects of the two design options by following practice guidance and required provisions developed by the FCH – a method that complies with the ISO 14040 and 14044 standards.

The need for LCA analysis in the MEGASTACK project relates to the understanding of the environmental consequences of the choices made towards the establishment of a new cost-efficient stack design that subsequently affect material- and energy requirements for manufacturing (components production and assembly of the stack) and operational performance of the MW-sized PEM electrolyser stack.

Results derived from the comparative LCA point towards an improved environmental performance of the new stack design demonstrated in the MEGASTACK project for all midpoint impact categories investigated in this study, i.e. for the abiotic depletion potential (ADP), global warming potential (GWP), acidification potential (AP), and eutrophication potential (EP). The life cycle impact assessment (LCIA) results can be observed in Table 1 and Table 2, while the relative results can be observed in Figure 1.

Table 1: The life cycle impact assessment results for the production of 1 metric ton of hydrogen from the 1 MW PEM MEP cell (MEGASTACK) stack in absolute values (within a 2% cut-off criteria).

Impact category	Unit	PEM Stack (MEP cell; MEGASTACK)	Electricity, {ENTSO-E} production mix	Water consumption	Total
Abiotic depletion	*kg Sb eq*	0.14	0.001	0.001	0.14
Global warming (GWP100a)	*kg CO_2 eq*	3 136	24 253	514	27 903
Acidification	*kg SO_2 eq*	172	99.0	2.23	274
Eutrophication	*kg PO_4 eq*	7.18	12.1	0.27	19.5

Table 2: The life cycle impact assessment results for the production of 1 metric ton of hydrogen from the 1 MW PEM LEP cell (existing technology) stack in absolute values (within a 2% cut-off criteria).

Impact category	Unit	PEM Stack (LEP cell; existing tech.)	Electricity, {ENTSO-E} production mix	Water consumption	Total
Abiotic depletion	*kg Sb eq*	0.34	0.00003	0.000004	0.34
Global warming (GWP100a)	*kg CO_2 eq*	9 810	24 260	1 231	35 301
Acidification	*kg SO_2 eq*	427	99.9	5.3	532
Eutrophication	*kg PO_4 eq*	19.2	12.2	0.70	32

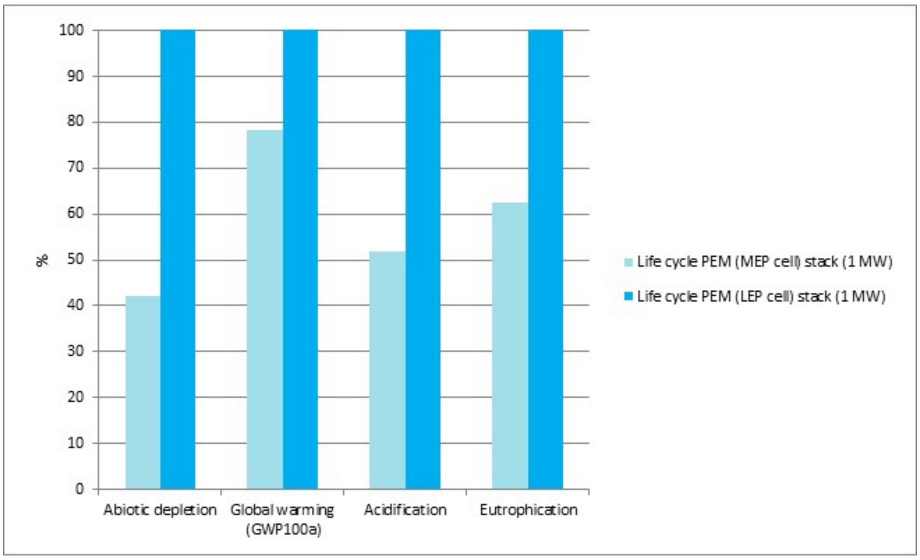


Figure 1: A comparison of the life cycle impact assessment of the two stack design options, normalised for each metric ton of hydrogen produced. (The MEP cell stack represents the MEGASTACK design, while the LEP cell stack represents the existing technology)

Less environmental impacts resulting from the new stack design are linked to both increased current density that reduces the quantity of active materials required for a given hydrogen production capacity, and the reduction of material requirements through the improved cylinder-formed stack design. The stack design for MW-sized PEM electrolysers demonstrated in the MEGASTACK project requires only 40% of the cells compared to the existing design.

The type of electricity mix applied for operation of the stacks has shown to be very relevant for the overall environmental performance. This is especially evident for global warming- and eutrophication potentials, where the usage of a European electricity mix during the stack operation represents between 67-86% of the life cycle emissions causing the global warming potential for the existing- and new stack design respectively. The electricity usage represents 63% of the eutrophication potential. Results derived from a sensitivity analysis on the use of various electricity mixes, has shown, however, that global warming potentials can be substantially reduced, - to represent 20-40% of the European electricity mix, if an electricity mix with an increased share of renewable energy is used, such as in the case of the Nordic- or Norwegian- electricity mix or in the case of German wind power. This would also lead to significant benefits for acidification and eutrophication potentials. Results for the sensitivity analysis on electricity mix usage for the two stack design options, can be seen in Figure 2.

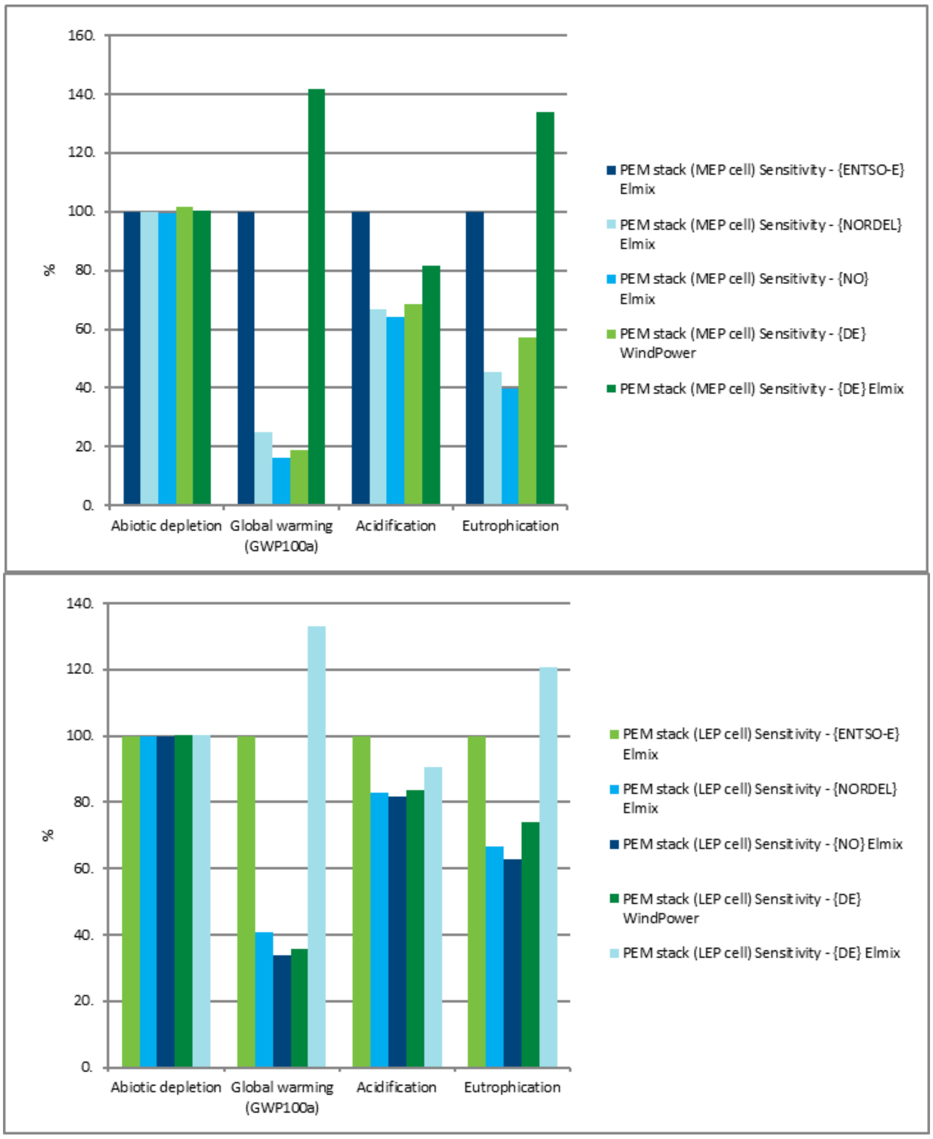


Figure 2: Results of the electricity usage sensitivity check for the MEP- (MEGASTACK) and LEP cell (existing technology) stack design.

