

A1115

## Development and validation of a reversible prototype system to test 1.5 kW SOC stacks

**Lucile Bernadet (1), Lilia Sutac (1), James Zapata (2), Maria Serra (3), Jaume Roqueta (2), Marc Torrell (1), Albert Tarancón (1,4)**

(1) IREC, Catalonia Institute for Energy Research, Dept of Advanced Materials for Energy Applications, Jardins de les Dones de Negre 1, 08930, Sant Adrià del Besós, Barcelona, Spain.

(2) AESA, Aragó 383, 4<sup>a</sup> Planta, 08013 Barcelona, Spain

(3) IRI, CSIC-UPCC/ Llorens i Artigas 4-6,  
08028, Barcelona, Spain

(4) ICREA, Passeig Lluís Companys 23, 08010 Barcelona, Spain

Tel.: + 34 933 562 615 (ext. 225)

[lbernadet@irec.cat](mailto:lbernadet@irec.cat)

### Abstract

Reversible solid oxide cell technology is an effective solution to deal with the intermittent nature of renewable energy sources, by producing hydrogen during excess of electricity generation and performing the reverse operation when electricity is needed. Many modelling studies of reversible systems are available in literature but few of them have been effectively built and tested. This work presents the development of a compact reversible system demonstrator able to operate SOC stacks up to 1.5 kW. The balance of plant has been designed to optimize the heat management, by integrating two heat exchangers to pre-heat the inlet gases with the exhaust ones. A special attention has been paid to ensure the compactness and reduce the cost of the system, fitting all the equipment (furnace, heat exchangers, steam generator, condenser, load, power supply, gas panel and control system) into two standard racks.

The prototype has been validated with a commercial SOC stack, leading to the production of 7 Nm<sup>3</sup>/day of H<sub>2</sub> and an electric production of 0.5 kW. Different operating regimes as well as the transition dynamics from SOEC to SOFC mode and its optimal alternation for coupling with photovoltaic power generation plants have been studied and discussed.

## Introduction

The use of renewable sources for energy production has to drastically increase by 2050 to limit the high level of greenhouse gases emissions from the fossil fuels use. The intermittent nature of those renewable power sources such as solar and wind energy is the main problem to power our 24/7 energy consuming society. Fortunately, there are periods of energy production excess that can compensate a lack of power, if storage solutions are implemented. Power-to-Gas (PtG) and the reversible process Gas-to-Power are an efficient way for storing electricity in form of gas such hydrogen, and regenerate electricity when necessary. Solid Oxide Cells (SOC) is one of the technology that can be used for this purpose, especially if both processes are performed by the same device [1]. Indeed, Glenk and Reichelstein recently estimated that reversible PtG systems based on SOC are more economically viable than separated units. Also, they found that these systems are cost competitive for medium- and small-scale customers and will remain competitive in the face of lower hydrogen prices thanks to a decrease of manufacturing costs [2]. Based on those findings, the development of reversible SOC systems is necessary to speed up their appearance on the market. Although, some modeling studies and experimental results from laboratory test stations are available in literature, pre-industrial reversible systems are scarce [3-8]. In this context, this paper aims to present the development of a compact reversible system demonstrator able to operate SOC stacks up to 1.5 kW.

## 1. Scientific Approach

A small-scale compact reversible demonstrator called VOYAGER has been designed with the goal of reaching high efficiencies and limiting the production costs. To do so, efforts were placed in optimizing the thermal management by limiting the thermal losses and preheating the inlet gases with the outlet ones. Commercial components were favored to manufacture the prototype in order to ease the reproducibility of the assembly and decrease the fabrication costs. Finally, a special attention was paid to the system compactness thinking in future applications in residential sector for example.

## 2. Experiments

### Description of the VOYAGER reversible prototype

Figure 1 presents the balance of plant (BoP) of the reversible prototype and Figure 2 gathers pictures of the different parts. Three main zones can be defined: the high temperatures zone, the intermediate temperatures zone and the cold zone.

