FRONT PAGE

PROJECT FINAL REPORT

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[1] Usually the contact person of the coordinator as specified in Art. 8.1. of the Grant Agreement.

Content: Final publishable summary report

Executive summary

The PURE project is a FCH-JU funded project in which a 500Watt auxiliary power system is developed, built and tested. The system is based on LPG as primary fuel which is in the system converted into a hydrogen rich stream. The hydrogen is used in a high temperature PEM fuel cell to produce the electrical power. The system is designed for operation on board recreational yachts. Special focus is given to reduction of size, weight and cost.

The consortium consisted of coordinator HyGear Fuel Cell Systems (HFCS, NL), who is responsible for the reformer en system design. The Danish Technical University (DTU, DK) for MEA development of the HT PEM stack, APTL/CERTH (GR) for the development of materials for sulfur management of the system and ATR catalyst development. The Joint research Centre (B) give input on the testing of the MEA's and the system , and tested the short stack . DAMEN shipyards (NL) gave input on the maritime requirements, code and standards en practical solutions for the on board application of fuel cells.

In the project two prototypes have been designed, constructed, tested in the laboratory and demonstrated on board of a yacht. The prototypes feature MEA's in the fuel cell stack which contain new binderless electrodes. The manufacturing method of these electrodes are environmentally friendly without the use of formic acid. Furthermore, the autothermal reformer for the on board hydrogen production contains a sulfur tolerant catalyst and a improved copper-zinc based high temperature sulfur adsorbent. A new manufacturing technology, 3D metal printing, for heat exchangers has been used for the production of small, complex shaped prototypes. A 50% reduction in system size and weight has been accomplished compared to the state of the art small scale APU fuel cell systems. The measured system efficiency of 25% is an improvements over the 15% efficiency of the same size generators for the same purpose.

Further reduction in size and weight of the system is within reach by increasing the performance of the fuel cell MEA's with hydrogen concentrations in the reformate of 35% versus the 45% which is the current operating concentration. Additionally, the MEA's can be improved to be used in an air cooled stack versus a liquid cooled stack as operated in the PURE prototype. Both MEA developments will result in a size and weight reduction of the system. The use of 3D metal printing is promising when the technology become more mature in the near future. Heat exchangers with complex designs by integration of various functions (steam generation, gas mixing, three phase heat exchange, etc) are possible with this upcoming manufacturing technology.

The technologies developed in this small scale application offer opportunities for scaling up, use in alternative platforms, both stationary and mobile. The PURE project increased the interest from the maritime sector for fuel cells and taught the fuel cell world a lot about the specific requirements of the use on board of ships.

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Context and objectives

The need for auxiliary power for recreational applications is widespread. Especially for recreational ships there are multiple cases where it is undesirable to generate power using the propulsion system. In such cases, there often is the desire to use electricity for board electronics, radio, lighting and other applications. On board electricity is generated by the engine and stored with batteries. Both have their limitation; diesel engines are noisy, create vibrations and have emissions of hydrocarbons and NO_x and to some extend SO_x. The application is of so high importance that 'emission control areas' (ECA's) along most European and North American coastlines have been established. Even at open sea, emissions are currently controlled and worldwide activities aim at reducing naval emissions drastically. At the same time, safety rules require decentralised power supply on large passenger vessels, a task that is hardly accomplishable with diesel gen-sets that induce noise, vibration and pollutants. Furthermore, batteries have a limited storage capacity and lifetime and are less reliable especially under cold and humid environments, where ships can be.

An auxiliary power unit (APU) working independent of the engine based on a fuel cell technology is an attractive solution. Preferably the APU is operating on a fuel, which is already available on the ship so that no modification of infrastructure and fuel storage would be needed. This eases the market acceptance of the technical solutions and also simplifies certification, as no additional fuel storage will be needed. Propane or LPG is available on many ships as it is used for cooking, refrigerating and heating. The fuel cell provides an efficient and environmentally friendly means for the power supply. It increases efficiency and minimizes noise, vibrations and pollution.

The recreational maritime industry is looking for more electric power in ships, both for propulsion and for the so-called hotel functions. They are very interested in the development of portable fuel cell technologies, as they are more and more looking for low noise/ zero emissions energy usage on board.

In the PURE project a portable, auxiliary power fuel cell system for use on board of a recreational yacht is designed, built and tested. The project is built based on 5 partners: The Technical University of Denmark (DTU) who develops fuel cell electrode assemblies, APTL/CERTH (APTL) from Greece who develop materials for sulfur management in the LPG base system and sulphur tolerant ATR catalysts. The system design and construction is in the hands of the coordinating party, HyGear Fuel Cell systems. Two systems were to be manufactured for laboratory testing guided by test protocols of JRC (B) and on board demonstration on a recreational yacht. Damen shipyards completed the consortium to provide information on the maritime requirements of a fuel cell device on board of a ship.

There was a constant focus to keep the cost of the system low. The target for mass-produced systems is €2500. The components were to be sourced based on developments from previous fuel cell projects in which the consortium partners were active like (e.g. Nextgencell, LOTUS, FURIM etc). Balance of plant components will need to be low cost, mass producible and reliable for commercial use.

The main technical objectives of the project are:

1. An APU for recreational marine applications consisting of an HT-PEMFC stack and an integrated LPG/propane reformer with the following specifications:
    - 0.5 kWe max fuel cell output
    - Max runtime 1000 hours per period with 100 start-stop cycles
    - An overall electric system efficiency of 30+% (LHV)
    - A portable system having a weight of 17.5 kg and a volume of 25 liters
    - Modularity of design to ease scale up into bigger power ranges

2. The HT-PEMFC stack module is specified as follows:
    - Development of a HT-PEM stack with a stack performance of 4 kg/kW and 7 l/kW at peak loads of 0.6 A/cm^2.
    - Integrated graphite bipolar plates with flat seals and cooling circuit
    - Design and construction of stack module with air supply, air-cooling, control and safety unit fulfilling the APU requirements

3. The cells (MEAs) will have the following specifications:
    - Selected PBI cross-linked/composite membranes with a proton conductivity of 0.1 S/cm
    - Identification/development of more durable catalysts based on modified carbon or non-carbon supports (as compared to state-of-art carbon black)
    - Optimization of MEA fabrication for catalyst spraying and hot-press
    - Single cell performance target of 0.7 V @ 0.2 A/cm^2
    - Durability target of 5000 hours with a degradation rate of 10 μV/hr under steady state operation or 200 μV per start up-shutdown cycle

4. A proof of principle prototype fuel processing module for production of hydrogen for a 0.5 kWe PBI fuel cell stack:
    - LPG reforming at 700-800°C
    - CO concentration lower than 10.000 ppm in the reformate
    - No CO clean up processor module requirement
    - Possibility for thermal integration with the stack

5. Construction of two fuel cell systems and testing
    - Testing in a laboratory environment
    - Testing on board of a recreational yacht.

The work on sulfur management by APTL/CERTH resulted in the objectives of developing an autothermal reforming catalyst which is sulfur tolerant and a sulfur trap system which is able to catch the sulfur put into the system by 1000hr of operating time on LPG.

The size requirements of the system led to technology decision early in the project. Especially the hydrogen production reaction was selected to be autothermal reforming, a reaction between LPG, air and steam in one reactor.

System description

The system requirements have led to a series of potential process flow diagrams which have been scored against the size, weight and cost targets. The most feasible system consists of an autothermal reforming reactor which produces a mixture of hydrogen and carbon monoxide form the LPG, steam and oxygen form air [1], followed by a water gas shift step which reduced the amount of CO and increases the hydrogen concentration [2]. The reactions are:

$$C_3H_8 + H_2O + O_2 \rightarrow 5H_2 + 3CO \quad [1]$$

and

$$CO + H_2O \rightarrow CO_2 + H_2 \quad [2]$$

The sulfur present in the LPG is converted in the ATR to hydrogen sulphide and captured in a zinc oxide bed between the ATR and the water gas shift. Partner APTL has developed new production methods to make highly porous catalytic actives structures for ATR

When the produced hydrogen containing reformate is coming out of the water gas shift reactor the amount of water in the gas should be decreased before going into the stack. This is done by a system of heat exchangers which use the heat to make steam required in the ATR. Next the reformate is fed into the stack where the DC electricity is produced. The oxygen for the hydrogen oxidation is added as air. Downstream of the stack the fuel cell tail gas is oxidised in the (catalytic) anode tail gas oxidiser (ATO) to combust the remaining hydrogen, CO and potentially formed methane. The heat formed in the combustion reaction is used to evaporate water to steam for the ATR.

Main S&T results/foregrounds

The PURE project consist of 9 work packages.

- 1 project management and dissemination
- 2 System specification and definition
- 3 Certification and techno-economic evaluation
- 4 Power module development
- 5. System and reformer development
- 6 System prototyping and integration
- 7 Testing protocols
- 8 Environmental testing
- 9 Field demonstration

The main results of those work packages are described in this section. The fist work package, which is non-technical is treated in the next chapter on impact and dissemination.

WP2 System Specification and definition

In this work package the system definition based on end-user and industrial requirements is described including the flow down at module level. The specification of the system have been described in task 2.1. There has been a strong interaction with the certification requirements collected in WP3. The maritime application sets a variety of specifications ranging from the safety regulations on board of ships to the effect of wave movements on the system as shown in Figure 1. These requirements are specific to maritime applications.

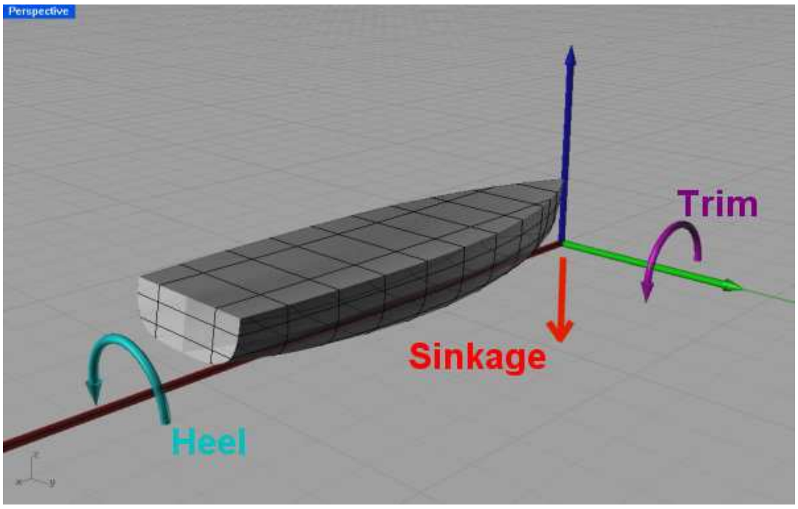

Figure 1: possible rocking movements in shipping

Other system specification are originating form the size and weight requirements set by the industry. These are 35kg and 50 liter per kilowatt of electrical power, which means 17.5kg and 25L targets for the 500We system in PURE.

The industrial specifications are based on the quality of LPG which can be obtained at marinas and other areas where LPG type fuel can be purchased. This fuel consist mainly of a mixture of propane and butane, which can be reformed to hydrogen rich gas by either steam reforming (SR), autothermal reforming (ATR) or catalytic partial oxidation (CPO). An important parameter in the fuel is the sulfur content. For LPG is this usually less than 10ppm but it can be as high as 50 ppm of sulfur containing mercaptanes.