The LCA-results obtained in this study, would in addition to information on environmental impacts from energy and additional materials for stack manufacturing (i.e. components production and stack assembling) and various End-of-Life (EoL) treatment options, contribute to a complete picture of the environmental burdens associated with the PEM electrolyser stacks, and would expect to provide valuable information about environmental consequences resulting from choices made towards the establishment of the new cost-efficient stack design. More research is thus recommended on investigating environmental impacts from the stack manufacturing and various EoL treatment options.

Mathematical modelling and verification

The main objective of this activity has been to develop and use multiscale and multiphase models as engineering tools for stack design and up-scaling. The mathematical models developed have been validated through an extensive set of experiments, including single cell tests, flow visualisation and measurement of permeabilities and fluid wetting properties in porous media. A public report of the results of measurements and model validation experiments are available on the MEGASTACK webpage (Deliverable D2.3)

FROM RESEARCH TO INDUSTRY cea tech

FREE DISTRIBUTION

Technical Report RT/DEHT/2016-137

MEGASTACK: D2.3
Functional and validated multi-scale and multi-phase models for PEMwater electrolyzer

Authors: G. Serre, M. Chandesris, F. Fouda-Onana, D. Brun-Buisson (CEA)
P. Skjetne, T. Bergstrøm (SINTEF)
K. Bromberger, T. Smolinka, J. Ghinaiya (FRAUNHOFER)

Project reference	13.04383
Project title	MEGASTACK
Period of the project	01/10/2014 – 31/09/2017
Nature of the report	☐ Progress Report ☐ Final Report ☐ Contribution to a global report ☒ Work package report (WP) ☐ Others : *specify the nature of the report* (ex : non included on the agreement, training report)
Appendices (to complete inevitably for « Restricted Distribution)	☒ YES ☐ NO If the report include appendices, specify : Appendices XX from page XXX to page XXX

	Writer(s)	Controller	Approver	Transmitter
Name(s)	G. SERRE	M. CHANDESRIS M.GERARD	D. JAMET	S. JOUANNEAU SI LARBI
Position	Research engineer	Project Leader Head of Laboratory	Head of Service	Head of Department
Signatures				
Date	16/12/2016	16/12/2016	16/12/2016	19/12/2016.

Commissariat à l'énergie atomique et aux énergies alternatives
T. | F.

Direction de la Recherche Technologique
Département : DEHT
Service : SAMA
Laboratoire : LMP

Etablissement public à caractère industriel et commercial | RCS Paris B 775 685 019

FOR 180 (GB) E Page 1/85

Figure 3: Front page, Megastack Deliverable 2.3

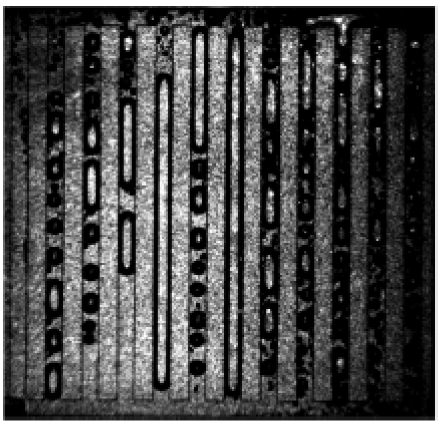
The goal of this activity was to develop a numerical tool that can be used as an engineering tool for the optimization of the electrolyzer stack. To reach this goal it has been necessary to develop mathematical laws that are able to capture the physical and electrochemical mechanisms involved in PEM electrolyzers, to implement them in a model and to validate them to be predictive enough to be able to give optimization recommendation. Since the optimization process requires numerous calculations, the numerical tool must be high speed. This constraint results in being capable to use coarse nodalizations since the CPU time is strongly related to the number of nodes. Therefore, the mathematical laws used in the engineering tool to describe the physical mechanisms must correspond to a coarse description scale to be coherent with coarse nodalization. Finer models (obtained on high number of nodes) are nevertheless necessary to study in detail the underlying physics, get reference results and to develop and validate the simplified laws used in the coarse model. The simplified laws depend also on several parameters that cannot be obtained by simulations. Thus, an important work of characterization has been carried out by the partners on the ITM cell components. The flow distributor, the PTL, the MEA and the whole cell have been characterized to obtain the properties and laws requested by the coarse model.

The modelling work has been performed by the partners as follows:

<u>SINTEF</u>

SINTEF has modelled the two-phase flows occurring in the liquid/gas distributor region using ANSYS FLUENT® and has performed several calculations in single phase and two-phase flows. These simulations have been compared to flow visualizations that demonstrated the good agreement between them. These simulations have been spatially averaged at large scale to derive the permeabilities requested by the Darcy-Forchheimer model used in the coarse nodalization code.

Relevant cold flow experiments have been designed for the purpose of validating this two-phase flow model. High speed camera was used during the experiments for image capture. Gas bubbles are supplied evenly through a porous plate at certain flow rates related to actual current densities. Water flowing at the other side of the porous plate comes in contact with the gas resulting in the bubbles moving with the water. The bubbles are captured and analyzed by means of image processing of high resolution camera pictures. Bubble properties, such as equivalent bubble size, bubble velocity, bubble number, and gas distribution, are then determined using a Digital Image Analysis technique. The results from the numerical simulations are processed in a similar way


Original image


Processed image

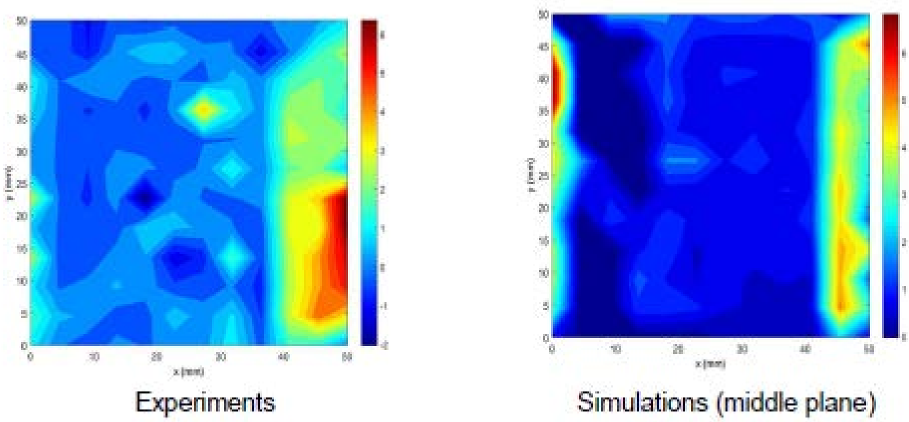


Figure 4:Image of bubble flow in lab cell and comparison of average axial bubble velocity (m/s) from experiments and simulations.

A good agreement was found between experiments and simulations for the different bubble properties. It can therefore be concluded, that the model predicts adequately the cold two-phase flow in this cell configuration.

To investigate the effects of cell design and operating conditions on the flow and gas distribution in the cell, a parametric study using the model has been performed.

In the parameter study, we have considered the water flow rate, applied current density, and the design of the flow distribution layer as the parameters to be varied. The parameter study was performed as a fractional factorial experiment with a total of 16 experiments. The modelled region of the cell is limited to the flow distribution layer on the anode side. The evolved oxygen gas is treated as an ideal compressible gas, while the water liquid is an incompressible fluid. The flow distribution layer is modelled as a porous material with a given porosity and inertial and viscous resistances that depends on the (flow) direction. The values applied for inertial and viscous resistances are based on measurements performed at ITM.

