E2P2H2 - 64013-0583 - Final report

1. Project details

Project title	Energy Efficient Production of Pressurized Hydrogen
Project identification (program abbrev. and file)	E2P2H2 J.nr. 64013-0583
Name of the programme which has funded the project	EUDP, Brint og Brandselsceller
Project managing company/institution (name and address)	Technical University of Denmark, Department of Energy Conversion and Storage, Frederiksborgvej 399, 4000 Roskilde
Project partners	Haldor Topsoe A/S
CVR (central business register)	30 06 09 46
Date for submission	31/3 - 2016

2. Short description of project objective and results

2.1 English version

The project objective is to develop pressurized solid oxide electrolysis cell (SOEC) technology and to assess the economy of pressurized operation of SOECs for hydrogen production. In the project a 1200 hour test of a 16 cm^2 cell was conducted at 750 °C and gas pressures ranging from 3 bar to 10 bar. Further a 1 kW SOEC stack was developed at Haldor Topsoe A/S and tested at pressures up to 25 bar at DTU Energy to characterize the stack performance as function of pressure. The characterization served as input for the techno-economic evaluation of hydrogen production using high pressure operation of SOECs.

2.2 Danish version

Projektets formål er at udvikle tryksat fastoxidelektrolysecelle (SOEC) teknologi og undersøge de økonomiske aspekter vedrørende brint produktion vha. tryksatte SOEC stakke. I projektet blev en 1200 timers test gennemført med en 16 cm^2 celle ved 750 °C og tryk fra 3 bar til 10 bar. Derudover blev en 1 kW SOEC stak udviklet af Haldor Topsoe A/S og testet under tryk fra 1.2 bar og op til 25 bar hos DTU Energi for at karakterisere stakkens performance som funktion af tryk. Disse data blev efterfølgende benyttet i den teknoøkonomiske vurdering af produktion af tryksat brint ved hjælp af tryksatte SOEC stakke.

3. Executive summary

The two dominant costs in hydrogen production are the system investment costs and the electricity cost. Systems based on high temperature electrolysers such as solid oxide electrolyser cells (SOECs) can be made very energy efficient because the thermodynamics of the H_2O electrolysis reaction improves with increasing temperature. Further, the SOECs are made from relatively cheap raw materials, i.e. without noble metals such that the technology holds a potential for low investment costs around 150€/kW.[1]

Pressurized operation of SOECs is expected to drive down costs for three reasons:

1) Cost efficient hydrogen distribution and storage typically requires high gas pressure. Thus hydrogen production based on low-pressure electrolysers necessitates costly electricity consuming compressors – something which can be avoided by pressurized operation of SOECs.

2) The size and thus the cost of auxiliary components such as heat exchangers and pipes decreases with increasing pressure since the volume of the gas decreases with increasing pressure. The cost of the auxiliary components is estimated to cost around 2/3 or the system cost price.[2]

3) The internal resistance in SOECs decreases with increasing operating pressure.[2,3] This enables hydrogen production at higher current densities which reduces the amount of SOEC required for a given hydrogen production rate which reduces the SOEC investment costs.

In the E2P2H2 project pressurized operation of solid oxide electrolysis cells (SOECs) and stacks was demonstrated. One of the two test setups developed and used in the project is shown in Figure 1.

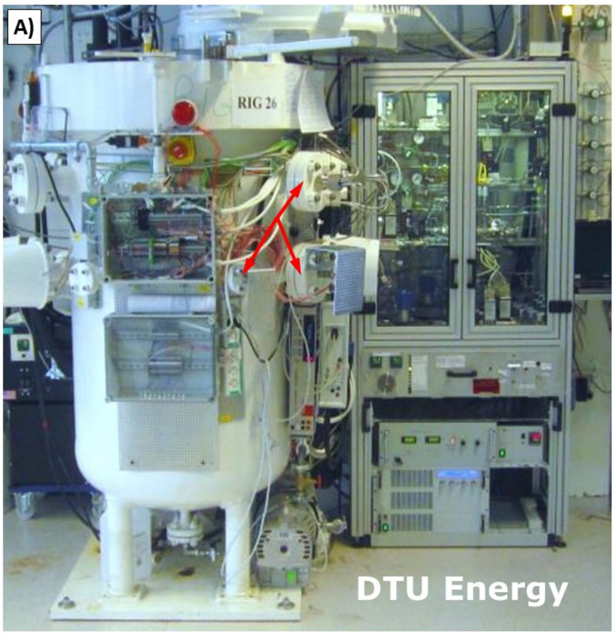


Figure 1. Photo of one of the pressure setup used for SOC stack testing in the E2P2H2 project.

The three main results of the project were:

1) A 1200 hour test of a 2.5G operated at 850ºC and -0.5A/cm^2 with 50% H_2O + 50% H_2 as inlet gas to the negative electrode (and oxygen to the positive electrode) was conducted in the project (Figure 2). The test shows that the cell is vulnerable to rapid changes in pressure caused by safety system trigger events, but also that the cell degradation doesn't seem to be negatively affected by the increased pressure.

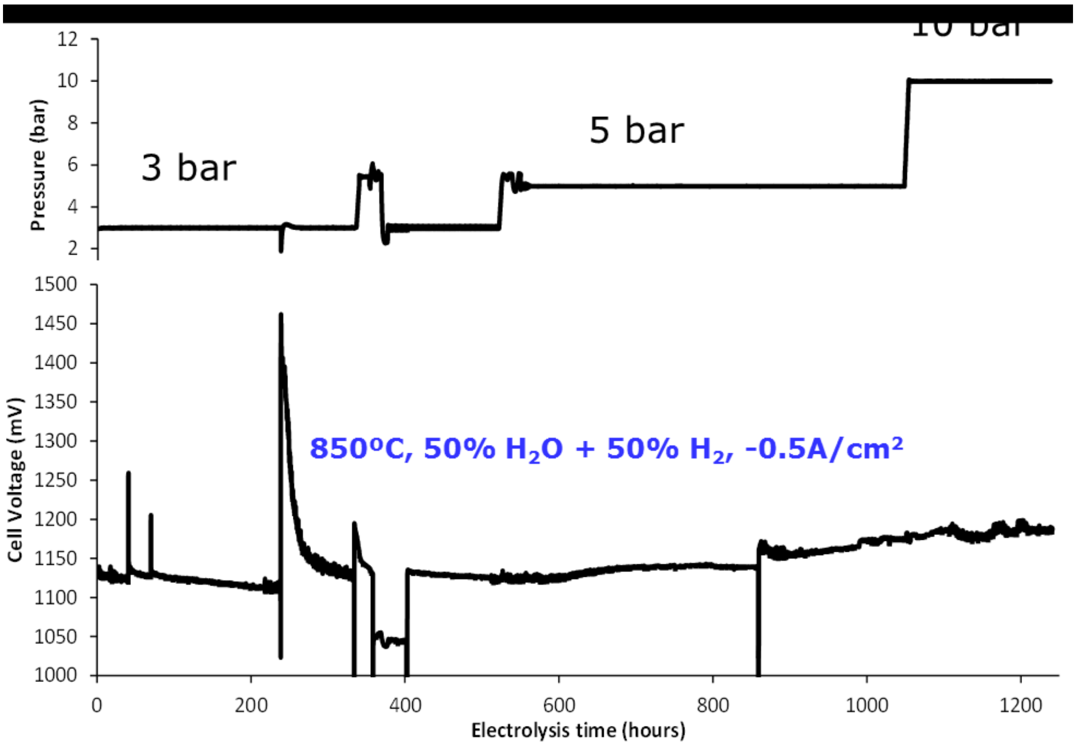


Figure 2. Cell voltage as function of time for a long-term pressure testing of a 16 cm^2 SOEC cell at pressures ranging from 3 bar to 10 bar.

