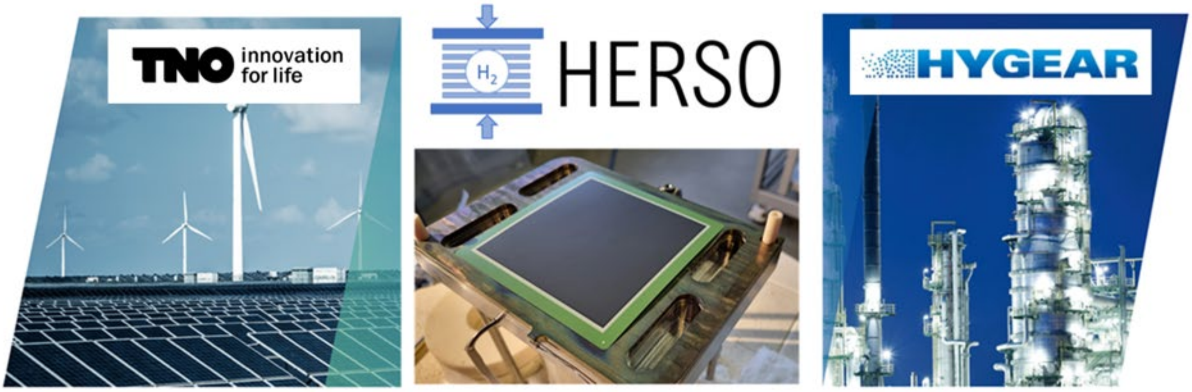
Development of a Highly Efficient and Robust Solid Oxide Electrolysis technology for hydrogen production

Final report HERSO project



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Development of a Highly Efficient and Robust Solid Oxide Electrolysis technology for hydrogen production

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1 Public Summary

Large scale green hydrogen production through steam electrolysis is one of the important solutions towards the Energy Transition and to meet the CO_2 emission reduction goals. Solid Oxide Electrolyzers (SOE) offer the most efficient way (20-30% more efficient compared to Alkaline and PEM electrolyzers) to produce green hydrogen, due to its operation at high temperature allowing favorable thermodynamics and kinetics for conversion of steam into hydrogen and direct industrial processes integration. The main technological challenges in the SOE technology development towards industrial integration has been defined by the Clean Hydrogen JU program 2021-2027 thought concrete KPIs , with 1/ CAPEX reduction of the SOE stack and system respectively below 150 and 500 €/kW to reach a hydrogen productivity below 3 €/kg H_2 , 2/ OPEX reduction with an operating life-time (> 60,000 hours) and 3/ upscaling of SOE technology towards multi-MW systems.

In the HERSO project, TNO and Hygear developed a novel concept and a unique and breakthrough SOE stack technology, which can contribute to achieve the cost (CAPEX and OPEX) reduction targets to accelerate the economically viable integration of the SOE electrolyzer system in the industrial environment. The novel approach in HERSO focused on a simple concept for a Solid Oxide Electrolysis (SOE) system that will operate at high pressures and different steam conversion has been developed, aiming at reducing the CAPEX and OPEX of the system, lowering the cost of hydrogen production. To accomplish this, a SOE system for hydrogen production was modeled for 10MW scale SOE electrolyzer. A case study was created to evaluate the impact of critical operating parameters. Twelve cases were defined to assess the impact of critical operating parameters on overall system efficiency. The critical operating parameters were identified as air side pressure, steam side pressure, and steam conversion. The cases were evaluated in three scenarios: Beginning, Middle, and End of Life at constant voltage and at constant hydrogen production by varying the critical operating parameters; steam conversion (40% and 80%) and pressure at the airside and steam side (1 atm and 10 bara versus 3 bara and 3 bara, respectively). Based on the results, the case with 80% steam conversion, 1 atm pressure at the air side, and 10 bara pressure at the steam side, is determined as the most efficient of all cases.

The unique and breakthrough demonstration of the pressurized short-stack developed by TNO in HERSO is a successful first step toward the LCOH reduction for hydrogen production towards industrial application. The stack performance contributes to CAPEX reduction with use of pressurized stack conditions and operations at higher current density compared to the state-of-the-art SOE technology. It also contributes to the LCOE reduction with use of high fuel utilization conditions (80%) for an economically viable integration in the industry. The next technological challenges of pressurized SOE stack will focus on understanding and improving the overall stack degradation, optimizing the stack design (manifold, gas distribution) for homogeneity in cell operations/degradation in a multi-cells stack and increasing the SOC cell/stack dimensions (>> 100 cm^2 active area/cell) to achieve relevant stack power (> 20 kW) for industrial operations, leading to the following stack performance targets of the HERSO project:

- Operations at high current density (1.3 A/cm^2) at thermal neutral voltage to increase the hydrogen productivity.
- High fuel utilization (80%) to increase the system efficiency.

- Stack operating under differential pressurized conditions (pressurization of the hydrogen compartment only).
- Improved cell/stack lifetime under high current density and high fuel utilization conditions establishment of robust SOE stack (<10 mV/kh).
- Improved compatibility of stack and balance-of-plant operations with low complexity of stack replacement scenarios.
- and operational compatibility between the stack and balance-of-plant with low complexity of stack replacement scenarios to for an operating life-time.

Based on the HHV of the hydrogen produced, a system efficiency of 76.5% is calculated at beginning of life, increasing to 92.4%, when the power demand for the generation of steam is not taken into account. The corresponding demand per kilogram of hydrogen produced was found to be 51.4 kWh/kg and 42.2 kWh/kg, respectively. The demand for steam generation can be met by a renewable energy source, or from the waste heat from industrial plants, eliminating the need to consider it.

Regarding the stack technology, the unique and breakthrough demonstration of the pressurized short-stack developed by TNO in HERSO is a successful first step toward the LCOH reduction for hydrogen production towards industrial application. The stack performance contributes to CAPEX reduction with use of pressurized stack conditions and operations at higher current density compared to the state-of-the-art SOE technology. It also contributes to the LCOE reduction with use of high fuel utilization conditions (80%) for a economically viable integration in the industry. The next technological challenges of pressurized SOE stack will focus on understanding and improving the overall stack degradation, optimizing the stack design (manifold, gas distribution) for homogeneity in cell operations/degradation in a multi-cells stack and increasing the SOC cell/stack dimensions (>> 100 cm^2 active area/cell) to achieve relevant stack power (> 20 kW) for industrial operations.