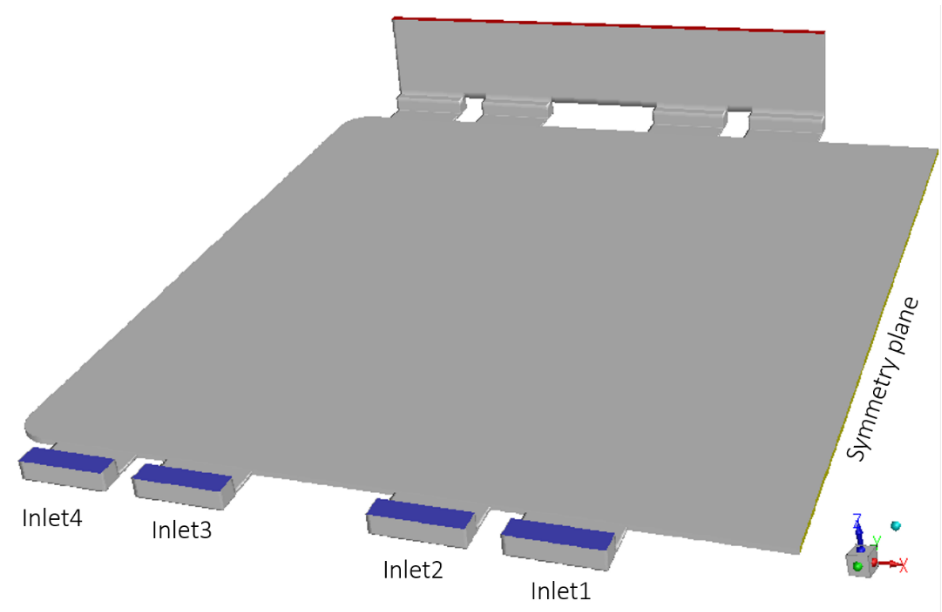


Figure 5: Schematic of the modelled domain in the MEGASTACK cell.

As the generation of gas leads to non-stationary flow distribution, a time-dependent solution was computed for the CFD simulations with ANSYS Fluent. Dependent on the initial conditions many time steps were necessary to reach a quasi-stationary state. A global Courant number ($u\Delta t/\Delta x$) of 2 was aimed for in the computations to secure convergent solutions. This led to typical time steps (Δt) of 20-30 μs.

Figure 6 shows the static pressure distribution along the mid plane of the lower mesh for case 4 with 7 l/min in water flow rate and 2 A/cm^2 in current density. For the other cases, the pressure distribution will look almost the same although the total difference between inlet and outlet will vary mainly with the amount of water flowing.

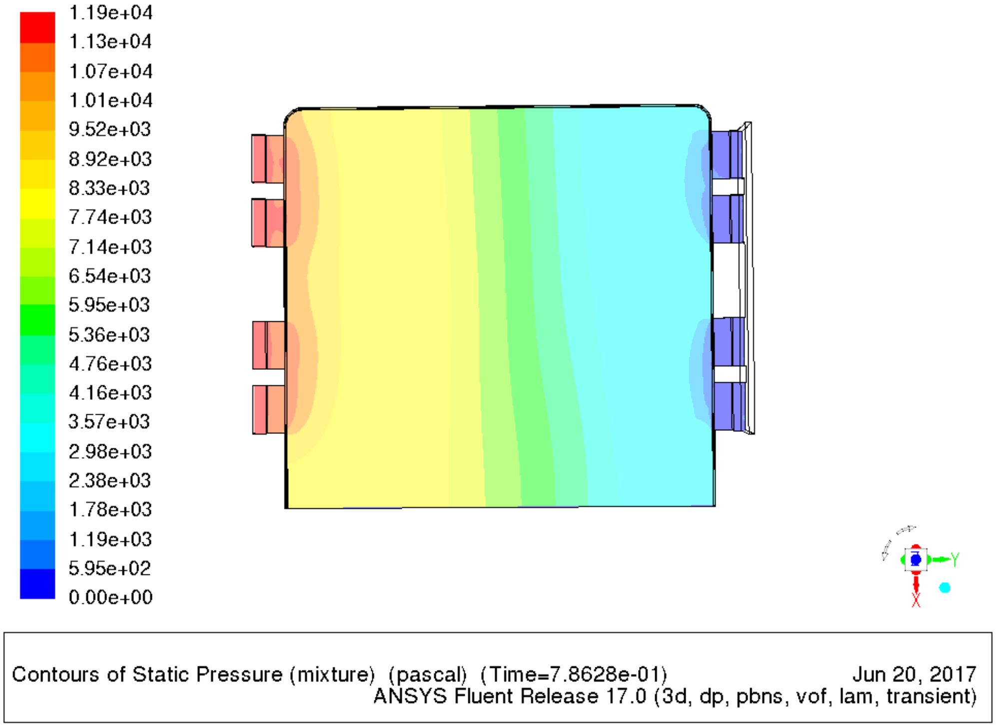


Figure 6: Pressure distribution in the mid plane for case 4 (Water flow rate 7 l/min, current density 2 A/cm2)

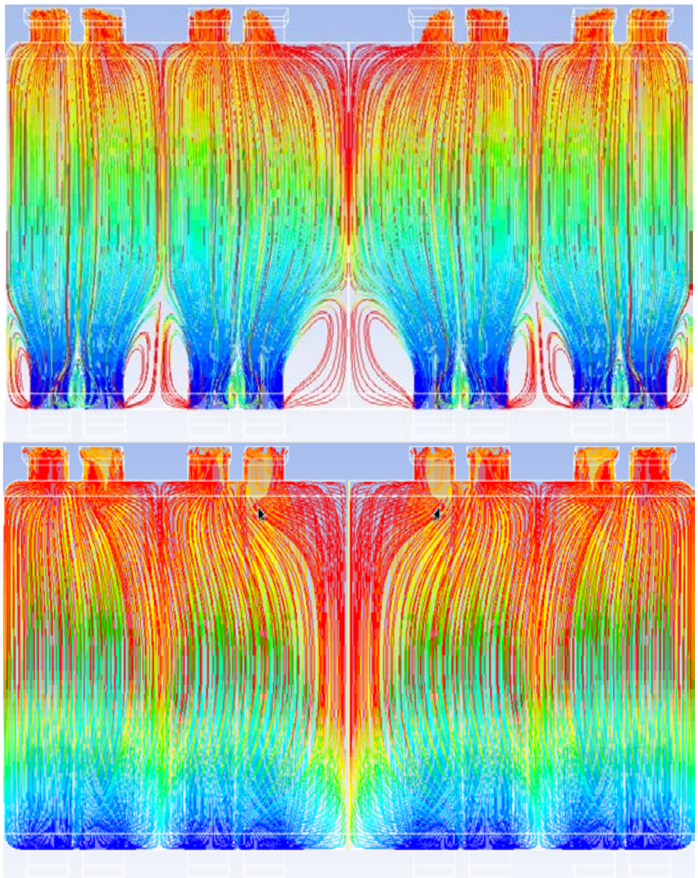


Figure 7: Top: Re-circulation zones apparent in the cell without flow field. Bottom: No re-circulation seen in same cell with flow field. Colour legend is linear in time from 0 (blue) to 2 seconds (red) in 20 levels (0.1 seconds).

Fraunhofer has performed a deep experimental analysis of the flow in the sinter (PTL). From their measurements, the parameters requested in the macroscopic models (capillary pressure Darcy) have been determined. The dependence of these parameters on the liquid saturation has also been explored.

Based on the experimental results, we propose a simple key parameter to describe the ability of partially saturated PTLs to transport gas in through-plane direction, termed "gas transportability". It is introduced and used to analyze polarization curves of different PTLs. Oxygen, generated at the anode side, has to be transported away from the catalyst layer - PTL interface across the PTL to the flow channel/mesh. It is an intrinsic characteristic of the PTL how easy gas is transported through it depending on the morphology and the surface character. In this context, we correlate the flow rate of generated oxygen to the CFP water wet curve in order to extract a new parameter termed as "gas transportability".