The specification as described in deliverable 2.1 were used to create a process flow diagram (Figure 2) and the separate module specifications which are used as input for the work packages 4 and 5 in which the power module and the fuel processor modules are developed.

The module specifications are documented in input-output-constraint (IOC) charts. This a tool to describe the functionality of system, module or component. The IOC charts are submitted as deliverable 2.3. The data in the IOC charts is generated not only from the specifications provided in the preceding tasks but also during interaction with work packages 4 and 5.

The PURE system is based on autothermal reforming of LPG. This means that LPG, steam and air are mixed together and preheated before it is allowed into a specific catalyst, developed by APTL/CERTH for its sulfur resistance. The reaction is [1]:

$$C_3H_8 + H_2O + O_2 \rightarrow 5H_2 + 3CO \qquad [1]$$

The reformate is fed to a high temperature desulfurization reactor (also filled with material made by APTL and a commercial water gas shift catalyst to reduce the CO to acceptable values for the fuel cell stack (1 vol%) following reaction [2]

$$CO + H_2O \rightarrow CO_2 + H_2 \qquad [2]$$

Then the reformate is cooled down in a series of heat exchangers to condense out the water The heat is used to make steam. The reformate enters the stack when this device is around 160°C. In the stack the electrical power is produced as DC power, which is lead to a converter or inverter depending on the electrical system of the yacht. Within the PURE project a DC-DC converter has been used on recommendations by DAMEN. The hydrogen depleted reformate leaves the stack and is mixed with air and fed to the Anode tailgas oxidser (ATO) in which all combustible gasses (H_2, CO, CH_4) are combusted to CO_2 and steam [3].

$$H_2/\ CO/\ CH_4 + O_2 \rightarrow CO_2 + H_2O \qquad [3]$$

The heat of combustion is used to make steam for the ATR. The stack is heated at start up and cooled during operation by a glycol loop. In this loop there are two heat exchangers, the first to heat up the glycol with hot off gas from the ATO for start-up and the second to cool the glycol when it comes out of the stack when it is heated by the exothermic stack reactions.

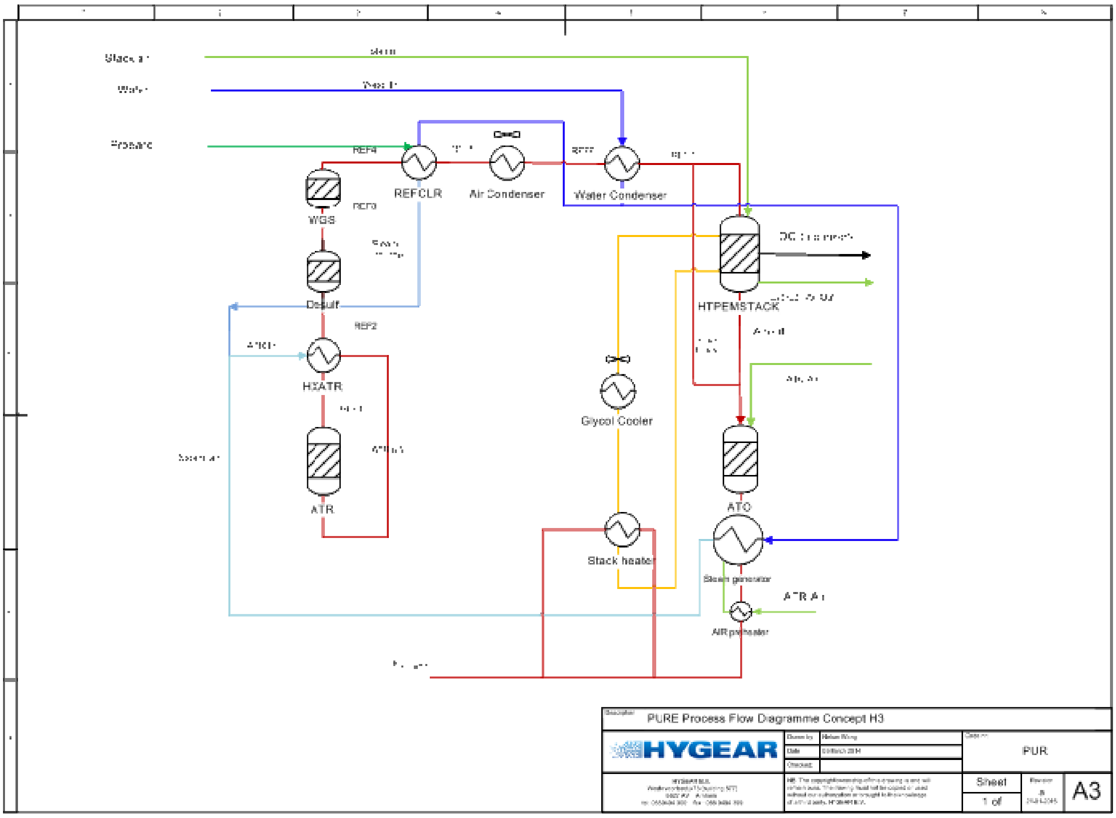

Figure 2: process flow diagram of the PURE system

WP3 Certification and techno-Economic evaluation

This work package describes the issues around safety and certification of fuel cell systems on board of a maritime application, in the project's case specially pleasure crafts.

Definition PURE system with ISO standards Pleasure craft

An overview was created by DAMEN shipyards, (DAM) of the most prominent applicable rules and regulations concerning ISO for pleasure crafts on H_2 and fuel cells. Due to the novelty of this application, no directly applicable standards are available, but multiple existing standards can be used as a basis, with the right interpretation of the intentions and goals, for the purpose of the PURE project. It was also found that automotive standards and rules might be useful in the development of a marine system for a small pleasure craft. The similarities between these two applications are obvious, i.e. mobile applications, vibrations and motions in all possible direction and non-expert end-users who will only accept intuitive plug-and-play functionality. Deliverable D3.1 "Report on ISO standards Pleasurecraft" is the result of the first tasks within WP3.

The project will use as baseline the Guidelines for Fuel Cell Systems Onboard Commercial ships issued by Bureau Veritas in 2009[2]. In this Guideline reference is made to automotive and stationary safety standards. Det Norske Veritas has issued many document on maritime certification including

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[2] Guidelines for FUEL Cell Systems Onboard Commercial ships (2009) guidance note NI 547 DR R00 E Bureau Veritas.

documents for fuel cells[3] and LFL fuels like methanol and ethanol[4] and those provide details on the applications of fuel cells and Low flammable fuels on board of ships. This latter document may also be applicable for hydrogen. The IGF code[5], which is for now only available in a draft version focusses on the use of LNG (Liquefied Natural Gas), but also comprises other low flame point fuels such as LPG, methanol and hydrogen.

Below is provided a summary list of titles and references of harmonised standards relating to recreational craft. Only the standards which have a connection with the PURE system are mentioned in this list.

EN ISO 10088: 2013	Small craft - Permanently installed fuel systems (ISO 10088:2013)
EN ISO 10133:2012	Small craft - Electrical systems - Extra-low voltage d.c. installations (ISO 10133:2012)
EN ISO 10239: 2008	Small craft - Liquefied petroleum gas (LPG) systems (ISO 10239:2008)
EN ISO 11105: 1997	Small craft - Ventilation of petrol engine and/or petrol tank compartments
EN ISO 13297: 2012	Small craft - Electrical systems - Alternating current installations (ISO 13297:2012)
EN 15609:2012	LPG equipment and accessories - LPG propulsion systems for boats, yachts and other craft
EN ISO 16147:2002/A1:2013	Small craft - Inboard diesel engines - Engine mounted fuel and electrical components (ISO 16147:2002)
EN 28846: 1993/A1:2000	Small Craft - Electrical devices - Protection against ignition of surrounding flammable gases(ISO 8846:1990)
EN 60092-507: 2000	Electrical installations in ships - Part 507: Pleasure craft (IEC 60092-507:2000)

Techno economic evaluation

The cost of the PURE system designed and constructed in the end is evaluated for mass production. The main outcome is that the cost of the system is now expected to be below the €2000 as shown in Figure 3. To reach these costs the stack cost must be reduced significantly and also the quality of the MEA's must increase to reduce the hardware in the reformer. Specially the heat exchangers to condition the reformate for the stack and the glycol cooled stack should be replaced by an air-cooled stack avoiding the heat exchangers and balance of plant equipment for the glycol cooled fuel cell stack. It has to be recognized that the shown costs are predictions for production volumes of more than 5000 pieces per year.

Additional cost reductions can be made by more integrating the gas-air delivery system, using one blower for air supply to both the stack and the ATR.

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[3] Fuel Cell Installations (2013) DNV

[4] Tentative Rules for Low Flashpoint Liquid Fuelled Ship Installations (2013) DNV

[5] IGF code: Draft International Code Of Safety For Ships Using Gases Or Other Low Flashpoint Fuels (2012), IMO

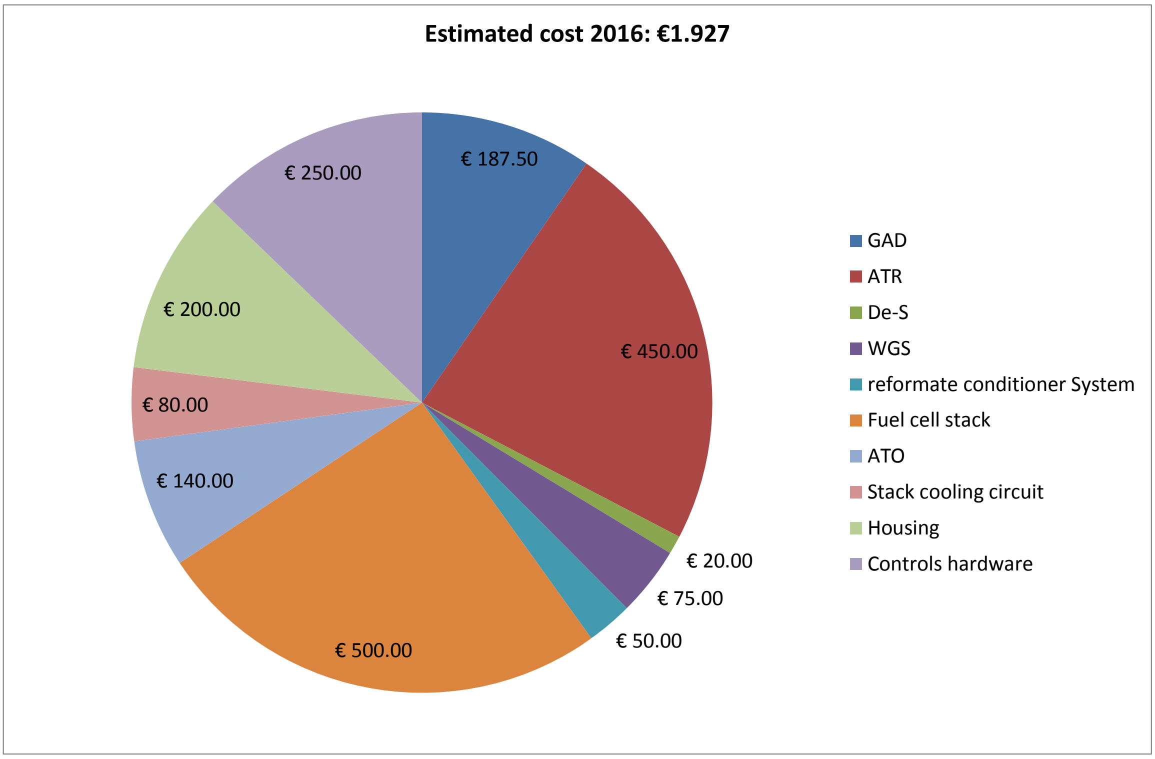

Figure 3: Cost estimate of the PURE system at the end of the project

WP4 Power Module development

In this work package the membrane electrode assemblies are developed by the Danish Technical University (DTU). They also manufactured the MEA's for short stack testing and the two full PURE stacks.