The high temperatures zone is composed by a furnace placed on vertical rails to be easily lifted up and stand above the stack during maintenance. The furnace cavity can contain a stack of ca. 10x10x10 cm<sup>3</sup> that is installed on top of a base plate where the inlet and outlet tubes are welded. Coils are used as inlet gas tubes as a security to ensure a final heating up of the gases before entering the stack, which protects it against any thermal shock. The base plate and the stack are sealed by the use of a compressive sealant impregnated with alumina solution (Fuelcell Materials, US). The required force is applied by a compressive plate placed on top of the stack and connected by four rods to the cold zone where springs are tightened with the help of a dynamometric key. Finally, two thermocouples are installed inside the cavity for an accurate control of the hot zone temperature.

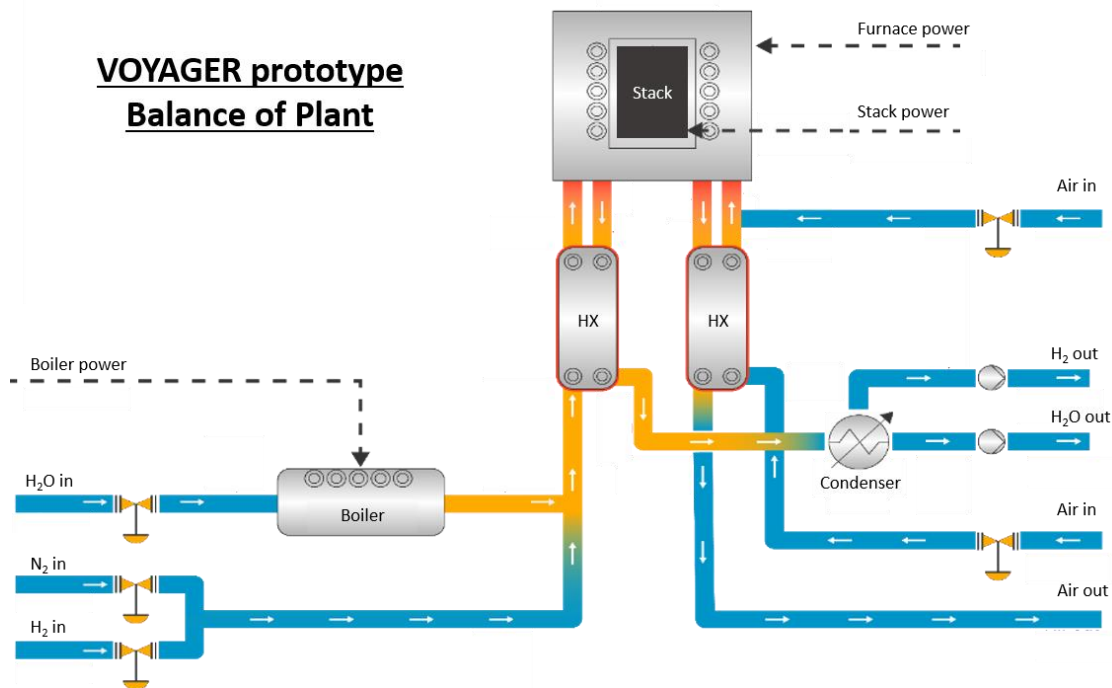


Figure 1. Balance of Plant of the reversible SOFC/SOEC prototype.

The intermediate temperature zone is composed by two heat exchangers placed right below the hot zone to minimize the gases path. They are confined inside a thermal insulated box. Those plate heat exchangers made of Inconel (Kaori, TW) were sized for each electrode taking into account the gas species and their flow range. A bypass gas line was placed between the air heat exchanger and the stack in order to send cold air and quickly cool down the stack in case of uncontrolled warm up due to leakages. Thermocouples were set inside the box, in contact with the upper and the lower part of the heat exchangers.

