EUROPEAN COMMISSION

SEVENTH FRAMEWORK PROGRAMME
FUEL CELLS AND HYDROGEN JOINT UNDERTAKING (FCH JU)
THEME SP1-JTI-FCH.2013.3.5
FIELD DEMONSTRATION OF LARGE SCALE STATIONARY POWER AND CHP FUEL CELL SYSTEM

GA NO. 621256

DEMCOPEM
2MW

DEMONSTRATION OF A COMBINED HEAT AND POWER 2MWE PEM FUEL CELL GENERATOR AND INTEGRATION INTO AN EXISTING CHLORINE PRODUCTION PLANT

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Nomenclature

BOL	Beginning of Life
BOP	Balance of Plant
EOL	End of Life
GHG	Greenhouse Gases
HX	Heat Exchanger
MEA	Membrane Electrode Assembly
PEM FC	Polymeric Electrolyte Membrane Fuel Cell
RH	Relative Humidity

Executive Summary

The chlor-alkali industry produces significant amounts of hydrogen as by product and an interesting benefit can be obtained by feeding hydrogen to a PEM fuel cell unit, whose electricity and heat production can cover part of the chemical plant consumptions. The estimated potential of such application is up to 1100 MW_{el} installed in the sole China, a country featuring a large presence of chlor-alkali plants.

This final report presents the modelling, development and first experimental results from field tests of a 2 MW PEM fuel cell power plant, built within the European project DEMCOPEM-2MW and installed in Yingkou, China as the current world's largest PEM fuel cell installation. After a preliminary introduction to the market potential of PEM Fuel cells in the chlor-alkali industry, it is first discussed an overview of project's MEA and fuel cell development for long life stationary applications, focusing on the design-for-manufacture process and the high-volume manufacturing route developed for the 2MW plant. The work then discusses the modelling of the power plant, including a specific lumped model predicting FC stack behaviour as a function of inlet streams conditions and power set point, according to regressed polarization curves. Cells performance decay vs. lifetime reflects long-term stack test data, aiming to evidence the impact on overall energy balances and efficiency of the progression of lifetime. BOP is modelled to simulate auxiliary's consumption, pressure drops and components operating conditions. The model allows studying different operational strategies that maintain the power production during lifetime, minimizing efficiency losses; as well as to investigate the optimized operating setpoint of the plant at full load and during part-load operation.

Making use of the experience obtained during the DEMCOPEM demonstration project, a roll out phase design was made. Operational cost for the technology improve as result of the project. The economic viability of the technology is strongly dependent of the specific circumstances. A viable business case, assuming an increasing market for PEM fuel cells leading to lower costs and longer life times of fuel cells, is described.

The last part of the report discusses the experimental results, through a complete analysis of the plant performance after plant startup, including energy and mass balances and allowing to validate the model.
The fuel cell performance decrease in China was found to be faster than expected, while the same stacks, and even returned stacks from China, showed a normal performance in a similar plant at the Nouryon site in Delfzijl, the Netherlands. It can be concluded that more attention should be paid to prevent and monitor feed stream contaminations, for both hydrogen and air.

Cumulated indicators over the operational period of more than 2 years regarding energy production, hydrogen consumption and efficiency are also presented.

1 Background of the project

Concept

Chemical industry accounts for nearly 10 % of world energy demand and 7% GHG emissions[1]. Among different chemical sectors, one of the most energy-intensive is the chlor-alkali industry. Its products (chlorine and sodium hydroxide or caustic soda) are widely used in a number of applications: chlorine is a basic 'building block' in the industry of vinyls and derivatives (polymers like PVC, resins and elastomers), while caustic soda is an alkali applied in a range of industries including alumina (where caustic soda is a major raw material for alumina refining process), pulp and paper, textile production, food industry, production of soap and other cleaning agents as well as water treatment and effluent control. Chlorine also plays an essential role in the production of high purity silicon used for the manufacture of solar panels and microchips.

Salt brine is the main raw material used to produce chlorine and caustic soda (Fig. 1), through an electrolysis process which typically requires from 2.2 to 2.8 MWh_{el}/ton_{Cl} and 27.4 GJ/ton_{Cl} in terms of primary energy. Electrolysis is mainly accomplished within membrane cells, a technology which has substituted the former mercury-diaphragm cells thanks to a superior environmental compatibility (use of mercury has been increasingly discouraged by legislation in several countries) and efficiency advantages. Energy consumption includes heat required for the concentration of salt brine, usually provided by means of high-pressure steam (about 0.8 ton/ton_{Cl} at 200 °C and 10 bar). An interesting feature of this production process is the generation of large quantities of hydrogen (340 Nm^3H_2/ton_{Cl}) as by product[2].

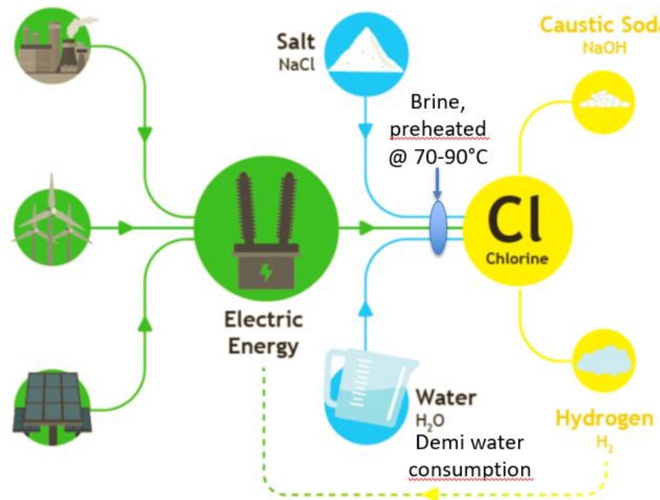


Fig. 1 - Working principle of a chlor-alkali plant (from [3]).

Different processes for NaOH and Cl production are also nowadays investigated, including the oxygen depolarized cathode (ODC) technology[3], which features a lower electrical consumption at the expenses of a more complex cell technology, requiring oxygen feeding and renouncing to hydrogen production; however, the electrochemical process shown in Fig. 1 is by far the most diffused worldwide in the chlor-alkali industry

In 2016, European chlorine production was nearly 9.7 Mton, while the U.S. production was nearly 10.8 Mton[4]. China is the largest chlorine producer worldwide, with more than 25 Mton/year production (about 42% of global production)[5] distributed over 180 plants and a continuous growth foreseen for next years.

Hydrogen recovery out of the electrochemical process depends on the installation: it reaches about 90% (usually as feedstock for nearby industries) in Europe, while the remaining is vented, but the share reduces in other countries [4]. In this framework, the possibility of using excess hydrogen to cogenerate electricity and heat, locally consumed by the chemical plant, finds an ideal candidate in the highly efficient and clean technology of PEM fuel cells (see Fig. 2). The deployment of

[1] IEA (International Energy Agency), "Technology Roadmap - Energy and GHG Reductions in the Chemical Industry via Catalytic Processes," OECD/IEA, Paris, France, 2013.

[2] T. Brinkmann, G. G. Santonja, F. Schorcht, et al., "Best Available Techniques (BAT) - Reference Document for the Production of Chlor-alkali," JRC (Joint Research Center EU), JRC91156, 2014.

[3] J. Kintrup, M. Millaruelo, V.Trieu, A. Bulan, E. Silva Mojica "Gas diffusion electrodes for efficient manufacturing of chlorine and other chemicals", The Electrochemical Society Interface, Summer 2017, www.electrochem.org, pp.73-76, DOI: 10.1149/2.F07172if, 2017.

[4] EuroChlor, "Chlorine industry review 2016-2017," Brussels, 2017.

[5] ResearchInChina, "Global and China Chlor-alkali Industry Report," 2013.

such technology could contribute through energy saving and global emissions reduction to the plant economics and environmental goals.

The European Project DEMCOPEM-2MW[6], coordinated by Nouryon [former AkzoNobel] (NL), aims at demonstrating the PEM FC technology scale-up, integrated at a representative scale (being also currently the world's largest PEM installation) in an actual chlorine production facility. Project goals include showing the system efficiency (at least 50% electrical and up to 85% total, including available heat) and lifetime. Economical design is supported by the development of specific cell membrane-electrode assembly (MEA) production processes at Johnson Matthey (JM, UK), with PEM stacks manufactured by Nedstack Fuel Cell Technology Ltd. (NFCT, NL). Moreover, the plant, designed and built by MTSA (NL), allows fully automated remote operation. Plant modelling, simulation and measurement validation is performed by Politecnico di Milano.

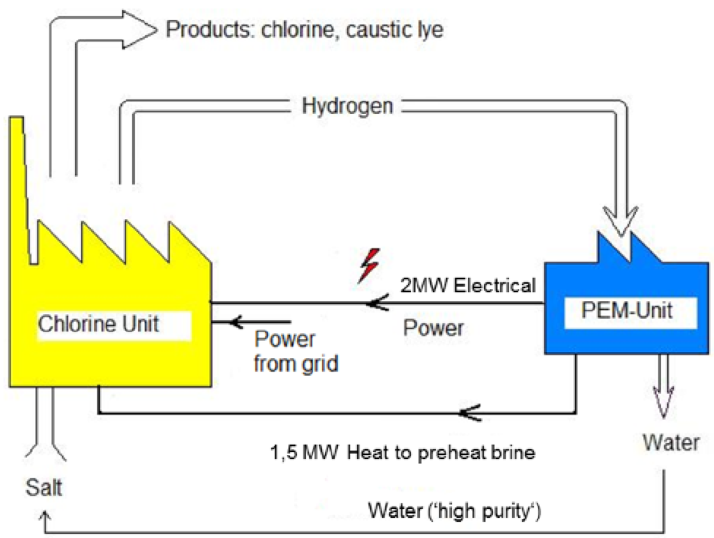


Fig. 2 – Conceptual integration of a PEM FC plant in a chlorine production unit explored by the DEMCOPEM-2MW project [6].