2) A 1kW SOEC stack test at pressures from 1.2 bar to 25 bar. iV curves are presented in Figure 3. The iV curves shows that the internal resistance (the slope of the iV curves) decreases with increasing pressure, although the improvement is smaller for the stack than for single cells. This is mainly because the pressure independent resistance of interconnect/electrode interfaces only adds to the stack resistance.

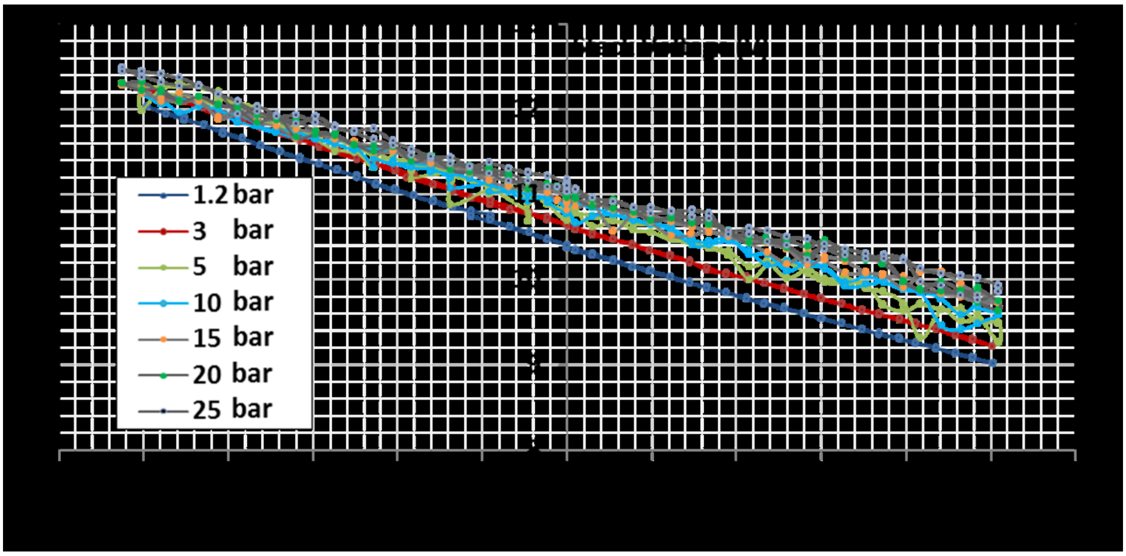


Figure 3. iV curves measured with a 1kW SOEC stack from HTAS. The slope of the iV curves decreases with increasing pressure. The fluctuations in cell voltage above 3 bar is caused by a poor control of the steam condensation.

One of the project goals were stack testing up to 30 bar. This was not reached due to unforeseen issues with heating inside the pressure vessel and furnace power. Rather than focusing on reaching 30 bar, it was accepted by EUDP to focus on solving issues with steam condensation and stable stack voltage at high pressure. Improved stability was achieved by heat tracing from the H_2O evaporator box to the fuel gas heat exchanger and from the fuel gas heat exchanger to the condenser bottle. The resulting iV curves with improved voltage stability is shown in Figure 4.

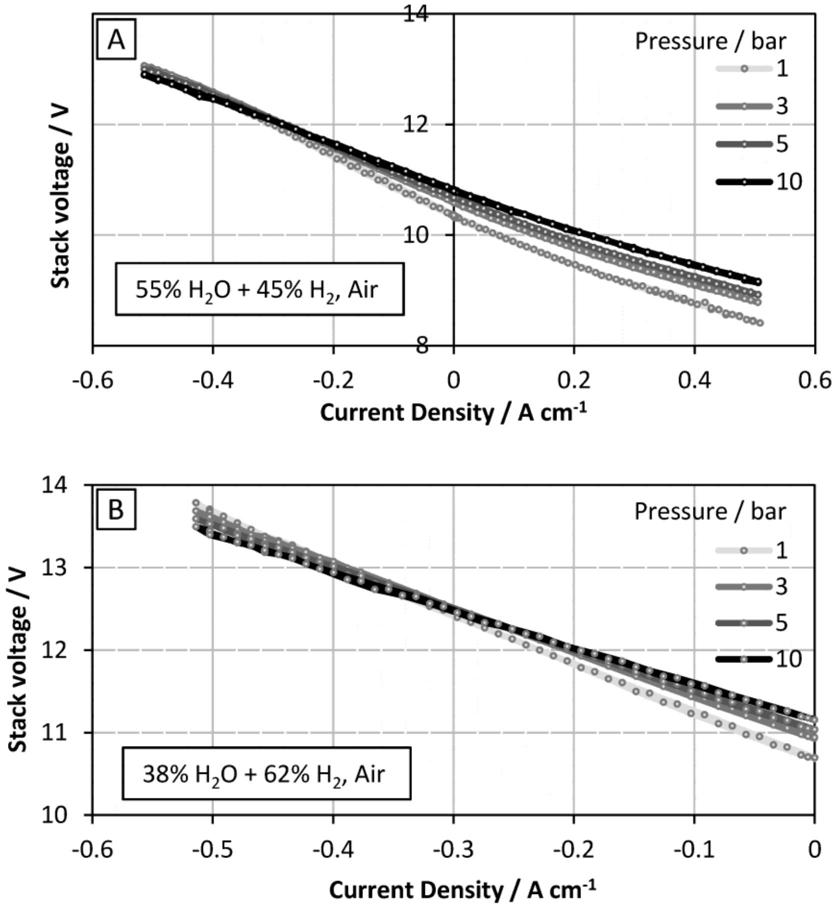


Figure 4. iV curves measured with a 1kW SOEC stack from HTAS at two different gas concentrations and with improved steam flow and voltage stability at high pressure.

3) A techno-economic assessment of pressurized operation of SOECs for hydrogen production.

3.1 Energy efficiency

Almost all of the end use applications for electrolytically produced hydrogen (or synthesis gas in the case of co-electrolysis) requires elevated pressures as shown in Table 1 below for some of the most relevant end products for future Power to Product technologies:

Table 1: Typical operating pressure

End use	Operating pressure (bar abs)
Hydrogen	10 - 900
Methane (SNG)	20 - 50
Methanol	50 - 140

If SOEC stacks were only able to operate at atmospheric pressure the hydrogen would need to be compressed mechanically. The following section will discuss the energy needed to perform such compression.

The ideal, reversible work needed to compress a gas can be calculated directly from the first law of thermodynamics for an open system

$$W = \Delta H - Q$$

where W is the work, ΔH the enthalphy change and Q is the heat removed from the system.