Finally, the cold zone is composed by the rest of the BoP. One can find on the same module as the heat exchangers (right part of the central picture on Figure 2) the steam generator and the condenser to separate the hydrogen from the steam at the fuel outlet. Steam generation reveals to be one of the most challenging part when building such prototype [8]. Indeed, almost no economical commercial solution is nowadays available on the market for low steam flows (ca.  $1 \text{ kg}\cdot\text{h}^{-1}$ ) with a precise flow control. It is expected that this problem will be solved when large volumes of SOEC or reversible systems for small-scale customers will have to be manufactured. In the meantime, a cost-competitive equipment (Nobeth, CN) has been chosen knowing that the steam flow could not be controlled by mean of electronic valves and that its efficiency was not optimal. This steam generator possesses two tanks to store a total of 8 L of water that can be automatically fulfilled. The principal tank is heated up to  $110 \text{ }^\circ\text{C}$  and its pressure increases while steam is produced. To ensure a constant steam flow three elements were added to the steam generator set-up: a micrometric valve placed at the steam outlet; a pressure sensor between the pressurized tank and the micrometric valve; and a potentiometer controlled as a function of the pressure to regulate the generator power and so, maintain a constant pressure of 2 bar inside the principal tank. Electro valves were also included to the circuit to disconnect the steam generator from the fuel inlet line during the heating up and stabilization phases of the steam generator and to purge the system in case of over pressure. The gas panel that includes a set of proportional valve coupled with a flowmeter (SMC, JP) for the Air and  $\text{N}_2$  lines and a mass flowmeter (Aalborg, US) for the  $\text{H}_2$  line was placed in the second module (left part of the central picture on Figure 2). All the electronics

were installed in a third module (below the gas panel module, down left part of the picture): the oven controller, a EA-EL 9080-85 B HP load for SOFC operation, a EA-PS 9080-60 power supply for SOEC operation (Elektro-Automatik, DE) and a programmable logic controller (PLC, Siemens, DE). The PLC has been programmed to allow a manual control as well as an automatized control, including emergency protocols. The prototype can be easily piloted by the mean of a touch screen and all the data can be saved for posterior analysis.