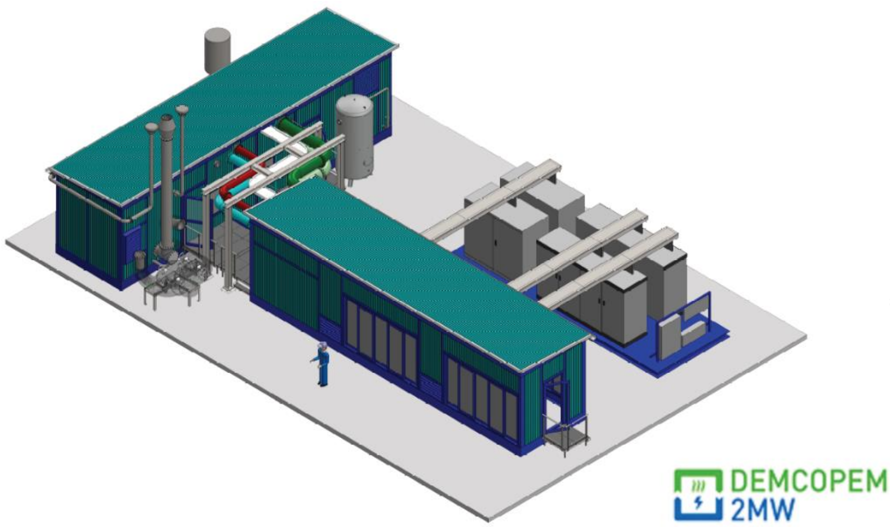
The demonstration plant has been installed by MTSA at the site of Ynnovate Sanzheng Fine Chemicals Co. Ltd in Yingkou, Liaoning province, China, where it has been successfully launched in October 2016. The high electricity prices (up to 2 times higher than in Europe) in several areas in China, the availability of waste hydrogen by many chlor-alkali plants and the rather common shortages in electricity supply make the plant economics and business case attractive. Based on the hydrogen availability, it is estimated that the potential of such application would be up to 1100 MW_{el} installed in the sole China.

[6] "DEMCOPEM-2MW Project official website." [Online]. Available: http://www.demcopem-2mw.eu/. [Accessed: 15-Dec-2017].

Objectives

The main objective of the four years DEMCOPEM-2MW project is to design, build and operate a 2 MW power generator, with the following attributes:

- Full integration of heat and power with an existing chlorine production plant
- High net conversion efficiency, i.e. > 50% electric energy on system level and > 85% for combined heat and power
- Long lifetime of system and fuel cells, i.e. over 2 years (16,000 hrs) for fuel cell stacks without any need for repair or maintenance of the membranes. The long-term target is 5 years (40,000 hrs) for fuels cell stacks
- Fully automated way of operation and remote control
- Economical design to reach a competitive price, i.e. < €2,500 / kWe with potential for reaching < €1,500/kWe in 2020. With membrane lifetime of 5 years and high-volume series (> 25 MWe/y) production the cost price of the electricity produced with a PEM power plant is estimated to drop from 0,075 to below 0,04 Euro/kWh.
- Demonstration of power and heat generation for over 2 years i.e. on-stream availability of > 95% for over 16,000 hours, in line with the Annual Implementation Plan 2013 objectives
- Contribute to the general goals of the JTI FCH, as stated in the revised Multi Annual Implementation Plan, to have > 5 MW @ € 3,000/kW installed fuel cell capacity in 2015 and > 50 MW @ € 1,500/kW installed fuel cell capacity in 2020.



3D Design of DEMCOPEM-2MW system

One of the DEMCOPEM-2MW container at Ynnovate

2 Technical and Scientific Aspects

MEA and Fuel Cell development

Johnson Matthey have for several years supplied a MEA with a bonded catalysed substrate (BCS) design for long-life, stationary power applications.
The membrane electrolyte is a proprietary JM design, with chemical stabilisation and mechanical reinforcement. Durable, stabilized cathode and anode catalysts were also made by JM.

The pre-project MEAs were made by a series of discrete, static processes. The sheets of electrode substrates were cut, wetproofed, and coated with catalyst and ion-conducting polymer. The electrodes, membranes, seals and subgaskets were then unitised, before being cut to the final planform. The whole process consisted of a large number of manual operations with minimal automation.

As part of the DEMCOPEM-2MW programme, Johnson Matthey committed to developing a capable volume manufacturing process to produce MEAs whilst maintaining quality and performance. In addition, for a significant volume of MEAs such as this, it is in JM's and the customers' interests that material yields are as high as possible. As the MEA has demonstrated excellent durability in similar applications[7] , the membrane has been retained unchanged from the pre-project design. Similarly, the highly durable Pt cathode and anode catalysts were retained unchanged from the pre-project design.
JM's initial approach was to source and qualify a commercially available roll-good gas diffusion layer (GDL) with appropriate wetproofing and microporous layer to replace the incumbent flat-sheet component. Because the selected GDL presented a highly hydrophobic surface for catalyst coating, the catalyst ink required significant reformulation. The catalyst deposition method developed in the project permitted the use of a single stage catalyst and ionomer deposition, with in-line coating and drying of the ink. Significant iterative development effort was needed to produce a layer by this method that gave the required composition of catalyst and ionomer. The target of this reformulation was to achieve appropriate water handling properties as evaluated by the polarisation performance of the MEA under realistic operating conditions.
To create the DEMCOPEM-2MW long life MEA, gas-diffusion layers were coated with catalyst layers and dried in line, then cut to size in a semi-automated process. A further reduction in the number of manual unit operations was achieved by sourcing and testing a single-layer edge protection and seal material; a heat-stabilised material was found to meet the demands of Nedstack's accelerated stress test. This single layer seal was bonded to the polymer-electrolyte membrane in a continuous roll-to-roll cutting and converting process, producing high quality membrane seal assemblies (MSAs). The MSAs were collated with the electrodes in a semi-automated process involving an automated hot melt glue bead, then laminated, inspected and packed for shipping to Nedstack. At NFCT, the MEAs were built into stacks, then arranged in modules and groups; as discussed in section 3.1, six groups were required for the 2MW system, for a total of 25,200 MEAs delivered, plus a quantity of spare MEAs.

[7] A. J. L. Verhage, J. F. Coolegem, M. J. J. Mulder, et al., "30,000 h operation of a 70 kW stationary PEM fuel cell system using hydrogen from a chlorine factory," Int. J. Hydrogen Energy, vol. 38, no. 11, pp. 4714–4724, 2013.

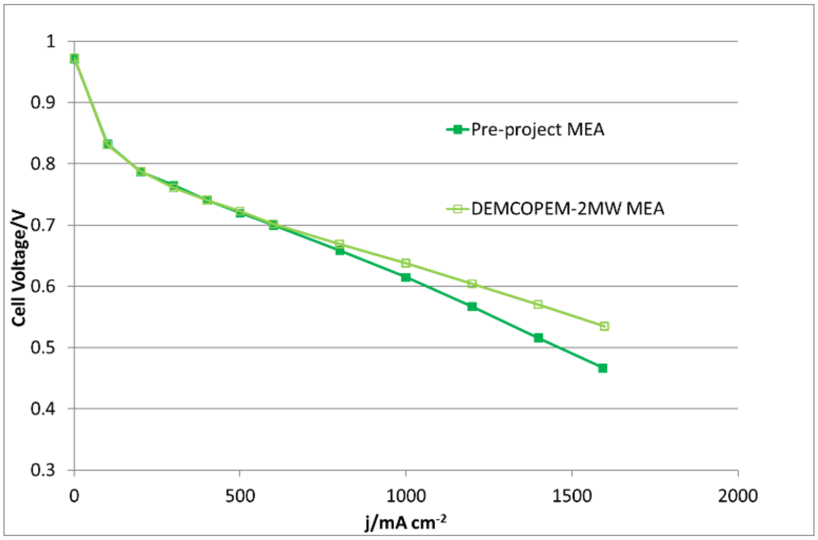


Fig- 3 - Polarisation at 65ºC, ambient pressure, cathode stoichiometry λ=2.0, 85% RH, anode λ=1.5, 85 % RH.

The performance of the MEAs was tested at JM's fuel cell test facility, in a single-cell hardware based on NFCT's stack design, and a short stack. Figure 3 shows the MEAs matched the performance of the pre-project long life MEA at lower current densities and exceeded it at higher current densities. This reflects the probable enhanced gas access to the catalyst-electrolyte interface due to the more open gas diffusion media structure, and possibly also an increased porosity of the catalyst layer.
In order to assess the early stability of the MEA to corrosion, the MEA was tested for 1000 h at the assumed operating point. Figure 4 shows the polarisation performance before and after the 1000 h stability testing; while Figure 5 shows the nature of this decay. After an initial 700 h of decay at 12 µV hr 1, the rate of decay levels off to create highly stable performance. Following an interruption for diagnostic testing at 1050 hr, the voltage at 600 mA/cm^2 climbed by around 34 mV.

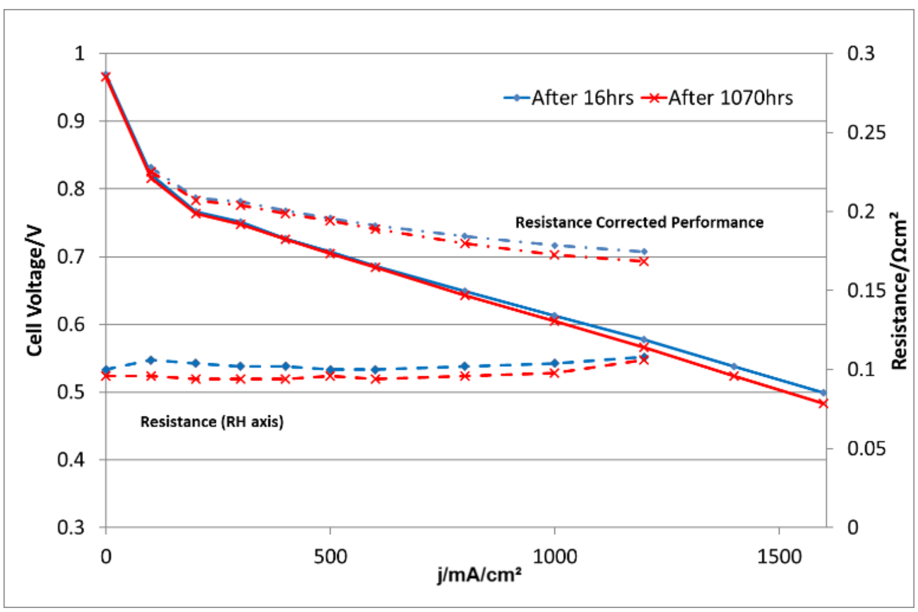


Fig. 4 - Air polarisation at 65ºC, ambient pressure, cathode stoichiometry λ=2.0, 85% RH, anode λ=1.5, 85 % RH.