The minimum work is needed for an isothermal, reversible compression and can be found from

$$W = \Delta H - T \Delta S$$

where ΔS is the entropy change (negative in the case of compression). The maximum work is found for an isentropic process, where the temperature increases to the adiabatic value and this is simply

$$W = \Delta H$$

It is important to use an adequate equation of state as hydrogen behaves highly non-ideal at higher pressure as the compressibility factor Z, defined by

$$PV = nRTZ$$

is substantially above 1.

In practice diaphragm or piston type compressors are used which approximate the isentropic case and they have at best a polytropic efficiency around 80 % due to friction, bypasses etc. In addition there is a mechanically loss of around 4 % in the drive motor.

Calculations have been carried out using proprietary Haldor Topsøe A/S software employing sophisticated equations of state, which has proven to be accurate even at high hydrogen pressures. The results are shown on Figure 5.

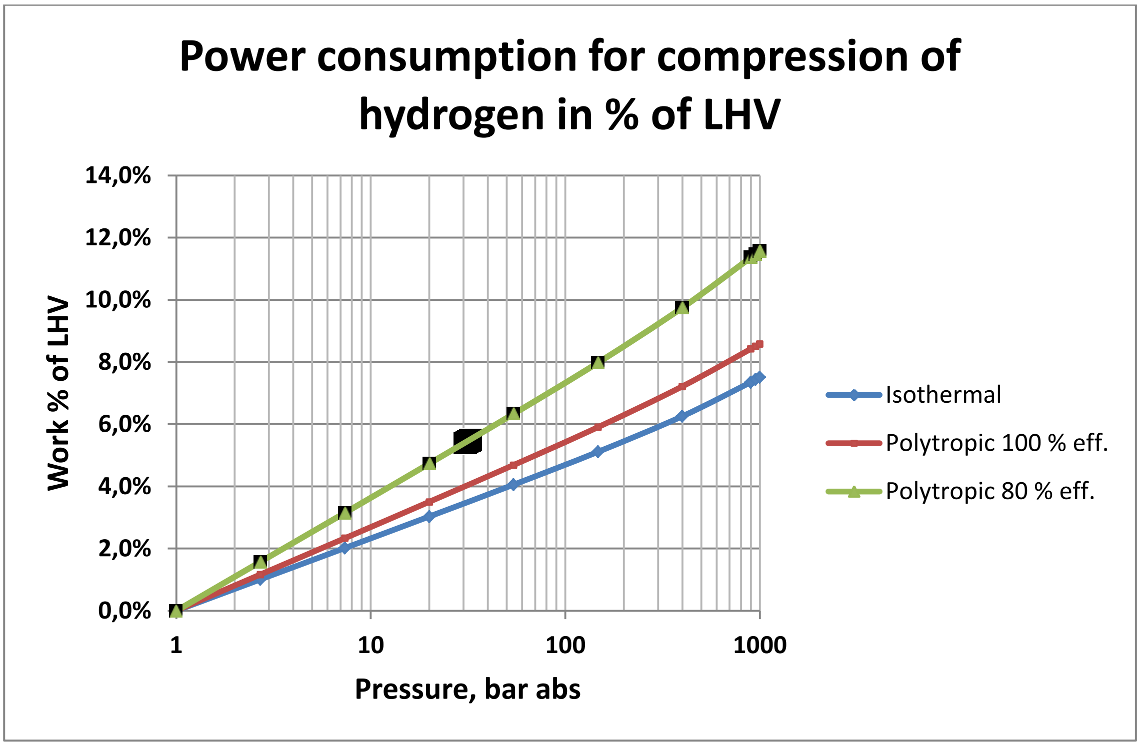


Figure 5. Calculated compression work as percentage of lower heating value of hyrogen(2.997 kWh/Nm3) for isothermal, 100 % isentropic and a polytropic case with 80 % effciency and 4 % work loss.

In the practical isentropic and polytropic cases the compression has been broken into several steps with compression ratios around 2.7 and intercooling to 20 °C, as this gives better effciency as well as limits the maximum outlet temperature from the compression steps to below 150 °C, which is the maximum allowable for safety and durability reasons.

The most demanding case is delivery of hydrogen for mobile application as in PEMFC vehicles, where the trend is to store the hydrogen at 700 bar on board the vehicle and at 900 bar for the final storage vessel at the dispensing station.

In this case the minimum, theoretical work for compression would be 7.4 % of the lower heating value of hydrogen which is 3 kWh/Nm3. In practice the practical compression energy would be closer to at least 11.4 % of LHV.

The relation ship between the required compression work for hydrogen and pressure is close to linear with the logaritms of the pressure except for the highest pressurre where the nonidealities becomes very pronounced, so 42 % of the compression energy needed to go to 900 bar is already expended when reaching 20 bar.

Delivering the hydrogen at 20 bar would thus entail substantial energy savings and investment in and maintenance of 2 to 3 compressor stages could be avoided if the SOEC stack operated at this pressure.

Obviously the minimum amount of electrical potential to accomplish water electrolysisi would increase as is evident from the Nernst equation:

$$E_{\text{min P bar abs}} = E_{\text{min 1 bar abs}} + RT/2F * \ln(\sqrt{P})$$

One of the great advantages of SOEC technology is the ability to utilise waste heat from internal resistances (defined as ASR = area specific resistance) to drive the water electrolysis. The required energy at isothermal conditions is the enthalphy change ΔH, which is composed of

$$\Delta H = \Delta G + T \Delta S$$

and

$$\Delta G = E_{min}/2F$$

The entropy term is the allowable waste heat utilisation at thermoneutral conditions

$$T \Delta S = Q = I^2 * ASR$$

The experiments have shown that the performance improves with pressure, e.g. the ASR decreases. If the ASR decreases by 15.5 % going from 1 to 20 bar this is enough to counteract the increase in minimum electrical potential. This is illustrated on Figure 6, where the thermoneutral voltage is reached at a current density of -0.6 A/cm^2, which is fairly typical for aged state of the art stacks from Haldor Topsøe A/S. The 25 bar test results presented above indicates the ASR decreases 21.3% when increasing the pressure from 1 to 20 bar, thus supporting this statement.

The thermoneutral enthalpy at 750 °C is 248.1 kJ/mol H_2. The LHV of H_2 is 241.8 kJ/mol, so the LHV effciency when operating at the thermoneutral voltage is 97.5 %.