2 Introduction

Large scale green hydrogen production through steam electrolysis is one of the important solutions towards the Energy Transition and to meet the CO_2 emission reduction goals. Solid Oxide Electrolyzers (SOE) offer the most efficient way (20-30% more efficient compared to Alkaline and PEM electrolyzers) to produce green hydrogen, due to its operation at high temperature allowing favorable thermodynamics and kinetics for conversion of steam into hydrogen and direct industrial processes integration. The main technological challenges in the SOE technology development towards industrial integration as been defined by the Clean Hydrogen JU program 2021-2027 thought concrete KPIs:

- Cost reduction of the SOE system to < 500 € / kW), via operations at high current density (> 1 A/cm^2) and SOE stack cost reduction towards < 150 € / kW (reduction of stack components content and cost
- Robustness of SOE stacks operation for OPEX reduction via sufficient operating life-time (> 60,000 hours) and improved compatibility of stack and balance-of-plant operations with low complexity of stack replacement scenarios
- Upscaling of SOE technology towards multi-MW systems
- Integration within the industry using hydrogen for chemicals and fuels production

Using pressurized steam electrolysis operations in the SOE stack technology can be an advantage for the overall efficiency of the SOE system, contributing to reduce the amount of the costly compression steps required to pressurize the H_2 product to relevant pressures in the multiple industrial applications (figure 1).

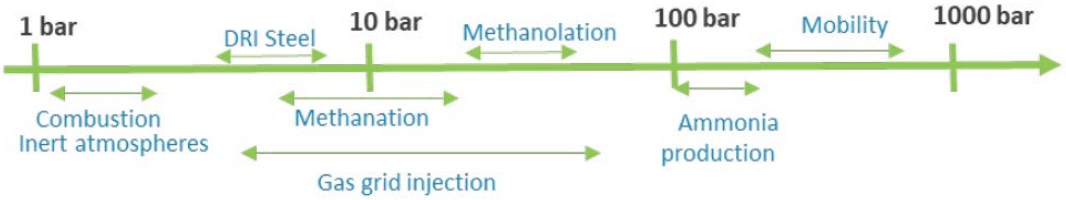


Figure 1: Range of pressure conditions needed for different use cases of hydrogen (note – DRI: Direct Reduced Iron).

In the HERSO project, TNO and Hygear developed a novel concept of Solid Oxide Electrolysis system for operations under pressurized electrolysis conditions, that does not rely on stack level on a pressure dome to maintain pressurized conditions to produce pressurized hydrogen. In this report, the outcome of the R&D activities carried out in the 2 years project will be presented and a roadmap towards the development of Pressurized SOE technology for industrial hydrogen production and use in fuel and chemicals processes will be established.

3 HERSO outcomes

The SOE development carried out in the HERSO project focused at developing a Highly Efficient and Robust Solid Oxide Electrolyzer system for hydrogen production. TNO and Hygear aimed at developing a new concept of Sold Oxide Electrolyzer stack and system technology able to operate under pressurized conditions for the production of pressurized hydrogen. The project activities has been divided according the Gant chart in figure 1:

- WP1 (led by Hygear) focused at developing a simplified Balance-of plant design for SOE system to define stack operations parameters for an efficient pressurized stack
- WP2 (led by TNO) consisted on developing Solid Oxide Cell technology that can operate at high current density (1.3 A/cm^2) at the thermal neutral voltage of 1.3V, with mechanical robustness for pressurized stack integration up to 3 bars.
- WP3 (led by TNO) focused its activities to develop a novel concept and realized a proof-of-concept of pressurized SOE stack operating without pressure dome to produce pressurized hydrogen
- WP4 (led by both Hygear and TNO) focused at realizing a technical economic analysis of the novel pressurized SOE system concept (Hygear) based on the input of the other work package to draw a technology roadmap toward industrial realization (TNO)

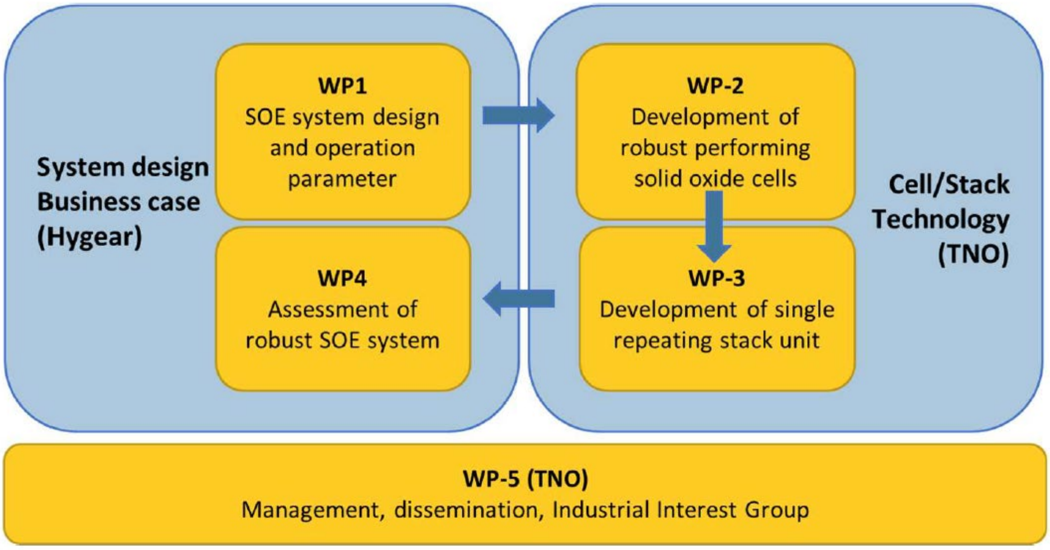


Figure 2: Gant chart of HERSO project activities.

For each work package, several outcomes have been achieved:

3.1 A novel system design with simplified BoP for high SOE system efficiency (WP1)

In WP1, a simple concept for a Solid Oxide Electrolysis (SOE) system that will operate at high pressures and different steam conversion has been developed, aiming at reducing the CAPEX and OPEX of the system, lowering the cost of hydrogen production. To accomplish this, a SOE system for hydrogen production was modeled for 10MW scale SOE electrolyzer. A case study was created to evaluate the impact of critical operating parameters. Twelve cases were defined to assess the impact of critical operating parameters on overall system efficiency. The critical operating parameters were identified as air side pressure, steam side pressure, and steam conversion. The cases were evaluated in three scenarios: Beginning, Middle, and End of Life at constant voltage and at constant hydrogen production by varying the critical operating parameters; steam conversion (40% and 80%) and pressure at the airside and steam side (1 atm and 10 bara versus 3 bara and 3 bara, respectively). Based on the results, the case with 80% steam conversion, 1 atm pressure at the air side, and 10 bara pressure at the steam side, is determined as the most efficient of all cases.