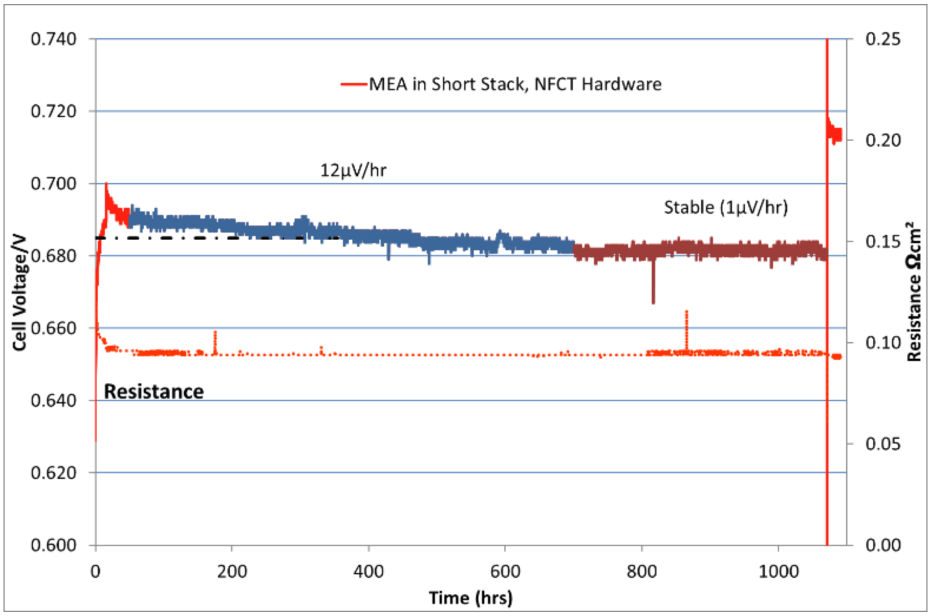


Fig. 5 - Durability of DEMCOPEM-2MW MEA in short stack, 600 mA/cm² at 65ºC, ambient pressure, cathode stoichiometry 2.0=85% RH, anode λ=1.5, 85% RH.

This regeneration in performance may be due to reduction of oxides or other surface contaminants caused by the rapid drop in the cathode potential when the air supply is interrupted, and hydrogen gas crosses the membrane[8] [8].

The more open structure is likely to allow increased gas access to the electrolyte membrane. Oxygen may cross or partially cross the polymer electrolyte, potentially reacting with hydrogen at the anode, or within the membrane as hydrogen crosses from the anode supply. This does not appear to have affected the early (>1000h) performance stability; the membrane has features to resist this method of degradation. A membrane further stabilised against degradation has been developed by Johnson Matthey. These have been integrated by Nedstack into improved stacks and durability tests have started in the Delfzijl plant.

[8] Baturina O., Garsany Y., Gould B., Swider-Lyons K. “Contaminant-Induced Degradation”, in book: “PEM Fuel Cell Failure Mode Analysis”, CRC Press, Taylor & Francis Group, Ed. Haijiang Wang, Hui Li, Xiao-Zi Yuan, pp.199-241, 10.13140/2.1.4394.1123, 2012.

Plant Modelling

A model of the plant has been set up, focusing on analysing component interactions, evaluating the effects of different operating conditions on plant global performances, simulating the plant mass and energy balances and validating the plant measurements. The simulation tool is Aspen PLUS®[9], a modular simulation code widely used for energy and chemical plant design and rating. It includes standard components (e.g. heat exchangers, pumps, chemical reactors and devices commonly used in the process industry) which can be interconnected by material and energy streams to reproduce the layout of a plant, and libraries for thermochemical properties of several fluids. Moreover, it allows custom components definition, used here to develop the PEM model.

The layout of the plant is shown in Fig. 6. The main component of the system is the PEM fuel cell, made up of several stacks, whose model is discussed in a specific section. Pure hydrogen, provided at a sufficient pressure by the chlorine plant, is humidified and fed to the stacks. Excess hydrogen is recirculated in a dedicated blower and mixed to the fresh feed.

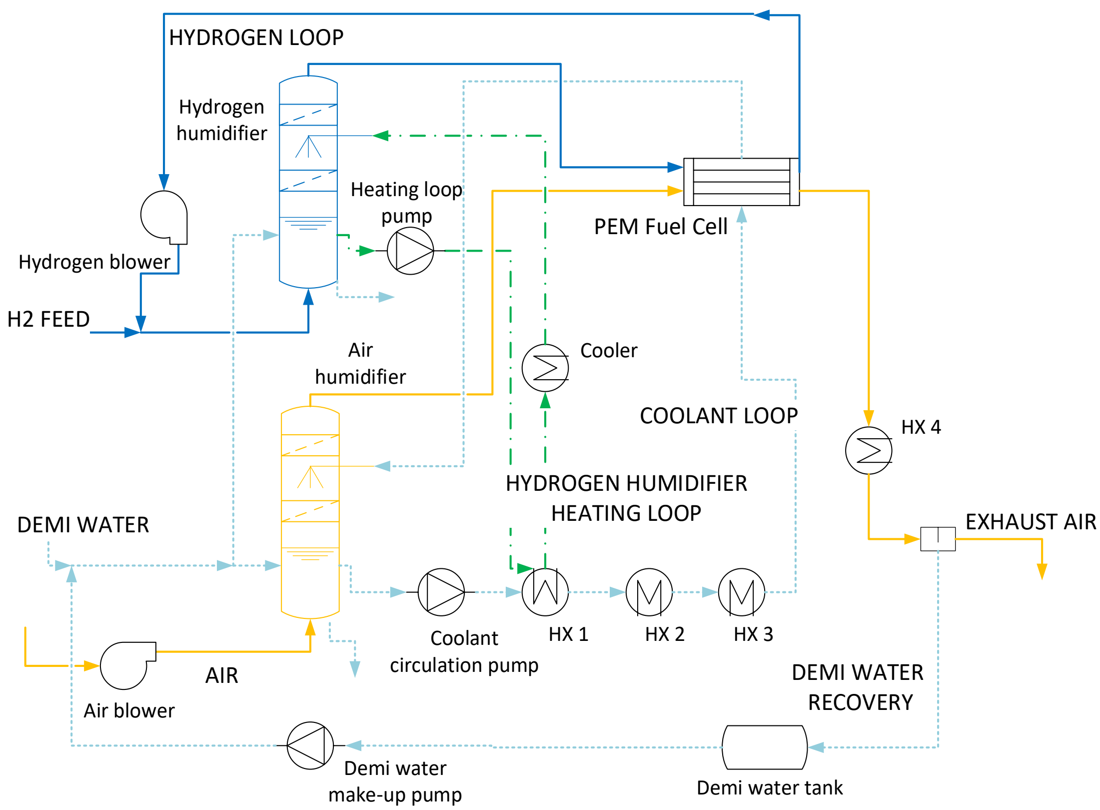


Fig. 6 - System layout and material streams.

Compressed air is humidified and fed to the stacks; exhaust air is cooled down (HX4) in order to recover demi water; the water production mass flow rate is higher than humidifiers requirement, yielding a positive contribution to chlorine plant consumptions.

A closed water loop provides cooling of fuel cell modules; heat is then removed by two heat exchangers, the first designed to recover useful heat (e.g. for brine pre-heating) (HX2), the second for temperature control (HX3). Another water loop provides heating for water evaporation in the hydrogen humidifier through an additional heat exchanger on the coolant

[9] "AspenTech software website." [Online]. Available: https://www.aspentech.com/. [Accessed: 15-Dec-2017].

loop (HX1); depending on plant operating conditions, the loop could also require rejecting heat through a dedicated cooler. All heat exchangers are calculated assuming free cooling power on the cold side (thanks to the large industrial plant cooling water circuit) and controlling the flow rates to match design temperatures. For the case of HX2, influencing the cogeneration performance of the plant, the global heat exchange coefficient U is varied vs. the volumetric flowrate (elevated to 0.2) where nominal values are calculated in design conditions from datasheets. Pressure drops in the loops are also calculated, being proportional to the square of volumetric flowrate through a constant evaluated on design data for heat exchangers and calculated from hydrodynamics models for piping[10].
The counter current spray humidification units are modelled with a lumped approach, solving mass and energy balances in order to match the relative humidity requirements of the cell (RH>85%).
Air and hydrogen blowers are modelled through their characteristic curves, allowing to simulate the effects of different flow rates and stoichiometry on their energy consumption.

Fuel cell modelling

The fuel cell model is set up to allow predicting the effects of variable operating conditions and voltage decay vs. lifetime. Given the size of the problem, where many stacks are connected in an arrangement which involves more than 25'000 single electrochemical cells, a detailed description and analysis of the internal structure of the electrochemical devices and operating conditions of single cells (like the one performed in 1D to 3D finite volume or finite element models[11]), is out of the scope and too heavy for a reliable model convergence. Moreover, it is not required by the final goal of the simulation, focusing on large scale effects.
A lumped 0D model of the stacks is therefore applied, neglecting internal cell geometry and material properties and concentrating on solving energy and mass balances for groups of stacks (Fig. 7), whose operating parameters (power and current) can be set individually, based on the assignment of inlet streams thermo-chemical properties according to the model of the distribution system (hydrogen, air and coolant water loops).
The stacks are considered to be built with several identical 'average' cells; identical stacks are then connected in series or in parallel in order to model larger modules in a single block. The 2 MW unit is divided into 6 groups of several stack modules, where each group is connected to a separated inverter, limited to a maximum power output of 360 kW.

[10] G. Guandalini, S. Foresti, S. Campanari, J. Coolegem, J. ten Have "Simulation of a 2 MW PEM Fuel Cell Plant for Hydrogen Recovery from Chlor-Alkali Industry", 8th Int. Conference on Applied Energy – ICAE2016, Energy Procedia, vol.105, p. 1839-1846, DOI: 10.1016/j.egypro.2017.03.538, 2017.
[11] C. Siegel "Review of computational heat and mass transfer modeling in polymer-electrolyte-membrane (PEM) fuel cells", Energy, vol. 33, no. 9, p. 1331-1352, 10.1016/j.energy.2008.04.015, 2008.

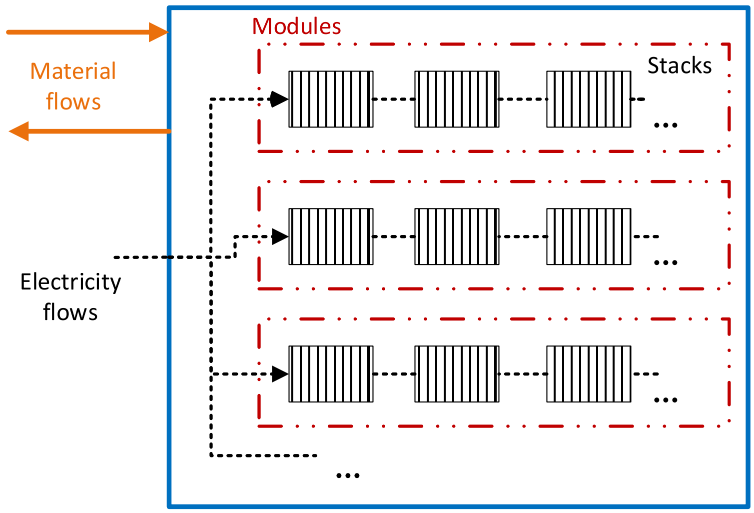


Fig. 7 - Modular structure of the PEM fuel cell system.