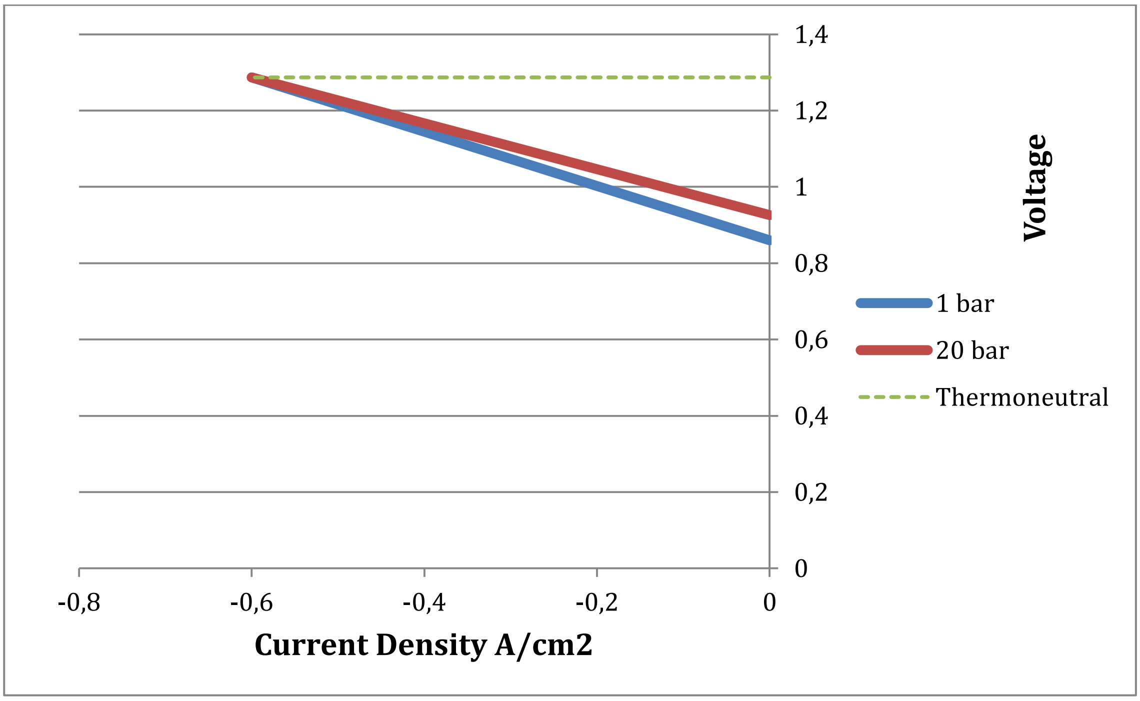


Figure 6. I-V curves for operation at 1 bar with an ASR of 0.71 Ωcm^2 and 20 bar with ASR of 0.60 Ωcm^2. The intercept is at the thermoneutral voltage of 1287 mV.

The energy consumption incurred for the balance of plant components obviously also need to be accounted for.

Here it is instructive to examine a flowsheet for stand alone hydrogen production like on Figure 7.

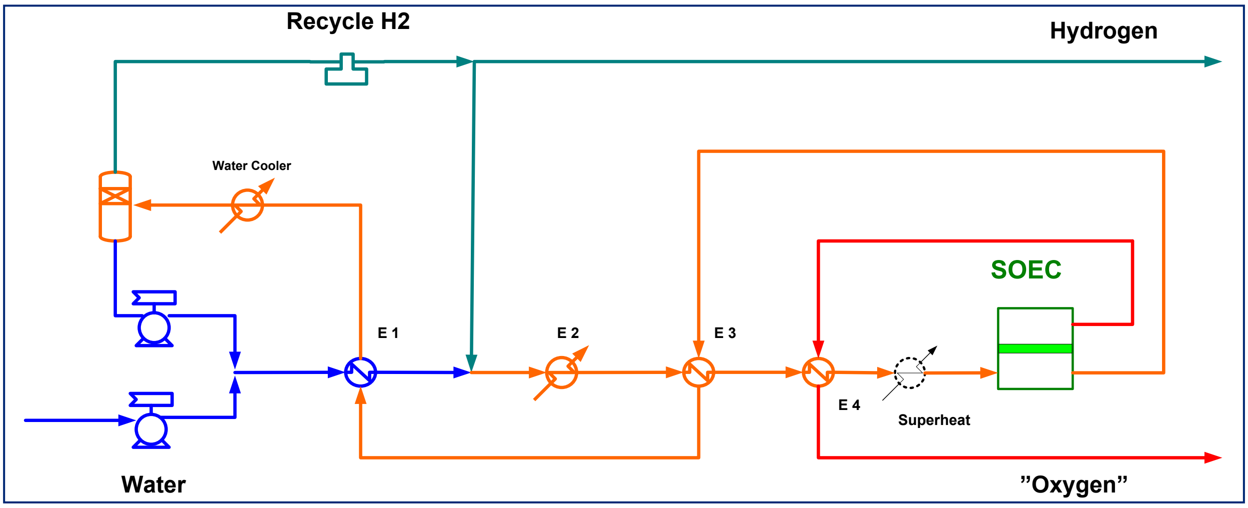


Figure 7: Generic flowsheet for a SOEC hydrogen plant

If the operating pressure is increased from 1 to 20 bar the water pumps needs to deliver a higher pressure but the power required is marginal (approx. 1 Wh/Nm^3 H_2). If the low and high pressure plant are designed for the same pressure drop the power consumption of the hydrogen recycle compressor will actually be higher in the low pressure plant due to the higher compression ratio.

In Table 2 below the consumption numbers are summarised for the two configurations. All the consumption and production numbers are in Wh/Nm^3 H_2.

Table 2: Consumption and production numbers in Wh/Nm^3 H_2

Operating pressure bar	**1**	**20**
Stack	3078	3079
Electric superheat	50	53
Evaporation	613	538
Recycle and pumps	15	6
H_2 compressors	150	0
Sum Consumption	**3906**	**3676**
Efficiency LHV %	76.7	81.5
Efficiency HHV %	90.7	96.3
District heating	158	121
DH effciency LHV	5.3	4.0

It may seem surprising that the need for power for steam generation is highest at low pressure but the heat of evaporation for water decreases with pressure. A pinch analysis has shown the same difference between the two cases. The power consumption for hot utility could be decreased somewhat for a more elaborate and fully optimised heat exchanger network, which however would become much more expensive and difficult to control.

3.2 Economy

In order to evaluate the investment and maintenance cost estimations have been made for a plant operating at ambient pressure SOEC versus a plant operating at 20 bar. Both plants deliver hydrogen at 20 bar.

In a the SOEC plant operating at ambient pressure the hydrogen compressors represent a major investment and maintenance cost. They are heavy and complex machines in order to avoid contamination of the produced hydrogen. Machines compressing from 0 to 20 bar are rather uncommon and diffcicult to get reliable quotes for. It can be mentioned though that the diaphragm compressor purchased in the EUDP project "El upgraded biogas" cost 177470 € without spare parts. It weighs 5500 kg and can compress 1.8 kg/h hydrogen from ambient to 43 bar g.

A drawing is shown on Figure 8. It has a footprint of 2 m x 2,1 m and is 2 m high.