The resulting gas transportability is strongly controlled by the capillary behaviour, porosity and PTL's thickness and it becomes obvious, that gas transportability is a function of the applied gas flow rate and hence the applied current density. The higher the current density, the higher the gas transportability will be. From this result, we expect that PTLs with low gas transportability have a higher risk of mass transport limitation and thus higher cell voltages compared to PTLs with higher gas transportability. We prove this hypothesis by comparing the determined gas transportability with results from the polarisation curves. To make a link between the applied current densities from polarisation experiments with the water wet curve from CPF results and calculation of gas transportability, the single steps are described and referred to measured data:

1. For a given current density normalized oxygen flow rate can be calculated.
2. Based on the capillary characteristics of PTL a specific capillary pressure has to be overcome to remove produced oxygen through the wetted PTL
3. The resulting normalized dry cross-sectional area is specific for the PTL
4. Gas transportability is calculated using normalized dry cross-sectional area and taking PTLs'thickness and porosity into account

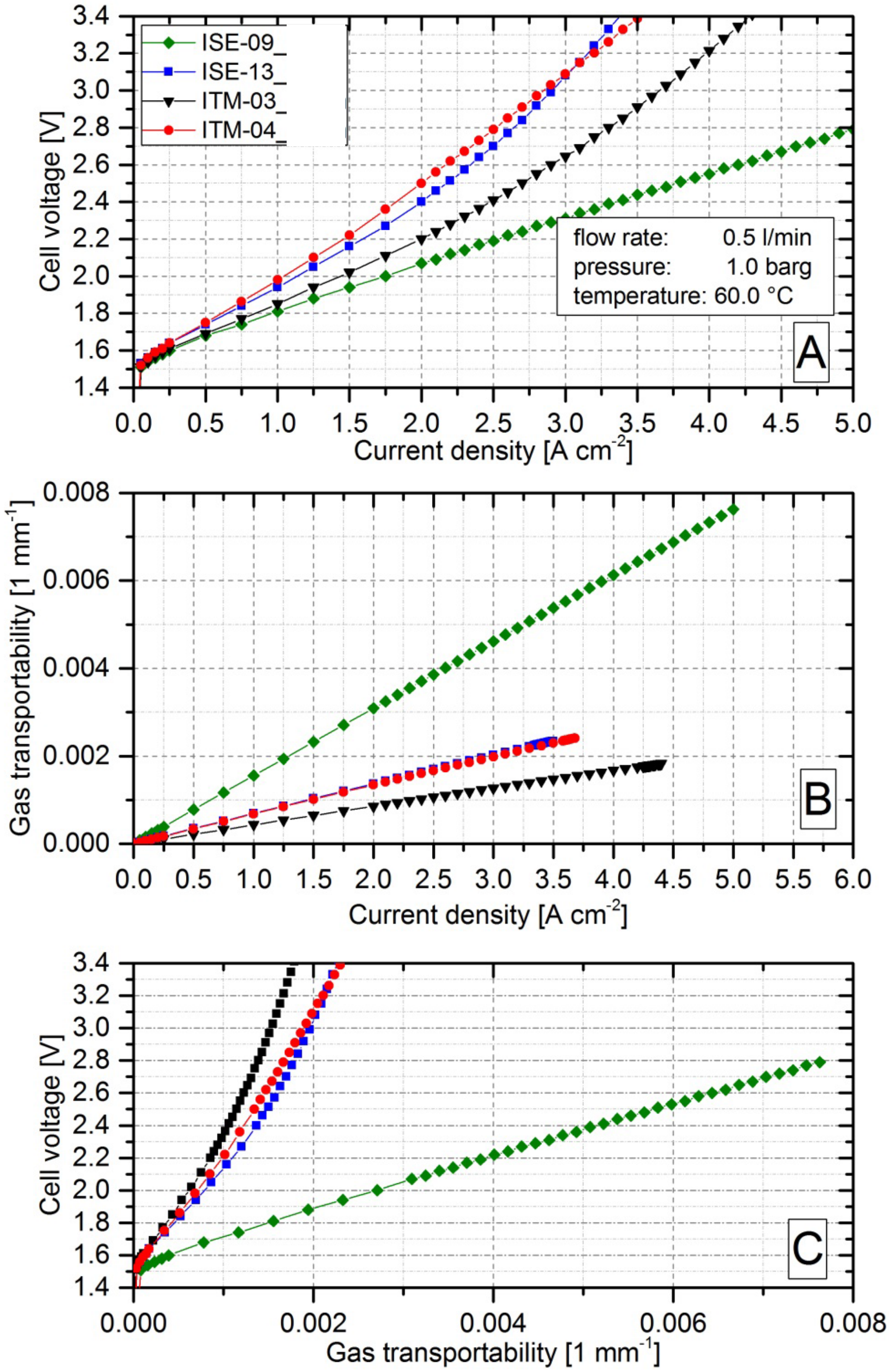
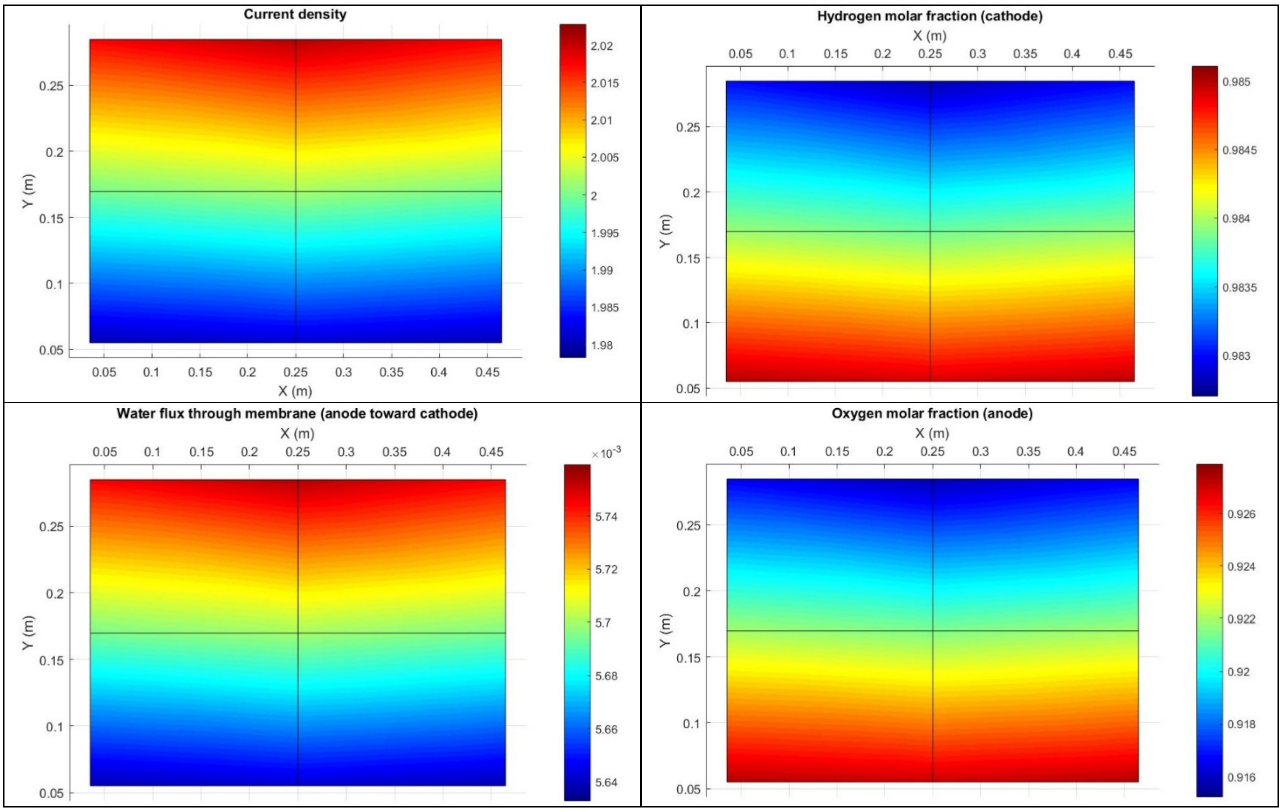


Figure 8: Polarisation curves with Greenerity E300 using different PTLs, (B) gas transportability vs. current density, (C) cell voltage vs. gas transportability.

CEA has developed an electrochemical law from various measurements. All the parameters and laws deduced from small scale simulations and experiments have been implemented in the MePHYSTO_WE code (based on Matlab/Simulink). Then a validation step using the experimental data has been driven successfully. Finally, CEA has performed several simulations of a one hundred cells stack, varying the geometry parameters and operating conditions to help the design of cells and stacks.