The fuel cell model is developed in Aspen Custom Modeler®, designed also to analyze the off-design operation, taking into account variations in the cell stoichiometry, operating temperature as well as the influence of cell performance decay. The analytical formulation of the polarization curve adopted for single cells yields the following voltage (V) vs. current density (i, A/cm^2) expression [12],[13]:

$$V(i, x_{H2}, x_{O2}, T) = A_T + B_T \ln\left(\frac{x_{H2}}{x_{H2,st}}\right) + C_T \ln\left(\frac{x_{O2}}{x_{O2,st}}\right)$$
$$+D_T i + E_T \ln\left(\frac{i}{i_0} + 1\right) + F_T \ln\left(1 - \frac{i}{i_L(x_{H2}, x_{O2})}\right) \quad (1)$$

including a temperature dependence, according to:

$$E_0 = -\frac{\Delta G}{nF} = -\left(\frac{\Delta H - T\Delta S}{nF}\right) \quad (2)$$

$$A_T = E_{0,T} - (E_0 - A)\frac{T}{T_{ref}} \quad (3)$$

$$B_T = B\frac{T}{T_{ref}},\; C_T = C\frac{T}{T_{ref}},\; E_T = E\frac{T}{T_{ref}},\;\; F_T = F\frac{T}{T_{ref}} \quad (4)$$

$$D_T = D\, exp\left(1268\left(\frac{1}{T} - \frac{1}{T_{ref}}\right)\right) \quad (5)$$

$$i_0 = i_0^{ref} \exp\left[-\frac{E_c}{RT}\left(1 - \frac{T}{T_{ref}}\right)\right] \quad (6)$$

[12] U.S. DOE (Department of Energy), Fuel cell handbook, 7th ed. EG&G Services, Inc., 2004.

[13] Larminie J., Dicks A. “Fuel cell systems explained – 2nd Edition”, Wiley, ISBN 0-470-84857-X , 2003.

where E_0 is the cell reversible potential at standard conditions (p_0=1 atm, T_0=25°C). The temperature variation is evaluated through:

- a linear correction of the coefficients A,B,C,E,F starting from a reference temperature (T_{ref}=338 K , ~65°C),
- a correction of ohmic loss in the coefficient D, according to the change in ionic conductivity vs. temperature for a reference membrane[14] ;
- a correction of activation losses through the exchange current density i_0, where E_c is the activation energy (assumed at $66\frac{kJ}{mol}$ for oxygen reduction on Pt).

The temperature dependence allows improving the accuracy in voltage prediction vs. the actual plant operating conditions, where the cell temperature sometimes deviates from the design value of 65°C; nevertheless, typical temperature variations are rather small, so that this part of the model does not influence heavily the calculation results.
Stoichiometry effects generally hold a more significant importance, since the power plant can be operated in a relatively wide range of air excess and, secondarily, hydrogen excess. Stoichiometry is taken into account through species molar fractions x_i [12]. Reactant concentrations are evaluated as average between inlet and outlet cell compositions, leading to the following expressions:

$$\frac{x_{H2}}{x_{H2,st}} = 1 + \frac{S_H - 1}{S_H - 1 - x_{sat}(T_{an}) \cdot RH_H} \quad (7)$$

$$\frac{x_{O2}}{x_{O2,st}} = 1 + \frac{S_O - 1}{S_O + 0.21(1 - x_{sat}(T_{cat}) \cdot RH_O)} \quad (8)$$

where S_H and S_O are the ratio to stoichiometry of hydrogen and oxygen respectively. The parameter RH is relative humidity, taking into account the difference in real operating conditions with respect to water fraction in saturation conditions $x_{sat}(T)$, which is evaluated at each stream average temperature. Pure hydrogen is fed to the anode, while standard air (21%$_{vol}$ oxygen) is considered for cathode side.
Coefficients *A-F*, as well as exchange and limiting current densities i_o and i_L are regressed on experimental data from stacks [7, 15] that were operated in Lillo and Delfzijl plants, using a type of MEA and stack technology very similar to the one employed in the 2MW plant.
An example is presented in Fig. 8.

[14] T. E. Springer, "Polymer Electrolyte Fuel Cell Model," J. Electrochem. Soc., vol. 138, no. 8, p. 2334, 1991.
[15] M. Smit, "Towards 40000 hours of operation for Nedstack's FCS XXL PEM fuel cell stacks," Fuel cells Bull., vol. 8, pp. 12–15, Aug. 2014

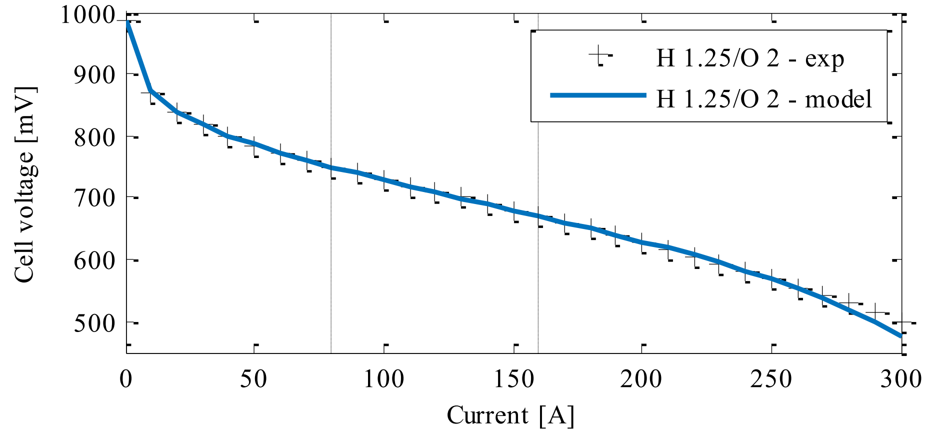


Fig. 8 - Example of regressed polarization curve for a given stoichiometry at BOL.

The model also takes into account the cell voltage decay vs. time. Two regression of the coefficients A-F have been done at BOL and EOL, then interpolating between the resulting polarization curves at mid-of-life conditions. Cell voltage is considered to decay linearly between the available dataset, an assumption justified by experimental evidences with similar stacks in a test installation [7, 15].

In addition, when going towards EOL, experiments showed further variation of losses vs. reactants concentration, which has taken into account through a dependence of exchange current i_0 and limiting current i_L on stoichiometry, included in the model by calculating the two parameters as linear functions of reactant molar fractions:

$$I_L(x_{H_2}, x_{O_2}) = I_{L,1} + I_{L,2}\left(\frac{x_{H_2}}{x_{H_{2,ref}}}\right) + I_{L,3}\left(\frac{x_{O_2}}{x_{O_{2,ref}}}\right) \quad (9)$$

In most operating conditions, i_L showed a dependence mainly related on the hydrogen stoichiometry and $I_{L,3}$ turned out to be negligible, so that it has been removed from the final model (Tab. 1).

Regressed parameter	Value at BOL	Value at EOL
A [mV]	961,23	952,4
B [mV]	27,7	6,49
C [mV]	116,4	3,15
D [mΩ]	-0,267	-0,43
E [mV]	-40,3	-24,44
F [mV]	81,9	195,48
I_0 [mA]	187	97,15
$I_{L,1}$ [A]	334,6	-1120,2
$I_{L,2}$ [A]	-	322,2

Tab. 1 – Regressed coefficients of the polarization curve model.

Figure 9 shows the resulting operating map for a given stoichiometry. The model then allows to evaluate the performances and optimize the plant operating point during lifetime, while maintaining the required electric output.

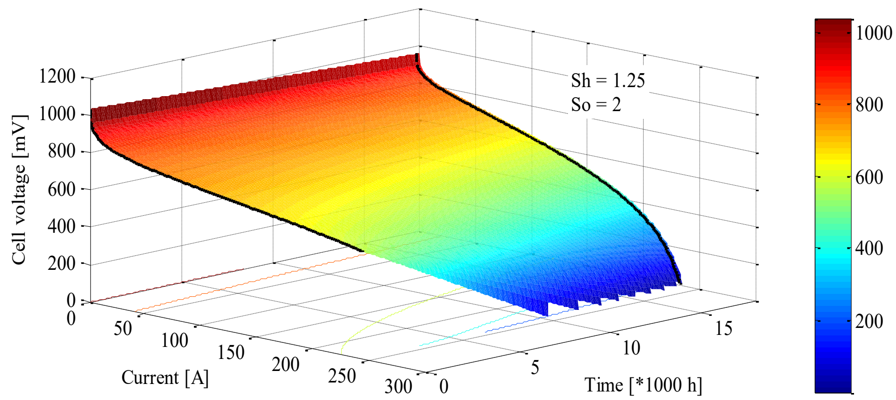


Fig. 9 - Regressed polarization curves as function of current and time.

Contribution of stacks to pressure drops is also included, validated against experimental data for different reactant stoichiometry.

Model Validation and operating results

Results of plant operation can be used for the model validation.
The plant energy balance is shown in Fig. 10. Note that, due to issues with one of the inverters, the plant operated in the first period with 5 out of the 6 groups, so that the 'full load' condition has a cap at approximately 1700 kW. The recoverable heat is estimated from the maximum temperature difference allowed on the cogeneration heat exchanger (HX2 in Fig. 6).

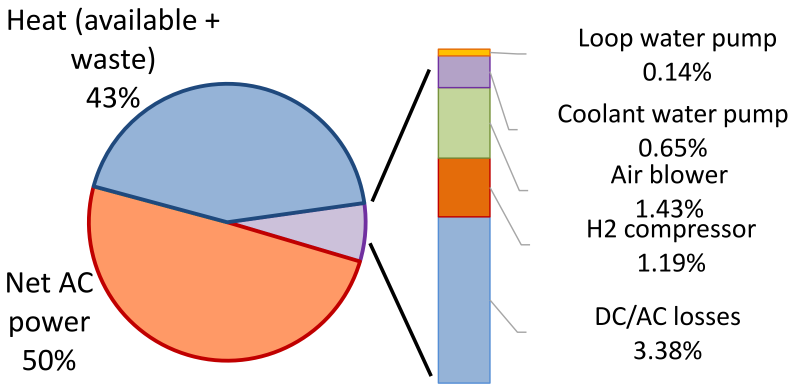


Fig. 10 - System energy balance at BOL (5 out of 6 groups running, net electric power 1.7 MWel).