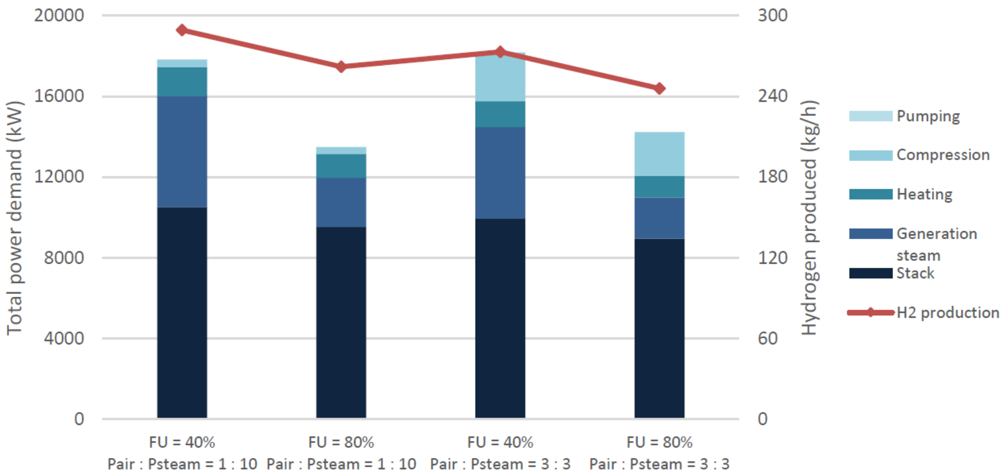


Figure 3: Distribution of the power demand in the novel system design for operations under pressurized conditions scenarios (1:10 bars and 3:3 bars), for different fuel utilization (40 and 80%).

Based on the HHV of the hydrogen produced, a system efficiency of 76.5% is calculated at beginning of life, increasing to 92.4%, when the power demand for the generation of steam is not taken into account (figures 3 and 4). The corresponding demand per kilogram of hydrogen produced was found to be 51.4 kWh/kg and 42.2 kWh/kg, respectively. The demand for steam generation can be met by a renewable energy source, or from the waste heat from industrial plants, eliminating the need to consider it.

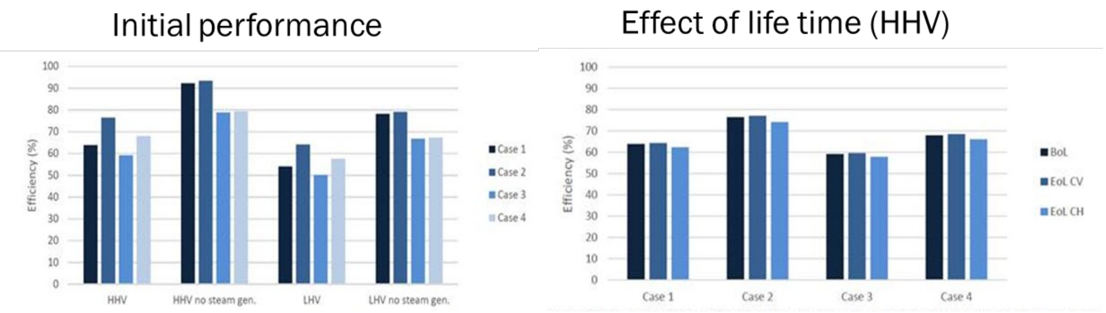
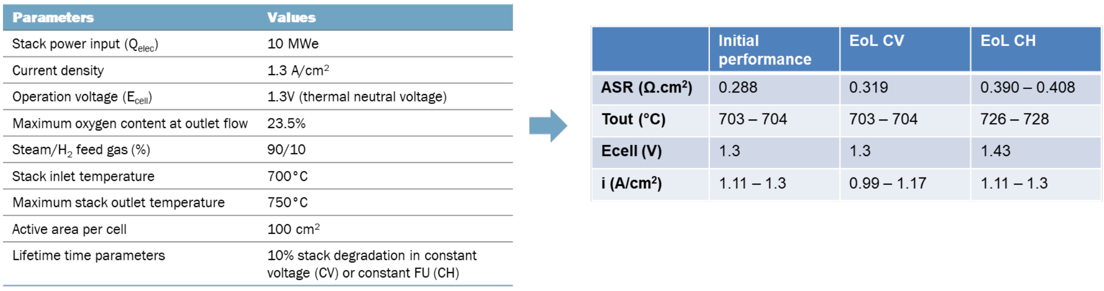


Figure 4: Efficiency (HHV and LHV) of the SOE system developed in HERSO taking into consideration steam and no-steam generation requirements for 4 different cases: Case 1 = 40%FU, 1:10 bars, Case 2 =80%FU, 1:10 bars, Case 3 = 40%FU, 3:3 bars and Case 4 = 80%FU, 3:3 bars.

Based on the outcome of the system study, KPI guidelines for the development of the SOE technology on cell (WP2) and stack level (WP3) has been established in figure 5.



Parameters	Values
Stack power input (Q_{elec})	10 MWe
Current density	1.3 A/cm^2
Operation voltage (E_{cell})	1.3V (thermal neutral voltage)
Maximum oxygen content at outlet flow	23.5%
Steam/H_2 feed gas (%)	90/10
Stack inlet temperature	700°C
Maximum stack outlet temperature	750°C
Active area per cell	100 cm^2
Lifetime time parameters	10% stack degradation in constant voltage (CV) or constant FU (CH)

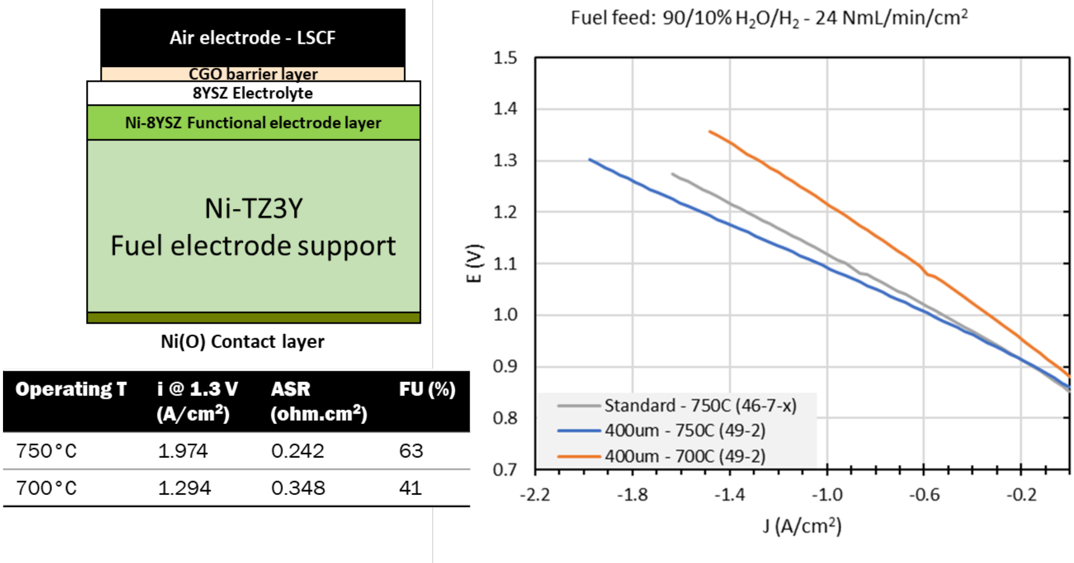
	Initial performance	EoL CV	EoL CH
ASR (Ω.cm^2)	0.288	0.319	0.390 – 0.408
Tout (°C)	703 – 704	703 – 704	726 – 728
Ecell (V)	1.3	1.3	1.43
i (A/cm^2)	1.11 – 1.3	0.99 – 1.17	1.11 – 1.3

Figure 5: KPIs definition for the SOE stack operating under pressurized conditions.