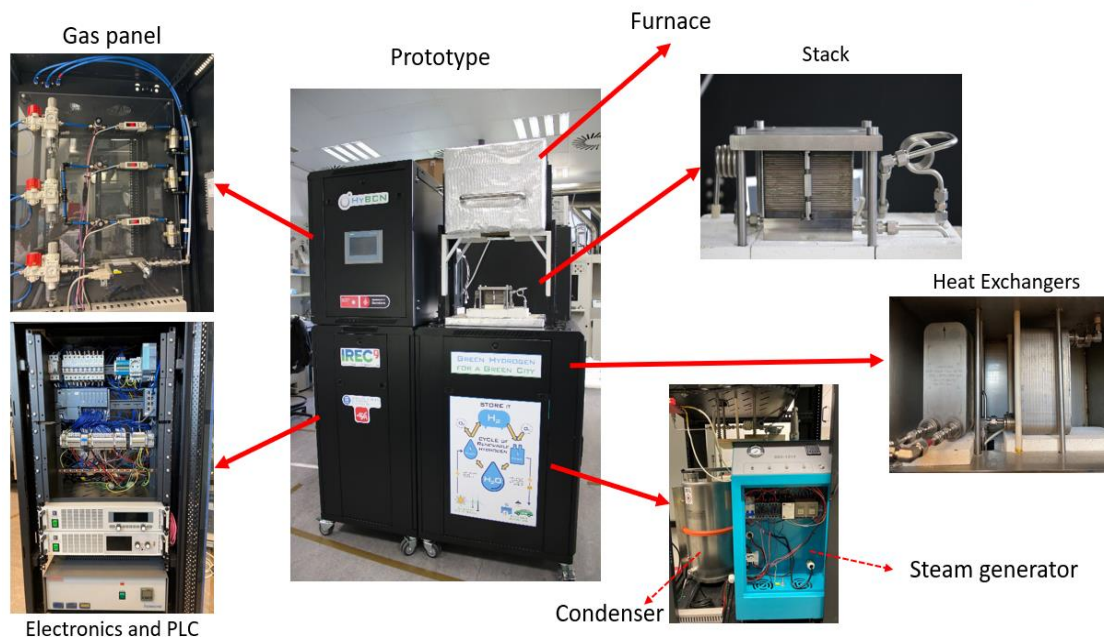


Figure 2. Picture of the reversible prototype with the different parts of the Balance of Plant.

### Stack

A commercial stack (Sofcman, CN) of 700 W in SOFC mode with an open cathode configuration was used to validate the prototype. It is composed by 30 anode supported cells made with an anode of Ni-YSZ, an electrolyte of 8YSZ, a barrier layer of CGO and an oxygen electrode of LSCF-CGO. An external loading force of 120 kg is required to maintain the stack sealed.

### Experimental procedure

After installing the stack onto the base plate and applying the required external load by mean of the compressive plate and the related springs, it has been heated up to 750 °C at 1 °C/min with N<sub>2</sub> at the fuel electrode and air at the oxygen electrode. The stack reduction was then performed during 2 h by progressively switching the N<sub>2</sub> atmosphere to H<sub>2</sub>. Once the stack had been reduced (open circuit voltage above 33 V or 1.1 V/cell), polarization curves were obtained in SOFC and SOEC mode first and then in reversible mode without changing the gas composition. Finally, a coupling with renewable energies was emulated. To do so, the energy consumption profile of a house located in Barcelona and equipped with solar panels was selected through the Polysun software (by Vela Solaris). Additional criteria were selected such as the auto consume of the electricity generated by the solar panels, the type of residents and date. Two active people working outside of their home were chosen, representing an electricity use mainly during the morning and the evening. By considering that the excess of energy produced during the day can be used to produced H<sub>2</sub> by SOEC, and then this H<sub>2</sub> can be used to produce electricity when the solar

panels are not producing enough, the profile of energy production excess and energy demand were obtained. In order to implement the current load profile onto the prototype controller, the profile had been normalized to match with the prototype maximum power.

### 3. Results

The demonstrator has been first tested in SOFC mode. Figure 3 reports the polarization curve obtained maintaining 60 % of fuel utilization (H<sub>2</sub> and air). The flows were initially kept constant until reaching 10 A and then were proportionally increased with the current to maintain a constant fuel utilization.