For illustration of the capability of the model we here provide results corresponding to a current density equal to 2A/cm². The spatial evolutions of various quantities in the plane of the cell are plotted Figure 9. These graphs show that most of the physical quantities vary along the anode axis. It is probably partially due to our discretisation of the meshes by a 1D equivalent mesh which underestimates cross flows. But it might also be related to the flow configuration where the main flow is driven by the anode side, imposing the gradient of species and temperature to the other side. This could explain that the variations along X axis (cathode axis) are quite small. The production of hydrogen and oxygen is proportional to the current density (Faraday's law). They increase slightly from inlet to outlet but the molar fractions of hydrogen and oxygen decrease in the same way since the vapour molar fraction increases (induced by temperature increase). The membrane temperature variation is about 3°C. The highest temperatures are reached where the current density is the highest: near the anode outlet.



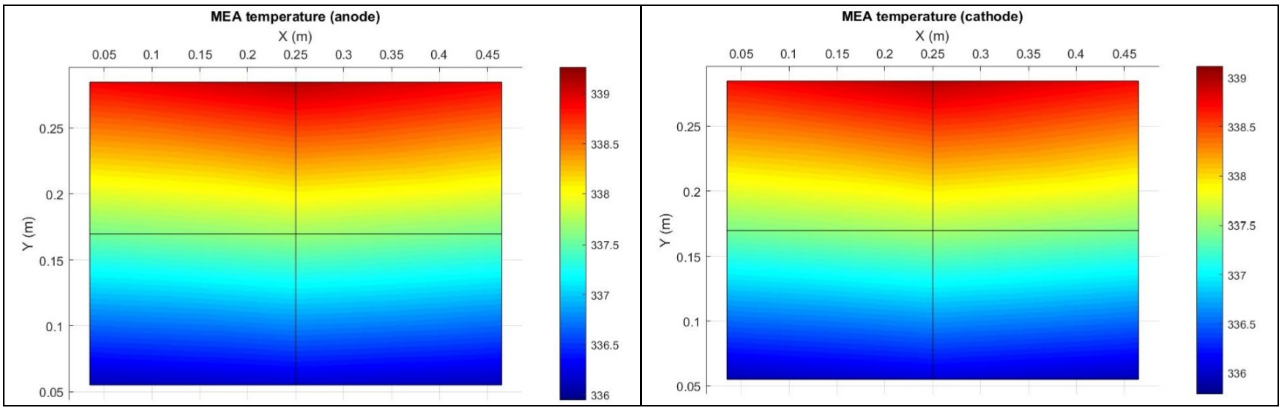


Figure 9: Spatial evolutions at 2A/cm². Current density: A/cm², Water flux: mol/s, Temperature: K

The model can also be used to investigate the sensitivity to change in construction materials or design or variations in operating conditions. The figures below show some of the model predictions for variations in the operating temperature of the stack.

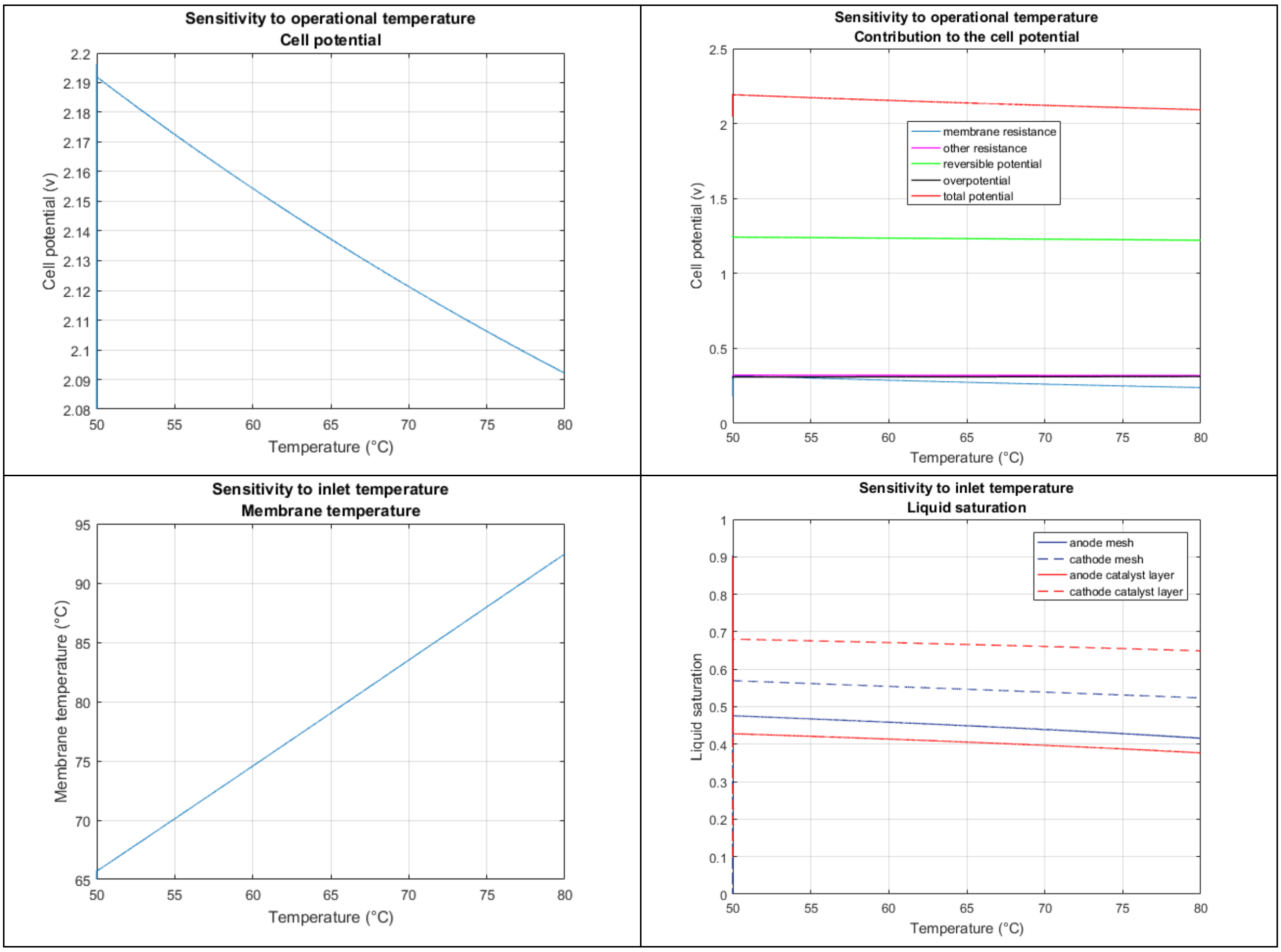


Figure 10: Sensitivity to operational temperature.

Membranes and MEAs

In the period, a screening and selection of MEAs for the project has been performed. A number of MEA suppliers across Europe were provided with a design plan, and in return a large number of MEA's were provided for testing. Over the range of MEA's received were the suppliers' standard MEA designs; however there were also several containing trial materials such as new membranes, low-cost catalysts and very low catalyst loaded designs. Several of these MEA's thus had the potential to offer significant cost-reductions of the electrolyser, reducing the overall Capex of the electrolyser system by reducing the cost of one of the more expensive components.

The MEA's underwent a standardized regime of tests covering a range of operating conditions. This allowed the down selection of the most efficient MEA designs based on their performance and resistance to adverse conditions such as frequent power cycling and high current density operation. Through this project new MEA tests were developed which promise to accelerate long-term MEA lifetime tests (which take several thousands of hours or even years) into tests which take only several days.

The evaluation of MEAs was based on multiple criteria, such as cell voltage at high current density, resistance to ITMs proprietary accelerated stress tests (AST) and the hydrogen crossover rate at differential pressures. More than four suppliers of MEAs have been tested and it was found that MEAs with low loadings of PGMs gives the best balance between cost, performance and durability.