An additional simulation showed that a 50°C difference in the SOE inlet temperature (700 vs 750°C) does not affect the overall system efficiency (differences are less than 1% for beginning of life scenario), while keeping the other stack KPIs (current density at 1.3 A/cm^2 at the thermal neutral voltage of 1.3V).

3.2 High performance Solid Oxide Cell for integration in pressurized short stack (WP2)

The activities of WP2 aimed at developing a Solid Oxide Cell (SOC) technology to increase hydrogen productivity (> 7 ml/min H_2/cm^2 cell area), improve SOC lifetime for stack operations (degradation rate < 10 mV/1000 hours), and deliver high mechanical integrity cells for operations under increased hydrogen pressure (3-10 bar). Through an in-depth manufacturing development of the TNO cell design on the fuel electrode level (integration of a robust thin (400 μm) fuel electrode support, improved functional fuel electrode) and the air electrode level (improved electrode design (50 μm) with increased lateral conductivity), successful cell performance was demonstrated with ability to operate at high current density (1.3-2 A/cm^2) at the thermal neutral voltage of 1.3V in the temperature range of 700-750°C (figure 6).



Operating T	i @ 1.3 V (A/cm^2)	ASR (ohm.cm^2)	FU (%)
750°C	1.974	0.242	63
700°C	1.294	0.348	41

Figure 6: Initial performance of the SOC technology developed by TNO in HERSO for operations at high current density for improved hydrogen productivity.

The novel SOC design developed in HERSO validated the ability of SOC technology to operate over time at a high fuel utilization of 80% as defined in the KPIs of WP1, with a 1.3 A/cm^2 at 1.3V for a durability test of 1200 h (figure 7). However, the use of high current density (1.3 A/cm^2) and especially high fuel utilization resulted in a degradation rate above the technology target with around 60-75mV/kh (around 5%/kh). While, operating at a current density of 1 A/cm^2 with a fuel utilization of 65%, the novel SOC concept developed by TNO reaches 2%/kh in a still on-going durability test of already above 3500h (figure 8). Despite a need of further development of improved SOC cell towards improved lifetime, the outcome of HERSO is a milestone in the development of state-of-the-art Solid Oxide Cell technology, currently commonly operated at current density in the order of 0.85 A/cm^2 with fuel utilization <60%. An additional milestone for the SOC design in HERSO consist in the fact that the technology demonstration with a design of 100 cm^2, has a suitable mechanical robustness for stack integration and operations under pressurized conditions up to 3 bar pressures.

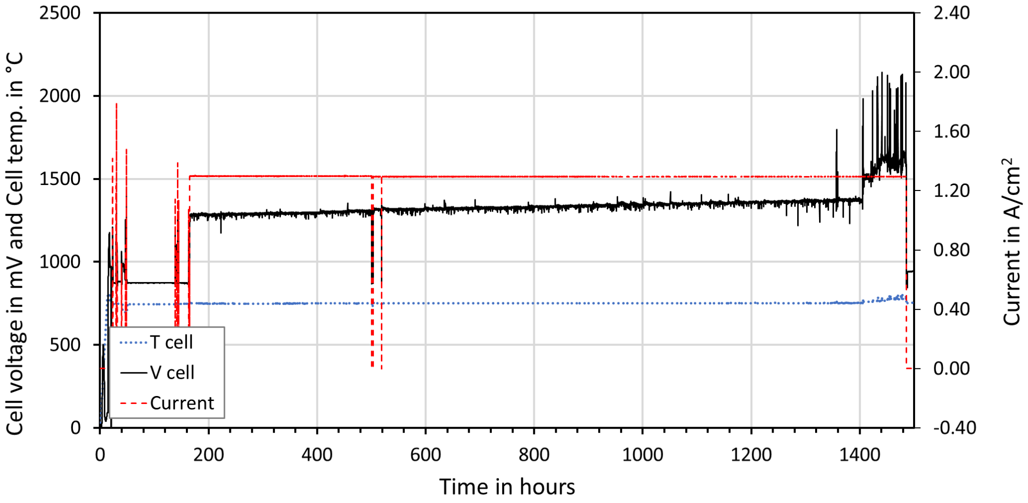


Figure 7: Durability test of the SOC technology developed by TNO in HERSO for operations at a current density of 1.3 A/cm^2 with 80% Fuel utilization.

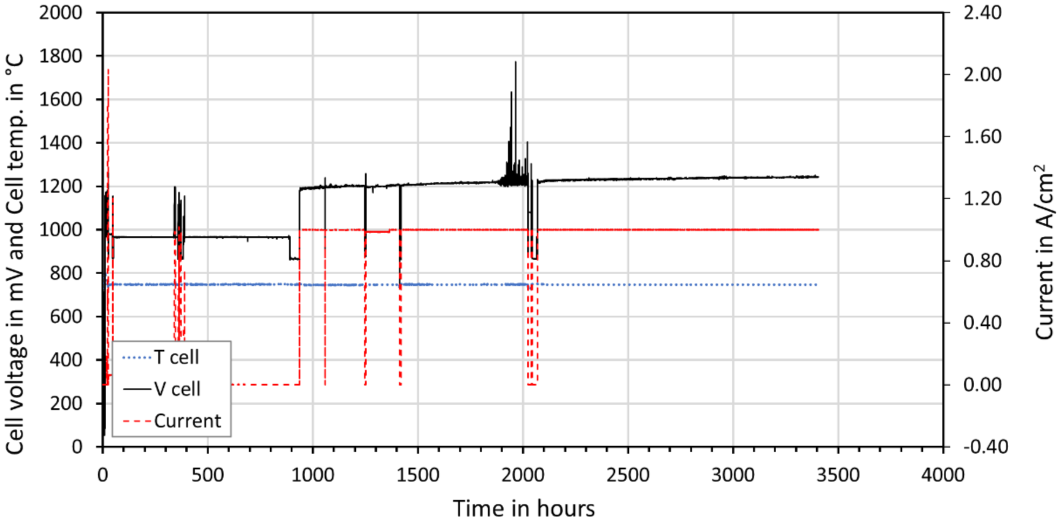


Figure 8: Durability test of the SOC technology developed by TNO in HERSO for operations at a current density of 1 A/cm^2 with 65% Fuel utilization.

3.3 Proof-of-concept of a pressurized SOE short stack (WP3)

In the HERSO project, TNO successfully demonstrated a novel concept of Solid Oxide Electrolysis (SOE) stack having the ability to operate under pressurized electrolysis conditions, not relying on a costly pressure dome to produce pressurized hydrogen.