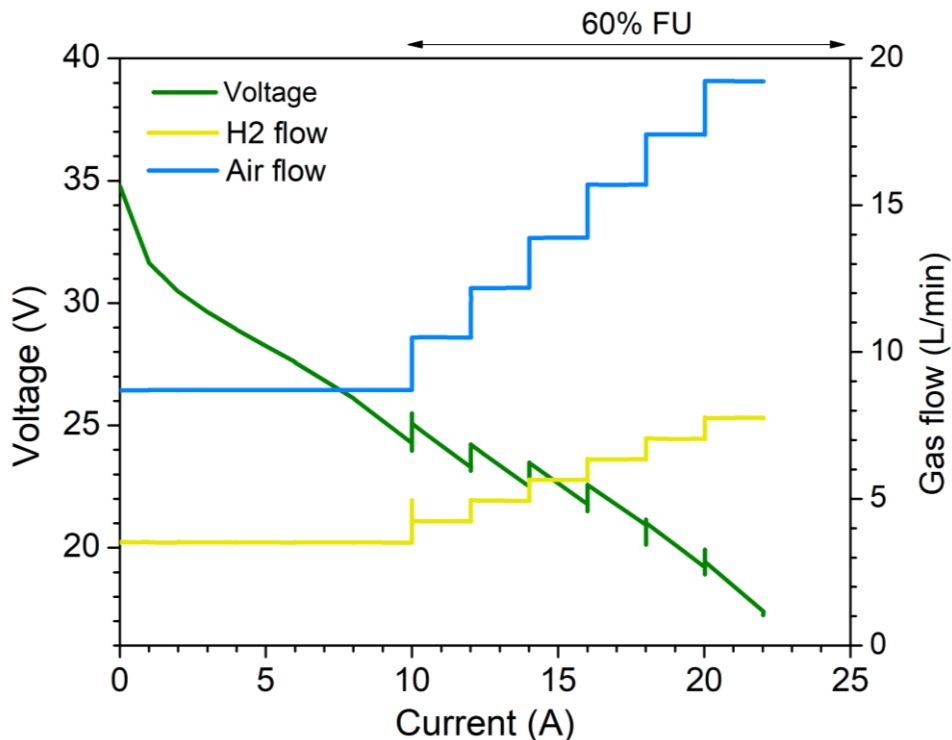


Figure 3. Polarization curve in SOFC mode, changing the inlet flows to maintain a fuel utilization of 60 %.

In SOEC mode, the inlet fuel composition had been estimated, based on the OCV value and the H<sub>2</sub> flow. Indeed, as mentioned in the previous section, the steam flow was controlled with a manual micrometric valve. By fixing the inlet H<sub>2</sub> flow, the valve had been adjusted until reaching an OCV of 27.6 V, corresponding to a proportion of 70/30 of H<sub>2</sub>O/H<sub>2</sub>. In those conditions, a current density of 0.35 A·cm<sup>-2</sup> was obtained at 39 V (thermoneutral voltage for a 30-cells stack) as seen on Figure 4.

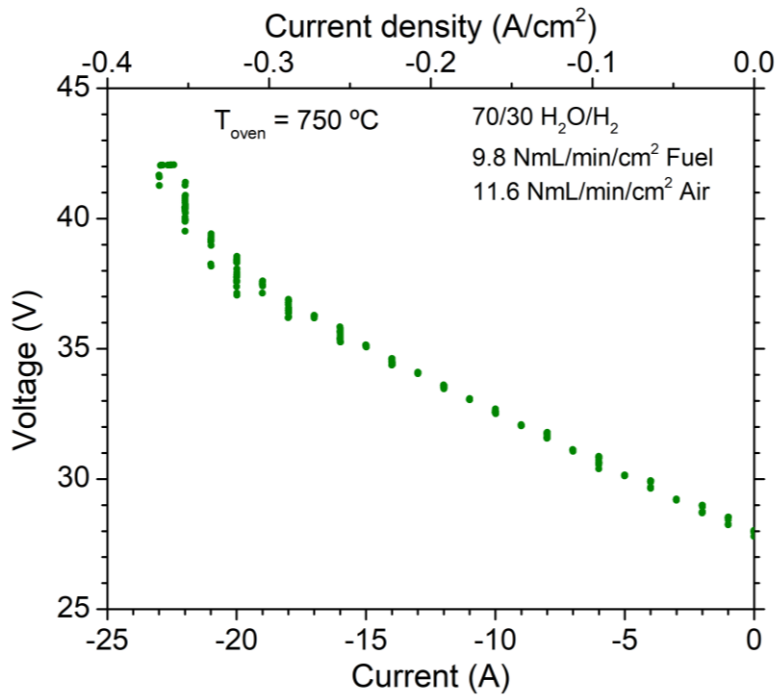


Figure 4. Polarization curve in SOEC mode.

Once the prototype validated in SOFC and SOEC mode, reversible operation was performed to directly switch from one mode to the other. For this test the composition was kept constant with a ratio of 50/50 in H<sub>2</sub>O/H<sub>2</sub> estimated the same way as described above. Figure 5 shows the polarization curve plotted in those conditions, where there is a smooth transition from SOEC (first applied mode) to SOFC. Indeed, the controller automatically switch between the load and the power supply. The iV curves present a similar slope but concentration overpotential seems to appear at lower current in SOEC (from 16 A) than in SOFC. This result is in accordance with the literature where diffusion limitations are reported to be more important in SOEC [1,9].