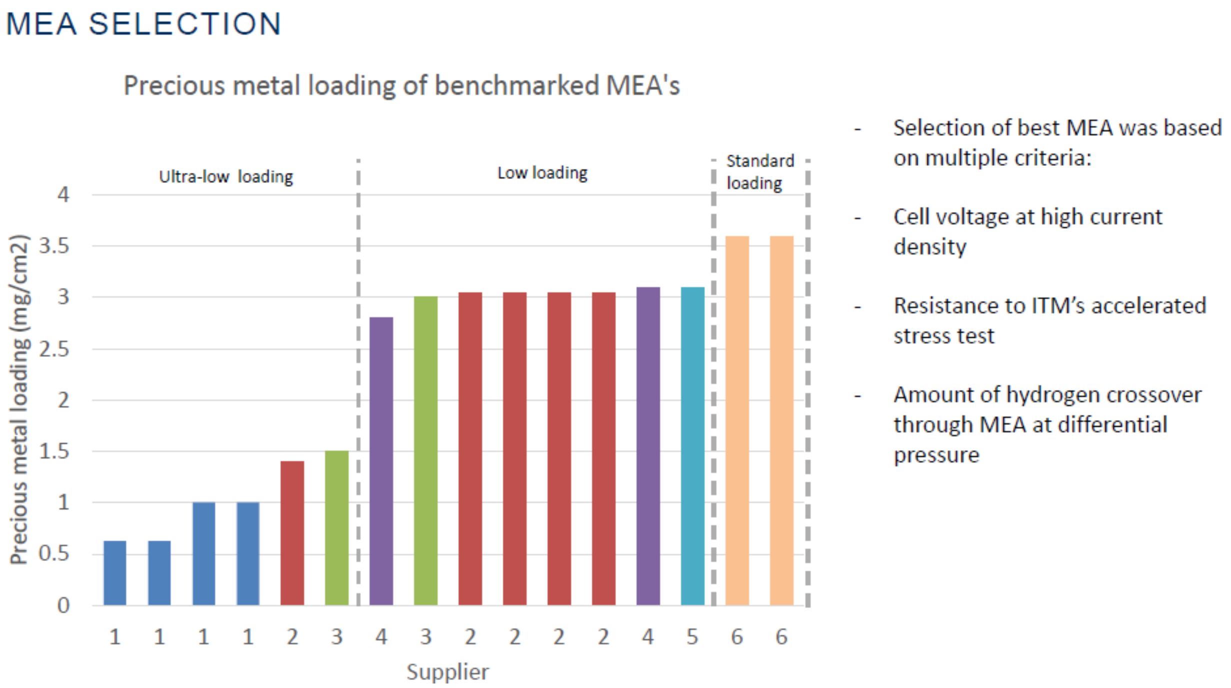
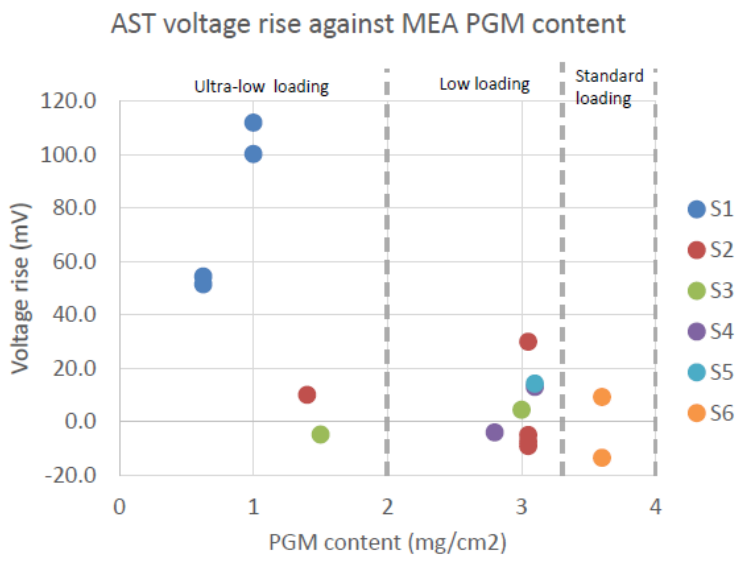
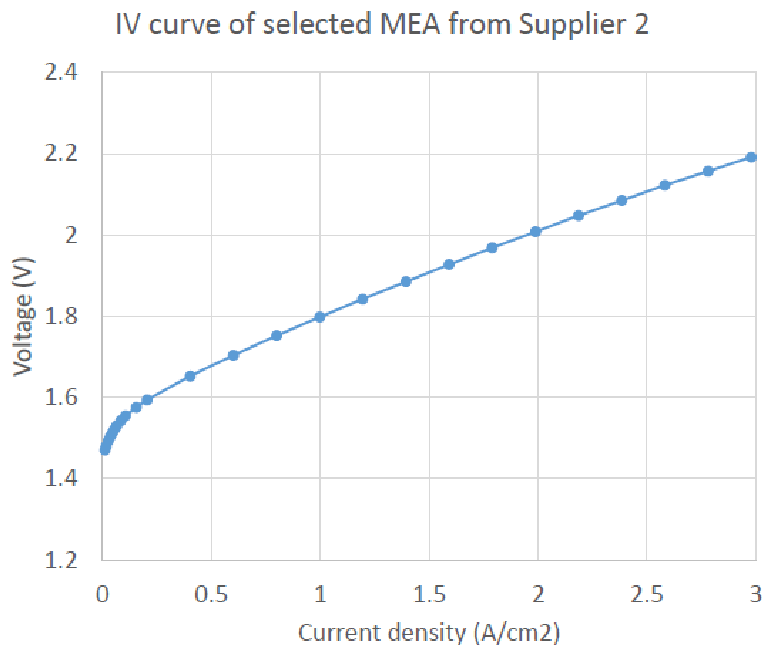


Figure 11: Overview of PGM loading of the different MEAs tested in MEGASTACK



- Ultra-low PGM loaded CCM's need further refinement. Poorer overall performance is not offset enough by the low PGM content
- Low-loaded MEA's give the best balance between cost, performance and durability
- Supplier 2 provides a number of appropriate MEA's:
    - No detectable crossover at 15 bar H_2 pressure
    - Low voltage rise through AST
    - Good performance at high current density

Figure 12: Resulting voltage increase for the different MEAs tested after exposure to ITMs proprietary AST.



- Selected MEA details:
    - Supplier 2
    - PGM - 3.05mg/cm^2
    - Membrane material - Nafion
    - MEA thickness - 180µm
- Results from MEA benchmarking:
    - <0.4% H_2 in O_2 at 1A/cm^2 15 bar H_2 pressure
    - No performance loss through AST
    - Ideal performance at high current density

Figure 13: Performance of selected MEA for the MEGASTACK project

Stack design and manufacturing strategies

The main objective for this activity has been to develop of a large-scale stack design for PEM electrolysis. This is based on taking existing concepts developed and used by ITM and upscaling them from 415 cm² to > 1000 cm². To achieve this objective comprehensive testing of individual cell and stack components (including the development of these tests)

Apart from increasing the cell area by more than a factor of 2.5, the main difference in the MEGASTACK design compared to previous ITMs designs is the move to a rectangular active area from the circular active area. The reasons for this are cost benefits due to material waste compared to circular systems. The design process followed is summarised below:

1. Cell assembly layout – this is based on proven layout from other systems with key cost saving ideas developed.

2. Material choices for both cell internals and pressure bearing components.

The goal of this task was the identification of appropriate components in interaction with the stack design process. Component level testing excluded MEA evaluation as it was already executed in a separate work package. Instead the focal point was put on accelerated corrosion treatment, corrosion measurement of porous transport layers (PTL) and subsequently ICR determination and (oxide) surface layer investigation to gain a better understanding of the effectiveness and performance of different coatings for PTLs. In addition to the corrosion testing, surface analysis was performed through x-rays photoelectron spectroscopy (XPS) and Auger electron spectroscopy (AES).

For these measurements at CEA and Fraunhofer, ITM provided different PTL samples comprising. Those samples were investigated simultaneously for transport properties in porous transport layers.

In terms of cell components testing a set of 4 porous transport layers (PTL) has been investigated with respect to their stability against anodic oxidation. For comparison, also a titanium sheet and a commercial Ti sinter were tested in the same way. Before and after this corrosion test, the samples have been investigated optically by measuring the reflectance spectra and electrically by measuring the contact resistance vs. a non-oxidized titanium sheet and vs. a carbon based MPL. For all samples, no significant bulk resistance was found after the anodic oxidation.