According to the plan the main parameters for improving the MEAs are new modified membranes and alternative catalyst supports. Implementation of the new materials requires a re-formulation of the manufacturing processes (electrode and MEA manufacture). During this a radically new electrode manufacturing process was discovered leading to electrodes without ionomer or binder. It is intuitively contrary to nature that an electrode basically made from inert powder can form a stable and easy to handle electrode and even an MEA, but that happened to be the case.

Previous state of art electrodes contain PBI which serves as a binder and an ionomer which contains phosphoric acid that conducts protons. PBI is only soluble in very few solvents like dimethylacetamide and formic acid, which are all problematic from a working environmental perspective. Both are harmful if inhaled or in the event of skin contact. Formic acid has so far been considered the least hazardous choice and thus used. Another complication with formic acid is that the ink used for spraying electrodes self-ignites under some spaying conditions. In addition, the catalytic inks made from this solvent require long time (24h) under ultrasonic stirring for dispersing the catalyst. All together a change of solvent has been long desired, and without the need for PBI in the ink it can be substituted by ethanol.

The development of the binderless electrode led to a temporary change of the immediate development strategy and series of experiments were made with standard catalysts and membranes in order to verify the new electrode formulation. The platinum (catalyst) content was varied and some durability experiments initiated, see below. The conclusion so far is that the binderless electrodes are at least as good as the previous state of art - perhaps even slightly better. The finding is reported in a paper in Journal of Power Sources, which is already accepted for publication.

Single cell test and MEA evaluation

Single cell testing started with a performance screening at different temperatures and with a fuel composition according to what can be expected from the ATR reformer, i.e. hydrogen diluted significantly more than it is when obtained from a steam reformer. The fuel gas contained different amounts of CO as well. The CO tolerance of HT-PEMFCs is well described, so the experiments were meant as verification. However, the voltage depression as a function of CO content was significantly more pronounced than expected which led to a more thorough investigation.

The tolerance or intolerance to CO is governed by adsorption energies on the platinum catalyst surface. The adsorption strength depends on temperature for both CO and the fuel, Hydrogen. The two species are in competition and at 60-80°C, the temperature of the classical PEMFC, CO adsorbs the strongest while at 140-200°C the ratio of adsorbed molecules are shifted in favour of hydrogen. The other factor that affects the adsorption competition is the concentration (activity) and if hydrogen is diluted then CO takes over a larger fraction of the active catalytic sites which lead to performance drop.

After a systematic study of different fuel gas compositions, the project consortium discussed a solution. One possibility was to increase the number of cells to compensate for the loss. This was rejected because it increases system size and cost and gives lower efficiency. Higher operating temperature will also help but on the cost of lifetime. The solution agreed on was to condense a major part of the excess water in the fuel stream in order to minimize the dilution. Cell tests with the new fuel gas composition hereafter verified a satisfactory performance.

Test of binderless electrodes

Many series of MEAs with binderless electrodes were subject to test. Polarization curves from electrodes with a Pt loading of 1 mg/cm^2 performed comparable to commercial electrodes from Danish Power Systems with higher Pt loading (1.6 mg/cm2) as can be seen in Figure 4. The absence of polymer inside the catalytic layer lead to less mass transport problems in the case of binderless electrodes. Then, the peak power density was higher in the case of binderless electrodes than with the electrodes from Danish Power Systems. The absence of the binder may also make more of the Pt surface available for reaction.

The loading of platinum in the cathode and the anode was varied independently and the results are plotted in Figure 5 for the anode PT content variations. It is evident that the performance varied a lot when the cathode loading was varied, while the anode was more or less independent of Pt loading.

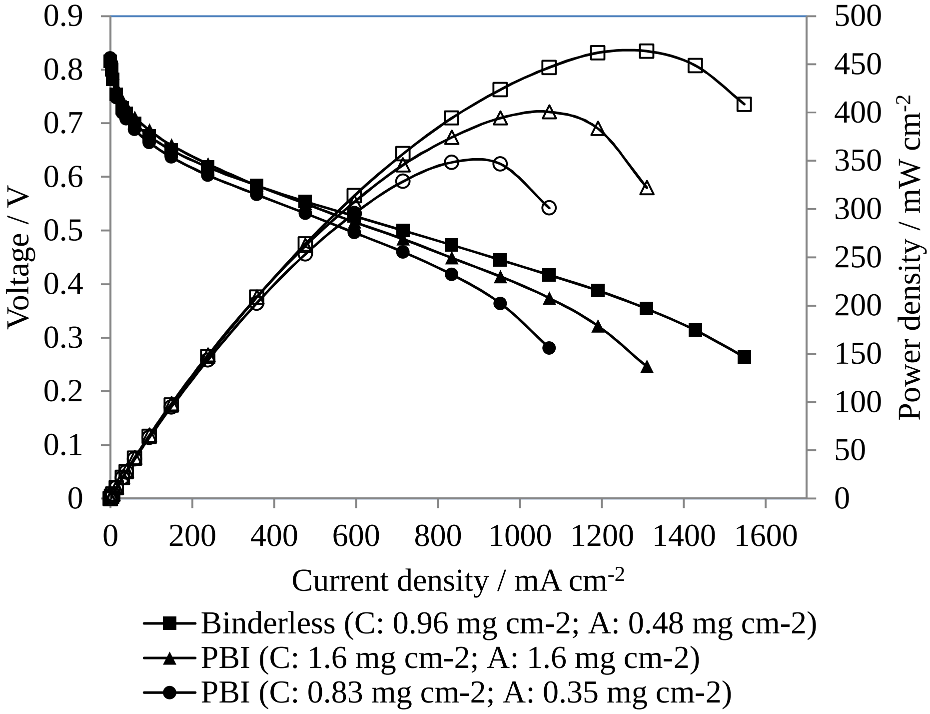

Figure 4: Polarization curve for comparison of new binderless electrodes and conventional PBI containing cells kindly supplied by Danish Power Systems. Temperature: 160°C.

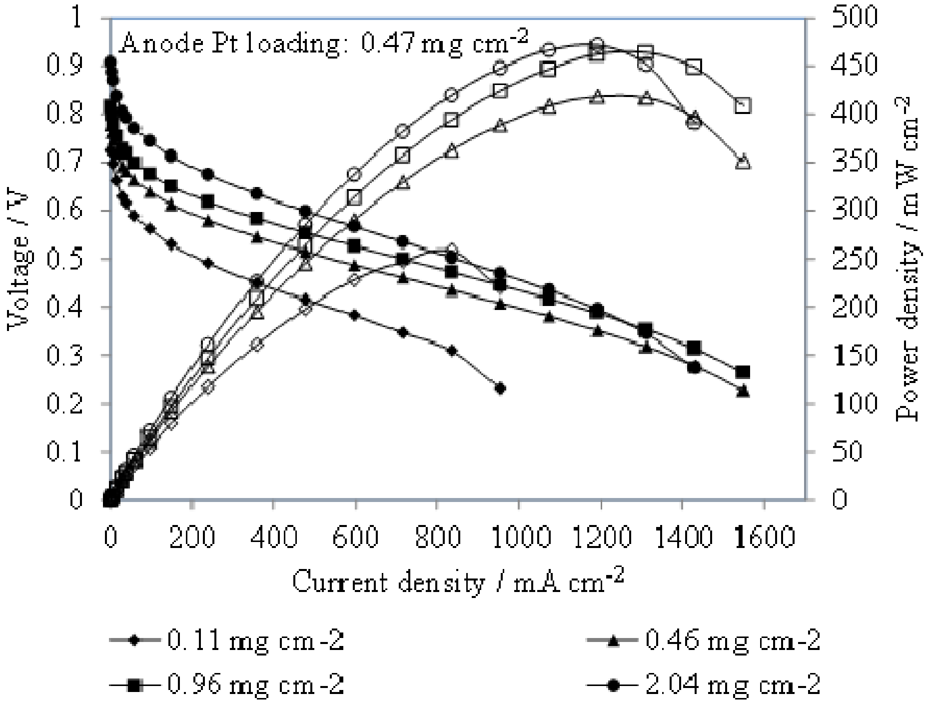

Figure 5: Polarization curves of binderless MEAs as a function of different cathode Pt loadings and the anode loading kept constant . Temperature: 160°C.

In the last months of the first period the focus moved also to the development of the stack itself. During the MEA development consultancies with some external experts initiated second thoughts about the air cooled stack envisioned for simplicity. Experiences gained the last years is that such stacks experienced cell failure during startup. The understanding is that the cell membranes are dried to a fatal extend not normally encountered because the stack is heated by hot dry air. In operation a stack produces water which counteracts the drying, but during heating alone the drying effect is strong. With recirculation of the air used for heating the stack possibly with the addition of a little water the problem can likely be solved, but this made the system more complex and not enough knowledge is available to what extent one should increase the water content to mitigate this failure mode. It was decided to play it safe and change to a liquid cooled stack instead. With a liquid coolant heat transfer is also more efficient.

Durability measurements

The demonstration of the durability of the binderless electrode technology was first carried out with the cell working with pure H_2 as fuel.

Figure 6 shows the performance of a MEA with binderless electrodes operating continuously for 4800 hours at a current density of 200 mA cm^{-2}. It can be seen that after a short break-in period in which the voltage decreased to a minimum, the cell voltage increased linearly in 18 mV during 600 hours. Then, the voltage of the cell attained a plateau with a stabilized voltage around 0.647 V staying around this value for 1100 hours. Therefore, for a total of 1700 hours the cell voltage didn´t decay significantly. After 1700 hours of continuous running, the cell voltage started to decrease with a slope of 17 µV h^{-1} until getting 4800 hours of operation. End of life was defined as a 10% voltage drop compared with maximum power level.

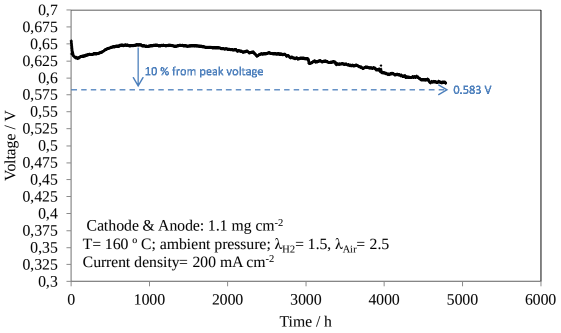

Figure 6. Long-term operation of a MEA prepared from binderless electrodes. Measurements with non-humidified H_2/Air at 160ºC.

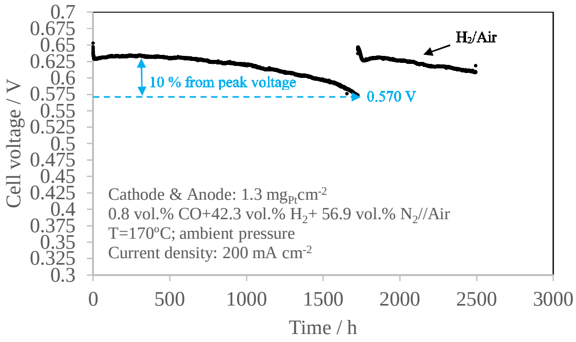

Figure 7. Long-term operation of a MEA prepared from binderless electrodes and 0.8 % CO + 42.3 % H2 + 56.9 % N2. The test was conducted with air as oxidant at 170ºC.