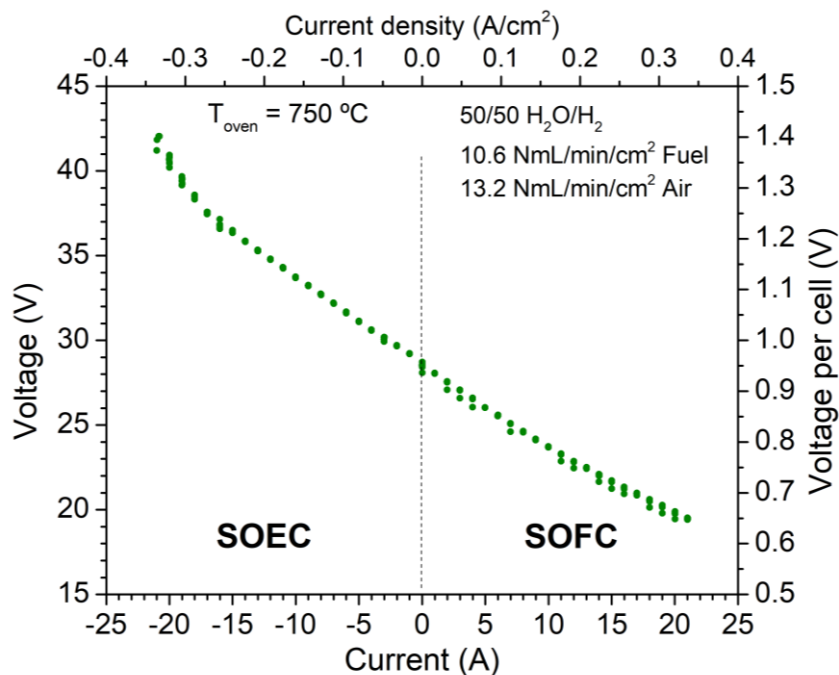


Figure 5. Polarization curve in reversible mode, starting in SOEC and ending in SOFC.



Finally, a current profile corresponding to 12 h (but shorten to 4 h) of electrical production and consumption, in February in Barcelona, of a house equipped by solar panels and occupied by a couple working outside of their home was applied to the prototype. In SOEC mode, the inlet fuel composition was set to c.a. 90/10 H<sub>2</sub>O/H<sub>2</sub> while the SOFC operation was performed with 100% of H<sub>2</sub>. One can see on Figure 6 that the voltage follows the current profile except after 2 h, which corresponds to the change in composition at OCV when switching from SOEC mode to SOFC mode. Also, one can remark that 15 min steps did not allow a perfect stabilization of the performance, probably due to the stack inertia regarding the changes in temperature related to the different operating voltages. A total of 1.5 m<sup>3</sup> of H<sub>2</sub> was produced during the SOEC phase of the profile (4.5 m<sup>3</sup> in real conditions) whereas 0.9 m<sup>3</sup> of H<sub>2</sub> was consumed in fuel cell mode (2.7 m<sup>3</sup> for 12 h of operation).