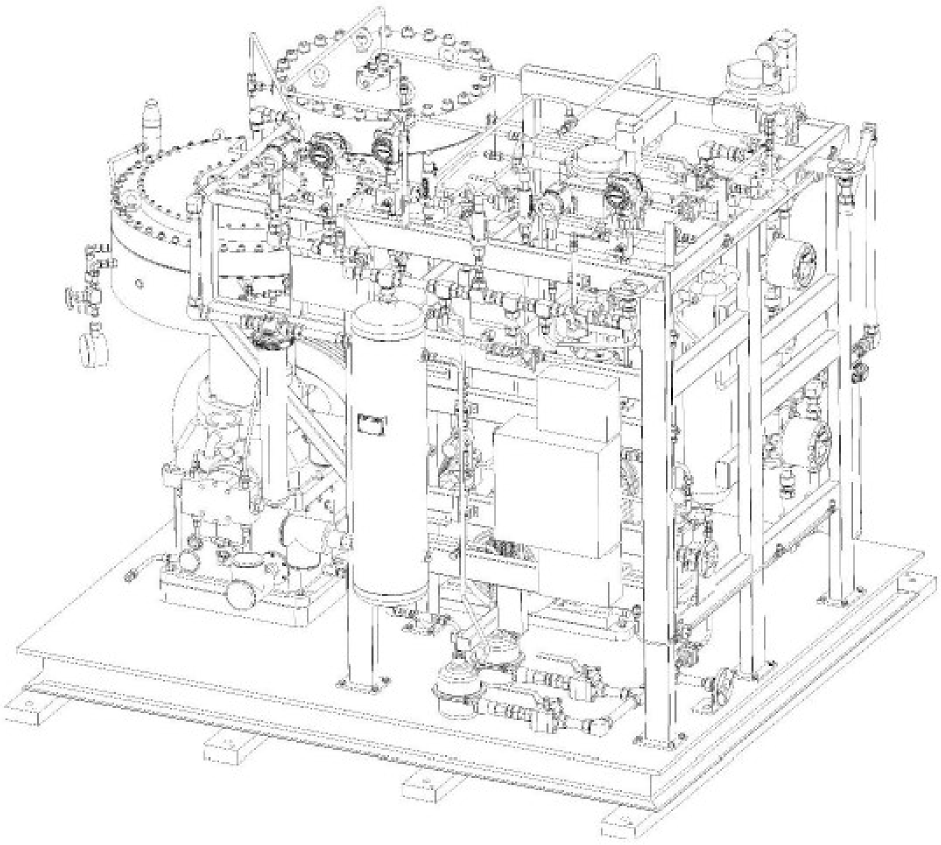
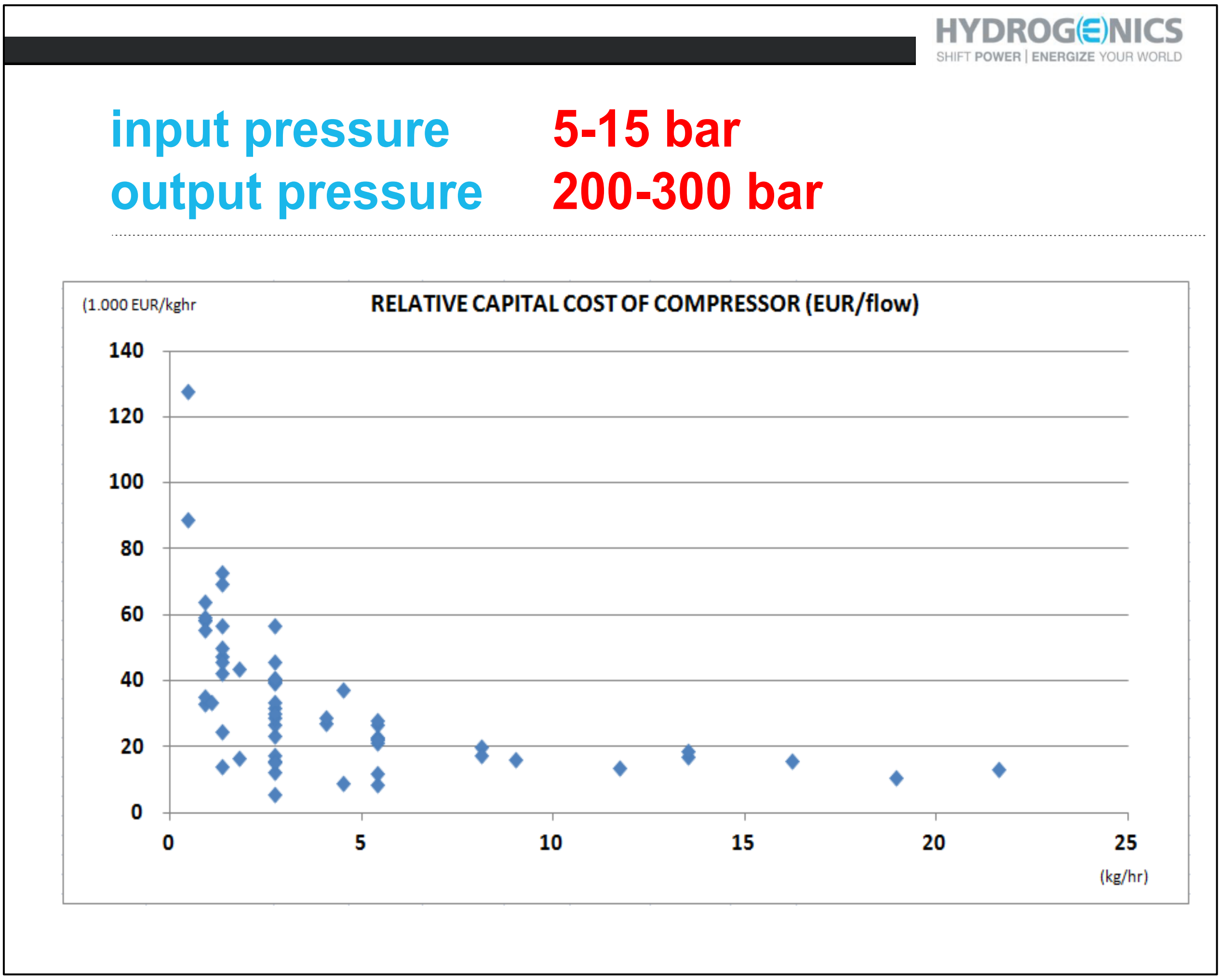


Figure 8. Drawing of SERA compressor bought in 2015 for EUDP project "El upgraded biogas". Nominal capacity 20 Nm^3/h H_2 from 0 to 43 bar g.

Haldor Topsøe A/S is participating in the IEA Hydrogen Implementing Agreement in Task 33 on small scale reformers and electrolysers. Hydrogenics has presented costs from 190 quotations from the last 6 years on hydrogen compressors and has allowed the use of these data for the present report. The prices were obtained from all the major suppliers: PDC, Hofer, PPI, Hydropac, Rix, Sera, Idromeccanica, Atlas Copco and Ventos. The data for compressors designed for 5-15 bar to 200-300 bar compression is shown on Fig. 9. It is seen that the prices per kg hydrogen per hour drops off in the 1-5 kg/h range and then stabilises around 10000 – 15000 €/kg/h.

It should be emphasised that the price is for a bare skid with only basic instrumentation.



HYDROGENICS
SHIFT POWER | ENERGIZE YOUR WORLD

input pressure 5-15 bar
output pressure 200-300 bar

Figure 9. Normalised investment cost in hydrogen compression from 5-15 bar to 200-300 bar

The cost of the last compressor compressing from 200-400 bar to 700 -1000 bar levelled out at around 5000 €/kg/h for larger capacities above 10 kg/h.

DOE has sponsored intensive work on modelling the costs of supplying hydrogen for automotive use and established targets for cost and efficiencies for the different components including compressors.

The program has been reviewed by a team of independent expert which by interviews with compressor manufacturers concluded that DOE's projected costs were to optimistic. A comparison of the values for DOE's projection and expert panel values are shown in Table 3. The values are for compression from 20 bar to 875 bar for a 1000 kg/day installation.