Once the durability test was passed with pure H_2 as fuel, then the life-test was carried out with the simulate reformate (i.e. a fuel composition of: 42.3 vol.% H_2; 0.8 vol.% CO; 56.9 vol.% N_2). In this case, the temperature was raised to that required in the PURE project, 170ºC. Figure 7 shows the voltage evolution of the cell during the long-term operation.

After 1720 hours operating with reformate, the cell was fueled with pure H_2 while the rest of test conditions where maintained. The response of the cell was a rebound of the voltage up to 0.647 V. After a relaxation transient the cell started to decay from 0.631 V with a slope of 30 µV h^{-1} (just the same slope than that displayed by the cell when running with reformate in the earliest stage of running) until 2500 h of total operation.

Lowering the platinum loading

The influence of the anode as well as cathode platinum loading on the cell performance was evaluated from electrodes prepared according to the new technology introduced in this project, i.e., electrodes without binder or ionomer in the catalytic layer. An example of the results is reproduced in Figure 8. Normally a thin catalyst layer is desired to minimize transport of ions. However, an important finding in contrast to this was that the best results were obtained with a rather tick catalyst layer. It was explained by the hypothesis that part of the catalyst layer is flooded with acid, but that flooding front changes position as a function of the water content in the electrolyte. For more details, the publication: S. Martin et al. *J. Power Sources* **293** 51-56 (2015)

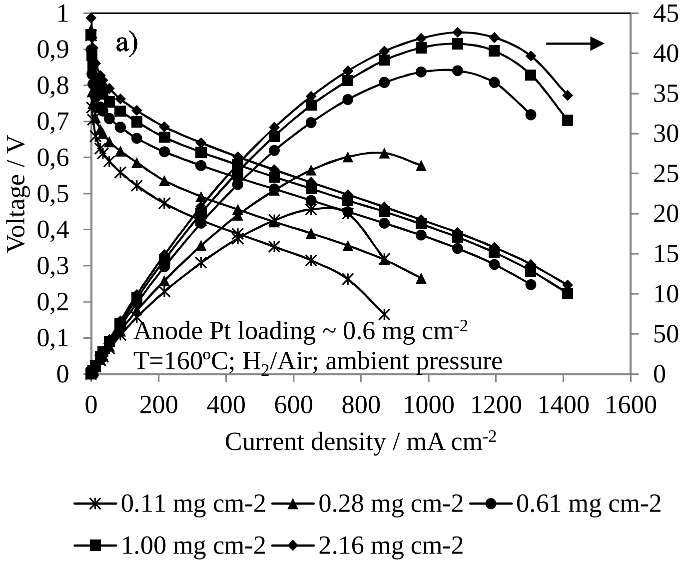

Figure 8. Polarization and power density curves for MEAs prepared from binderless electrodes with a fixed anode Pt loading of 0.6 mg cm^{-2} and different cathode Pt loadings.

CO tolerance under realistic hydrogen dilution

Series of cells were made and operated on different combinations of hydrogen concentration, CO concentration and temperature. The poisoning effect reflects a competition on adsorption on the catalyst sites between hydrogen and CO. In Figure 9 the effect of hydrogen dilution to 40 % is seen as a shift down of the polarization curves, while the effect of the changing CO content only affects the curves gradually with increasing current density. In Figure 10 the effect of a lower catalyst loading, i.e. fewer sites to compete over, the effect is different. Here the low current performance is practically unaffected while limiting current behavior appears at higher currents.

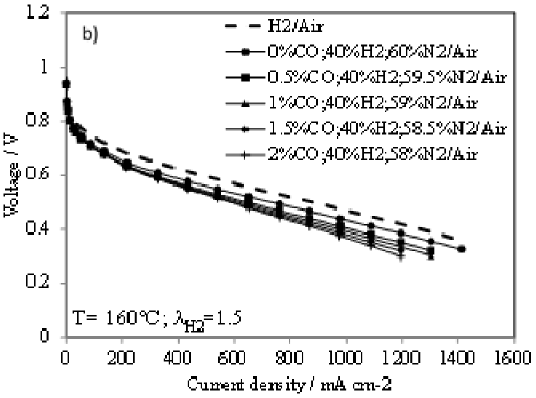

Figure 9. Polarization curves with 40 % hydrogen and a varying amount of CO, all at 160°C

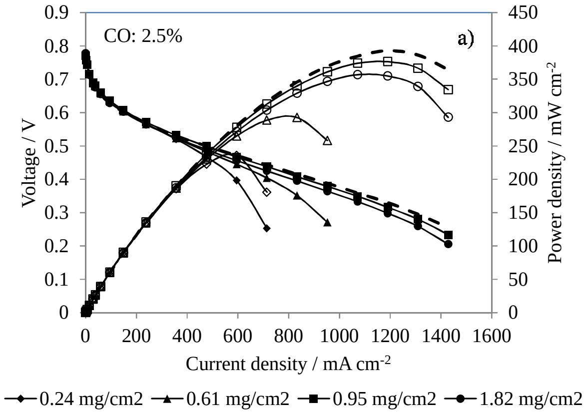

Figure 10. Polarization curves with 2.5 % CO in hydrogen with different catalyst loadings, all at 160°C

Tests with sulphur contamination

Singe cell tests of MEAs with binderless electrodes were conducted to investigate the tolerance of sulphur contamination on either anode or cathode. As the reformer fuel often contains sulphide species originating either from the raw product or added as odorant, ppm levels could potentially reach the anode side of the fuel cell. On the cathode side the sulphur species, primarily SO_2, could originate from air pollution.

The classical low temperature PEMFC is not able to tolerate even trace amounts of sulphur species, which effectively and irreversibly reduces the cell performance to zero within minutes of operation. With the increased temperatures of the HT-PEMFC the poisoning effect was believed to be reduced, but it could still prove detrimental to cell performance. In that case, desulphurisation units will be necessary to scrub both the fuel and air feeds, significantly increasing system size.

Tolerance tests were performed on MEAs utilising electrodes with 1 mg/cm² Pt loading prepared by the binderless method developed earlier in the project. One cell was subjected to increasing amounts of H_2S in the fuel stream (0.2 – 50 ppm) with very little effect in the operating range of 200-300 mA/cm², regardless of concentration. The main influence was seen at high currents and concentrations higher than 10 ppm. Additionally, the degradation was found to be reversible to a very large degree.

Since the effect of catalyst poisoning is often time dependent, it was decided to investigate the effect of prolonged exposure towards H_2S contamination. A series of MEAs were subject to an overnight break-in procedure with pure hydrogen fuel and then operated with different amounts of H_2S, ranging from 1 to 50 ppm for 5 days, at the working point of 200 mA/cm². Polarisation curves were recorded daily to monitor changes over the whole current density range. The reversibility of the poisoning have been investigated by comparing the initial polarisation curves with pure hydrogen immediately after break-in with the ones obtained two days after contaminated fuel was switched back to pure hydrogen.

The results can be seen on Figure 11.The high current density region did not fully recover upon purging with clean fuel. The practical operation range, however, seemed to be unaffected by the H_2S poison. Another positive feature seen from the comparison was that the MEA to MEA variation has proven to be very small. The conducted experiments show a clear improved tolerance towards sulphur species contamination in both anode and cathode compartments, as compared to the conventional LT-PEMFC technology. Additionally, it implies that hydrogen sulphide slip from the reformer might be disregarded, making the need for a desulphurisation unit redundant. However, as has been shown previously with CO contamination, the dilution effect can have a negative impact on sulphur tolerance. The final conclusion can thus only be drawn after MEA tests with reformate resembling real operating conditions.

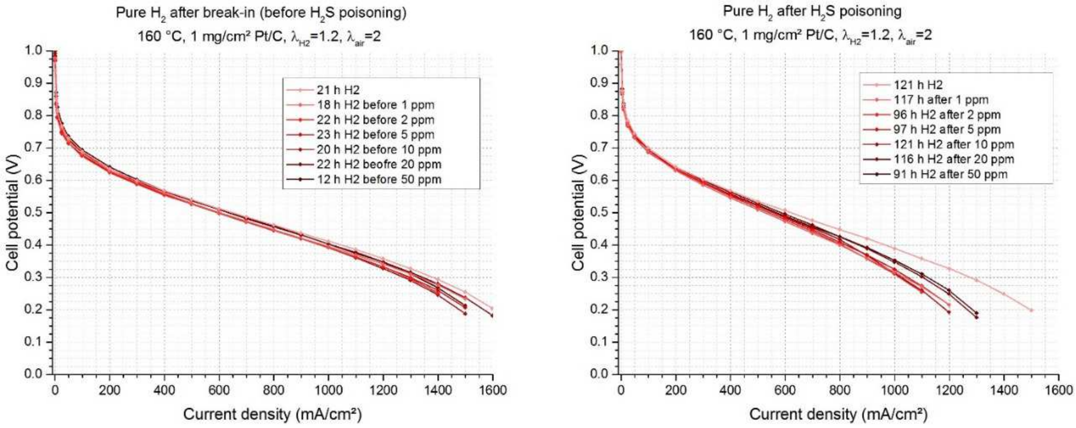

Figure 11: Polarisation curves with pure H_2 before and after H_2S contamination.

Short stack testing

The DTU MEA’s have been tested in a short stack, built from 5 MEA’s, to check if the MEA’s are compatible with the stack (end) plates and gaskets. Therefor the short stack has been leak tested and the performance beginning of life and after 100 hours of steady state operation are measured. All MEAs for the short stacks were supplied by DTU. They were made by in-house binderless electrodes and commercial membranes (Danish Power Systems). In Figure 12 the performance of the short stack is shown before and after the 100 hours of operation at the $0.2A/cm^3$ point. The data have been measured at the JRC fuel cell laboratory. The data has been compared with a state of art commercial available stack of SerEnergy.

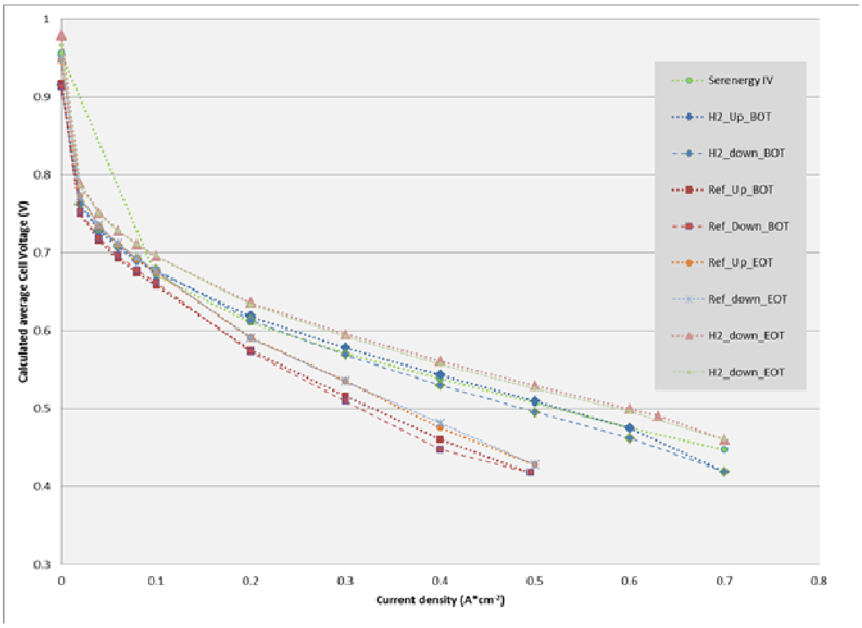

Figure 12: Short stack data of the PURE MEA's

Polarization curves both on simulated PURE reformate and on 100% hydrogen have been measured. The data show that the operation of 100 hrs do not have a strong effect on the performance of the MEA’s. Also the test proves that he MEA’s are suitable for use in a HT-PEM stack.