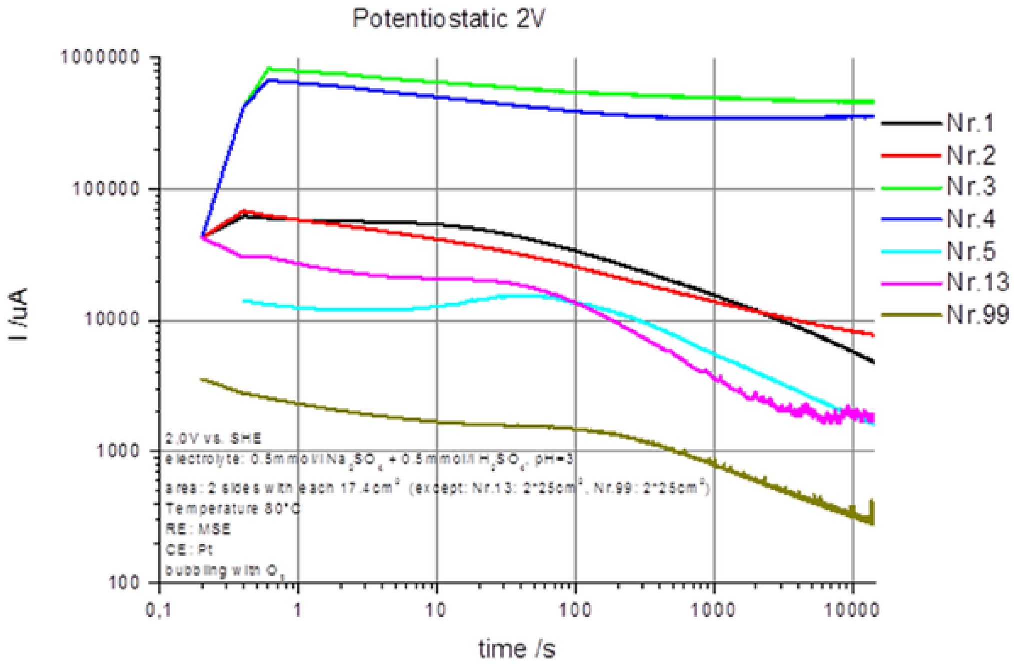


Figure 14: Chronoamperometry with constant potential of 2.0 V (vs. SHE) of the investigated Ti based porous transport layers and plane Ti sheets (for comparison). For all non-pcoated samples and the first 100 sec, the current is constant but decrease after 100 sec. This is typical for passivation of titanium. Sinters 3 and 4 are coated and thus show a comparable high current over time.

The anodic oxidation of the PTLs according to the procedure as described above results on an oxide layer formation on the surface of the PTLs. If a protective layer is applied the oxide layer formation should be suppressed mainly.

The ICR of the samples measured vs. a hard Ti sheet before and after the corrosion procedure are low due to scratching of the oxide layers, except samples sinter 4 and side 1 of sinter 2, see Figure 16 (left). Side 1 of sinter 2 had been oxidized already before corrosion test, which was found in the optical measurements. Here, it shows a high contact resistance before corrosion test. However, this oxidation layer formed before the corrosion test does not show high barrier properties against further oxidation. At least, the contact resistance values after corrosion test are even higher, also vs. MPL, see Figure 16 (right). Sinter 4 also shows a comparatively high contact resistance vs. Ti and vs. MPL. Therefore, no effect of the coating against formation of a high contact resistance can be found. It should be mentioned that there is some, but no strict correlation in between the contact resistance vs. Ti and vs. MPL as well as in between before and after corrosion test. Sinter 3 (coating A) shows an impressively low contact resistance before and after corrosion test vs. Ti as well as vs. MPL. This corresponds to the high stability of the optical properties before and after the corrosion test. Therefore, one can conclude an efficient protection against formation of high contact resistance at least for the specific corrosion test of this study, which was limited to potential of 2.0 V and a duration of 4 hours.

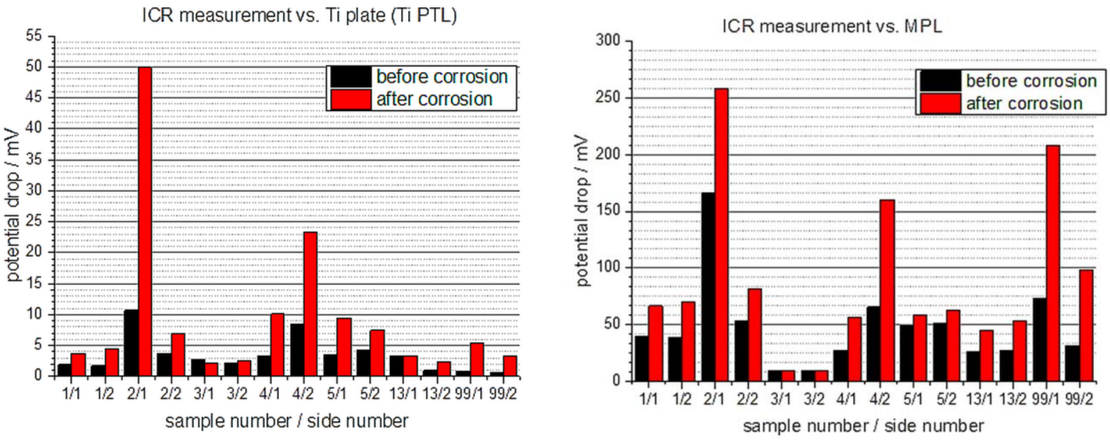


Figure 15: Interfacial contact resistance of all samples vs. Ti sheet (Ti TPL in case of Nr. 99) before and after anodic oxidation (left) and ICR of all samples vs. GDL based on carbon paper before and after anodic oxidation (right)

3. Structural analysis covering both pressure resistance and gas tight sealing between anode and cathode sides.

The cell plate analysis (performed using FEA package CREO Simulate) has been split into two sub categories. Initially, the frame deflection was looked at with the goal of keeping the deflection low (this is partly covered above when reviewing the hoop stress DVP targets) when subjected to system test pressure (1.43 x operating pressure). Secondly, the uniformity of the load was analyzed over the proposed manifold features. **Error! Reference source not found.** shows the result of the deflection analysis.

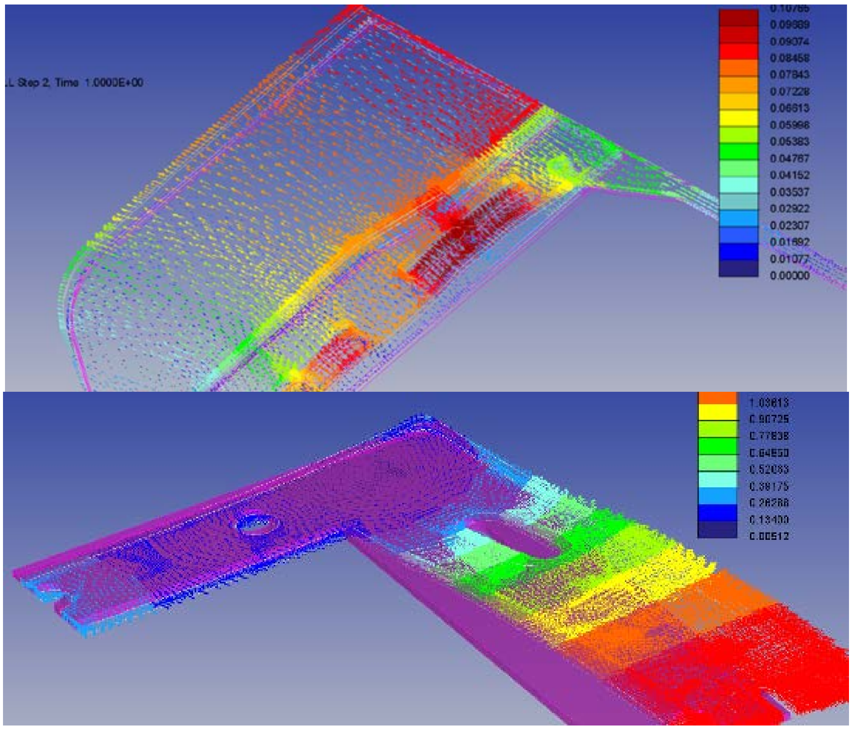


Figure 16: FEA analysis of the MEGASTACK cell plate

When looking at the sealing requirements an engineering development test was developed to ensure that even contact pressure is achieved across the manifold slots. Still using CREO Simulate, this test involved a Hertzian contact analysis using nonlinear geometry to analyze the contact force variation.