Table 3: Investment cost for hydrogen compressors from 20 to 875 bar according to DOE sources. 1 € assumed to be 1.35 $

	DOE H2A model	Panel Base case	Optimistic	Pessimistic
Capex 1000 kg/day $	670000	1042000	695000	1409000
$/kg/h	16080	25008	16680	33816
€/kg/h	11910	18500	12360	25000

Referring to the data from Hydrogenics above it seem fair to assume that the cost of the last 400 to 875 bar compressor is about 5000 €/kg/h leading to an investment cost for the two diaphragm compressors bringing the pressure from 20 to 400 bar to around 13500 €/kg/day in good accordance with the Hydrogenics data. The expert panel assumes that the cost can be brought down by approx. 25 % by mass production e.g. to 10000 €/kg/h and that the isentropic efficiency could be increased from the present around 65 % to 80 %.

As the 20 to 400 bar steps have the same compression ratio as the compression in focus in this chapter from 1 to 20 bar it seem in view of above fair to assume an investment cost in the order of 10000 – 12000 €/kg/h or 1000 € per Nm^3/h of hydrogen.

Data from the literature and from Hydrogenics also indicate a maintenance cost of around 4 % of the investment cost per year.

Calculations of the needed heat transfer area in the heat exchangers have also been carried out for the ambient pressure as well as the 20 bar case using Haldor Topsøe A/S proprietary software for the generic SOEC based hydrogen plant. The needed heat transfer area drops by a factor of 2 if the pressure drop across the heat exhangers is kept constant. This more than compensate for the need for a thicker enclosure of the heat exchangers. In fact the cost of the pressurised heat exchanger will be only 64 % of exchangers for ambient pressure operation.

The pressure vessel enclosing the SOEC stacks has conservatively been cost estimated to cost around 100 €/Nm^3/h extra.

A SOEC hydrogen plant producing 1000 kg H_2/day has been projected to cost around 925,000 € in 2020 for pressurised stack operation > 20 bar provided that the stacks are mass produced in a factory having a yearly capacity above 200 MW per year. If the stacks can only operate at ambient pressure the cost will based on above estimates increase by 40 – 50 %. Furthermore over a 5 year period with 8000 hour operating time per year the saving in electricity 0f 0.23 kWh/Nm^3 H_2 (see Table 2) amounts to 128,000 €. The saved maintenance cost of the compressors amounts to 93,000 €.

Although these estimates are rather approximate they are precise enough to indicate that there exist a strong incentive to further develop pressurised SOEC stacks and balance of plant technology.

4. Project objectives and results

4.1 Project structure and objectives

The project is organized in four work packages, reflecting the tasks necessary to reach the overall project objective of development of pressurized SOEC technology.

The work packages were **WP1**) Testing of single cells at elevated pressure, **WP2**) Manufacturing of a 1 kW SOEC stack, **WP3**) Preparation of test setup for 30 bar SOEC stack tests, and **WP4**) Techno-economic evaluation of hydrogen production using high pressure SOEC technology.

The project milestones were:

M1. Necessary cooling equipment is installed in single cell test setup. Gas sensor accuracy improved and more rugged test house finalized.
M2. A single SOEC cell durability tested for more than 1000 hours at elevated pressure.
M3. 1 kW high pressure SOEC stack assembled, reduced and prepared for test in WP3.
M4. The 1 kW high pressure SOEC stack made in WP2 is tested at 10 bar.
M5. The 1 kW high pressure SOEC stack is tested at 30 bar.
CM1. Key CAPEX and OPEX figures for high pressure SOEC operation are quantified in CM1
CM2. Early markets identified, dates estimated for market entries and a high pressure SOEC roadmap developed.

4.2 Development of Test Setup (M1)

A few single cell tests were conducted before the onset of the E2P2H2 project. These tests revealed that instable gas sensors frequently caused the test safety system to trigger. This was in particular problematic in relation to long-term testing. To remedy this, new improved gas sensors with optimized sensor ranges were purchased and installed in the beginning of the project, as part of M1. Additionally, condensers for gas cooling were installed in the single cell test setup (and also in the stack test setup) as outlined in M1. The condensers are crucial for stable operation of the cell (and stack), since they help stabilizing the H_2/H_2O flow rate. If the H_2O is not condensed inside the pressure vessel, it will condense in MFC's controlling the flow rate downstream the cell (stack). Although the condensers were installed, it proved more difficult than expected to enable a flow rate. To circumvent condensation in the MFC's extra condensors were installed outside the pressure vessel. This ensured no condensation occurred in the MFC's.

Additionally a few tests in previous projects had shown that the test houses were vulnerable to trigger events which turned off the furnace. For this reason a metal house was purchased, further developed, and used for cell testing. The metal house is shown in Fig. 10A. Although the metal house proved to be much more robust relative to rapid heating and cooling, the house also induced very poor cell performance. This was identified to be related to non-optimized gas flow geometry. After a few tests with the metal house it was decided to use the ceramic house. To avoid damaging the ceramic house, two measures were taken: 1. The safety system was optimized to avoid furnace-power shut-down except for the most extreme alarm situations. 2. To avoid cracking of the ceramic pipes experienced in previous high pressure tests, metal pipes surrounding the ceramic pipes were applied to minimize the heat gradients where the pipes penetrate the furnace lid. Further another ceramic house was purchased as a backup house to avoid long idling periods due to purchase of a new ceramic house should the house break. The improved ceramic cell house configuration is shown in Fig. 10B. The improved ceramic cell house with the improved safety system was used for the long-term single cell test (Figure 2).

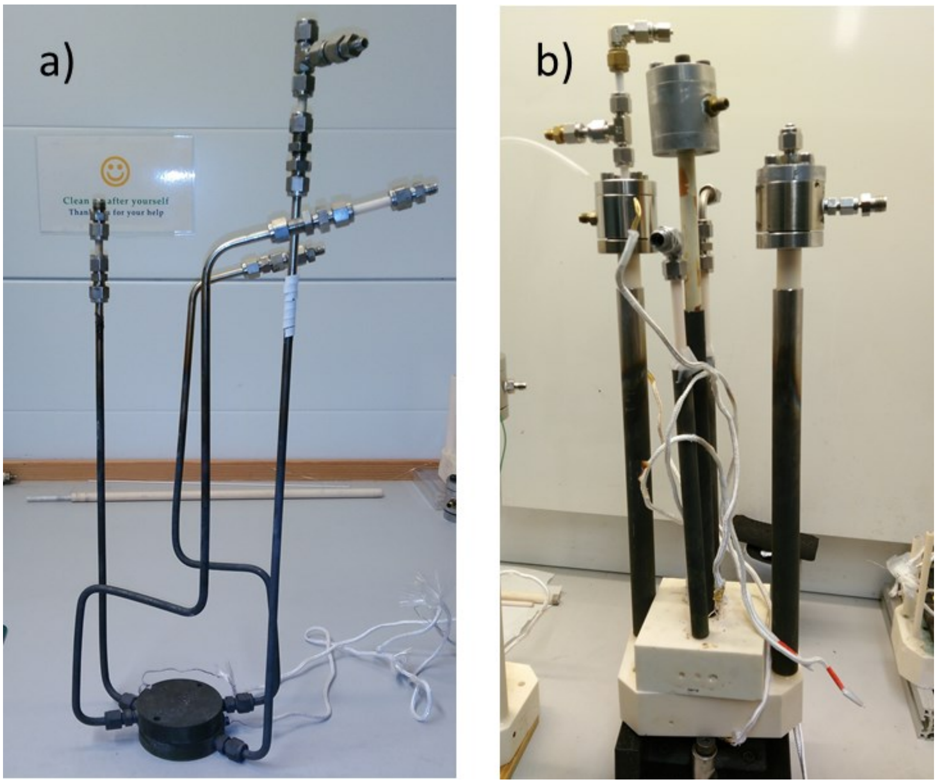


Figure 10. a) Metal cell test house. b) Ceramic cell test house. The metal house is superior in handling rapid temperature changes, but not as good as the ceramic house in terms of ensuring good contact to the cell and avoiding electrode contamination. Improved test-rig safety-system design enabled stable operation ant testing with the ceramic cell house.