Final stack module

Two stack have been built using the MEA’s manufactured(2 x 30 pieces) by DTU. They were made by in-house binderless electrodes and commercial membranes (Danish Power Systems)

Figure 13: Full stack built from DTU MEA's

The polarization curve for the entire stack has been measured prior to integration in the PURE prototypes. The result is shown in Figure 14 as comparison with the short stack data. The 100% H2 data are exactly the same as in the short stack and the reformate data fall a little below that as expected and measured previously in the single cell as well. Both stack have been integrated in the PURE prototypes.

Power electronics

In view of the requirement document in WP2 there were discussions about the electrical power supplied to the ship. It can be AC power immediately usable for the AC equipment on board, but it can also be DC power to load the batteries, which are on board anyway. The second option is favourable from a size, weight and cost point of view. An inverter is usually a heavy piece of equipment and besides that the DC coming out of a fuel cell requires special inverters for low voltage and high amperages which require additional DC-DC converters. The voice-of-customer does not care if the system produces AC power through the batteries or directly from a fuel cell. Together with Damen it was decided to connect the system to the DC-bus of the ship and use the existing inverters on the ship to provide AC to the user as all modern ships are built with a common DC-bus these days.

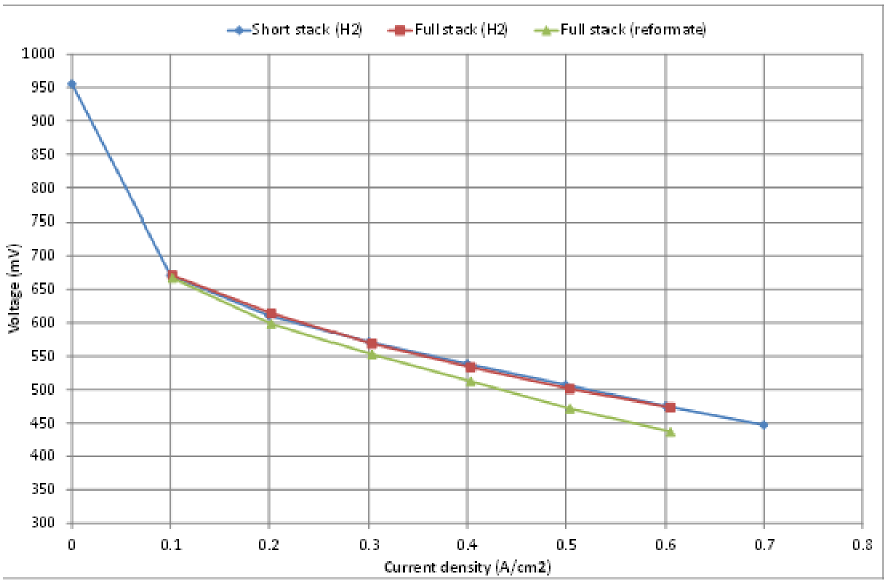

Figure 14: comparison of short stack data and full stack data

WP5 System and reformer development

There are 6 tasks in this work package. The first two deal with the development of the system design, task 3 and 4 with the sulphur management of the system and the last two with the design of the fuel processing reactors and the controls, both based on the modelling of task 1.

System Modelling

The system requirements have been discussed already partly in WP2. The main conclusion of the modeling study is that the PURE system will be an ATR based system with a water gas shift reactor and a reformate cooling/ water condenser system to bring the reformate composition to the required quality (Figure 15). The reformate is fed to a liquid cooled HT PEM fuel cell stack. The anode off gas is combusted in a catalytic oxidation reactor to convert remaining hydrogen, carbon monoxide and methane to water and carbon dioxide. The reaction step produces heat to make steam for the ATR reaction.

The modeling results show a efficiency of more than 28% for a small system which has an outlook to meet the size and weight requirements.

The process model has been used to form the base of the piping and instrumentation diagram (P&ID). After the first draft this document has been expanded with sensors, valves, blowers and other BOP components

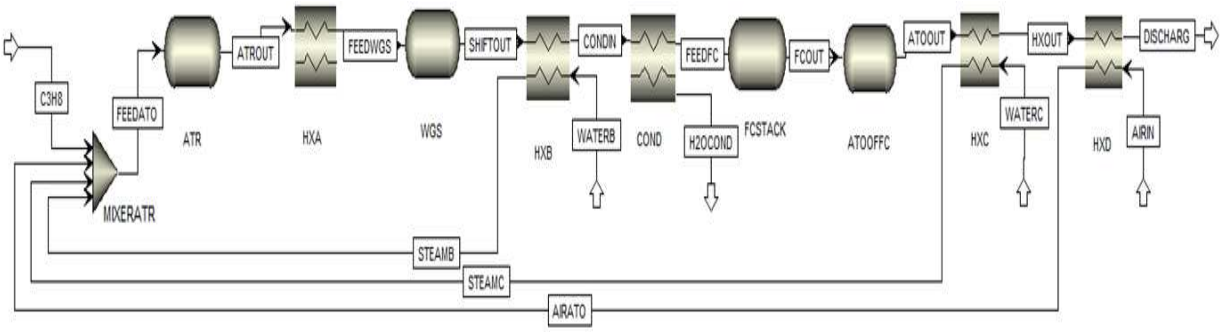

Figure 15: block diagram of the chosen PURE system configuration

Synthesis and evaluation of sulfur –tolerant catalysts

In this part of the project sulfur tolerant catalysts for the ATR of the PURE system were developed. This catalyst should be compatible with the PURE ATR reformer operating conditions (temperature range, space velocity) and demonstrate tolerance to sulfur levels presented in ATR feed to maintain reforming performance in line with the PURE system's performance targets (efficiency, volume and cost). Special efforts was placed in lowering the Precious Metal (PM) content of the catalyst to keep the system's cost within the project's target.

Figure 16 shows the hydrogen production per mass of catalyst in the ATR reactor for several ATR catalyst samples developed by APTL. These figures reveal that the best performance was demonstrated by the LPSHS-synthesized perovskite catalyst (without and without Rh) and the alumina-based as well as the reference catalyst. The alumina-based catalyst as well as the perovskite catalysts have also been tested at GHSV of 200,000 h^{-1}. Although the space velocity of 200,000 h^{-1} might be considered as an extreme condition, it is still useful in order to proceed with the proper sizing of the reformer. The alumina-based catalyst demonstrated a loss of only 7 % in the conversion efficiency, the perovskite with Rh catalyst demonstrated an approximate 18 % decrease but the perovskite with Ni catalyst revealed a significant conversion loss of over 55%.

As a next step, the best performing materials (the perovskites, the alumina-based and the reference catalyst) were tested for their sulfur tolerance under reforming conditions. For this reason a concentration of 33 ppm of hydrogen sulfide (H_2S) was employed in the feed. From the maximum allowed amount of sulfur compounds in propane gas for transportation one can estimate that the maximum amount of sulfur in the feed would be approximately 3 ppm. The artificially high H_2S concentration (33 ppm) was used for acceleration of tests in this phase of the testing program although catalyst deactivation is a strong function of the sulfur concentration in the ATR feed

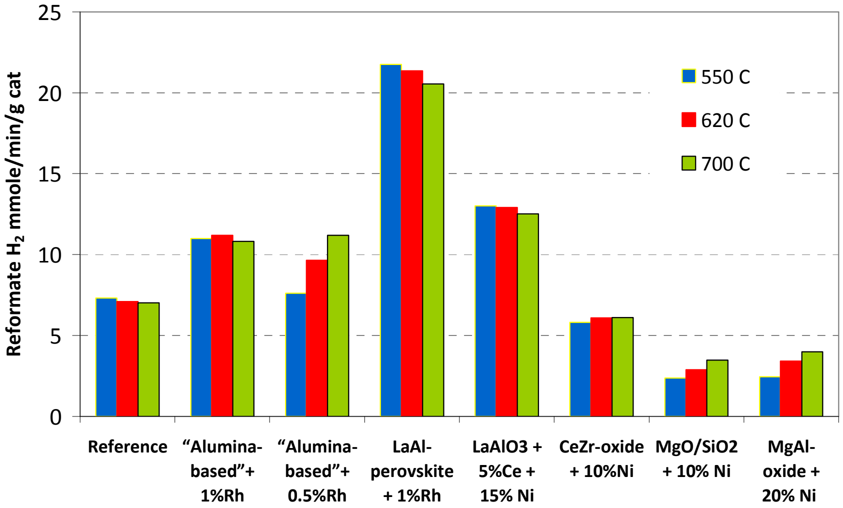

Figure 16. H_2 flowrate in reformate per g of catalyst powder for the different materials synthesized.

The introduction of H_2S led to rapid decrease of the produced H_2 due to the deactivation of the catalyst. This was also evident by the rapid increase of the propane concentration in the reformate. A certain amount of the reduced metal is reacting with the sulfur forming metal sulfide. Sulfidation stopped after a certain time period and the H_2 and propane concentrations reached a plateau. The same was also true for the CO and the CO_2. As a next step the H_2S concentration in the feed was zeroed. H_2 production was increased but it did not reach the level before the exposure to sulfur atmosphere.

Initial tests revealed that the perovskite catalyst containing Ce-Ni suffered of an appreciable deactivation due to the exposure to sulfur. Therefore the evaluation concentrated on the reference as well as the alumina and the perovskite catalysts containing Rh. Figure 17 demonstrates the effect of sulfur exposure on the fuel conversion for the three catalysts comparing fuel conversion for the fresh and the exposed catalyst without any sulfur in the feed. Both the reference and the Alumina-based catalysts revealed a loss of the fuel conversion activity of about 18 %. The fresh Alumina-based catalyst revealed a better fuel conversion efficiency and therefore the exposed sample showed slightly better conversion efficiency than the exposed reference sample. The perovskite catalyst revealed a loss in the conversion efficiency of about 32 %. Nevertheless the amount of catalyst used and consequently the amount of Rh employed was very small compared to the other cases. If the amount of catalyst employed is taken into consideration the picture of the catalysts' performance is changed showing significantly superior H_2 production rates for the perovskite catalyst even after the exposure to sulfur.

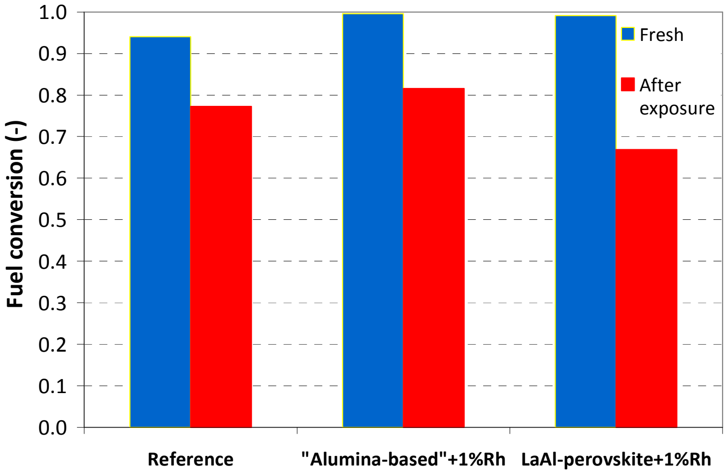

Figure 17. Effect of 33 ppm sulfur exposure on the fuel conversion of the examined catalysts.