TNO SOE stack technology: The Solid Oxide Cell stack concept developed by TNO in the HERSO project has been design for operations under pressurized steam electrolysis conditions for pressurized hydrogen production. The novelty of the SOC stack lays in 1/ Cost reduction and ease of stack manufacturing and assembly with integration of a low-cost compressed single-seal concept per Single Repeating Stack Unit, with the ability to operate under pressurized condition, 2/ Improved performance with a novel IC plates and manifold design to optimize the IC/cell current contacting and gas flow distribution, 3/ Improved stack lifetime with integration of a protective ceramic coating technology with optimized manufacturing to prevent Cr-evaporation on the air side detrimental for the SOC lifetime and 4/ Potential for scalability towards integration of enlarged Solid Oxide Cell technology (up to 30x30cm). The current stack design has currently a priority date for Patent publication (P133378EP00).

Figure 9: TNO Stack

TNO SOE stack performance under pressurized conditions: The proof-of-concept of pressurized SOE 3-cells short-stack validated in HERSO has been demonstrated for pressurized conditions up to 3 bara with ability to operate at high current density operations (1.4 A/cm^2) and high fuel utilization (80%) at the thermal neutral voltage of 1.3V for an operating temperature of 750°C. This performance demonstration (figure 10) results from technological improvements on cell and stack levels:

- Improvement of the Solid Oxide Cell (SOC) technology design with optimization of the air electrode and fuel electrode design (HERSO - WP2).
- Improvement of the SOC integration in stack environment (dimensional accuracy, improvement of the cell/stack interconnector contacting and current collection) making full use of the SOC technology efficiency used in the stack.
- Optimization of TNO SOE stack design regarding stack sealing technology and stack compression distribution allowing operations under steam electrolysis pressurized conditions up to 3 bara, with cross-over leakages <0.5%.

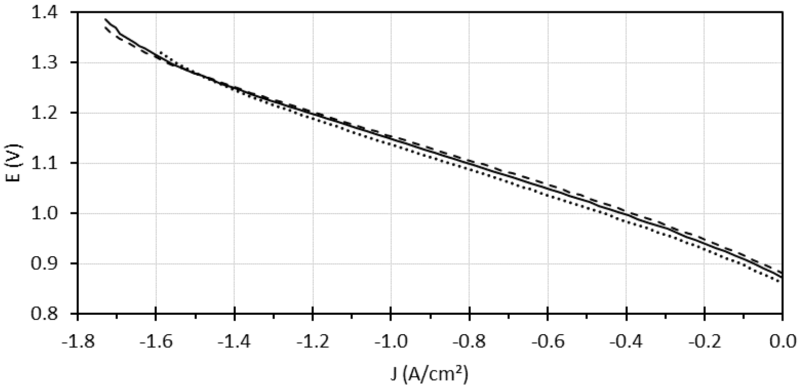


Figure 10: J-V curves of one of the HERSO SOCs in the improved 3-cell TNO stack under steam electrolysis conditions at different operating pressure; 1 bara (dotted), 2 bara (solid), 3 bara (striped). Fuel inlet composition of 90/10% H_2O/H_2 at an operating temperature of 750°C. Gas pressures are equal on fuel and air side. Fuel feed flow: 14.8 NmL/min/cm^2; active electrode area: 81 cm^2.

The operations of the stack under pressurized conditions (2-3 bara) have been validated over a durability test at high current density (1.3-1.4 A/cm^2) with fuel utilization in the order of 80%, showing degradation rates of ~60 mV/khr. Additionally, the 3 cells degradation was shown to be different, may point to inhomogeneities in the pressure drop and flow rates over the individual cell compartments based on their location in the 3-cell short stack, which could result in localized fuel starvation at the high fuel utilization rates that were maintained during operations.

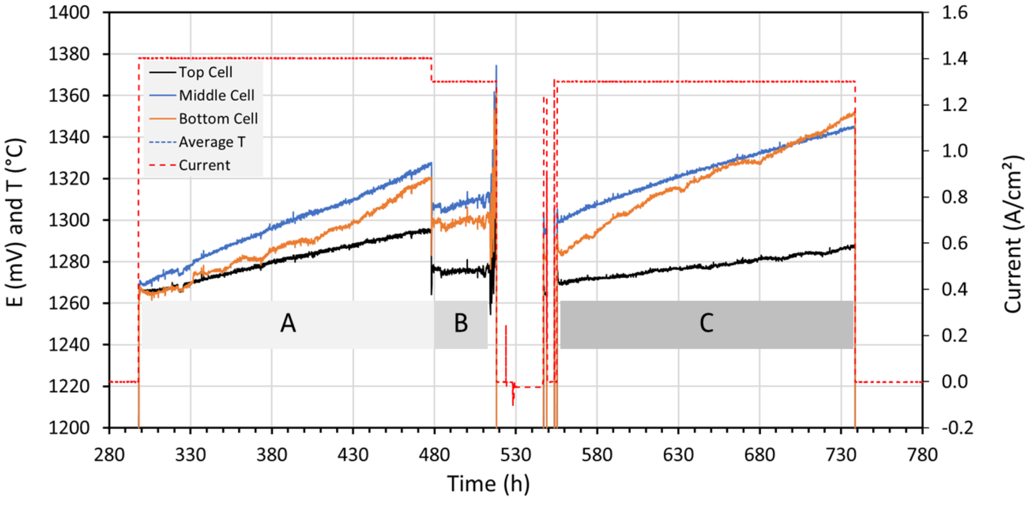


Figure 11: Graph of the long-term testing of the TNO stack at 750°C. The cell voltages of the three individual cells are shown, as well as the current density. Three different phases of the test are marked (A, B, and C), in which the operating conditions were modified (details in Figure 12). Fuel inlet composition of 90/10% H_2O/H_2.

	Phase A	Phase B	Phase C
Pressure (bara)	3	3	2
Current Density (A/cm^2)	1.4	1.3	1.3
Fuel flow (NmL/min/cm^2)	13.6	12.6	12.8
Fuel Utilization	80%	80%	79%
Degradation top (mV/khr)	164	24	86
Degradation middle (mV/khr)	328	161	254
Degradation bottom (mV/khr)	308	73	358
Duration (hours)	176	27	164

Figure 12: Conditions and degradation rates during the different phases of the durability test.

The unique and breakthrough demonstration of the pressurized short-stack developed by TNO, in the SOE development field is a successful first step toward the development of the next generation of SOE stack to reach the technology KPIs performance and CAPEX reduction for a viable-economic integration in the industry. The next technological challenges of pressurized SOE stack will focus on understanding and improving the overall stack degradation still significantly higher than single SOC operations (~60 mV/khr), optimizing the stack design (manifold, gas distribution) for homogeneity in cell operations/degradation in a multi-cells stack and increasing the SOC cell/stack dimensions (>> 100 cm^2 active area/cell) to achieve relevant stack power (> 20 kW) for industrial operations.