Stacks performances in real operating conditions were compared with the model prediction in terms of voltage at given current, assuming a given hydrogen and air flows. The comparison shows that the BOL voltage at nominal current is well modelled (errors around 5 mV corresponding to 1-2%) and grows to 7-16 mV for lower current (where the real stoichiometry is out of the optimal validity range of the original calibration) and different temperatures. Further observed deviations can be attributed to reactant purity and reversible decay issues.
The results for the overall plant model were checked against measured data in the first months of operation, yielding the comparison in Tab. 2. Most deviations are within 2%, demonstrating a good model accuracy.

Operating conditions				
Air inlet flow	Nm^3/h	5314		
Stoichiometry cathode / anode	-	2.3 / 2.0		
T coolant, FC inlet	°C	60.0		
Power DC (gross)	kW	1653		
Results		Measurement	Model	Difference
H_2 inlet flow	Nm^3/h	972	978	0.6%
Temperature air humidifier	°C	63.0	62.7	-0.4%
Coolant flow	m^3/h	317	315	-0.6%
Coolant temperature at stack outlet	°C	64.7	63.9	-1.3%
Voltage (average)	V	728.7	742	1.8%
Current (average)	A	113.4	111	-1.8%
Auxiliary power	kW	106	105	-1.2%

Operating conditions				
Available Thermal power (HX2)	kW	-	735	-
Power AC (net)	kW	-	1450	-
Efficiency (gross)	%	56.7	56.4	-0.5%
Efficiency (net)	%	-	49.5	-
Net water production	kg/h	-	534	-

Tab. 2 – Operating conditions at BOL (5 out of 6 groups running) and modeling results.

Humidified hydrogen and air are fed to the stacks in a quantity higher than the stoichiometric (2.0 and 2.3 respectively). Heat available for recovery from FCs to the industrial site is about 735 kW, bringing about an additional useful effect in the plant operation, weighting nearly 25% in terms of heating value if the hydrogen input. Despite heat integration with the chlor-alkali process has not been completed in this installation, the availability of a large and emission free heat source suggests the integration of further processes, e.g. adsorption or absorption cooling or low-temperature preheating.

The plant also produces 534 kg/h of demineralized water which can be a valuable contribution to the industrial site consumptions.

By the point of view of electricity generation, gross efficiency of the FC system is nearly 57% (ref H_2 LHV). Main auxiliary consumption is ~105 kW, mostly concentrated on inverter system and air and hydrogen blowers, followed by coolant pumps. Electrical losses in the inverter could be avoided through a direct coupling with chlor-alkali process electrolysers; nevertheless, this type of connection would require a specific DC/DC converter and control system, an option which – although theoretically feasible - was not adopted in the DEMCOPEM-2MW project for simplicity and investment cost reduction.

The developed simulation model allows exploration of possible modifications for the plant operating conditions and layout (e.g. increasing the operating temperature or pressure, operating at different stoichiometries, process optimization). Indeed, the main factors affecting the plant performances and potentially subjected to further development and optimization are:

- the air and fuel stoichiometry; a possible increase of air excess can for instance be considered both for performance recovery towards EOL as well as for new plant optimization;
- cell operating pressure and temperature; the Nernst potential increases with pressure, despite requiring higher parasitic losses in the air / fuel compressors, while an increase of temperature allows decreasing the cell losses, with a global gain on cell voltage and efficiency.
- MEA and stack design; further evolution will address loss reduction and increase of compactness and power density.

3 Performance

During the operating period only a limited number of stacks was returned to NFCT due to cell failure. These were predominantly due to particle contamination from external sources.
However, the fuel cell performance decrease in China was found to be faster than expected, while the same stacks, and even returned stacks from China, showed a normal performance in a similar plant at the Nouryon site in Delfzijl, the Netherlands. This was observed for both reversible and irreversible decay. During numerous plant visits it was noticed that the site utilities were not always according to the required specifications. For example, installation of an additional hydrogen scrubber in October 2017 reduced the decay rate in the subsequent period by a factor 2. It can be concluded that more attention should be paid to prevent and monitor feed stream contaminations, for both hydrogen and air.

In terms of long-term operation energy balances, the average net electric efficiency calculated over the first year of operation has been in the range 49-50% (LHV), while the average first law efficiency was 76% (LHV) with peaks at 80% depending on environmental temperatures [27]. By this point of view, the plant confirmed the possibility to achieve the energy savings discussed in the introduction.
A cumulated analysis of results during the first two years of operation is reported in Fig. 11. More than 13.7 GWh_{el} have been produced and the heat available for recovery has been about 7.3 GWh_{th}. Operating hours were slightly lower than expected (with availability about 83%), influenced by variation in production capacity of the upstream industrial plant and total uptime limited by actual high-quality hydrogen availability and grid limitations. The total quantity of hydrogen recovered by the plant was nearly 870 tons, with a final GHG emission avoidance of over 15000 t_{CO2}.

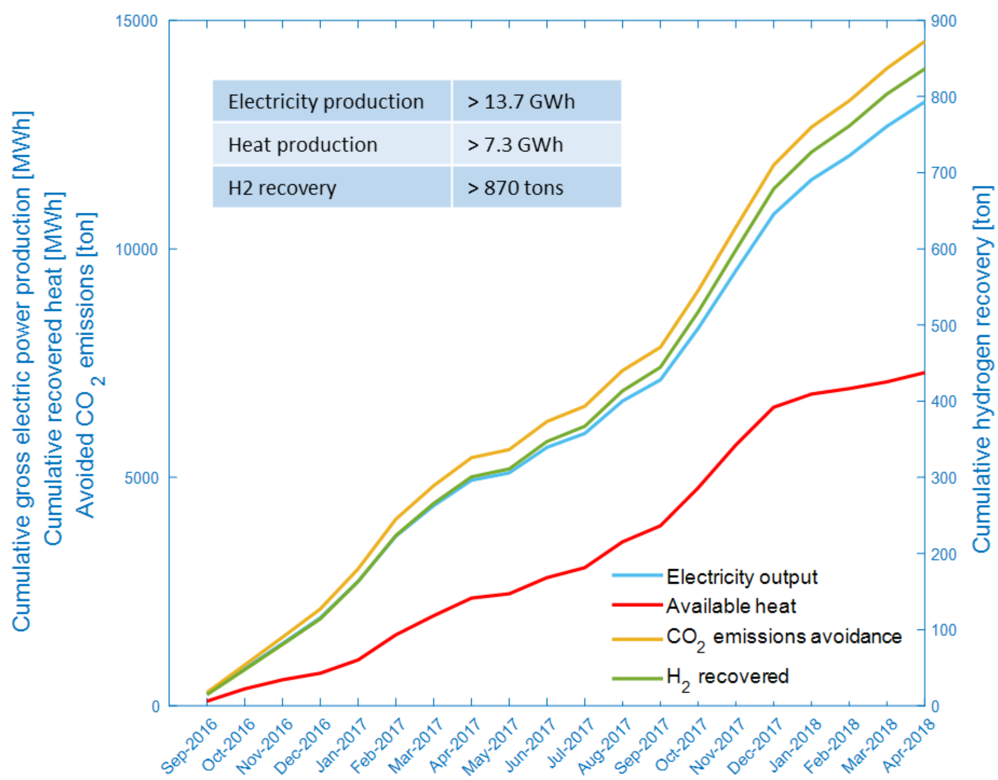


Fig. 11 - System cumulated energy indicators in the first two years of operation.

4 Roll out phase design and economics

Roll out phase design

Since the roll put phase is planned soon after the DEMCOPEM project finishes, no fundamental design changes in the stack design are considered; the design is based on the current proven technology, with additional incremental developments. This means that the 200 cm^2 stack platform will be used, but with an increased cell count and operating point. The feasibility of these improvements has been validated in the meantime. Also increasing stack group size is considered and included in the roll out phase design to decrease the costs of power electronics and reduce the amount of valves and sensors .
The design of the Balance of Plant, defined as the not fuel cells part of the installation, is for an important part determined by the specifications of the fuel cell design and specification for integration. Improvements in the stack design therefore lead to cost improvements of the Balance of Plant. Other parts of the Balance of Plant, not directly related to the fuel cells, will be optimized as well by an improved design.
Standardization and production in series for the roll out phase will reduce CAPEX, while applying smart and dedicated designs will also support in reducing operations cost. Result is a concept design with implementation of the defined improvements. The concept design is illustrated by means of a 3D plot of the design for the roll out phase design.

After consideration of costs and benefits, a number of actions and measures are proposed for the roll out phase:

- Optimization of process flows by using modelling.
- Case by case investigation of opportunities for thermal energy recuperation.
- Increased stack size, reducing the number of stacks
- Increasing stack group size leading to 4 groups for a 2 MWe fuel cell generator.
- Equipment with higher efficiency.
- Standardization and optimization design for production in series.
- Application, if appropriate, of standard electrical grid connection units.
- Monitoring of the refreshment rate of the humidifiers.