Sulfur trap materials development

APTL developed new sulfur trap materials for capturing H_2S at about 300°C, which makes this material an ideal option for a downstream of the ATR reactor . The successful tests concerned the LPSHS prepared (ZnCu)O in powder form in comparison to commercial ZnO powder (Figure 18). Test conditions resembled the PURE reformate conditions: H_2O=32%, H_2=30%, N_2=balance). The H_2S content was set to 10 ppm for accelerating the test, the GHSV was set at 40,000 h^{-1} (i.e. circa double of that inside the PURE system) and the temperature was set at 310°C. Note that this temperature is the one calculated for the PURE system at the desulfurization unit inlet with the use of numerical simulation tools. Emissions of SO_2 during both tests were negligible and are not shown in this graph. The sorbent mass used in the reactor was in both cases 0.14 g, while the limit for sulfur at the outlet of the reactor was set at 100 ppb. Both materials showed excellent trapping efficiency (>99.5%) at the fresh state. The capacity of the reference (commercial) material was exhausted very quickly. The capacity of the mixed (ZnCu)O was measured to be 1.9 % (i.e. 0.019 g of S per g of active material), while for a sulfur outlet limit of 1 ppm (10% of the feed) its capacity was approximately 2.4%. It should be mentioned that the theoretical capacity of the (ZnCu)O material is about 39.5 %, which implies that only 5-6 % of its theoretical capacity was achieved. Nonetheless, the performance value measured was within the literature reported values of 1.5 – 2.8 %, for state-of-the-art sorbent materials with varying compositions and space velocities. One should also consider that in the case of the reported tests, the GHSV utilized was high enough, thus increasing mass transfer limitations and possibly promoting flow channeling in the powder bed and, consequently, negatively affecting the capacity. On the basis of these results and the apparent difference in trapping capacity of ZnO c.f. (ZnCu)O evidenced, it was decided to proceed with coating of cordierite monoliths for the latter material.

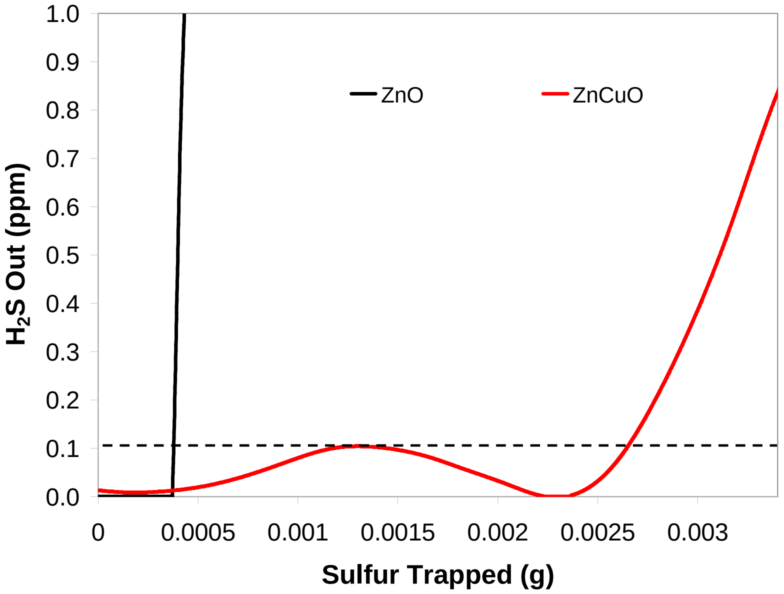

Figure 18. Sulfur trapping performance test for the LP-SHS synthesized (ZnCu)O and the reference material (ZnO).

The trapping target for the PURE system has been defined to be 5.6 g of S per 1000 h of system operation using a standard transportation-grade propane feed (50 ppm of S). The available volume of the trap was set to 200 ml (initially 235 ml, but reduced later for more space savings), this trap will operate at 310°C and the actual space velocity at the final prototype will be 19000 h^{-1} as calculated based on the actual reformate flow (29.7 slpm, calculated by HFCS).

Development of fuel processing hardware

The ATR reactor is a monolithic catalyst connected to a recuperative heat exchanger. The main areas of development are the way the fuel, air and steam are mixed and preheated and insulation. Various ways of combining heat exchangers with insulation have been investigated. Various types of insulation have been analysed. It turns out that the special high performance insulation materials are pre-shaped parts and it is not possible to change these shapes as the parts contain a vacuum which should not be destroyed. This leaves the insulation to be conventional materials based on fibrous and porous silica-aluminas. For serial produced systems such materials can be used as the required high tooling costs can be depreciated across the high number of produced products.

A CFD study was performed in various inlet designs ranging from a just flowing into the chamber upstream of the ATR heat exchangers and using impingement structures to block the flow and force it around into the heat exchanger.

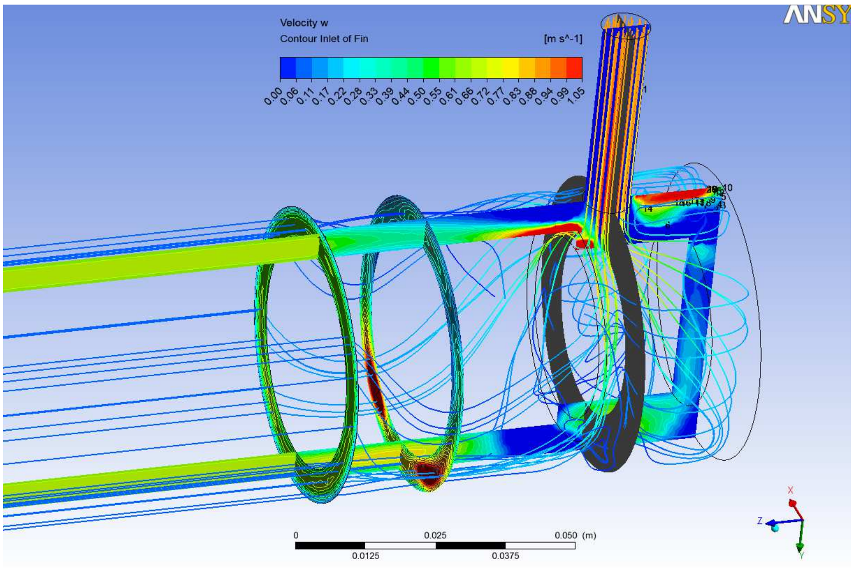

Figure 19: CFD calculation of the ATR inlet

Figure 19 shows the entire flow field of the feed stream in the inlet of the ATR heat exchanger. It shows that between the inlet pipe of the feed stream and the inlet of the heat exchanger a space of 5 cm is needed to ensure an even velocity distribution in the heat exchanger.

Two iteration of the ATR/ desulfurization/ water gas shift reactor combination have been made. Based on the modelling and the measure data of the first iteration the size of the ATR heat exchanger could be significantly reduced. The diameter of the fins is kept the same as it fits around a standard size of metal pipe and standard size insulation can be used as well. To reduce the heat transfer, the length of the second design is 100 mm. The size reduction has an additional benefit: the desulfurization and water gas shift reactor could be integrated with the ATR catalyst and heat exchanger in one reactor. Reducing heat losses and costs. A 3D drawing is shown in Figure 20.

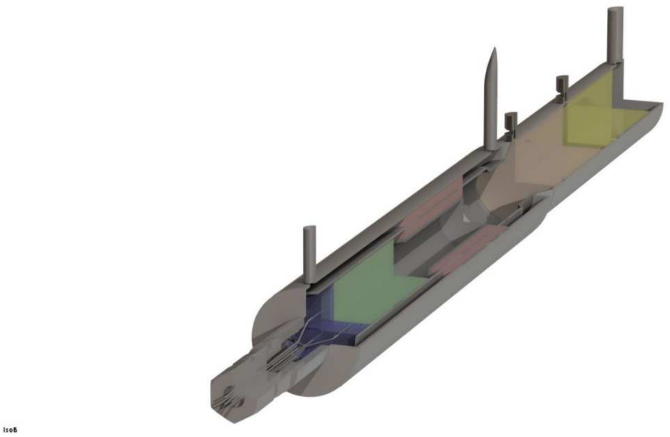

Figure 20: 3D model of the second generation PURE reformer

The green colored section is the ATR catalyst and the pink one downstream is the recuperative heat exchanger. Upstream, in purple, is the ATR heater. Further downstream is the desulfurization (orange) section and the yellow colored water gas shift catalyst. This should minimize the heat losses in the connections between the reactors.

The performance of the reactor was measured in the complete system. The gas composition of reformer is shown in Table 1. The main difference to the modeled composition is the amount of nitrogen in this reformate. The amount of air added to the ATR had to be bigger to maintain the temperature in the ATR and the reactors downstream. This also resulted in a high inlet temperature of the ATR of around 800°C, which is limiting the operation. Higher temperatures would damage the electrical heater. The CO is low as a result of the water gas shift activity. The CH_4 concentration is low as expected out of the ATR under the given conditions. Reducing heat losses of the system will reduce the needed air and operation temperatures.

Table 1: gas composition out of the second iteration reformer measured by GC

species	concentration (vol%)
H2	45.3
O2	0.6
N2	37.7
CH4	0.2
CO	0.3
CO2	16.0
total	100.0

3D printed heat exchangers

In the PURE system, several heat exchangers are required to operate the fuel cell stack. Traditionally heat exchangers are made by welding and brazing of metal parts together. In the last years rapid manufacturing techniques become available and are therefore of interest. Applications in fuel cell systems are specially suitable when compact and small construction is required like in the PURE project where size and weight matter. In Eindhoven, in the Netherlands a consortium of companies are exploiting a 3D metal print company (AddFab) which is developing this technology. One of the companies in this consortium is Machinefabriek de Valk. In collaboration with this company HyGear designed the heat exchangers, which were manufactured by De Valk. Figure 21 below shows the printed heat exchangers

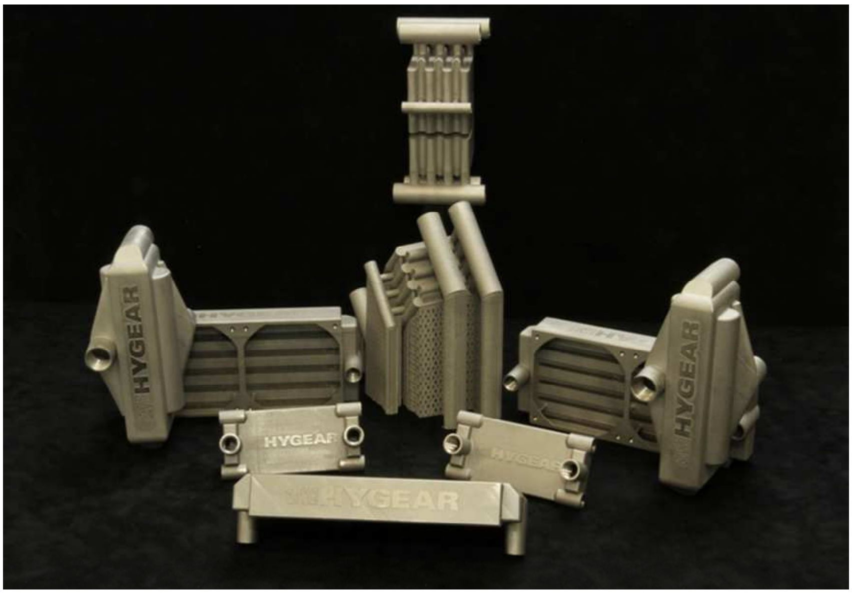

Figure 21: 3D metal printed heat exchangers for the PURE system (Photo by Machinefabriek deVALK)

The first heat exchangers that were build and tested performed according to design and were leak-tight. Finally, once the systems had been built, it appeared that several of the latest printed heat exchangers leaked. It appeared that the 3D metal print technology does not produces a stable, reliable product yet. Some of the heat exchangers performed well, others leaked. Investigation together with De Valk contributed such difference to the still existing unit to unit manufacturing variance.