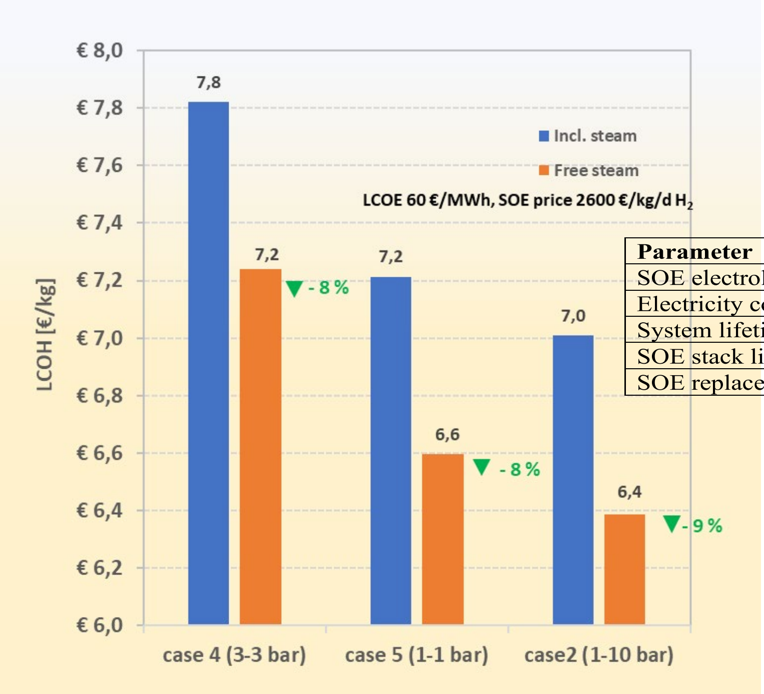
3.4 Improved business case for pressurized hydrogen in the industry (WP4)

In the framework of the HERSO project, a Technical-Economic Analysis has been performed to evaluate the levelized cost of production of hydrogen for a plant based on a 10 MW Solid Oxide Electrolyzer (SOE). A cost model has been settled to complement the physics-based model developed within WP1 (system design). Together, they form a technical-economic model which has been used:

- To allow for quantitative comparison of the different study cases the scenario with and without free steam generation for 3 different pressurized system conditions: no pressure case (1 – 1 bara), equi-pressure case (3 -3 bara), and steam pressure case (1-10 bara).
- To identify the main cost drivers.
- To evaluate the changes in the costs of H_2 production, depending on specific system parameters.

<u>Technical-economic analysis of Pressurized for a 10 bars hydrogen production.</u>

The baseline values for cost and system parameter (e.g., SOE electrolyzer cost, LCOE, system lifetime and stack lifetime, etc.) have been chosen after critically assessing the literature and based on HERSO project working team feedback. A summary of these baseline value is reported in figure 13. The main outcome from process modelling (WP1) is that the most cost-efficient case is the 1 – 10 bara with free steam. This outcome is also confirmed from economical point of view (figure 14): the possibility of having a free steam supply has a significant impact on the economic performance of SOEC technology. For this studied case, a HHV system efficiency equal to 93.4% and a power demanded of 42 kW per kg/h of produced hydrogen have been estimated. The expected LCOH has been valued to be ca. 6,4 €/kg H_2, which is 9% lower than the case without steam available. Thus, it can be beneficial by coupling a SOE electrolyzer plant with a plant where steam at low pressure can be available. This result is widely confirmed also in the literature[1][2][3].



Parameter	**Base value**
SOE electrolyzer cost	2600 €/kg/d H_2
Electricity cost (LCOE)	60 €/MWh
System lifetime	15 years
SOE stack lifetime	5 years
SOE replacement cost	100% of SOE cost

Figure 13: LCOH for the different analysed SOE operating pressure levels (cathode pressure – anode pressure), with and without free steam available, assuming a final H_2 delivery pressure of 10 bara; LCOE of 60 €/MWh and a SOE electrolyzer cost of 2600 €/kg/d H_2. Percentage cost reduction (▼) for free steam cases are reported.

Impact of using pressurized stack operations up to 10 bars

Concerning the pressure impact, the ideal operation would be the pressurization of the steam compartment of the stack only, as there is a penalty by pressurizing the oxygen side, requiring a larger amount of power. Indeed, the case where both anode a cathode side are pressurized is the one demanding the largest power per kg of produced hydrogen, with the lowest efficiency and the highest LCOH. From system efficiency point of view there are not advantages by pressurizing the air side, unless it is assumed to produce pure oxygen that could be a by-product; in this case, by producing oxygen already pressurized could add some extra value. However, pressurized high-temperature oxygen could be difficult to work with and it definitely adds extra cost in term of special materials needed to handle it. A detailed cost allocation shows that OPEX (including, maintenance cost, TOT Manufacturing, replacement of the SOE stack and the power & utilities) are the major contributor in the LCOH cost, by counting for more than 70% on the overall costs. Moreover, within the OPEX, the electricity cost is the driving one, by contributing for more than 99%. Beside the electricity cost, the SOE electrolyzer cost and its replacement are the other two major cost factors.

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[1] Energy Conversion and Management 269 (2022) 116162
[2] International Journal of Hydrogen Energy (September 2017) I-II
[3] IRENA. Green Hydrogen Cost Reduction: Scaling up Electrolyzers to Meet the 1.5 C Climate Goal; 2020

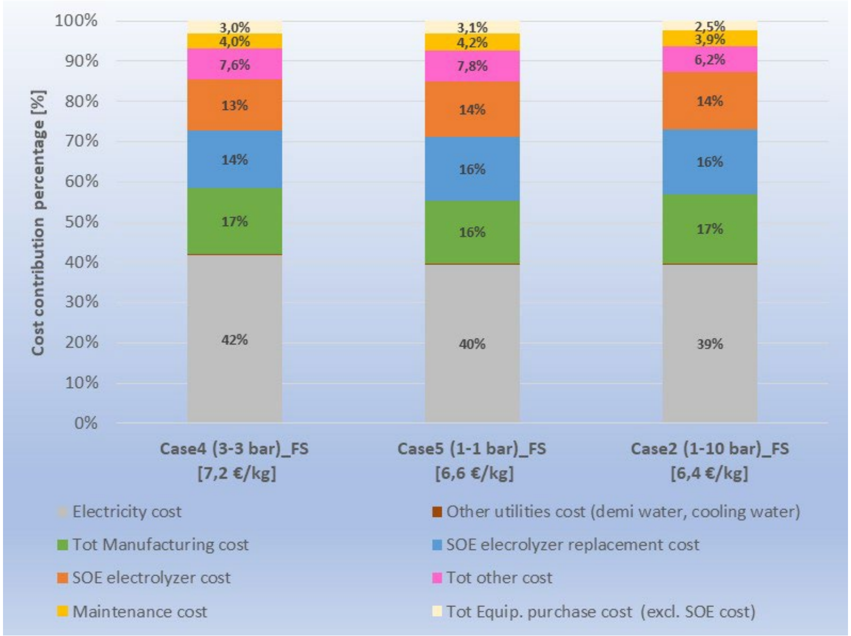


Figure 14: Cost breakdown of the H_2 production for the different SOE operating pressure levels, assuming free steam available (LCOE = 60 €/MWh, SOE electrolyzer cost 2600 €/kg/d H_2, system lifetime 15 yrs., SOE lifetime 5 yrs., SOE electrolyzer replacement cost equal to 100% of stack cost).