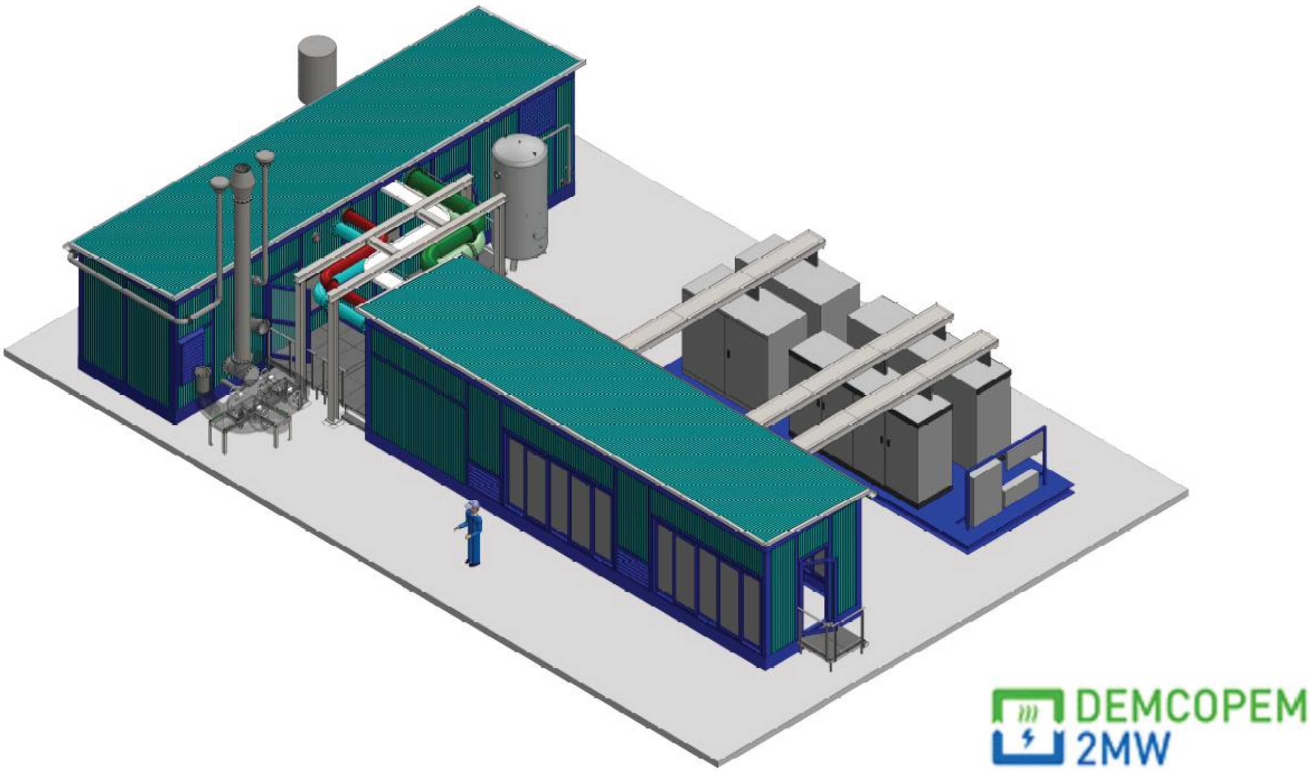
During electricity production a substantial amount of heat comes available as hot water. For a 2 MWe PEM fuel cell generator about 1 MW is available for energy recovery purposes. A heat exchanger including automatic capacity control system is applied in the stack cooling circuit to recover this heat.
In case of application of a PEM fuel cell generator in a chlor-alkali process, possible applications for use full application of the heat are the Lithium Bromide refrigeration process or for heating of the incoming brine. Both possibilities pending the current set-up of the local facilities.
In case of possible use for the refrigeration process, a relative cost intensive cost heat pump system is required. The economic feasibility will mainly be dependent on the longer term energy price level. Also other applications for the heat source need to be assessed case by case. The opportunities are dependent of the local circumstances and facilities at the site of the user. This is applicable for chlor-alkali applications and for all other possible applications of the PEM fuel cell generator, e.g. for renewable energy applications, as well.

The proper functioning and the design of the power plant is dependent on the specification of the locally available utilities. As these specifications generally differ case by case, in each project in the roll out phase these have to be specified, agreed and secured in close cooperation with the user.
Based upon experience in the demonstration project, special attention needs to be paid to the quality of the hydrogen and local ambient air. Also the check on appropriate technical execution and confirmation of specification of utilities prior to start up / commissioning needs to be incorporated in project plans.

The roll out phase optimizations lead to a modified process flow set up. Main difference with the version of the demonstration phase is that the stack configuration is changed. By applying fuel cells with a higher nominal power (8,3 kW instead of 6,0 kW) the number of fuel cells decreases significantly and another configuration is chosen. Several other improvements as mentioned will be implemented as well.

A plot plan with the main components of the installation is drawn up. See the figure below.

Due to easy transportability the generator consists of 3 units. This set up in units makes prefabrication in series and factory testing possible.



The unit right under in the figure is the stack container. Depicted are 4 groups of fuel cells, 2 groups an each side. The fuel cells are accessible from the outside because of maintenance purposes. In the front side of the stack container the operating / control room is included. This compartments also houses the central low voltage installation.
The unit at the top left is the process container. This unit houses the main part of the process related sub systems. Examples are the hydrogen and air humidification, cooling systems, energy recuperation and compressor units for hydrogen and air.
At the top right the inverter / transformer unit is depicted. Starting point is the application of a standard available unit.

Roll out phase economics

The DEMCOPEM project was made possible by financial support of the EU. The roll out phase design is a major step in the direction of economic viable systems, which in specific cases can already lead to a positive business case. Local circumstances and financial starting points have an important influence on the economic viability of the system. It should be noted that this is a full 0-emission technology, and not dependent on variable natural resources such as wind and solar power. In general it nevertheless can be concluded that the technology only will be viable if CAPEX and OPEX cost are further improved in the future.
Improvements in the stack design and other improvements of the Balance of Plant lead to an improvement in CAPEX.
An important factor in this development will be the increasing market of PEM fuel cells for transport applications, leading to e.g. decreasing cost and possibly longer life times of fuel cells. With this development as starting point an economic viable case is specified.

Although the economic viability is strongly dependent on the starting points used, in general the OPEX calculation shows that without subsidies on CAPEX or electricity production, the application is not enough viable yet. Target nevertheless must be that projects are economically viable without subsidies.
According to current market information, electricity production prices of approximately EUR 0,05 / kWh are assumed to be obtained, although these cost will vary case by case. In order to reach this target, a number of starting points regarding the CAPEX and the lifetime of fuel cells are to be assumed. An extra calculation column is included in which these assumptions and targets are depicted. A main

factor will be the required strong cost reduction of fuel cells and an increase in lifetime. A strong increase in the use of fuel cells for mobile applications are expected to be determining for this required development in costs. Assumed is that this development will also lead to the opportunity for a more optimised design of the Balance of Plant. It may be expected that the development leading to this target requires several years.

In the figure below, the estimated OPEX for a 2 MW PEM Power Plant in the roll out phase is specified. The DEMCOPEM project is used as reference. The column with the target calculation gives an indication of the required OPEX cost per cost item in order to obtain economically viable projects without subsidies on CAPEX and / or electricity prices. It is assumed that maximum electricity production prices of approximately EUR 0,05 / kWh need to be obtained in order to reach a viable business case. In practice this price will vary case by case. The same applies for the starting points. Therefore the calculation has to be considered as “typical calculation” and needs to be adapted pending the actual project starting points.

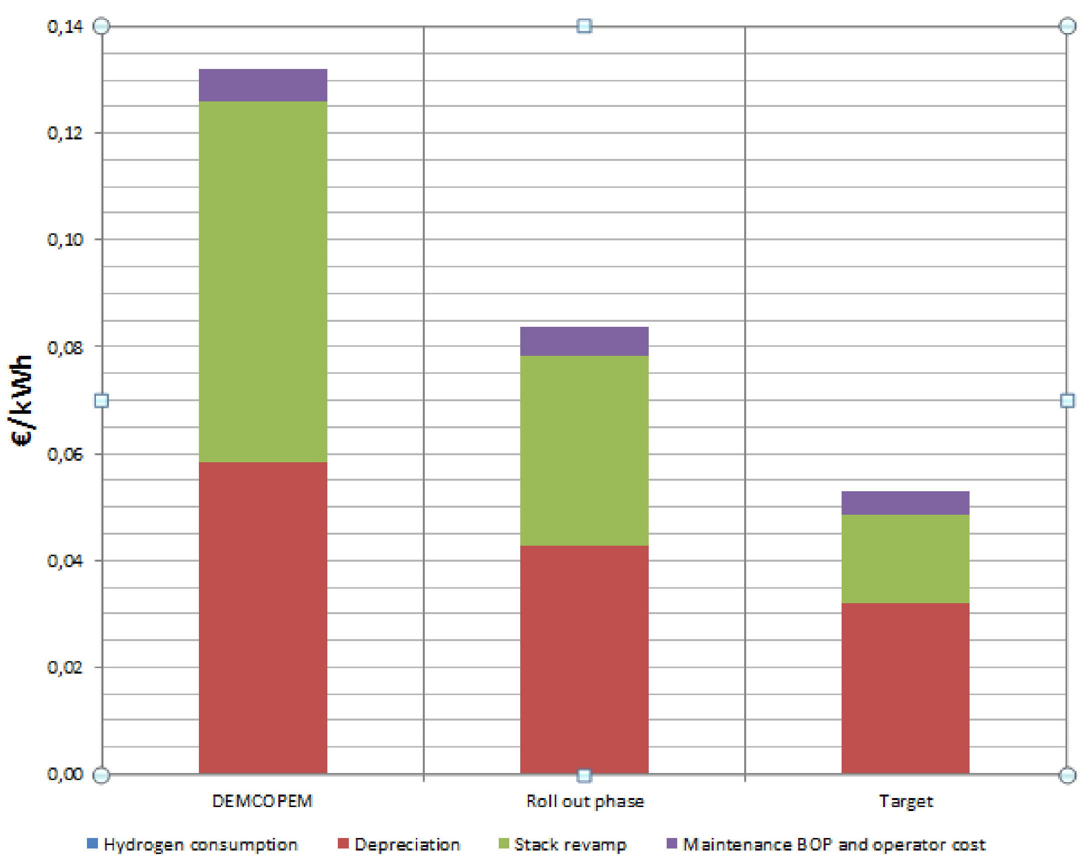


Figure 12 - Cost structure production electricity

The electricity production cost turn out to be highly dependent on the total investment, lifetime of the fuel cells and the cost for revamp. Cost for operators and maintenance of the Balance of Plant appear to be relatively low.

5 Project Results

The world's first 2MW PEM fuel cell power plant has been successfully designed, constructed and integrated into a chlor-alkali (CA) production plant, in Yingkou China.
The chlor-alkali production plant produces chlorine and caustic soda (lye) and high purity hydrogen. The hydrogen contains almost 45% of the energy that is consumed in the plant. In many cases this hydrogen is vented. The project demonstrated the PEM Power Plant technology for converting the hydrogen into electricity, heat and water for use in the chlor-alkali production process, lowering its electricity consumption by 20%.

The main project technical results/KPIs are summarized below:

- Integration of heat and power with an existing chlorine production plant
  - 2MW power achieved in operation
  - Heat available @ 60°C
  - Additional treatment hydrogen / air required; H2 scrubber installed
- High net conversion efficiency 50% electric energy on system level and 80% for combined heat and power
- Demonstration of power and heat generation for over 2 years
- On-stream availability of up to > 95% in an operational period for over 2 years
  - Influenced by OSBL (H2/grid availability) and stacks but successfully demonstrated end 2017
- Fully automated way of operation and remote monitoring
- Investment demonstrated for €3,000 / kWe
- A decrease in capital an operational cost for the roll out phase and the specification of a viable business case, assuming an increasing market for PEM fuel cells leading to lower costs and longer life times of fuel cells.

Other results and achievements:

- The plant produced more than 13GWh and made available 7 GWh of thermal energy at 65C̊
- More than 850 tons of hydrogen have been recovered avoiding emission of 15.000 tCO2
- New MEAs technology production developed (with lower Pt cost)
- Developed open-source calculation tool for preliminary economical assessment.
- Two project workshops successfully organised in China
- Several publications and presentations at conferences.