Figure 22 shows the hardware of the ATO construction; on the left side from top to bottom, the inner side in which the catalyst monolith is placed. Then the middle shell where the water and air are added and heated. Finally the outer shell with the water and air inlet and off gas outlet. At the right side the entire combination of the parts is shown. This reactor has been tested successfully stand-alone prior to introducing it in the PURE system. Both the combustion reaction and the steam production proved to be satisfactory for installation in the prototype.

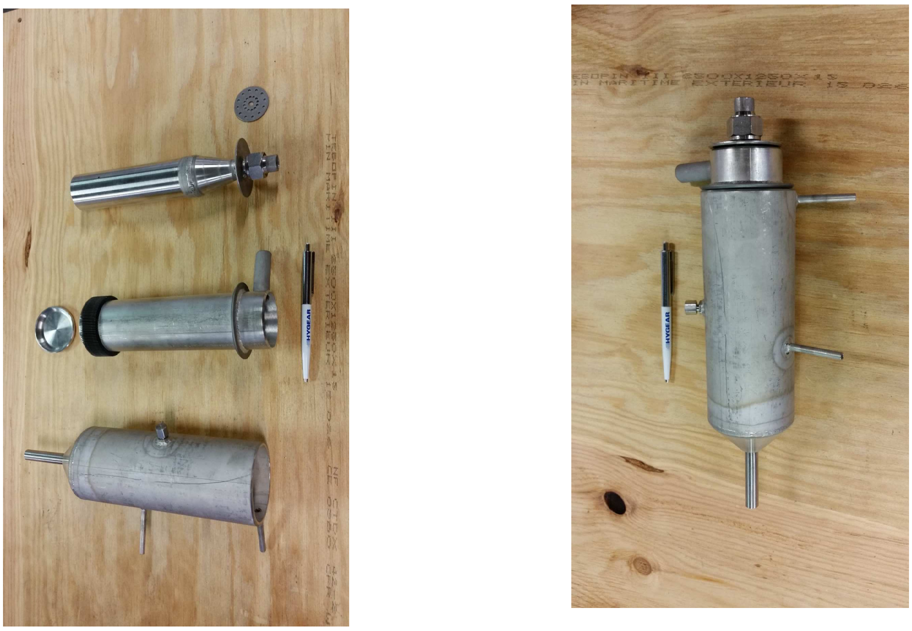

Figure 22 Hardware of the PURE ATO/steam generator

Controls development

In this task the control of the PURE system are developed. This development process is started at the beginning of the system design and is followed during the entire design and construction phases. Next to the nominal operation mode the start-up and shut-down modes need special attention. Control hardware is selected, procured and installed. This includes a PLC, sensors, valves, blowers and pumps. An example of this software interface is shown in figure 23.

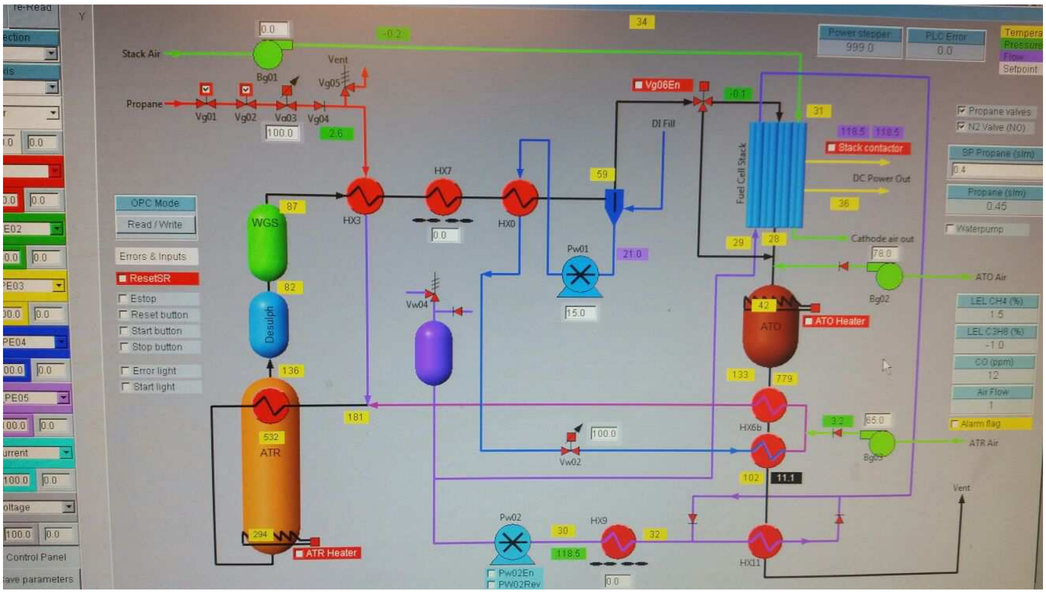

Figure 23: example of software interface in HPVee

WP6 System prototyping and integration

In this work package the two PURE prototypes have been built. First all components have been sourced, including the ATR catalyst and desulfurization monoliths from APTL. and construction of the hardware and software has taken place.

The system as it was ready to show on the dissemination workshop is shown in Figure 24. The wiring is attached afterwards and connected to the control box for testing. Although the system did not reach the afore set targets, the size and weight of the system is closer to the target then the state of the art. As can be seen in Figure 25, the weight of the PURE system is 50 kilogram and the volume is 90 liter. The main reasons for a larger and heavier system are the needs to add the additional heat exchangers for reformate conditioning and the additional balance of plant required for a liquid cooled stack. The system size and weight will benefit from an air cooled stack with MEA's which can be operated with lower hydrogen concentration coming out of an ATR.

Figure 24: PURE system ready for shipping to European Fuel cell conference

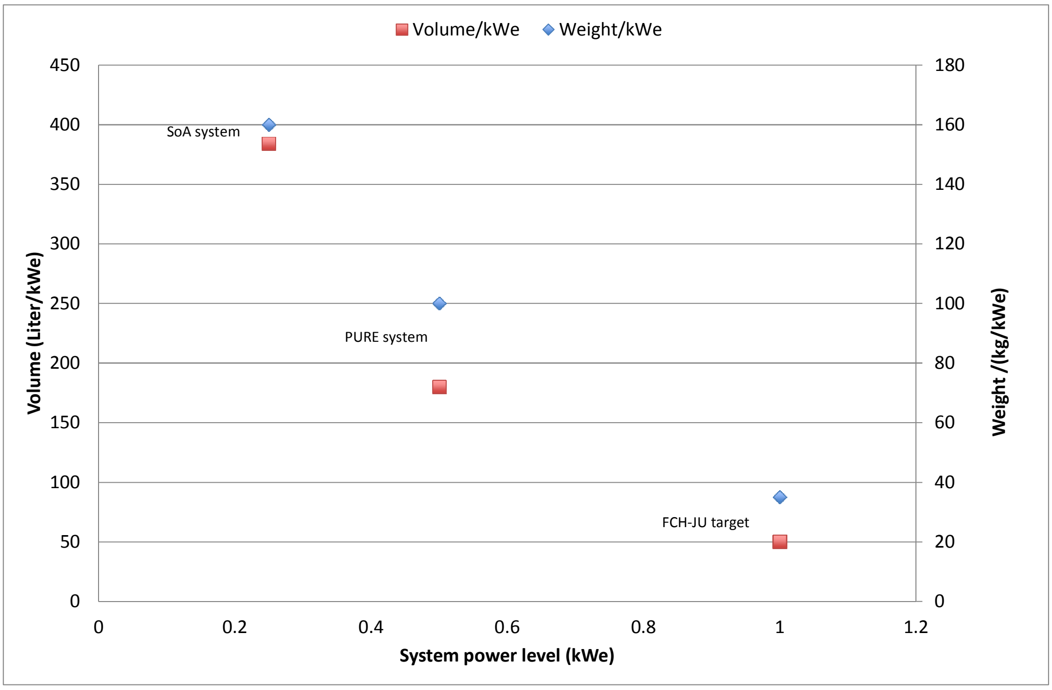

Figure 25: comparison of size and weight of the PURE system compared with SoA and FCH-JU target

After the systems have been build the wiring to all sensors and other control hardware were connected to the system and to the control box which contained the PLC and all other control hardware (relais etc). The control program was written in HPVEE software program to control the valves, pumps etc. and rea out the pressure, temperature and electrical data from the stack.

WP7 Testing protocols

In this work package the test protocols for harmonized testing of HT PEM fuel cell MEA's were developed. Also protocols for environmental testing of complete systems for the maritime industry have been written. These protocols can be used in the testing of the system under simulated conditions. The results can be compared with data measured in real maritime conditions.

WP8 Environmental/ System testing

In this work package the PURE system has been tested under variations of power production, start stop cycles and steady state operation (Figure 26). The system has been running for 800 hrs without observed degradation of the catalysts or the stack. The running time was limited by the failure of the ATR heater. Details and results of these tests have been reported in D8.1.

Figure 26: Pure system in test container

Summarizing the tests, the modulation of the system could be done using the entire system between 100 and 500 We with stable performance and efficiency. Lower power levels were limited by the reformer heat losses. The 50We power level can be maintained from the stack but required increased reformer gas input. This resulted in a decrease of efficiency. An overall system efficiency of 25% has been recorded running the system at multiple power levels. The Target of 30% could not be reached as the system layout suffers too much heat loss due to heat exchangers for reformate conditioning and the need to use of a liquid cooled stack with all required peripherals.
The start-up time of the system is close to 2 hours. A reduction in start-up could be reached by using a separated start up burner and the reduction in number of heat exchangers which also would decrease the size and weight of the system

WP9 Field testing

The system has been tested on board of a recreational yacht the “Batavier” which was in the marina of Hattem, the Netherlands. A photo of the yacht is shown in Figure 27 and Figure 28.


Figure 27: Recreational yacht the Batavier, used for on board testing of the PURE system

The system was operated and could produce about 400 We. A small sailing tour was held during calm weather in which some heeling and trimming of the yacht occurred. No effects of these movements of the ship were noted during the fuel cell operation, showing a stable performance.


Figure 28: PURE system installed on a yacht

In Figure 29, a plot with the electrical current and the voltage measured at the fuel cell on board of the yacht are given. The electrical parameters were similar as measured in the lab during the testing of the stack outside of the system.