In term of cost distribution, operating under pressurized conditions on stack level with the optimal case analysed in HERSO (1:10 bars), a cost reduction of 13% can be achieved by reduction of the power contribution for the additional compression of hydrogen up to 10 bars (figure 14).

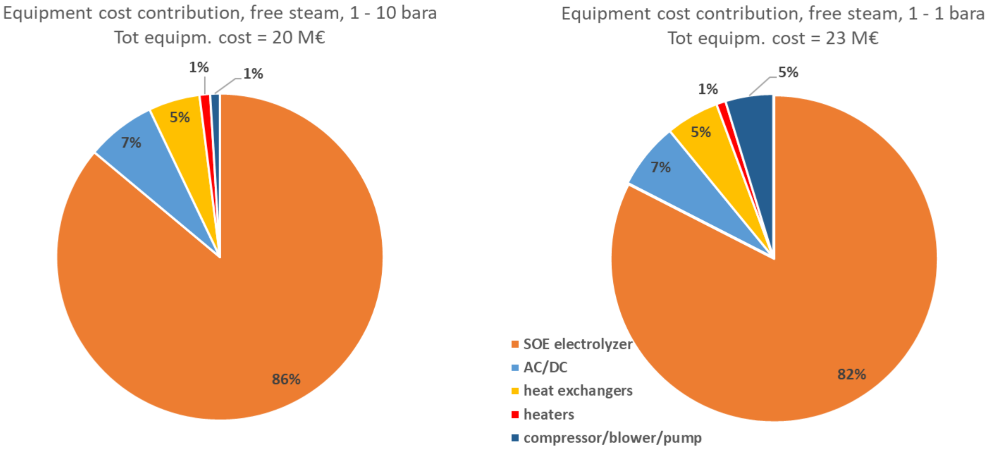


Figure 15: Equipment cost contribution for free steam cases for different SOE operating pressure level: low pressure case (1 -1 bara, right figure), pressurized steam side case (1 -10 bara, left figure).

Towards a reduction of LCOH at 3.3 euros/kg

A sensitivity analysis aiming towards the LCOH reduction has been estimated by varying the levelized cost of the main contribution parameters within a certain range (figure 16): electricity (LCOE), the SOE electrolyzer cost, the system lifetime and the SOE stack lifetime. As outcome of the sensitivity analysis, a drastic cost reduction can be achieved with a reduction electricity consumption/cost, followed the CAPEX of the SOE electrolyzer and the stack replacement (figure 17). A reduction of LCOH towards 3.3 euros/kg can be achieved in a case where LCOE = 30 €/MWh, system cost = 580 €/kg/d H_2, 15 yrs SOE Life time (figure 18).

Parameter	Base value	Range
SOE electrolyzer cost	2600 €/kg/d H_2	1160 – 4045 €/kg/d H_2
Electricity cost (LCOE)	60 €/MWh	30 – 100 €/MWh
System lifetime	15 years	5 – 25 years
SOE stack lifetime	5 years	3 – 15 years
SOE replacement cost	100% of SOE cost	

Figure 16: Baseline values for cost and system parameters

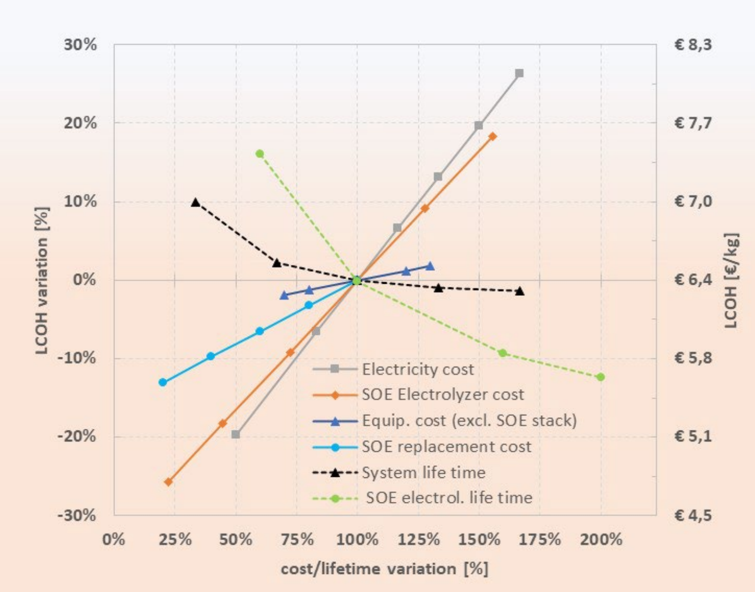
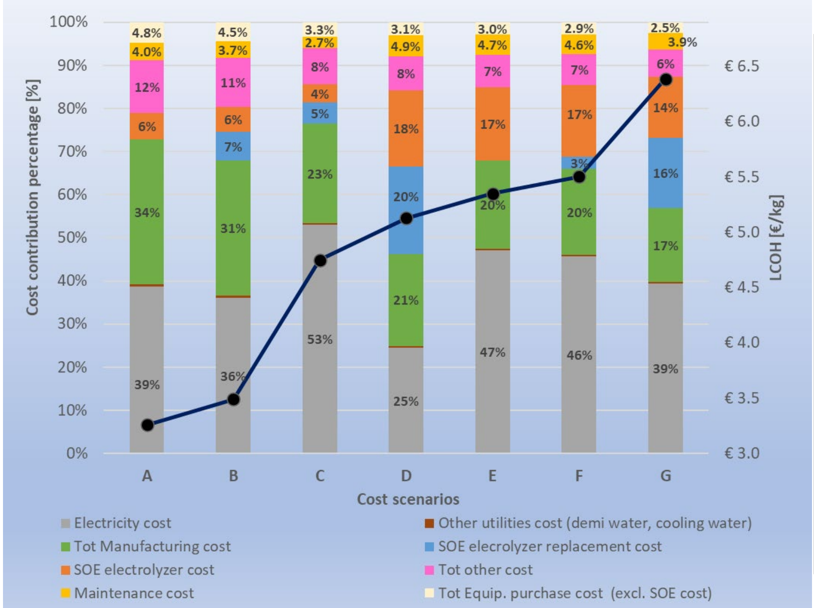


Figure 17: Cost sensitivity of the LCOH for different parameters: electricity cost (b.v. = 60 €/MWh), SOE electrolyzer stack cost (b.v. = 2600 €/kg/d H_2), equipment cost - excl. SOE (b.v. = 3 million Euro), SOE replacement cost (b.v. = 100% of SOE cost), system lifetime (b.v. = 15 yrs.), SOE electrolyzer lifetime (b.v. = 5 yrs.). Points at 100% correspond to parameter base values (b.v.).