Several chlor-alkali plants have shown serious interest and for a PEM power plant and at least 25 show an attractive business case for the next series PEM power plant. The final selection of the chlor-alkali plant for the demonstration will be based on the attractiveness of the business case and the suitability to act as showcase.
Worldwide the amount of hydrogen produced by chlor-alkali plants would be sufficient to produce about 3,000 MW with a PEM power plant. The ultimate target would be to have at least 1,000 MWe/h produced via a PEM power plant worldwide.

6 Impact

DEMCOPEM-2MW designed, built and integrated a 2 MW PEM fuel cell power generator in an existing chlorine production plant in China, and started demonstrating power generation with one set of fuel cell stacks and over 95% on-stream availability. Further, it developed MEAs and fuel cell stacks with improved performance and lifetime that will be validated in ANIC's PEM pilot plant in Delfzijl (and in the PEM demo plant in China) and a roll out plan (exploitation plan) for the Market Entry.

In the figure below a scheme of the project exploitation plan as well as DEMCOPEM-2MW's position in respect to the road map towards full implementation of PEM power plant in 2020 onwards.

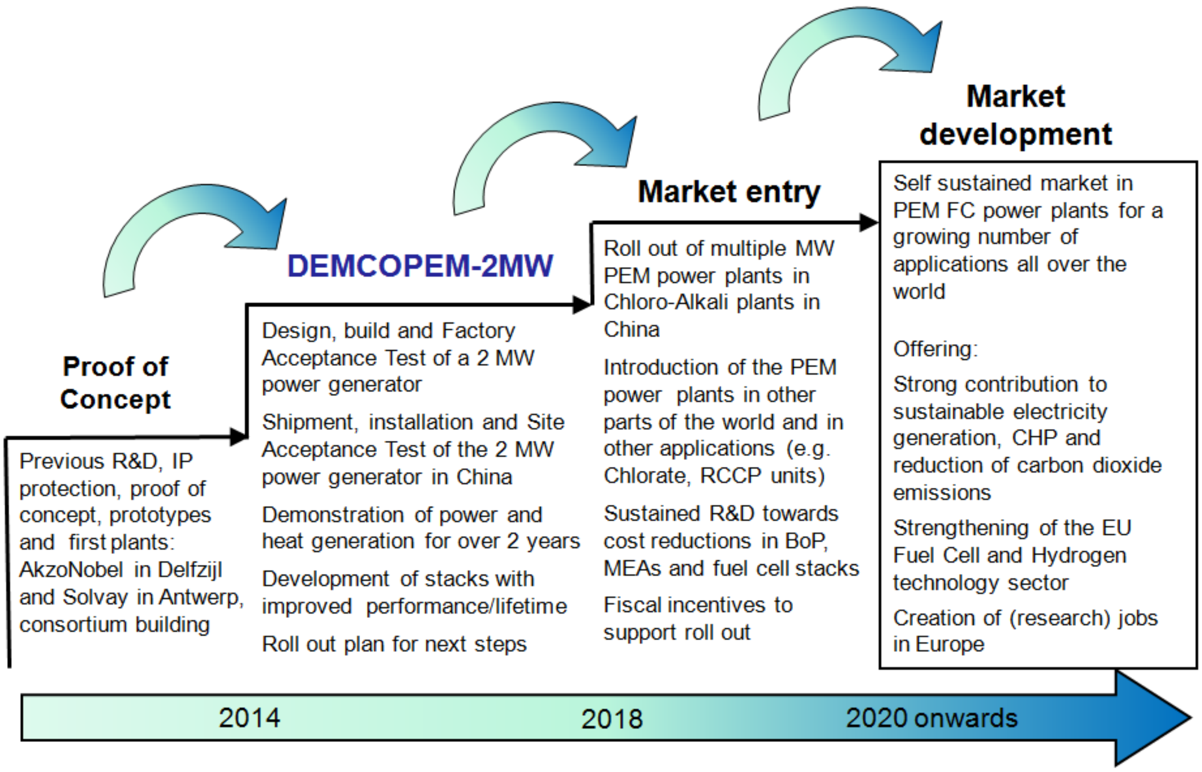


Figure 12 DEMCOPEM-2MW's position and roadmap towards full implementation in 2020 onwards.

For the **Market Entry** phase the plan is to roll out multiple PEM power plants in Chlor-Alkali plants in China together with Chinese partners. ANIC has already made an inventory of potential customers and locations that have been informed of the demonstration and its results during the demonstration period through newsletters, workshops and site visits.
The roll out phase is described in deliverable D2.7 : Report Design first series PEM Power Plants for the roll out phase; main subjects of this report are design, CAPEX and OPEX aspects in the roll out phase.

To understand the potential of the list of potential customers and locations presented in the table one should realize that a 2 MW PEM Power Plant requires a hydrogen capacity of 1,300 Nm^3/h. In other words, **the list cumulates at least 25 plants and in total over 100 Megawatts**.

The manufacturing possibilities in Europe are as follows:
1. JMFC will produce and sell improved MEAs to NFCT;
2. NFCT will purchase MEAs from JMFC and produce and sell improved fuel cell stacks
3. MTSA will develop and build series of the PEM Power Plants, integrate the fuel cell stacks, and ship the plants to China.

Project Impact for consortium partners

Johnson Matthey Fuel Cell

The market for stationary fuel cell power is growing significantly, and Johnson Matthey Fuel Cells continues to offer high-quality, cost effective components for it. Thanks to its work in the DEMCOPEM-2MW project, the MEA developed in task 6.1 and 6.2 is now a mature product available for sale at Johnson Matthey Fuel Cells and is volume-production compatible. The project MEA replaces an earlier MEA for the stationary fuel cell power market which was made in a large number of manual operations; the DEMCOPEM-2MW MEA is largely made on continuous, automated production equipment. The MEAs produced were tested thoroughly to improve JMFC's understanding of production consistency and quality control problems, and to suggest likely lifetimes in operation. This in turn led to the development of improved MEAs in the latter part of the project.

Following the production and supply of around 27,000 MEAs to NFCT and the building of stacks, which were incorporated into the 2MWe power plant, JMFC were able to gain valuable experience of real-world MEA operation in the challenging environment of a Chinese chlor-alkali plant, and an understanding of how the MEA performance and likely lifetime are adversely affected by contaminants in the reactant gases.

JMFC will take the experience gained in the DEMCOPEM-2MW project forward into the GRASSHOPPER project (FCH JU Project 779430) which intends to develop a flexible, modular grid-assisting fuel cell stationary power plant; this project calls for an MEA at a reduced cost and offering increased dynamic performance.

JMFC are therefore in a position to supply MEAs to the developing stationary fuel cell power market as it continues to grow beyond 2020, when the power plant costs are expected to further reduce. JMFC anticipate that MEA development work carried out in the DEMCOPEM project will contribute to the growth of the stationary fuel cell power market within the EU due to the ability to produce a consistent, high quality MEA for stack and system developers

Politecnico di Milano (POLIMI)

The DEMCOPEM-2MW has allowed an increase of competences in fuel cell plant modelling and performance analysis at the Gecos research group of Politecnico di Milano, Department of Energy (www.gecos.polimi.it), which took part to the project. POLIMI will take the experience gained in the DEMCOPEM-2MW project forward into the GRASSHOPPER project (FCH JU Project 779430) which intends to develop a flexible, modular grid-assisting fuel cell stationary power plant. In this new project, POLIMI will leverage the capacity to develop a highly accurate model of the plant performances to support the optimization of the plant design and the definition of plant operating strategies. The experience will be further evolved through the definition of a plant dynamic model aimed at investigating and enhancing the PEM plant dynamic performance. Moreover, POLIMI will apply the new competences in the field of more complex power-to-gas-to-power systems, where the dynamic behaviour of PEM units plays a central role, as well as in projects related to transport an mobility applications.

Socio-economic Impact

At the moment commercialization is most interesting for cases where hydrogen is a waste product, vented to the atmosphere. Large reduction of CO_2-emission is possible when the energy content of the otherwise vented hydrogen is used. To enter the market the production of electricity with by-product hydrogen should be competitive with the price from the local grid, taking into account the avoided CO_2-emission. The chlor-alkali industry, and to a lesser extend the chlorate industry, generally has favourable contracts with electricity companies as cost of electricity is crucial. In Europe, these tariffs can be as low as € 40/MWh and sometimes even less. Therefore, China has been selected as, in this strongly growing economy, the electricity prices can be as high as €70 to €80/MWh. Moreover, rationing of energy is common practise in various regions of China as the build-up of power plants does not keep pace with the economic growth and growing energy demand. In these situations, *i.e.* a high electricity prices and rationing of electricity, the business case for a PEM power plant is economically viable as showed in the beginning of this section.

Chlorate plants in the world produce a quantity of hydrogen that would enable PEM fuel cells to generate 300 MW of power continuously. Three molecules of by-product hydrogen are released for every molecule of sodium chlorate. These plants are connected to wood pulp factories, associated with the paper industry. They are often positioned in remote areas with limited possibilities for the utilization of hydrogen. Technically a multiple MW PEM-unit can readily be fitted, but commercial criteria for cost and lifetime, similar to those of the chlor-alkali industry, must also be met.

Some years ago, AkzoNobel developed Remote Controlled Chlorine Production units (RCCP units) as an environmentally friendly alternative for chlorine transportation and as an economic and environmental alternative for smaller plants based on the mercury electrolysis process. The coupling of a PEM FC power unit to an RCCP unit is promising as the hydrogen is freely available in most cases. The size of 1-3 MW is a perfect match for the RCCP-unit as it takes all by-product hydrogen, reducing the intake from the grid by 20 %. The utilization of the heat from the PEM-unit means extra savings in fossil fuels.

The specific benefits of the DEMCOPEM-2MW fuel cell stack are in particular interesting in the following applications (in China, Europe and worldwide):

- Range extension in EV's; this market has gained substantial traction in Europe and in Asia. TCO and lifetime are essential and will be outcomes of the DEMCOPEM-2MW project
- Grid-balancing and reduction of CO_2 emission in electricity production. Fuel cell technology can play an important future role here and relevant companies as State Grid should be made aware of the advancements and reliability of fuel cell technology for large scale power supply
- Base-load power or extended back-up in telecom and utility market. These units typically provide < 10 kW power and with ongoing developments in reformer-technology these markets become within reach. Especially in the larger Southeast Asian region exists a huge demand for reliable (implying very long lifetimes) and clean power supply.