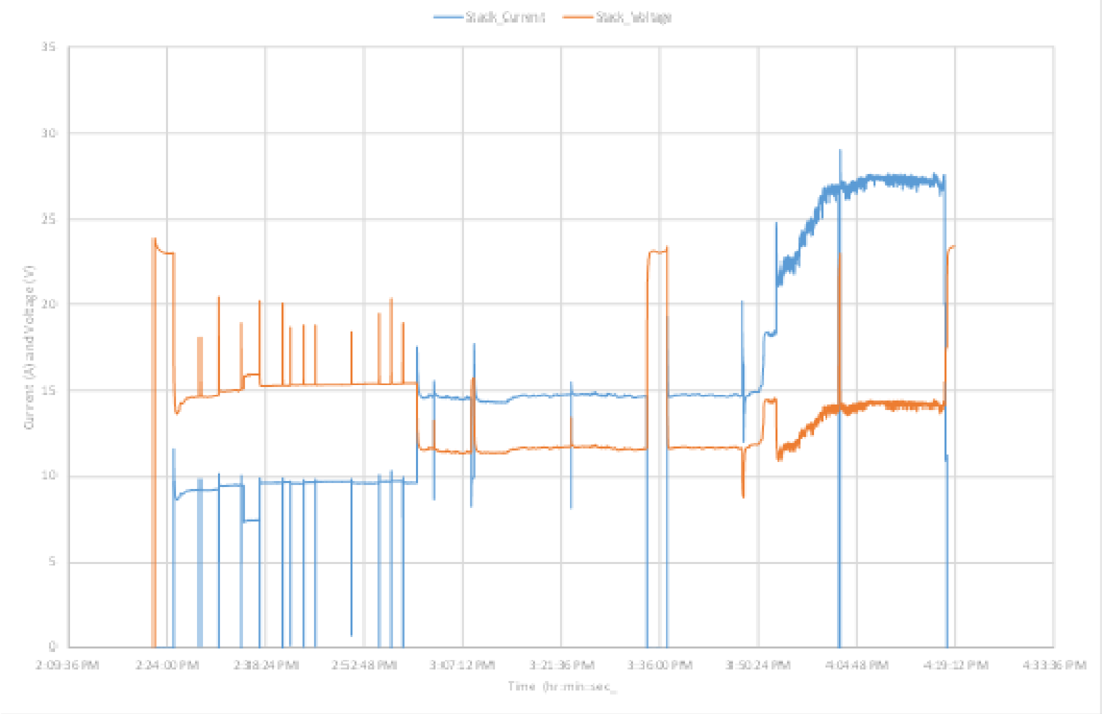

Figure 29: Current and voltage measured in the PURE system on board the yacht

Conclusions and recommendations

The PURE system has been tested under various conditions. It has been operated up to almost 800 hours with multiple start/stops and different power levels. There has not been observed any degradation over the time of testing. The system continued to run over time and it will easily run 1000 hours with 100 start stops, reaching the targets. The stack and the MEA's performed very well as well as the hydrogen production catalysts. The catalysts are running on thermal equilibrium, which makes the system reliable to control.

There are two fundamental points which need to be tackled to reach the desired size, weight and operational requirements. The first item is the size and weight requirements. These could only be reached when high temperature PEM MEA's will be improved to run at reformate with a hydrogen content coming out of the ATR, which is about 30%. As proven in the current project it is possible to condense out the water and thus increase the hydrogen concentration, but this requires heat exchangers to condition the reformate. These heat exchangers increase the size and weight of the system and also increase start up time, while reducing overall efficiency by enlarging heat losses.

The current high temperature MEA's also have an issue with drying out with an air cooled stack design. For this reason a liquid cooled stack system was designed. The decision caused the presence of additional hardware (Heat exchangers, glycol pump, glycol) which made the system heavier, bigger, more expensive and also increasing start-up time

The second point is the manufacturing of 3D metal printed heat exchangers. During the project the technology to print these devices showed that it requires to be improved with better reproducibility of results. The first small HX0 heat exchanger had been tested in the lab and proven to work well. The next devices that were printed leaked. The devices were treated with impregnation resins which was a partly improvements against the leakages. Some of the heat exchangers could be used, but others were replaced by state-of-the-art heat exchangers which are bigger than the 3D printed ones. These changes required a redesign and remanufacturing of the PURE systems. The resulting PURE systems experienced an increased heat loss due to the enlarged surface area of those modules and additional piping. In the future it is expected that the 3D metal printing technology will greatly reduce the manufacturing variations and that the technology will be usable for small APU’s.

The PURE system is able to run under nominal conditions of 500We and modulate in power of 80% (100 We) is possible. It showed around 25% system efficiency, compared to engines of the same power class, these have a typical efficiency of 12% (500W) to 15% (1000W). The PURE system this has about doubled the efficiency with additional benefits of low noise and no smells.

The potential impact and the main dissemination activities and exploitation of results.

The impact of the PURE project is on the technical and on the marketing level. The technology developed can be used inside, but surely also outside the maritime sector.

Technical impact

All technical developments in the project are made based on application on board of a ship. This means in general that the requirements are more stringent than for instance for stationary or automotive applications for reliability and safety reasons. Both the reformer and stack technology can be used in maritime and other applications.

Reformer

Autothermal reforming has a short start up time, catalysts are commercially available and the engineering of such systems is well understood. The same is true for the water gas shift reactor.

A big impact is the sulfur tolerance of the ATR catalyst, which is also suitable in all application both maritime and non-maritime. Currently, most desulfurization in small fuel cell systems is done using an adsorbent upstream of the reformer. This results in a relatively big vessel which has to be exchanged regularly. The sulfur tolerant ATR gives the opportunity to use high temperature adsorbents which have a 10 times higher adsorption capacity. The high uptake capacity makes a small reactor size possible or a less frequent exchange of desulfurization material. The advances DTU has made on the sulfur tolerance of the fuel cell MEA's opens the door for a system without desulfurization at all. Note that those sulfur tolerance technologies go beyond the fuel cell industry; these are also important for use in the hydrogen production industry in which the produced H_2S can be separated by a pressure swing adsorption step.

The ATR technology is fully scalable towards bigger systems and can be used for other hydrocarbon fuels (natural gas, LNG etc) as well.

Fuel cell stack

The advancements DTU has made in the production of MEA's have an impact in several ways. First, the use of non-toxic, environmental friendly reactants in the production of the binderless electrodes of the fuel cell has a beneficial effect on the sustainable manufacturing and with that on the production cost of the fuel cell. Secondly, the reduction of precious metal is in principle an advantage as cost reduction of the fuel cell. However, the reduction has an impact on the reformer as the less expensive MEA's need a higher hydrogen concentration in the reformate and with that they add hardware in the reformer making this part more expensive and bigger. This means a good balance between the stack and the reformer cost should be made to have an optimal system both technically and economically. Thirdly, the advances in sulfur tolerance of the MEA's, already mentioned, can also have a big impact on the use of fuel cells in various environments. Note that when the catalysts are sulfur tolerant, additional attention has to be paid to the tubing and balance of plant components with respect to compatibility with H_2S containing gases.

3D metal printing manufacturing technology

In the PURE project the design focus was put on scaling down system size and weight. This leads towards the scouting of alternative manufacturing technologies to produce integrated, complex shapes for heat exchangers and reactors. Within the project it was decided to look at 3D metal printing as new manufacturing technology. In cooperation with Addlab, a company in Eindhoven, (NL) design were made for several heat exchangers for 3D metal printing. The main purpose was to learn how to design hardware for 3D printing, what are the benefits and the shortcomings. With successful evaluation of this manufacturing technology for heat exchanger applications, several parts in the PURE system could be redesigned like manifolds and other tubing parts with many connectors which are nowadays designed with many expensive Swagelock parts.

In the project it became clear that the printing technology needs to maturizes several of the heat exchangers leaked. The printer company has shown already some improvements as they did some additional test runs after the parts were installed in the PURE systems.

Next to the metal 3D printing also printing of other materials can become interesting for parts in the fuel cell and hydrogen industry. In the PURE project a small trial of printing a 3way valve in plastic, the trial was not successful as the gas tightness of the seals could not be created.

3D printing of ceramic parts for fuel cells is studied in a Horizon 2020 project called “Cell3Ditor” in which HyGear plays a small role in the definition of system requirements for SOFC based fuel cell devices.

The size and weight of the PURE system is 50% of the size of the start of the art at the start of the project. This means a considerable jump into the direction of the targets of the industry. The weak points in the current system have been identified, the MEA intolerance of low H2 concentration, the drying out of the membranes during start up and the immaturity of the 3D printing technology. With those improvements the weight and size requirements come within reach.

Commercial impact

In the PURE project the projected cost of a system are shown to be come lower than the €2500 target set in the FCH JU implementation plan. This would require to have improved MEA’s and an air cooled stack design. Also the manufacturing technologies for complex metal heat exchangers and other part should mature. With those improvements also the cost requirements come within reach.

PURE has given the maritime industry a look into fuel cells and what the benefits and challenges of this technology are. This holds for the small systems in the recreational sector but also for bigger systems (10 - 100kW) in the professional sectors of the market. (Ferries, off shore supply vessels etc.). The low noise, low emissions and high efficiency at the low power levels are very attractive for the maritime applications.

There is, however, a decrease in the market size of recreational yachts of the size in which a 500We system would be applicable. On the other side there is a growing interest of bigger size yachts for fuel cell power. It is recommended to enter the leisure maritime market with systems capable to power air-conditioning systems as well as gyro-stabilising systems, totaling 10-20kWe. For commercial maritime APU's power sizes of 100kWe and up are needed. For those markets size and volume constraints remain as on-board space is limited and comes at a premium. The use of PBI technologies for simple and small APU's out of the PURE project seem very suitable.

Dissemination

Several scientific contribution in the shape of peer review publications and conference contributions have been made in the course of the project. The list of all publications and other dissemination contributions is given in part 4.2 section A in this final report.

The PURE project has been orally presented in the FCH-JU program days in both 2014 and in 2016, next to posters on all review days from 2013 to 2016. In 2013, the project has been presented at the fuel cells for the maritime industry workshop of the FCH JU in Venice, Italy .

Dissemination workshop

The dissemination workshop as planned in deliverable 1.3 was held in parallel with the "Piero Lunghi" European Fuel cell conference in Naples, Italy on December 15, 2015. All partners presented on their part of the work in PURE and there were discussions on the implementation of Fuel cell in the maritime industry Figure 30. In total 15 persons attended the workshop.

Figure 30: Pieter Huyskens from DAMEN presenting on Fuel cells in the maritime industry at the dissemination workshop

The system was presented on the workshop and on the exhibition of the conference itself (Figure 31). It was shown between other fuel cell systems for stationary and motive applications.

Figure 31: The PURE system at the European fuel cell conference exhibition

Connections with other initiatives

The PURE project has a strong connection in several other maritime initiatives in Europe and beyond. The partners are in several other European projects to develop fuel cell and hydrogen in those areas. Examples are the FP7 JOULES project in which among many about 40 maritime oriented organizations DAMEN and HyGear work on defining zero emission solutions in the future maritime industry. HyGear and DAMEN have worked on a national Dutch project HySeas to develop a LT PEM system including a reformer for ethanol and LNG for freight carriers. Damen is also active as coordinator in the EU horizon 2020 project LEANSHIPS. HyGear is invited to join the IEA-HIA task 39 on hydrogen in the marine applications.

Due to the PURE project its partners are more involved in maritime projects and initiatives, which is a positive impact for the fuel cell industry.