4.3 Long-term Pressurized SOEC Test (M2)

Active pressure balancing was tested but proved difficult with the equipment applied in the pressure test setups. For this reason it was decided to operate both the cells and stacks with passive pressure balancing. The design principle for passive pressure balancing of both cells and stacks is sketched in Figure 11B (the same principle is used for cells and stacks) and further discussed in the published results.[4] Using passive pressure balancing, and with the completion of M1 as described above, it was possible to conduct a long-term Pressurized SOEC test as presented in Figure 2.

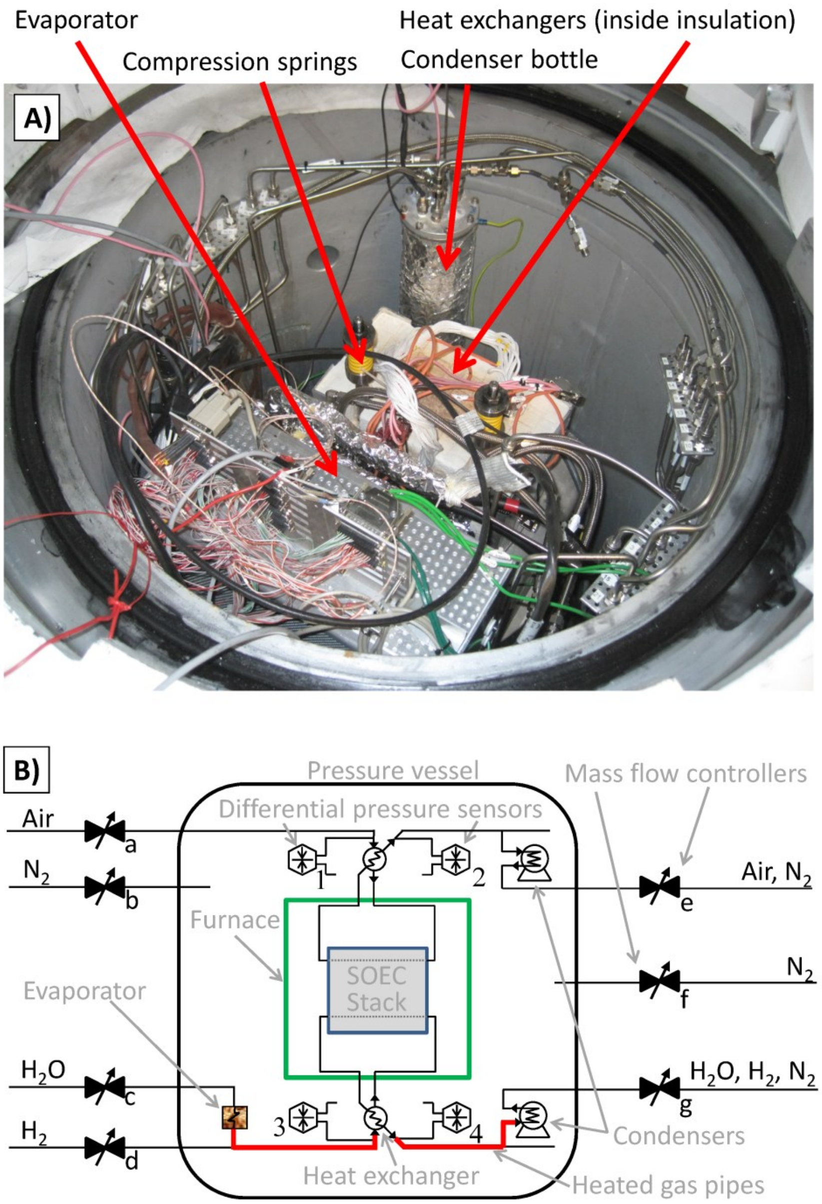


Figure 11. Part A. Photo of various parts of the setup inside the pressure vessel.

4.4 1 kW SOEC stack (Delta-design) for pressure testing (M3)

HTAS manufactured and delivered two SOEC Delta stacks to DTU Energy which were mounted in the stack test setup and pressure tested. HTAS have ended their production of Delta stacks, to increase their focus on the development of a more advanced setup, the TSP1 stack. In future projects, such as “Maturing SOEC” the test setup at DTU will be further developed to enable testing of TSP1 stacks.

4.5 SOEC stack test at 10 bar (M4)

The single cell tests (WP1) were conducted in the beginning of the project. Specifically the single cell tests were conducted before the 1 kW stack test. This provided valuable knowledge about critical conditions required for high pressure operation which helped ensuring a successful stack test. The 10 bar SOEC stack test (Fig. 4) used for the completion of M4 was in fact conducted after the SOEC stack test at 25 bar (Fig. 3). Issues with steam condensation and stable stack voltage at high pressure observed in the 25 bar test was removed by heat tracing from the H_2O evaporator box to the fuel gas heat exchanger and from the fuel gas heat exchanger to the condenser bottle as outlined in Fig. 11. (heat tracing is shown as red lines in Fig. 11B). Fig. 11A shows various components inside the pressure vessel used for the stack-pressure tests.

4.6 SOEC stack test at 25 bar (M5)

Although the test setup is designed for operation up to 45-50 bar, the furnace power was insufficient to maintain the stack temperature above 25 bar. For this reason the stack performance was investigated from 1.2 bar to 25 bar. The power cabling is now improved so it should be possible to operate the furnace at pressures above 25 bar. However, at pressures above 25 bar hot gas inside the pressure vessel could harm crucial components.[4] A careful examination of the various components, cables, feed throughs etc. is required before the safety temperature inside the pressure vessel can be increased above 100 °C.

Due to the complications related to operation above 25 bar, EUDP accepted that the 25 bar test could be accepted as completion of M5. It was agreed that instead of aiming for a 30 bar test, improved cell voltage stability at elevated pressure should be sought achieved. This was achieved by improved steam handling, as discussed above and presented in Fig. 11 and Fig. 4.

One important finding in the project - which was not considered before launch of the project - is that the leak rate increases with increasing pressure as indicated in Fig. 12. The leak rate level off at ~5 bar. This is possibly because gas leaks at seals near the internal stack manifolding become limited by binary diffusion at higher pressures.

