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Pressurized hydrogen produced by high temperature steam electrolysis: the European project PressHyous

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Abstract

Electrolysers appear to be a competitive solution to help reaching the clean H_2 production level set by the EU. However, the use of H_2 requires various pressure levels depending on the chosen processes and applications, which systematically involves additional pressurisation steps after the production to allow storage, transportation or usage. As the compression of H_2 is very energy-intensive, especially for the first bars, producing pressurised H_2 directly in the electrolyser can bring major relief on the compression costs, reduce the technological complexity and positively impact the global process efficiency. In this context, PressHyous, an EU R&D project funded by the Clean Hydrogen partnership, is aiming to produce low-carbon pressurised H_2 at reduced cost. It will prove the concept through the operation of a 20 kWe pressurised lab-scale device (eq. 13.5 kg of pressurized H_2/day). This lab-scale device will be composed of a Solid Oxide Electrolysis stack located in a pressurised vessel, and will be operated up to 30 bar at least at 1 A/cm^2 during 4000 hours. The project also aims to investigate an innovative stack concept, without pressure vessel, thus reducing the cost of BoP, by testing this solution up to 10 bar at a short stack scale, at similar current density to the stack operated in the pressurised vessel. To reach the set objectives, both stacks will integrate optimised component, notably electrochemical cells and sealings, improved for operation under pressure. To complement the practical testing of the PressHyous concepts, the project will deliver model-based insights for H_2 production under pressure for up to 5 identified use cases, on expectable performances of both stack concepts towards large scale developments up to 100s MW_e, coupled with techno-economic and life-cycle analysis.

Introduction

To enable the shift from non-renewable, carbon-based energy sources to clean, low-carbon energy sources, hydrogen (H_2) is a major asset. H_2 holds potential to be a powerful enabler of this transition, as it is a clean, sustainable, and flexible option as a resource for industrial processes (cement, steel, ammonia, semi-conductors, glass…), as a fuel for transportation, as a resource for producing other e-fuels and as a vector for high-capacity and/or long-distance electricity storage.

Water electrolysis, and especially high temperature steam electrolysis (so-called HTE or SOEL for Solid Oxide ELectrolysis) presents a key opportunity in producing H_2 in an affordable, and low CO_2 emissions. The SOEL technology provides the highest electrical efficiency, as the dissociation of H_2O molecules at high temperature requires less electricity, the remaining part of the dissociation energy being added as heat, available at a lower price level since taking advantage of industrial local heat sources.

However, the use of H_2 requires given levels of pressure depending on applications: between 5 and 70 bar for industrial applications and grid injection, up to 200 bar to fill gas cylinders or ammonia synthesis, as well as up to 350 and 700 bar in refueling stations (Figure 1). Therefore, the H_2 production requires its pressurization before being stored, transported or used, which is currently done relying on additional pressurization stages plugged to the production process to reach relevant pressures.

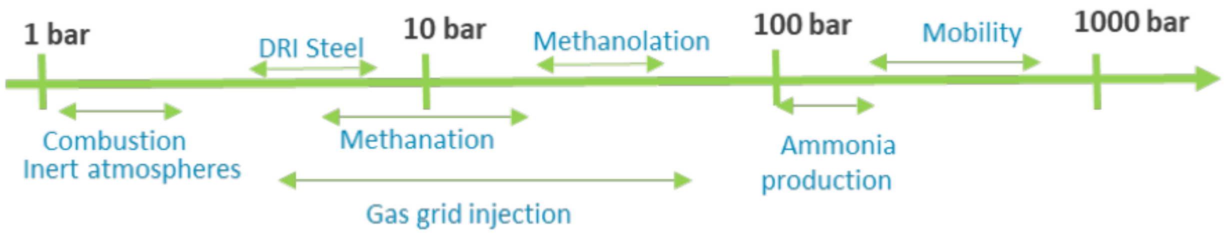

Figure 1 - *Range of pressure needed for different use cases of H_2 (note - DRI: Direct reduced iron)*

These compression steps impair the overall process efficiency, up to one third of the energy consumption when considering refueling station [1], and thus, the levelized cost of hydrogen (LCOH). More energy is required to compress H_2 than other gases, such as methane, and the first bars of H_2 compression are the most energy-intensive [2]. Producing pressurized H_2 directly in an electrolyser, up to 30 bar, will bring a dramatic relief on compression costs and technological complexity of the downstream, by removing or simplifying these compression steps.

Supplying water under pressure as fluid upstream of the electrolyser requires less energy than for the first levels of H_2 compression at the electrolyser outlet [3-5]. Therefore, producing directly pressurized H_2 by operating the electrolysis step itself under pressure can be an efficient alternative to optimize the system design, operation and efficiency.

Although, while the pressurized operation of electrolysers has the potential to increase the system efficiency and to reduce the investment and maintenance costs, challenges remain [6-8]. In this view, it is necessary to investigate the pressure impact on the electrolysis step (SOEL in PressHyous) to ensure an overall gain at the system level for the use-cases considered.