(A) 30 €/MWh, 580 €/kg/d H_2, 15 yrs SOE Life time

(B) 30 €/MWh, 580 €/kg/d H_2

(C) 580 €/kg/d H_2

(D) 30 €/MWh

(E) SOE Life time 15 yrs.

(F) SOE replacement cost 15% of the SOE base value cost

(G) base values

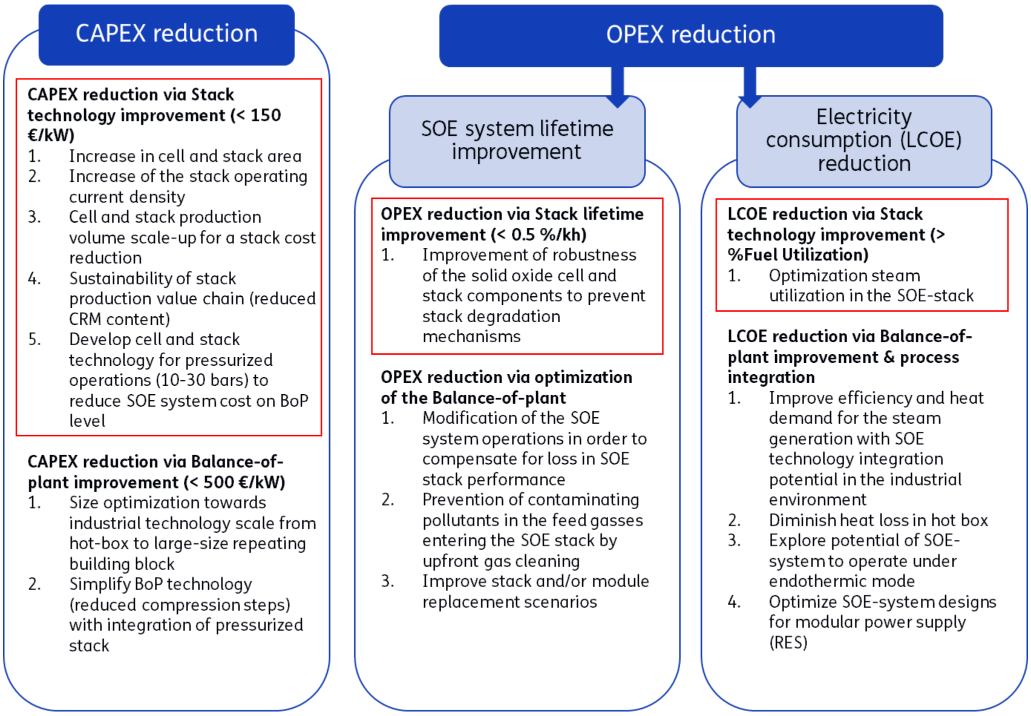
Figure 18: Cost breakdown of the H_2 production for the different cost scenarios. LCOH is also shown (solid line, left y- axis).

Based on the technical-economic analysis results obtained in HERSO, the following conclusions can be built:

- SOE electrolyzer system should be coupled with a plant where steam (typically at a low-pressure range) can be available.
- The steam side of the SOE electrolyzer (stack) should be pressurized, at least, if a H_2 delivery pressure up to 10- 15 bar is aimed.
- The air/O_2 side should not be pressurized (costly process), unless pure O_2 can be produced and reused in industrial processes.
- A SOE cost below 600 €/kg/d H_2 should be targeted.
- A long SOE lifetime (for instance, of the same order of the system lifetime), and lower cost of the SOE replacement, could partially counterbalance the larger SOE cost.
- The lower is the electricity cost the larger is the LCOH cost reduction, at least, for LCOE in the range 30 – 100 €/MWh.

4 Roadmap towards the development of Pressurized SOE technology

Based on the system/TEA analysis outcome for a 10 MW scale system design carried out in HERSO and the technology KPIs defined by the Clean Hydrogen program for the development of SOE towards large scale deployment of hydrogen production for the industrial sector (see introduction chapter), a roadmap toward the development of SOE systems could be established.



CAPEX reduction

CAPEX reduction via Stack technology improvement (< 150 €/kW)

1. Increase in cell and stack area
2. Increase of the stack operating current density
3. Cell and stack production volume scale-up for a stack cost reduction
4. Sustainability of stack production value chain (reduced CRM content)
5. Develop cell and stack technology for pressurized operations (10-30 bars) to reduce SOE system cost on BoP level

CAPEX reduction via Balance-of-plant improvement (< 500 €/kW)

1. Size optimization towards industrial technology scale from hot-box to large-size repeating building block
2. Simplify BoP technology (reduced compression steps) with integration of pressurized stack

OPEX reduction

SOE system lifetime improvement

OPEX reduction via Stack lifetime improvement (< 0.5 %/kh)

1. Improvement of robustness of the solid oxide cell and stack components to prevent stack degradation mechanisms

OPEX reduction via optimization of the Balance-of-plant

1. Modification of the SOE system operations in order to compensate for loss in SOE stack performance
2. Prevention of contaminating pollutants in the feed gasses entering the SOE stack by upfront gas cleaning
3. Improve stack and/or module replacement scenarios

Electricity consumption (LCOE) reduction

LCOE reduction via Stack technology improvement (> %Fuel Utilization)

1. Optimization steam utilization in the SOE-stack

LCOE reduction via Balance-of-plant improvement & process integration

1. Improve efficiency and heat demand for the steam generation with SOE technology integration potential in the industrial environment
2. Diminish heat loss in hot box
3. Explore potential of SOE-system to operate under endothermic mode
4. Optimize SOE-system designs for modular power supply (RES)

Regarding the stack technology, the unique and breakthrough demonstration of the pressurized short-stack developed by TNO in HERSO is a successful first step toward the LCOH reduction for hydrogen production towards industrial application. The stack performance contributes to CAPEX reduction with use of pressurized stack conditions and operations at higher current density compared to the state-of-the-art SOE technology. It also contributes to the LCOE reduction with use of high fuel utilization conditions (80%) for a economically viable integration in the industry. The next technological challenges of pressurized SOE stack will focus on understanding and improving the overall stack degradation, optimizing the stack design (manifold, gas distribution) for homogeneity in cell operations/degradation in a multi-cells stack and increasing the SOC cell/stack dimensions (>> 100 cm^2 active area/cell) to achieve relevant stack power (> 20 kW) for industrial operations.

Signature

TNO ⟩ Energy & Materials Transition ⟩ Petten, 16 February 2024

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