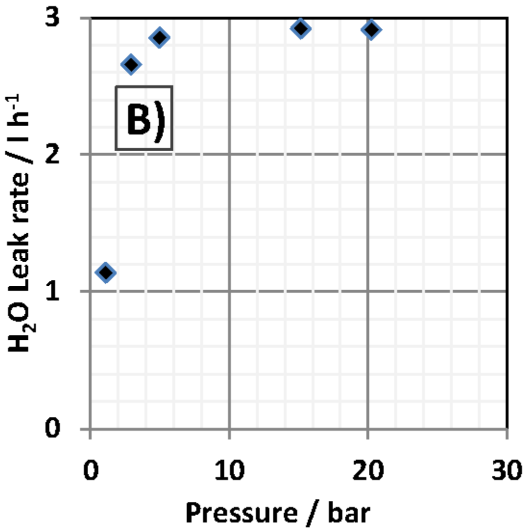


Figure 12. H_2O leak rate as function of pressure. The leak rate seem to level off at ~5 bar.

4.7 CAPEX and OPEX figures for high pressure SOEC operation (CM1)

The CAPEX for a hydrogen plant operating at 20 bar and producing 1 metric tons per day has been estimated to be 925,000 € if a large scale SOEC stack manufacturing plant is built. The only major operating cost will be for electricity where the consumption has been calculated to be 3.7 kWh(DC)/Nm^3 hydrogen.

4.8 Market identification and roadmap development (CM2)

One of the earliest markets for the technology would be on site small scale generation (<200 Nm^3/h of hydrogen). A substantial market could develop after 2020 if the roll out of PEMFC vehicles is successful.

In parallel a market will probably develop for delivery of hydrogen for biogas upgrading, SNG and methanol production coupled to biomass gasification. The delivery of pressurized oxygen is interesting for these segments.

Detailed engineering of the pressurized components will therefore need to be carried out within the next few years and the technology should be demonstrated in a scale of at least 50 kW. Special attention should be paid to material and safety issues connected to the handling of hot, pressurized oxygen.

4.9 Execution of the project plan

The project got delayed mainly due to complications in development of stable cell and stack operation delays in finishing the collaboration agreement between DTU Energy and HTAS, however all of the milestones in the project have been met.

5. Dissemination of results

The 1200 h test was presented at the European Fuel Cell seminar.[5] Single-cell test results op to 15 bare were presented in *Fuel Cell*.[3] The 25 bar stack test results were presented at the Fuel Cell Seminar 2015 in Los Angeles.[6] Techno-economic evaluations and the pressure test results were presented at the American Ceramic Society 2016 conference in Florida.[7] Additionally, the 25 bar stack test results are published in *Fuel Cell*.[4] The 10 bar stack results together with the results from the techno-economic evaluation will be published in paper currently under preparation.

6. Utilization of project results

The project results provide a strong incentive to proceed with the development of pressurised SOEC plants which can be used for stand-alone hydrogen plants or providing feedstock for SNG or methanol plants.

The market potential is huge (several billion euros per year) provided the political framework will be established allowing competition with cheap fossil fuels.

The competing electrolyser technologies - e.g. alkaline and PEM based – is already providing pressurised stacks so making this option available also for SOEC will further strengthen its competitiveness. The present project has demonstrated the highest operating pressure for SOEC stacks worldwide. Previous studies in the US by Idaho national lab[8] and in France by CEA[9,10] has been limited to 10 bar.

The technology will be a key enabler for realisation of the energy policy of eliminating fossil fuels as carbon neutral transportation fuel can be provided. Furthermore the technology has been identified as the most promising one for solving the storage aspects related to intermittent power production from wind and solar.

The work in the project has created ideas for at least two patent opportunities which is presently under investigation.

7. Project conclusion and perspective

25 bar operation of planar solid oxide electrolyser stacks have successfully been demonstrated in the project.

The competing electrolyser technologies - e.g. alkaline and PEM based – is already providing pressurised stacks so making this option available also for SOEC will further strengthen its competitiveness.

The presented analysis shows that pressurized operation can reduce the hydrogen production cost and at the same time improve the system efficiency.

For these reasons the project results provide a strong incentive to proceed with the development of pressurised SOEC plants which can be used for stand-alone hydrogen plants or providing feedstock for SNG or methanol plants.

Delivery of pressurized hydrogen is interesting for biogas upgrading, SNG and methanol production coupled to biomass gasification. Co-delivery of pressurized oxygen from the SOEC plan is also interesting for these segments.

8. References

[1] J. Thijssen, The impact of scale-up and production volume on SOFC manufacturing cost, NETL Report **2007**.

[2] S. H. Jensen, X. Sun, S. D. Ebbesen, R. Knibbe, M. Mogensen, Hydrogen and synthetic fuel production using pressurized solid oxide electrolysis cells, *Int. J. Hydrogen Energy*, 35 (**2010**) 9544.

[3] X. Sun, A. D. Bonaccorso, C. Graves, S. D. Ebbesen, S. H. Jensen, A. Hagen, P. Holtappels, P. V. Hendriksen, M. B. Mogensen, Performance Characterization of Solid Oxide Cells Under High Pressure, *Fuel Cells*, 15 (**2015**) 697.

[4] S. H. Jensen, X. Sun, S. D. Ebbesen, M, Chen, Pressurized Operation of a Planar Solid Oxide Cell Stack, *Fuel Cells* (**2016)**, Published online DOI: 10.1002/fuce.201500180.

[5] X. Sun, A. D. Bonaccorso, C. R. Graves, S. D. Ebbesen, S. H. Jensen, A. Hagen, P. Holtappels, P. V. Hendriksen, M. Mogensen, 'Performance characterization of solid oxide cells under high pressure' *in* Proceedings of 11th European SOFC and SOE Forum, B1301, Luzern, Zh. July 1-4, **2014**.

[6] S. H. Jensen, X. Sun, M. Chen, S. D. Ebbesen 'Hydrogen Production by Pressurized Operation of a Planar SOEC Stack' *in* Fuel Cell Seminar & Energy Exposition, Los Angeles, CA. November 16-19, **2015**.

[7] J. B. Hansen, S. H. Jensen 'Pressurised operation of Solid Oxide Electrolyzers' *in* 13th International Symposium on Solid Oxide Fuel Cells (SOFC): Materials, Science, and Technology, CACC-S3-012-2016, Daytona Beach, Fl. January 24–29, **2016**.

[8] J.E. O'Brien, Zhang,X.,Housley,C.K.,Dewall,K.,Moore-McAteer,L.,Tao,C., High temperature electrolysis pressurized experiment design, operation and results, in: DE-AC07-05ID14517, DOE, **2012**.

[9] L. Bernadet, G. Gousseau, A. Chatroux, J. Laurencin, F. Mauvy, M. Reytier, Influence of pressure on solid oxide electrolysis cells investigated by experimental and modeling approach, *Int. J. Hydrogen Energy*, 40 (**2015**) 12918.

[10] L. Bernadet, G. Gousseau, A. Chatroux, J. Laurencin, F. Mauvy, M. Reytier, Assessment of pressure effects on high temperature steam electrolysis based on solid oxide technology, in: K. Eguchi, S.C. Singhal (Eds.) 14th International Symposium on Solid Oxide Fuel Cells, SOFC 2015; held as part of the Electrochemical Society, ECS Conference on Electrochemical Energy Conversion and Storage, Electrochemical Society Inc., **2015**, pp. 3369-3378.