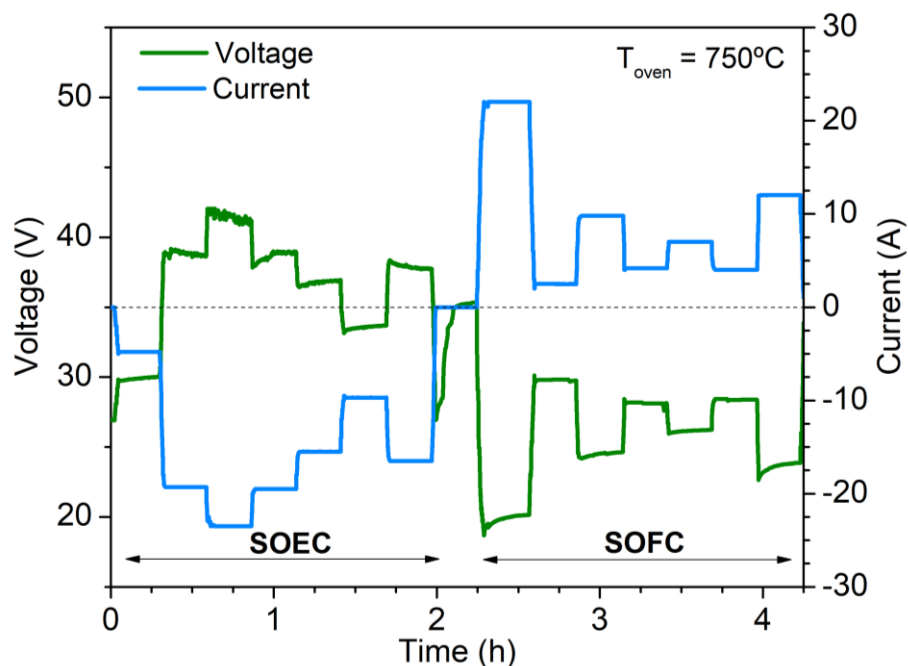


Figure 6. Evolution of the voltage with time when applying a current profile simulating a 12 h (shortened by 3) excess of energy production (SOEC) and demand (SOFC).

## Acknowledgements

The research leading to these results has received funding from the Hi-FV (n° ACE014/20/000048) and DEFINE-SOEC (n° ACE034/21/000001) projects.

## References

- [1] S. Y. Gómez and D. Hotza, Current developments in reversible solid oxide fuel cells. *Renewable and Sustainable Energy Reviews*, 61, 155, 2016
- [2] G. Glenk and S. Reichelstein, Reversible Power-to-Gas systems for energy conversion and storage. *Nature Communication*, 13, 2010, 2022
- [3] Z. Zong, J. Zhou, Z. Zhang, H. Zhao, J. Wang, W. Ma and K. Wu, Dynamic analysis of current overshoots in reversible solid oxide cells. *International Journal of Hydrogen Energy*, 46, 34896-34911, 2021

- [4] J. Aicart, Z. Wullemin, B. Gervasoni, D. Reynaud, F. Waeber, C. Beetschen, Y. Antonetti, A. Nesci and J. Mougín, Performance evaluation of a 4-stack solid oxide module in electrolysis mode. *International Journal of Hydrogen Energy*, 47, 3568-3579, 2022
- [5] V. Saarinen, J. Pennanen, M. Kotisaari, O. Thomann, O. Himanen, S. Di Iorio, P. Hanoux, J. Aicart, K. Couturier, X. Sun, M. Chen and B. R. Sudireddy. Design, manufacturing and operation of movable 2x10 kW size rSOC system. *Fuel Cells*, 1-10, 2021
- [6] S. Santhanam, M.P. Heddrich, M. Riedel and K.A. Friedrich, Theoretical and experimental study of reversible solid oxide cell (r-SOC) systems for energy storage. *Energy*, 141, 202-214, 2017
- [7] M. Franka, R. Dejaa, R. Petersa, L. Bluma and D. Stolten, Bypassing renewable variability with a reversible solid oxide cell plant. *Applied Energy*, 217, 101-112, 2018
- [8] A. Chatroux, M. Reytier, S. Di Iorio, C. Bernard, G. Roux, M. Petitjean, J. Mougín, A packaged and efficient SOEC system demonstrator. *ECS Transactions*, 68, 3519-3526, 2015
- [9] N. Q. Minh, and M. B. Mogensen, Reversible solid oxide fuel cell technology for green fuel and power production. *The Electrochemical Society Interface*, 22, 55, 2013

---

*Keywords: EFCF 2022, Reversible Solid Oxide Technologies, SOEC, SOFC, Reversible Prototype*