Some H_2 production technologies are operating under pressure, e.g., the reference Steam Methane Reforming process (> 30 bar), Alkaline electrolysis (AEL) and Proton-Exchange Membrane electrolysis (PEMEL) (20-30 bar) in most cases [9]. Regarding SOEL, very few experimental studies have been dedicated to pressurized operation. While some degree of understanding have been obtained under atmospheric SOEL conditions, knowledge of high pressure (HP) SOEL is limited and provides additional challenges, for instance pressure effects on brittle ceramic cells, tightness issues, pressure regulation, thermal management difficulties. Experimental work on HP SOEL mode is performed by several teams around the world (in which PressHyous partners are largely involved), at both single cell [10-15] and short-stack level [12, 16-20], and a few at larger scale (few kWe-stacks in SOPHIA [21] and HELMETH [22] projects). However, these pieces of knowledge lack industrial commitment around a strong concept to bring it from laboratories to the industry. The comprehensive approach developed in PressHyous, in addition to the commitment of the Advisory Board (AB), will deliver such a technology validated in the lab to gain industrial maturity.

1. Objectives

First, PressHyous will tackle the technological challenges to develop advanced durable SOEL cells, stacks and their components able to achieve high H_2 production rate and high durability for operation under pressure up to 30 bar. Components (cell, stacks, interconnect and sealings) will be optimised. Research activities will focus on the identification of degradation mechanisms and boundary operation of the stacks, and their components with respect to pressure, temperature, load, in stationary and transient conditions. PressHyous will specifically investigate two technological concepts for pressurised operation:

-An atmospheric stack concept placed inside a pressurised vessel, which means that internal pressures in the two stack compartments (H_2 and O_2) are equal to the external pressure applied by a counter atmosphere in the vessel. This concept will be considered for the lab-scale device to be demonstrated at the 20kWe scale in electrolysis mode up to 30 bar.

-A stack under development for pressurized operation without being inside a pressure vessel, i.e. a pressure difference between the inside and the outside of the stack will exist. This disruptive concept requires an advanced cell and stack design, especially for the sealing solutions, and will be tested experimentally at small scale (short stack). These tests aims to prove the concept up to 10 bar with the possibility of operating with differential pressure between fuel and air compartments. This concept will reduce system cost since no pressure vessel, and associated BoP components, are needed, and consequently improve the SOEL system efficiency.

Second, capitalising on the work conducted at components level, PressHyous will prefigure larger units with the validation of a 20-kWe lab-scale device, to produce pressurised H_2, in a vessel operating up to 30 bar in SOEL mode by 2026. These steps require to address durability and performance in the long-run (4000h of aggregated tests) and to apply conditions representative of real operation, including pressurisation/depressurisation cycles. Large-scale systems will also be addressed through thermal optimisation, BoP development and safety aspects. In addition, as part of the circular economy, the project will consider eco-design to reduce the solution's impacts at each step of its life cycle.

Third, PressHyous outputs will allow evaluating and comparing the potential interest of the proposed solutions for large systems from a techno-economic point of view. Scale-up concept designs will be based both on the PressHyous technological breakthroughs and the specifications provided by industrial needs and will deliver concrete and efficient solutions to reach an LCOH below 3€/kgH2 for large-scale units. PressHyous will thrive on constant interactions between experimental and industrial feedbacks.

2. Methodology/Definition of use-cases

CEA, HYGEAR, EPFL and TNO will provide their skills and infrastructure to conduct performance and durability tests, first at cell level to support ELCOGEN in the cell optimization work and enable their use in pressurized conditions, second at stack level to achieve the targeted proof-of-concepts, stack developers and manufacturers being TNO and GENVIA. Those activities will be supported by modelling at different scales, with the additional support of VTT and GENVIA from stack to system level. Therefore, PressHyous will strongly increase the level of investigation and development on pressurized SOEL, with:
- optimized cells,
- a disruptive stack design able to operate under pressure without a pressurized vessel,
- a 20 kWe stack operated into a pressure vessel up to 30 bar as a proof-of-concept,

All will be evaluated experimentally at high performance (high current density) and with long durability tests (more than 2000h). EPFL and HES-SO will contribute in the techno-economic analysis (TEA) and life cycle assessment (LCA), respectively, in strong link with the AB.

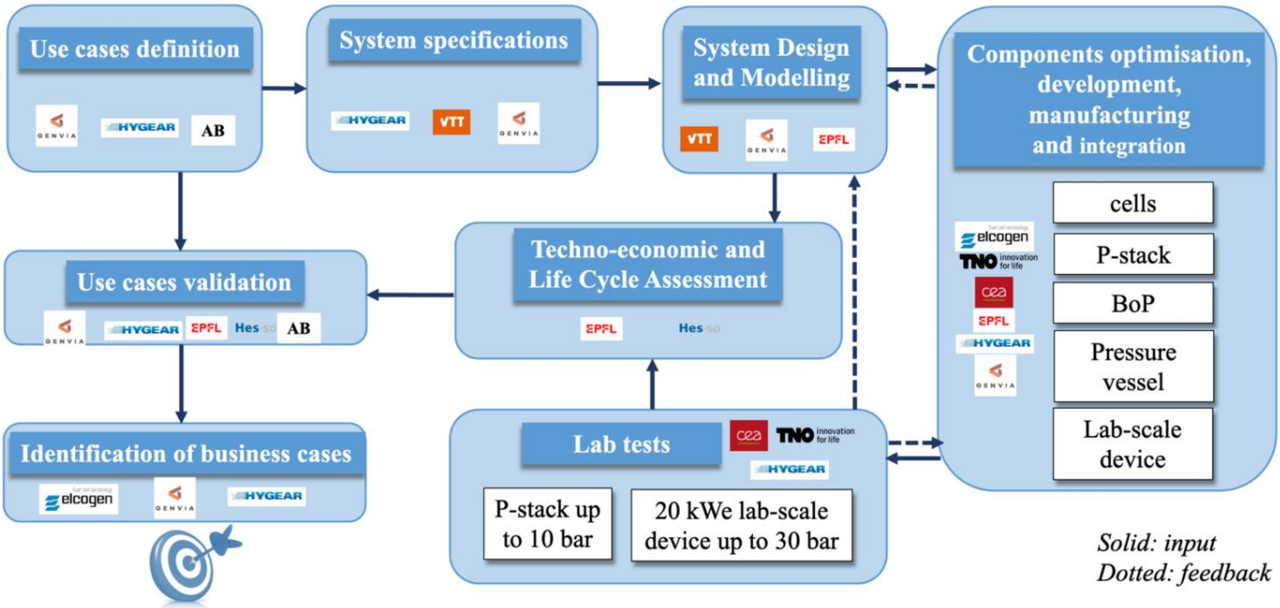

Figure 3 - *PressHyous methodology*

The methodology of PressHyous can be depicted by the sequence of macro-tasks (see Figure 3):
- Definition of relevant use-cases from a market and business perspective.
- Definition of system specifications from small (hundreds of kWe) to large scale (hundreds of MWe), based on these use-cases.
- Those specifications will serve as input data for the system design at large scale, supported by modelling tasks. Though a rather “generic” design will be defined, some alternatives will be explored, if needed, to cope with specifics for the different use-cases, in case a difference pressure is needed and/or for the needs of integration at the site of the end-user.
- The system design with its associated operating conditions is a cornerstone for the project. It will provide the requested information for a thorough TEA on one hand, as well as for the LCA. On the other hand, it will support the experimental work of the project, since it will bring input data for the SOEL individual components and lab-scale device construction: cell, P-stack pressure vessel and associated BoP components, 20 kWe stack and finally integrated lab-scale device, as well as the relevant operating conditions of the stacks under pressure.

- Once the SOEL components and lab-scale device built, they will be subjected to several lab tests, first at single components scale for individual validation of performance and durability, and second at the scale of the integrated lab-scale device for final proof-of-concept.
- Those lab tests will provide data, as a feedback loop, for system design activities to allow refinements if needed, and for TEA and LCA.
- The TEA and LCA will enable to validate the envisioned business cases, the final output being, for the industrial partners of the project, the identification of the most relevant business cases.

As mentioned in the previous section on the project methodology, the first task was to identify the case studies based on process/industrial heat available and business/market considerations.

Relevance	Use-case	H_2 pressure
1	Steel – Direct Reduction Iron	10-15 barg
1	e-Methane – H_2 for methanation	10-35 barg
1	Cement – e-Methanol & Oxy-combustion	80-90 barg
2	Coil annealing furnace- H_2 as fuel	≤30 barg
2	Refinery – Synthetic chemical feedstock	30 barg
2	High-end steel annealing line	<10 barg
3	H2 injection into rededicated pipeline	30-80 barg

Table 1. Use-cases based on process/industrial heat available and business/market considerations

3. Conclusion and acknowlegment

PressHyous aims to study and provide SOE solutions for pressurized H_2 production whose specifications can vary from few bars to several hundreds. The project will open up a new pathway for H_2 production at high temperature for designated applications, which will be developed and operated in a laboratory at a scale up to 20 kWe (i.e. 13.5 kg_{H_2}/d) for at least 4,000 hours and simulated up to few tens of MWs. This will be achieved by defining use-cases showing the applications and the benefits of the pressurized steam electrolysis technology then demonstrating the industrial interest for this solution on stack level by 2026, supported by TEA and LCA, with a comparison with other electrolysis technologies.

Project objectives:

- Definition of use-cases to determine most relevant pressure level for each application, thanks to the expertise of the consortium and Advisory board members
- Decrease of LCOH by 7% with PressHyous compared to SOEL at atmospheric pressure.
- -15% CAPEX for the stack without the pressure vessel A Hydrogen production cost <3 €/kg
- The pressurization of the system, in addition to suppressing the first compression step of H2 production, increases by a factor 2.4 of the compactness of the stack and

up to 1.3V its density, which contribute to improve the use ratio of raw materials thus the total energy efficiency of the system

- Development of high current density cells and stack, up to 1 A/cm2

Through a dedicated thinking about LCA and TEA, PressHyous aims to ensure circularity by design for materials and for production processes, minimizing the life-cycle environmental footprint of HP SOEL electrolysers.

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