Wider Societal Implication

In December 2015, at the Paris climate conference (COP21), 195 countries adopted the first-ever universal, legally binding global climate deal in order to avoid dangerous climate change by limiting global warming to well below 2°C. This agreement is due to enter into force in 2020.
Before that date countries need to work on their 'National Climate Action Plans' (already prepared before the Paris conference).
One of the most important possible solution for limiting global warming is to reduce or completely eliminate the use of fossil fuel. With this vision in mind the renewable energies became/ will become main actors.
The technology developed in the DEMCOPEM project will provide main advantages in this direction.
The climate will benefit by the reduction in CO_2-emission.

The PEM power plant technology, developed within the DEMCOPEM project, will be introduced in other parts of the world and in other applications (e.g. Chlorate, RCCP units). In this phase it is important that sustained R&D efforts are taken to realise continuous cost reductions in Balance of Plants, MEAs and fuel cell stacks. Incentives for supporting the roll out, *e.g.* subsidies or fiscal measures for customers will be useful in the Market Entry phase.
The next step is the **Market Development** phase. In this phase, the market in PEM FC power plants has become self-sustained and cost-efficient for a growing number of applications all over the world.

The chosen project structure and approach ensures that the technology value chain in Europe now gets the opportunity to launch and develop as the business case for a PEM power plant in China is economically favourable. A successful field demonstration will pave the way for commercial introduction of PEM power plants in China (over 20 sites and potential for over 50 similar sized PEM power plants), will open up opportunities for introduction of the PEM power plant technology in other parts of the world and in chlorate and RCCP processes and will enable sustained research and development efforts to achieve cost reductions in fuel cell stacks and BoP, improved performance and longer lifetimes.
Demonstrating in China means a continuation of the development of the PPP technology. As soon as the PPP technology becomes cost competitive in Europe, it is ready for introduction in the EU.

External factors that may determine whether the impact will be achieved

Tax on CO2-emission would raise the price of electricity from the grid appreciably and would make the PEM-unit more competitive. Electricity produced with the most efficient natural-gas-fired units (50 % efficiency) leads to an emission of 0.4 tons of CO2 per MWh. A charge of € 50 per ton of CO2 raises the electricity price by € 20/MWh. Power produced with coal-fired units would be more expensive by € 60/MWh.

Further, the possibilities will be assessed at the Chinese Government to acquire subsidy for the introduction of this type of sustainable and energy saving technology; especially after a successful demonstration.

For fuel cell stacks also outside the chemical industry important opportunities in China and the Southeast Asian region are imminent.
The DEMCOPEM-2MW fuel cell stack (commercialized as XXL stack) is designed for high efficiency and exceptionally long lifetime. The actual demonstration of these features in the power plant will help to convince potential Chinese stack customers of the benefits of this specific stack technology over other suppliers.

7 Conclusions

The chlor-alkali industry features large electricity and heat requirements and produces significant amounts of hydrogen as by product. Hydrogen can feed a PEM fuel cell unit, generating electricity and heat production to cover part of the chemical plant consumptions.

This work presents the development and first experimental results of a 2 MW PEM fuel cell power plant, developed within the European project DEMCOPEM-2MW and installed in Yingkou, China (a country featuring a large presence of chlor-alkali plants) as the current world's largest PEM fuel cell installation.

A specific MEA and fuel cell development programme, targeting volume production capability while maintaining quality, performance and lifetime, was carried out by Johnson Matthey and Nedstack Fuel Cell Technology.

However, the fuel cell performance decrease in China was found to be faster than expected, while the same stacks, and even returned stacks from China, showed a normal performance in a similar plant at the Nouryon site in Delfzijl, the Netherlands. It can be concluded that more attention should be paid to prevent and monitor feed stream contaminations, for both hydrogen and air.

A model of the PEM voltage-current behaviour and of plant performances (including detailed mass and energy balances) was built and validated successfully against experimental results collected through the plant measurement setup and data acquisition system. Operation showed good availability can be achieved and over the 2 year operating period more than 13.7 GWh of cumulated electricity production, recovering over 870 tons of hydrogen and avoiding nearly 15000 tons of CO2 emissions; thus demonstrating the possibility to achieve significant energy savings. Target of 50% electrical efficiency was achieved, including the demonstration of thermal recovery which allows adding up to 25-30% in terms of total efficiency (ref. hydrogen LHV).

The analysis of plant energy balances suggests further exploitation routes for the available heat, while further simulation activities will explore optimization in plant operating conditions and layout.

8 Reference

The project has a peer review publication (2018): "*Modelling, development and testing of a 2 MW PEM fuel cell plant fuelled with hydrogen from a chlor-alkali industry*", DOI 10.1115/1.4042923, ASME Journal of Electrochemical Energy Conversion and Storage.

Further, below the list of all the papers and papers in proceedings at conference/workshop submitted:

#	Title	Authors	Paper/ Proceedings	Date of publication	Start Date	End Date	Publisher
1	Modeling, Development, and Testing of a 2MW Polymeric Electrolyte Membrane Fuel Cell Plant Fueled With Hydrogen From a Chlor-Alkali Industry	Stefano Campanari, Giulio Guandalini, Jorg Coolegem, Jan ten Have, Patrick Hayes and A. H. Pichel	J. Electrochem. En. Conv. Stor. 16(4), 041001 (Mar 12, 2019) (doi 10.1115/1.4042923)	12-03-2019	/	/	J. Electrochem. En. Conv. Stor.
2	Simulation of a 2 MW PEM Fuel Cell Plant for Hydrogen Recovery from Chlor-Alkali Industry	Giulio Guandalinia, Stefano Forestia, Stefano Campanaria, Jorg Coolegem, Jan ten Have	The 8th International Conference on Applied Energy – ICAE2016	8-10-2016	8-10-2016	10-10-2016	© 2016 The Authors. Published by Elsevier Ltd. Selection and/or peer-review under responsibility of ICAE
3	Modeling, development and preliminary testing of a 2 MW PEM Fuel Cell Plant fueled with hydrogen from a Chlor-Alkali Industry	Stefano Campanari, Giulio Guandalini, Jorg Coolegem, Jan ten Have, Paddy Hayes, Ton A. H. Pichel	ASME Power 2018	24-6-2018	24-6-2018	28-6-2018	ASME
4	Investigation of 2 MW PEMFC power plant for hydrogen recovery from chlor-alkali industry	Giulio Guandalini, Stefano Campanari, Stefano Foresti, Jorg Coolegem, Jan ten Have	PEFC 2017	4-7-2017	4-7-2017	7-7-2017	PEFC
5	DEMCOPEM-2MW COGENERATIVE PEM FUEL CELL UNIT FOR HYDROGEN RECOVERY FROM CHLOR-ALKALI INDUSTRY IN CHINA: FIRST MONTHS OF OPERATION AND PRELIMINARY DATA ANALYSIS	G. Guandalini, S. Foresti, S. Campanari, J. Coolegem, J. ten Have	EFC 2017	12-12-2017	12-12-2017	15-12-2017	EFC

6	MODELING OF A MW SCALE PEM FUEL CELL POWER PLANT INTEGRATED IN INDUSTRIAL CHLOR-ALKALI PROCESS	G. Guandalini, S. Foresti, S. Campanari, J. Coolegem, J. ten Have	EFC 2015	16-12-2015	16-12-2015	18-12-2015	EFC

The list of all the general dissemination activities is reported below:

#	Type of Activties	Partner	Kind/Title	Date	Place
1	Presentations	Nedstack	Bali presentation 2015	2015	Bali
2	Press releases	MTSA	Press release 2MW fuel cell powerplant	30-1-2015	
3	Articles Published in the popular press	MTSA	Mega order MTSA - Nedstack	21-2-2015	De Ondernemer
4	Articles Published in the popular press	MTSA	Proefopstelling Chinese 2-megawattcentrale in Arnhem	21-11-2015	De Gelderlander
5	Oral presentation to a scientific event	PoLiMi	EFC 2015	16-12-2015	Naples, Italy
6	Articles Published in the popular press	MTSA	Elektriciteitscentrale op brandstofcellen	17-3-2016	TW.nl
7	Oral presentation to a scientific event	PoLiMi	Modeling of 2-MW co-generative PEM fuel cell for hydrogen recovering from chlorine industry at WHEC 2016	13-6-2016	Zaragoza, Spain
8	Oral presentation to a scientific event	PoLiMi	The 8th International Conference on Applied Energy – ICAE2016	8-10-2016	Bejing, China
9	Oral presentation to a scientific event	Nedstack	The 8th International Conference on Applied Energy – ICAE2016	8-10-2016	Bejing, China
10	Oral presentation to a scientific event	MTSA	The 8th International Conference on Applied Energy – ICAE2016	8-10-2016	Bejing, China
11	Oral presentation to a scientific event	PoLiMi	PEFC 2017	4-7-2017	Luzern, Swiss
12	Oral presentation to a scientific event	PoLiMi	EFC 2017	12-12-2017	Naples, Italy
13	Articles Published in the popular press	PoLiMi	La ricerca si fa internazionale contro il riscaldamento globale	27-2-2018	Italy
14	Oral presentation to a scientific event	Nedstack	CA Conference Fuzhou, China 2018	28-3-2018	Fuzhou, China
15	Oral presentation to a scientific event	MTSA	Booth at the Hannover Messe 2018	23-4-2018	Hannover
16	Oral presentation to a scientific event	PoLiMi	ASME 2018	24-6-2018	Florida, USA
17		Akzo Nobel	Enquiry of Ventura Energy Pty.Ltd -Australia		
18		Akzo Nobel	Search for potential synergy with CAESH2 project		
19	Organisation of Workshops	Akzo Nobel	Workshop: Creating more value out of hydrogen with the DEMCOPEM technology	7-11-2018	Foshan, China
20	Oral presentation to a scientific event	Nedstack	9th International Chlor-Alkali & Vinyls conference	10-12-03-2015	Bali, Indonesia

21	Oral presentation to a scientific event	Johnson Matthey	MEA Technologies, IMPACT Young Researchers Summer School	22-9-2016	Grenoble, France
22	Oral presentation to a scientific event	Johnson Matthey	EuCheMS	26-8-2018	Liverpool, UK
23	Oral presentation to a scientific event	MTSA	9th International Chlor-Alkali & Vinyls conference	10-12-03-2015	Bali, Indonesia
25	Films	MTSA	Power to Power application of fuel cells	2016 - 2018	Europ + China

Acknowledgment

This project is co-funded by the 7th FP (Seventh Framework Programme) – Fuel Cells and Hydrogen Joint Undertaking

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Disclaimer
The FP7 project has been made possible by a financial contribution by the European Commission under Framework Programme 7. The Publication as provided reflects only the author's view.

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