Due to the complex 3-dimensional shape of the cell plate and the number required to produce a MW range system it was identified early on in the project that the only economic way to manufacture these would be injection moulding. An engineering polymer has been selected for its structural properties but also its mouldable properties. In order to make manufacture as cost effective as possible, the anode and cathode plates have been designed so that a single tool can be manufactured with interchangeable inserts for the subtle differences between them.

Multiphase polymer mould flow analysis has been carried out on the component to define the following, the detail of which can be seen in MEGASTACK D4.1

- Number and position of injection points
- Projected fill time
- Areas of possible flow hesitation
- Temperature variation across the component
- Weld line positions
- Injection pressure and clamp force (to help with the selection of a mould company)

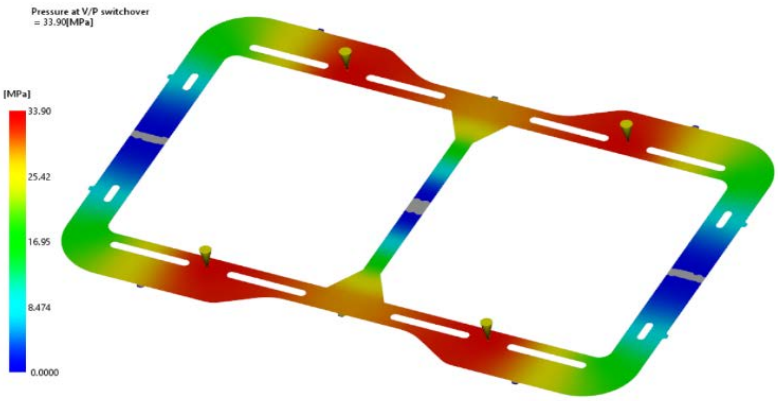


Figure 17: Results from multiphase polymer mould flow analysis.

4. Manifold design covering water flow in the oxygen side of the system this has been analysed for system cooling and reactant flow. The manifolds on the hydrogen side has been analysed for gas and osmotic drag water leaving the cell.

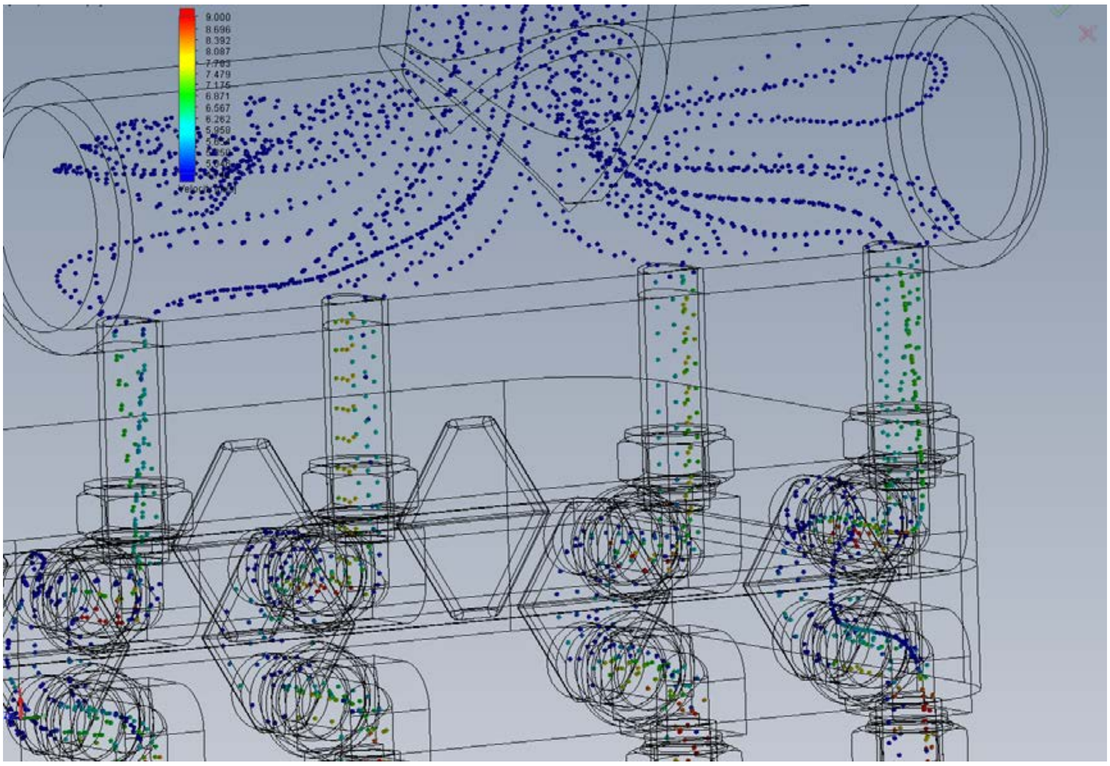


Figure 18: Modelling of flow in manifold structures

Large scale stack prototype construction and testing

The main objective for this activity was is to progress from the stack work carried out on the design verification plan (DVP) and prove that the Engineering Design (ED) tasks were successful by carrying out Design Verification (DV) a brief description of the process can be found below:

Using techniques currently used on ITM systems, the cell plates will be housed in structural frame (called the stack skid) which is a patented design. This allows the variation of cell sealing pressure without the need to use spanners and Bellville washers. ED goals devised using petrochemical gasket maintenance factor values and empirical data from previous systems to set a sealing force requirement.

Based on these values the skid was designed and analysed against EN13445 and EN13121-3 using long hand calculations and 3D nonlinear FEA contact analysis. Once the beam conforms to this, material is added to ensure that that the ED goals related to sealing force variation are met. At the same time consideration must be given to operational requirements such as water input, electrical power connection and gas removal.

Figure 19: Megastack skid design

The BoP design has been based around existing ITM product knowledge. Certain control aspects were developed from understanding gained from the previous FCHJU PEM project "Phaedrus"

Vessel and pumps were selected based on theoretical flow rates required for an up scaled system of this size. A bespoke Siemens S7 1200PLC control system was developed to allow accurate control, safe operation and data logging capabilities.

Figure 20: CAD rendering of BoP and Megastack skid with short stack installed

The stack assembly for this project has focused on short (5 – 10 cells) stacks, but methodology and equipment for assembly and mounting of full scale stacks was also developed in the project.

Figure 21: Finalised balance of plant, skid and short stack during testing.

Potential impact and the wider societal implications of the project

In the MEGASTACK project, the development of a stack design for realisation of cost efficient MW-sized electrolysers have had the highest priority. In addition to the design and construction of the upscaled stack all the accompanying components and balance of plant have also been scaled up and improved. An increased understanding of the transport phenomena in the porous layers and flow fields as well as processes causing cell degradation have been achieved through extensive modelling and experiments.

The MEGASTACK stack and balance of plant design is now in final prototype testing and full scale stacks and electrolysers are already in the process of being constructed for placement in the field as commercial products. The new stack from ITM is expected to significantly reduce 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.

Main dissemination activities and the exploitation of results

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.

MEGASTACK Partners

Stiftelsen SINTEF	Norway	Magnus Thomassen Magnus.s.thomassen@sintef.no
Fraunhofer Gesellschaft zur Förderung der angewandten Forschung e.V.	Germany	Tom Smolinka, tom.smolinka@ise.fraunhofer.de
Commissariat A L Energie Atomique Et Aux Energies Alternatives	France	Guillame SERRE guillaume.serre@cea.fr
ITM Power	United Kingdom	Frederic A L. Marchal FALM@itm-power.com

Coordination contact details, public website and logo

Website:
www.megastack.eu

Relevant contact details:
Coordinator: Magnus Thomassen
Address: SINTEF Materials and Chemistry
NO-0373 OSLO, NORWAY
Email: magnus.s.thomassen@sintef.no
Phone: +47 98243439

Megastack logo: