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Development of an efficient rSOC based renewable energy storage system

Julie Mougin^a, Geraud Cubizolles^a, Anne Hauch^b, Jari Pennanen^c, Joaquin Alvarez^d,
Sergii Pylypko^c, Marc Potron^f, Bastien Marquillier^f, Stephane Hody^g, Gianna Cesareo^h,
Sabina Fiorotⁱ, Guillermo Perez^j

^a Univ. Grenoble Alpes – CEA/LITEN, 17 rue des Martyrs, F-38054 Grenoble, France

^b Dept. of Energy Conversion and Storage, Technical University of Denmark, Fysikvej
310, 2800 Kgs. Lyngby, Denmark

^c VTT Technical Research Centre of Finland Ltd, P.O. Box 1000, FI-02044 VTT, Finland

^d GPTech, Avda de Camas 28, 41110 Bollullos de la Mitación, Spain

^e Elcogen, 23 Valukoja street, 11415 Tallinn, Estonia

^f SYLFEN, 266 avenue de Savoie, 38570 Le Cheylas, France

^g Engie Lab Crigen, 4 rue Joséphine Baker, 93240 Stains, France

^h Engie Servizi, Viale Ribotta 31 00144 Rome, Italy

ⁱ Environment Park, Via Livorno 60, 10144 Torino, Italy

^j University of Seville, Avda. De los Descubrimientos s/n, 41092 Seville, Spain

While renewable energies locally installed in buildings are increasing; there is a potential or even a need to store them to promote their self-consumption. Being efficient, modular and scalable, reversible Solid Oxide Cell (rSOC) technology can play a key role. Works undertaken in the frame of the REFLEX European project are presented, starting with the optimization of each individual component, ie. cells, stacks and BoP components such as power electronics. With the support of modelling activities, the rSOC based system, made of 3 modules of 4 stacks each, coupled with a battery storage has been designed in such a way to ensure achieving maximum efficiency, while still operating the system in safe and lifetime-optimal conditions. The site where the system will be installed has been prepared. Furthermore, techno-economic simulations have been carried out to evaluate market driven requirements on system sizing and costs to be competitive with other storage solutions.

Introduction

According to the European Green Deal and Europe's clean energy transition, renewable electricity is expected to decarbonise a large share of the EU energy consumption by 2050 (1), but not all of it. Hydrogen has a strong potential to bridge some of this gap, as a vector for renewable energy storage, alongside batteries (2).

On 25 February 2015, the European Commission adopted "A Framework Strategy for a Resilient Energy Union with a Forward-Looking Climate Change Policy" (3). Resilient energy systems need to be developed and deployed, with a central aspect being the energy storage of rapidly increasing intermittent and low predictable renewable energies. According to IEA (4), as the share of the world's population living in cities rises, ambitious

action in urban areas can be instrumental in achieving long term sustainability of the global energy system – including the carbon emission reductions required to meet the climate goals defined at COP21 in Paris. Indeed, buildings and eco-districts are increasingly becoming energy producers, with growing amounts of PV panels and wind power installed. Optimizing the self-consumption of this locally produced energy becomes a priority issue for the energy transition in order to avoid putting strain on the transmission and distribution network. Storing this energy to restore it locally, while having the option to produce locally with the same equipment combined heat and power (potentially also from methane or bio-methane and not only H₂), will ensure that the electricity supply matches demand at all times. The reversible Solid Oxide Cell (rSOC) technology allows this. Indeed, it is able to operate either in SOEC (solid oxide electrolysis) mode to store excess electricity to produce hydrogen or in SOFC (solid oxide fuel cell) mode in order to produce electricity (and heat) again, from hydrogen or any other fuel locally available when energy needs exceed local production. The rSOC system is advantageously completed with an electrochemical storage solution allowing fast response to the electrical energy needs.

In this context, the REFLEX European project will demonstrate, in-field, the high power-to-power (P2P) round-trip efficiency of this rSOC based technology (as compared to other H₂ based solutions) and its flexibility and durability in dynamic operation (power transient and switch between electrolysis and fuel cell mode; ie. load cycling). Both cells and stacks have been optimized to increase performance (+20% compared to the one considered at the beginning of the project) in both SOFC and SOEC modes, To increase overall system efficiency by minimizing the energy losses in the Balance of Plant (BoP) components, specific reversible power electronics have been developed. With the support of modelling activities, the rSOC based system, made of 3 modules of 4 stacks each, coupled with a battery storage has been designed in a way to ensure achieving maximum efficiency, while still operating the system in safe and lifetime-optimal conditions. The site where the system will be installed has been prepared. Furthermore, techno-economic simulations have been carried out to evaluate market driven requirements on system sizing and costs to be competitive with other storage solutions.

Experimental

Cells developments

Different cell microstructures have been produced by Elcogen and compared with a reference structure. The reference structure was a fuel electrode supported cell, consisting of ~380 μm Ni/3YSZ support layer, a ~5 μm Ni fuel contact layer, a ~12 μm Ni/8YSZ fuel active layer, a ~7 μm thick LSC oxygen electrode, a ~2μm 8YSZ electrolyte and a CGO barrier layer of similar thickness. The modifications targeted the active fuel electrode, the fuel electrode support, the barrier layer and the oxygen electrode. Specifically, porosity, layer thicknesses and Ni/YSZ ratio were refined for the active and support fuel electrode structures whereas different thicknesses were produced for the oxygen electrode. The modification of the barrier layers aimed for the adjustment of the layer density, thickness and its manufacturing process. Additionally, a contact layer on oxygen electrode was added.

After testing those improvements at single cell level in terms of performance (5), two optimized cells were selected for further durability tests (6) in rSOC conditions still at

single cell (53x53 mm²) level. Following the results obtained, and taking into account the ability of the cells to be produced in large amounts for the needs of the project and beyond, one of the two cells was considered as Generation 2 (G2) cell for the project.

Then full scale cells have been developed for integration into stacks for both lab tests at stack scale and for integration in the stacks to be embedded into the modules for in-field tests. Those cells are square, 120x120 mm, 100x100 mm (100 cm²) active area.

In parallel, to increase the power density further, enlarged cells have also been manufactured. The cell active area was nearly doubled passing from 100 cm² for reference cell to 196 cm², cells dimension being 160x160 mm². For this work on enlarged cells; the reference microstructure was applied. Figure 1 illustrates the two sizes of cells considered for stacks in this project.

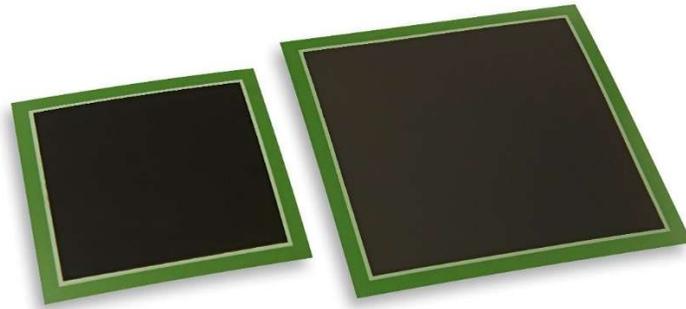


Figure 1. Picture of the 100 cm² and 196 cm² active area cells developed and delivered for integration into stacks in the project; left: 120x120 mm² cell; right: 160x160 mm² cell

For the purpose of the project, Elcogen produced and delivered 552 single cells, 527 100 cm² active area cells (50 reference cells and 477 G2 cells) and 25 196 cm² active area cells. Also, few dozens of small area experimental cells were manufactured for testing of new microstructures during development and validation of the Generation 2 cell type.

Stacks developments

Starting from the reference CEA 25-cell stack, comprising ~ 500 µm thick cells which was designed for a highly efficient SOEC operation (7), first an adaptation has been performed to integrate the reference ~ 400 µm thick aforementioned cells. Afterwards works have been performed to improve the fluidic distribution to the cells, especially on air side to cope with high flow rates as those needed for SOFC operation. Most of the work has been carried out to decrease the pressure drop on air side. Stack design modifications have been validated first at small scale, (5-cell short stack) and then at 25-cell scale considering reference cells (5).

A first 25-cell stack made of G2 cells was manufactured. In addition to the design optimizations described in (5) and to the integration of G2 cells, this stack integrates a manifold and an electrical insulation for an electrical connection in series of stacks into the modules for in-field test. After validation in lab of the improved behaviour of this G2-cell based stack, all stacks needed for the modules have been produced.

In parallel, 196 cm² active area cells have been integrated first in a small scale stack (5-cell stack) and then a full-scale stack (25-cell stack) for performance validation.

For the purpose of the project, CEA produced five 5-cell stacks (four with 100 cm² cells and one with 196 cm² cells) and twenty-two 25-cell stacks (twenty-one with 100 cm² cells and one with 196 cm² cells). Out of those twenty-two stacks twelve stacks plus four spare stacks are dedicated to the integration into the modules for the in-field tests.

Cells and stacks testing

The overall protocols considered for cells and stacks testing at DTU and CEA are presented into REFLEX public deliverable D2.1 (8). As an example, figure 2 presents the overall strategy for the performance and durability tests at stack level. For the rSOC cycling tests, two types of sequences were considered. Test #1 was conducted alternating from SOFC to SOEC mode by steps of ≈ 100 h, stack being fed with 50/50 H₂O/H₂ at total flow rate of 12 NmL/min/cm² on fuel side and air (clean and dry) on oxygen side. Tests were operated galvanostatic in SOFC and SOEC to reach respectively 0.8V (min) and 1.3 V (max) at test beginning, which corresponds to current density of 0.35 and -0.5 to -0.6 A/cm² at 700°C. Then test #2 was performed alternating from SOEC to SOFC by daily cycles of respectively 8h and 16h. Further details about the testing conditions can also be found in (5-6, 9-10). In addition, the stack performance has been tested in SOFC considering CH₄ as a fuel (considered as representative of natural gas which will be considered for the real system in-field).

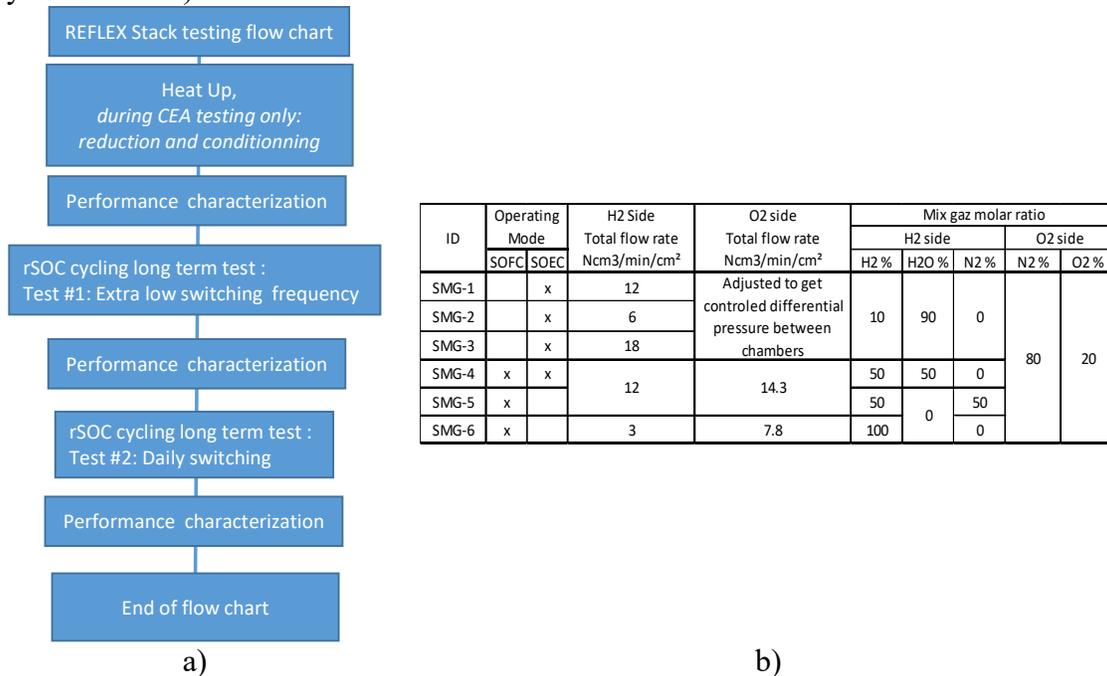


Figure 2. a): Stack testing flow chart; b): Mix gas composition set for i-V curves for 3 temperatures: 800, 750 and 700°C

Modules design and modelling

The technology developed by Sylfen is called Smart Energy Hub (SEH). It is based on rSOC technology, that is to say able to operate either in SOEC (solid oxide electrolysis) mode or in SOFC (solid oxide fuel cell) mode in order to either store excess electricity to produce hydrogen, or when energy needs exceed local production, to produce electricity (and heat) again, from hydrogen or any other fuel locally available (natural gas, in particular). To be more effective, the rSOC system is completed with an electrochemical

storage solution (Li-ion battery) allowing fast response to the electrical energy needs. The prototype designed in REFLEX intends to demonstrate the high power-to-power (P2P) round-trip efficiency of this technology (as compared to other H₂ based solutions) and its flexibility and durability in dynamic operation (power transient and switch between electrolysis and fuel cell mode).

The system architecture (electric, thermal, electro-chemical, gas, ...) has been defined by Sylfen. The product breakdown structure is given in Figure 3.

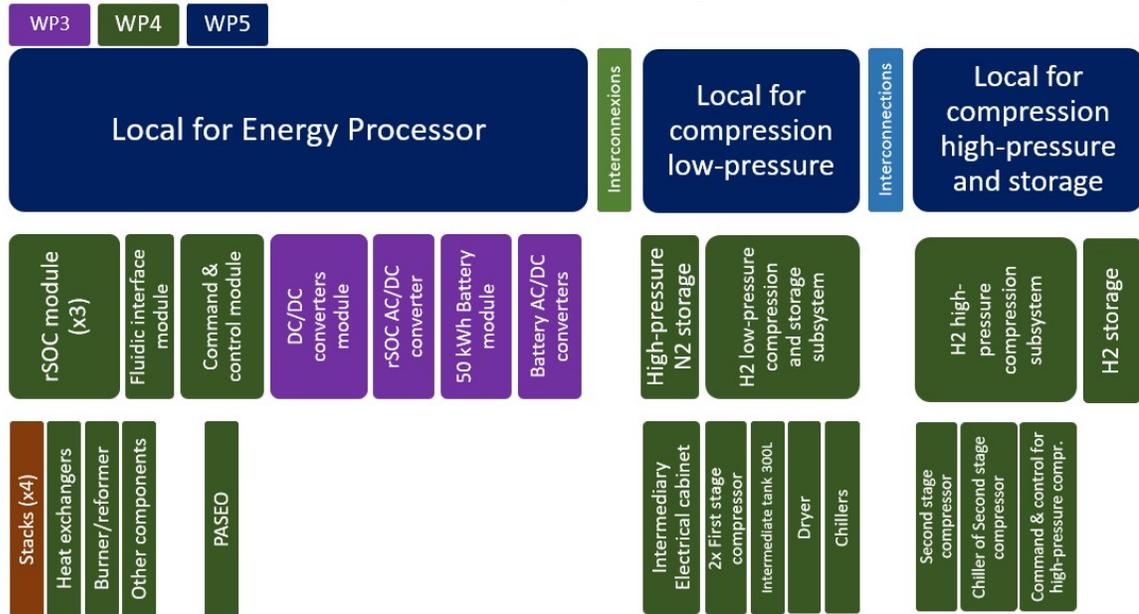


Figure 3. Product breakdown structure

Its main characteristics are:

- For the rSOC system: 3 modules of 4 stacks, with 3 operating modes: SOEC for H₂ production, SOFC fed with H₂, and SOFC fed with natural gas (NG) (table 1). For each mode 3 setpoints are defined, a minimum power P_{min}, a nominal power P_{med} and a maximum power P_{max}. The maximum H₂ production is 16 Nm³h⁻¹ in SOEC mode. In SOFC mode, the maximum electrical power is up to 15 kW in SOFC, fed in H₂ or NG. A standby mode and a safety mode are also defined.
- For the batteries: a 50 kWh battery electrochemical storage system has been manufactured, including 7 Li-Al cells modules, with 4 cell packs per module and 144 unitary cells per pack.
- Heat management is optimised in order to: 1) maximize system heat self-consumption, and 2) transfer a large amount of residual heat to the building hot water network.

Modelling tasks have been performed both to support the understanding and optimisation of the stack behaviour in terms of thermal management, to optimise the system design and to defined the best operation strategy. System modelling was performed using Simulink software utilizing the MATLAB-based ProSOFC component library developed by VTT. The system modeling activity was divided into 4 different phases, where each phase has objectives adapted to the current design level of the project: 1) concept level system design; 2) system modelling for design phase; 3) system modelling for operational phase; 4) interface to the end-user application. Results for the two first phases will be presented in next section.

The REFLEX Smart Energy Hub will be installed at ENVIPARK, in Torino, Italy. ENVIPARK is a Technology Park structured as a site of 10 building units that hosts offices and Laboratories operated by the various companies located in the Park. With real renewable energy sources upstream (a Hydroelectric power plant, 450 kW_e power, 1700 MWh/y, and a Photovoltaic plant of 17 kW of peak power (13 MWh/y) integrated into the park's energy grid, and with real usages of electricity and heat downstream, the behaviour of the rSOC based Smart Energy Hub developed in REFLEX will be evaluated in real operating conditions.

Power electronics developments

Power electronics systems were manufactured by University of Seville and GPTech and developed according to the specification defined, taking into account two stacks in series in order to improve the DC/DC converter efficiency, and the battery modules, mainly the capacity and the peak charging and discharging powers.

The DC/DC converter system consists of six individual DC/DC modules of 20kW each, total system is 120kW power capable. Each one of the six individual DC/DC converters has the following structure (figure 4).

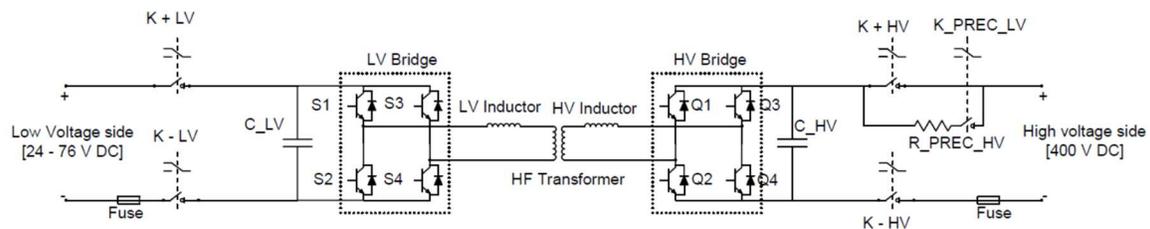


Figure 4. DC-DC converter electrical schematic

The DC/DC converter is connected in the low voltage side to the rSOC system, that acts as a fuel cell (in SOFC mode) generating electrical power. Or in the other hand, it acts as an electrolyzer (in SOEC mode) generating hydrogen from electrical power. All modes are in the specifications table, corresponding to the setpoints targeted for the modules (Table 1).

TABLE I. DC-DC converter electrical operating specifications in agreement with the rSOC system setpoints.

Operating mode		Current	Voltage	Voltage	Power	Power
		(A)	min (V)	max (V)	min (W)	max (W)
SOEC	Max	-130	56	76	7280	8840
	Med	-80			4480	6080
	Min	-40			2240	3040
SOFC-H ₂	Supermax	63	24	48	1512	3024
	Max	50			1200	2400
	Med	38			912	1824
	Min	24			576	1152
SOFC-NG	Supermax	75	24	48	1800	3600
	Max	60			1440	2880
	Med	50			1200	2400
	Min	24			576	1152

The DC/DC converters have been built and all the possible tests have been performed, confirming the correct operation in both SOFC and SOEC modes, according to the maximum power capabilities. Finally, AC/DC power converter and the associated control system have been tested with the DC/DC devices and the battery storage.

Techno-economic studies

Smart Energy Hubs integrate a rSOC technology, coupled with Li-ion batteries. Such a system has then to be seen in this context, as a power storage solution for buildings. It competes with two types of power storages: batteries and the combination of a low temperature water electrolyzer (alkaline or PEM) and a fuel cell.

The techno-economic study performed by ENGIE aims at evaluating the long-term market potential of this new solution developed by SYLFEN. A first phase was to study through simulations the best sizing of Smart Energy Hubs for several building markets in Europe. This meant here, defining the main parameters of the system (electrolyzer power input, fuel cell power output, hydrogen storage size, and battery capacity), assuming performance objectives for the technology (efficiencies). Based on those results, the requirements on CAPEX and OPEX (maintenance cost) have been defined for Smart Energy Hubs to be competitive with other storage technologies.

Four cases studies (building type) have been considered: offices, hotels, malls and aquatic centres. For each building type, one unique building has been considered, and studied over four different countries (France, Germany, Italy and United Kingdom). The maximum CAPEX and OPEX for Smart Energy Hubs have been calculated, based on simulations over one year. The requirements on CAPEX and OPEX have been defined for each reference solution that Smart Energy Hubs have to compete with that are: 1) Power and gas from the grid, and without PV nor power storage; 2) Power and gas from the grids, PV panels, without power storage, with or without export tariff; 3) Power and gas from the grid, PV panels, battery-based power storage; 4) Power and gas from the grids, PV panels, low-temperature hydrogen-based power storage.

In terms of OPEX, a five-years lifespan of rSOC stacks has been considered in this study, twice lower than those of low-temperature electrolyzer/fuel cell storage system and batteries. Stack replacement has been integrated here within annual OPEX.

Results

Cells and Stack Testing

Detailed results are presented in (5-6, 9-10). The purpose of the results presented here is to highlight the main achievements of the project as compared to the targets set. In terms of performance, REFLEX targets were to reach -1.2 A/cm^2 at 1.3V at 700°C in SOEC mode, and 0.6 A/cm^2 at 0.8V at 700°C in SOFC mode. Due to the developments performed by Elcogen for G2 cells, this goal has been achieved (figure 5), achieving high steam/fuel utilization (80% or even higher), highlighting a good electrode microstructure without or with minimum mass transport limitation. It corresponds roughly to 20% of improvement

of current density at the thermoneutral voltage as compared to reference Elcogen cells tested in the same conditions.

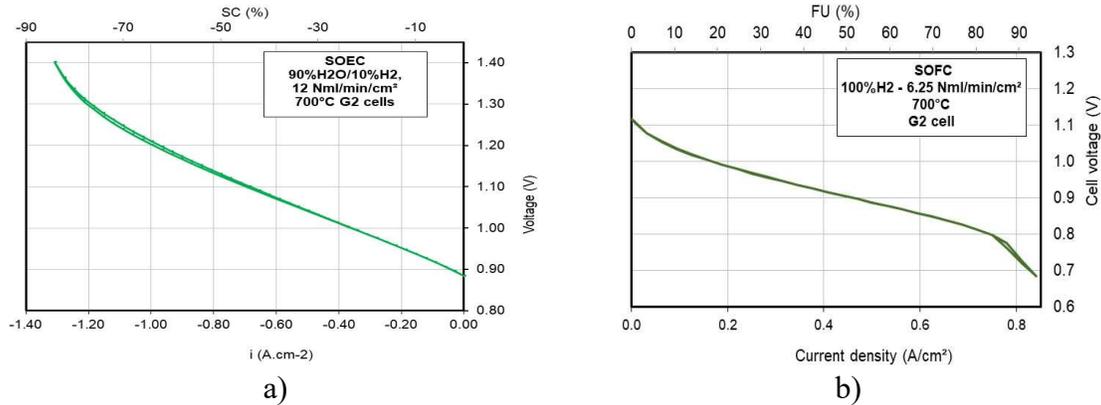


Figure 5. i-V curve of G2 cells recorded at 700°C; a) in SOEC, 90% H₂O/10%H₂; b) in SOFC in 100% H₂ at fuel electrode, synthetic air at oxygen electrode; steam conversion in SOEC and fuel utilization in SOFC are reported on upper secondary x-axis

The benefit of G2 cells has also been confirmed at stack level (figure 6). Indeed, the maximum current density achievable without exceeding 1.4 V on the less performing cell is shifted from -1.0 A/cm^2 to -1.05 A/cm^2 , and the scattering between the 25 cells of the stack is decreased, confirming the trend already reported at the scale of a 5-cell short stack (6). As compared to single cell the stack performance in similar conditions is a bit lower. It might be due to the stacking and the possible additional contact resistance which does not exist in single cell test setup, and/or to thermal effects, the exact temperature of the stack being more difficult to determine than for a single cell.

The operating window of the stack has been determined in SOEC and in SOFC fed with H₂ and CH₄ (representing in lab the NG case). Table 2 presents the values achieved, which will be the reference setpoints for the modules. They exceed the targets defined in the project, which were 50-100% in SOFC, and 70–100% in SOEC.

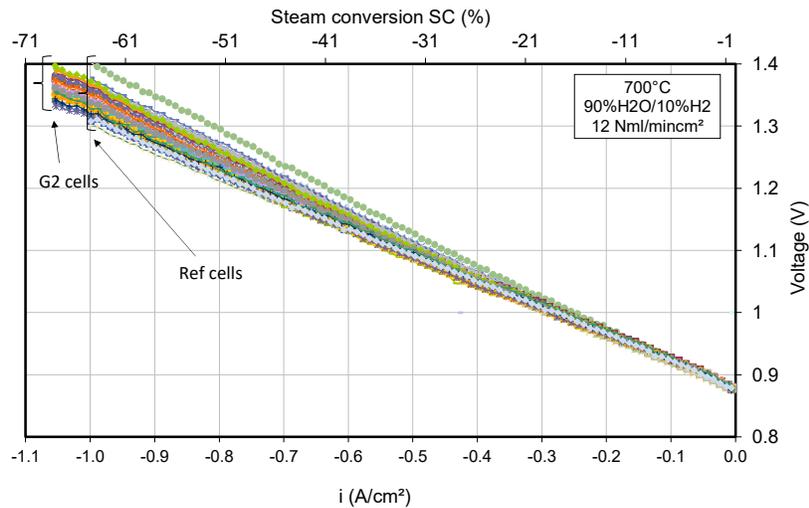


Figure 6. Comparison of i-V curves recorded on 25-cell stacks with G2 cells and reference cells recorded at 700°C in SOEC, 90% H₂O/10% H₂ at fuel electrode, compressed air at oxygen electrode; steam conversion is reported on upper secondary x-axis

Nearly double active area cells have been successfully integrated into stacks, with the same level of performance achieved as with standard size cells (10).

TABLE II. Operating window determined at the scale of a 25-cell stack made of G2 cells, given as a percentage of the max power

Power (%)	SOEC	SOFC-H ₂	SOFC-CH ₄
Pmin	58	23	13
Pmed	80	66	75
Pmax	100	100	100

System modelling

Modelling activities have been performed to support the concept level system design. The system modelling has started on the basis of a rough description of the 3D structure of the planned system, considering all operating modes (SOEC, SOFC-H₂ and SOFC-NG). Several options for the insulated hotbox have been tested in order to choose the best design to reach the overall performance. System modelling has shown that with a careful planning/construction it is possible to build an rSOC system capable of achieving the efficiency targets set. As an example, the figure 7 presents results for SOEC Pmax mode and shows that combinations of hotbox size and insulation thickness that meet SOEC efficiency requirements can be identified. This exercise has been repeated for all operating points and modes to select the best geometry possible for an operation of the SEH at the best performances on all operating windows.

Subsequently, system modelling activities have supported the design phase to find a feasible system layout and dimensions including its BoP components to allow the system to meet its performance requirements. One key task was to determine the size of the operational windows for each mode. Figure 8 presents the operating window for the SOFC-H₂ mode as an example, where heat management problems arise at high operating current densities. More detailed simulations related to the operational phase can be performed as the final 3D structure is designed and the final BoP components therein are experimentally characterized.

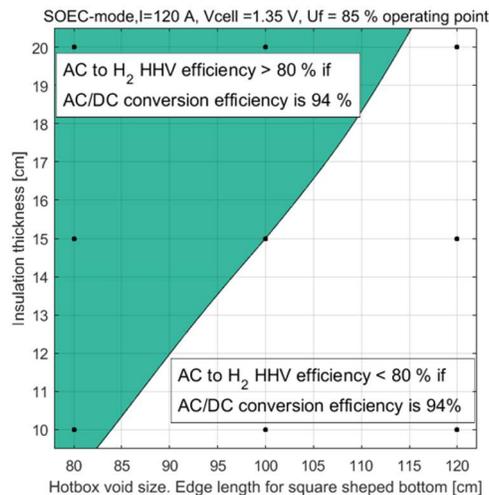


Figure 7. Combinations of hotbox size and insulation thickness that meet SOEC efficiency requirements (AC to HHV efficiency target of 80%), identified in green area.

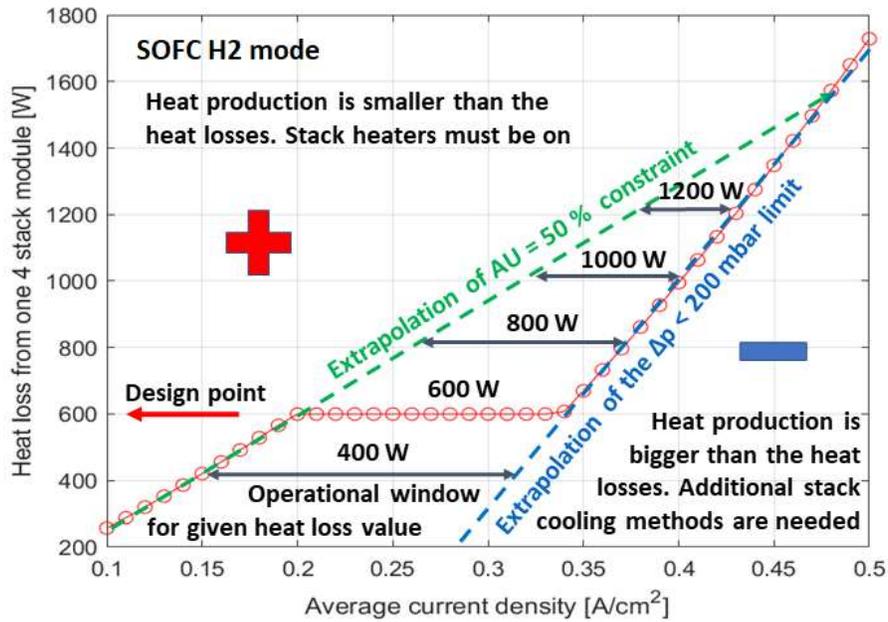


Figure 8. Operating windows for SOFC-H₂ mode; black lines show width and location of the operational window (in current density) where the stack temperature can be controlled by the air flow rate for selected stack module heat loss estimate. The design value for heat loss from one four stack module is 600 W. The modelled design case is shown using red markers. The extrapolation trend is found by repeating the same analysis using different heat loss estimates for the same stack module

Power electronics validation

DC/DC converters were tested in both modes: SOFC and SOEC at their maximum power capabilities with the test bench shown in figure 9. First, tests were made to each DC/DC converter separately and the results obtained were compared. The results showed similar behavior for all converters. The best efficiency achieved in the laboratory for the DC-DC converter was 96% (figure 9) which is in line with the initial objective of the project (95%).

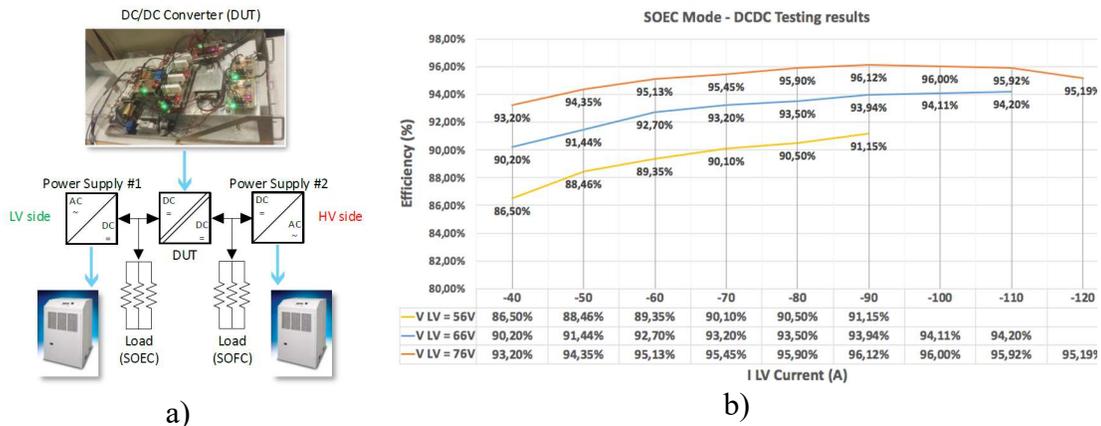


Figure 9. a) Test bench used for lab validation of the DC/DC converters; b) Efficiency of the DC/DC converter recorded in SOEC mode as function of the current applied for three voltage values

Techno-economic results

Among the different types of buildings, the hotel case appears to be the most interesting for power storage, from a “technical” point of view. Indeed, the hotel case is the one which allows to consider a significant increase of building’s autonomy thanks to power storage, as illustrated in Figure 10 for the Italian hotel case.

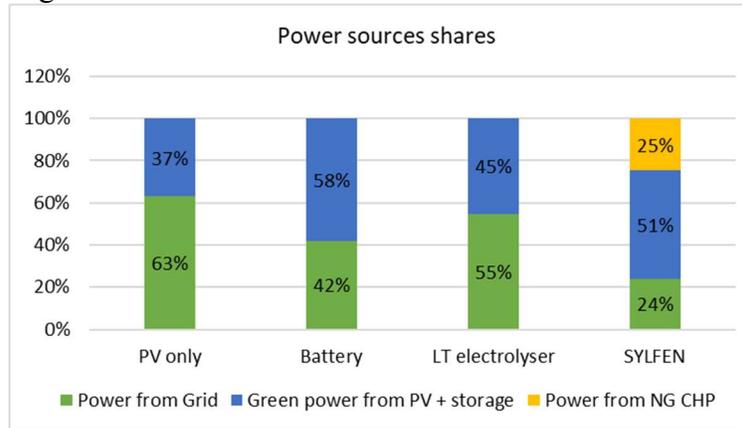


Figure 10. Origin of the power consumed by the hotel with PV panels covering 100% of roof surface, with and without storage, in Italy

Another service that can be provided by the rSOC based power storage, is its ability to provide renewable heat to the building in addition to power. Indeed, only hydrogen-based storage is able to release heat that can be valorized within the building, through a water loop. For low-temperature electrolysis and fuel cell systems, the share of renewable heat remains however very limited (<1.5%). High-temperature rSOC system can contribute more significantly to the building’s thermal needs, up to 7.5% for the considered case studies. However, a significant share of that heat provided by the storage comes from the operation of the system in natural gas CHP.

When considering reference solution 1), i.e. a building without storage and PV panels, the add-on installation of an rSOC based storage and PV panels allows to reach lower Total Cost of Ownership (TCO), as soon as rSOC module CAPEX is in the range of 2000 – 5000 €/kW, depending on use case and country, except for France, where lower CAPEX are required due to lower power prices. The higher maximum CAPEX are achieved for the office, aquatic centre and shopping centre (figure 11).

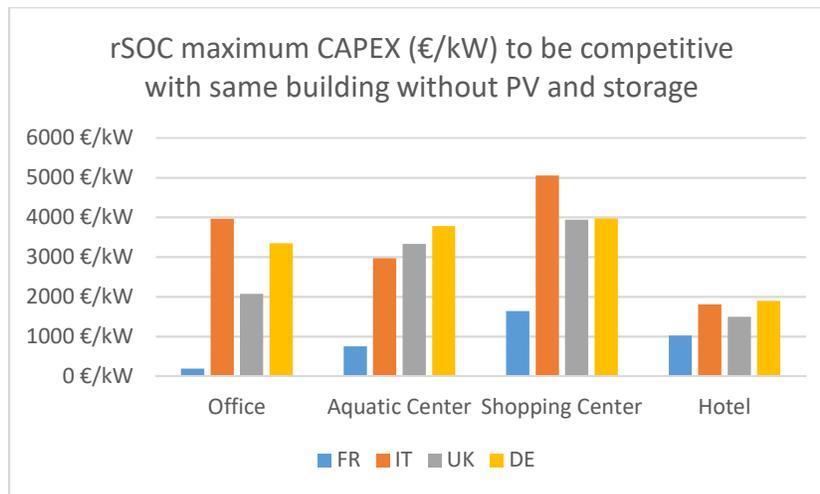


Figure 11. Maximum CAPEX for the rSOC based storage solution to reach the same TCO of the same building without PV nor storage solution, depending on building's typology and country. These maximum CAPEX are expressed in €/kW of electrolysis, and refer only to the rSOC module, without H₂ storage and batteries

When considering reference solution 2), i.e. a building already equipped with a large PV surface, but without any power storage system, the add-on installation of a rSOC based storage system allows to reach lower TCO, as soon as rSOC module CAPEX is in the range of 1000 – 1700 €/kW, depending on the use case, and mainly for countries as Germany, UK and Italy. While with reference 1, competitiveness is mainly achieved thanks to the installation of PV, with reference 2, which considers that PV panels are already installed, the addition of a power storage solution requires much quite low CAPEX, in order to achieve the same TCO.

Consideration of reference solution 3) is a way to compare directly the competitiveness of rSOC based solution with battery-based solution. For a building already equipped with PV panels, rSOC solution appears to be better from a TCO point of view than batteries, when rSOC CAPEX are lower than 2000 €/kW for the aquatic centre and the shopping centre, and in the range of 1500€/kW max for the hotel. The office use case shows more competitiveness for rSOC than batteries, with acceptable rSOC CAPEX in the range of 2000 to more than 6000 €/kW.

Consideration of reference solution 4) is a way to compare directly the competitiveness of rSOC based solution with low temperature electrolysis and fuel cell-based storage solution. For a building already equipped with PV panels, rSOC solution appears to be better from a TCO point of view than low temperature electrolysis / fuel cell, when rSOC CAPEX are lower than 2000 €/kW for the aquatic centre, the shopping centre and the office, and in the range of 1000 - 1500€/kW max for the hotel.

Sensitivity studies on the impact of power and gas prices showed that power price as a high and significant impact on rSOC system competitiveness whatever the reference solution is (figure 12). The higher the power price is, the more rSOC system is competitive with the reference solutions, allowing therefore higher CAPEX to equal or lower the TCO. The impact is the highest when compared to solutions without storage systems, as adding a storage when power price is high, allows to reduce the energy bill, thanks to a higher self-consumption of PV. As rSOC system has also the ability to produce power from natural

gas in CHP mode, its competitiveness is also increased with higher power prices versus battery and low-temperature electrolysis / fuel cell storage systems.

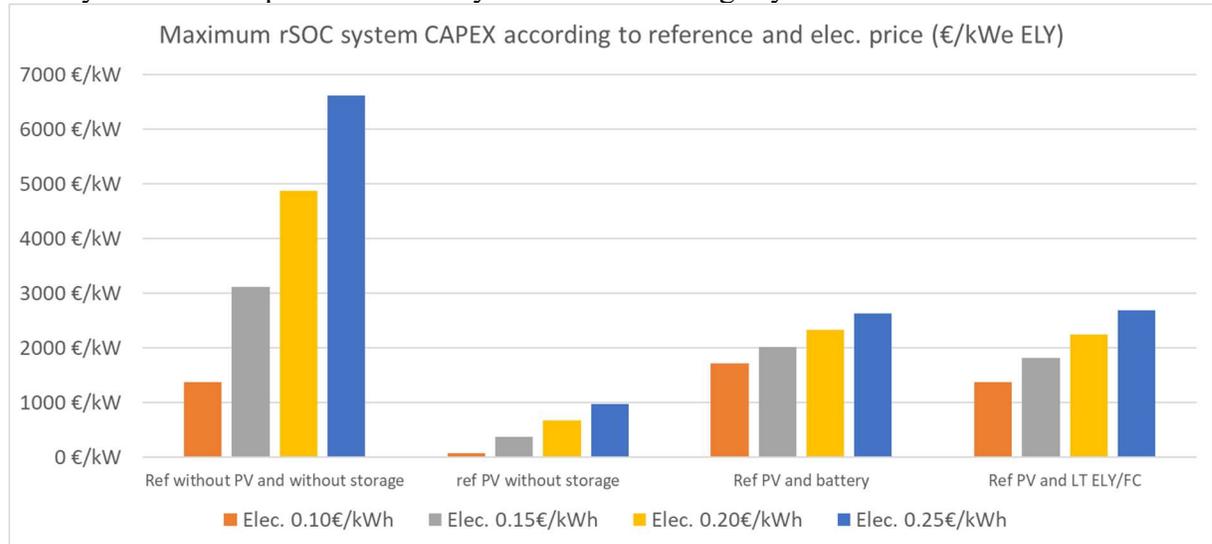


Figure 12. Sensitivity of maximum CAPEX for the rSOC solution with power price, depending on reference solution, for the shopping centre building in Germany. Natural gas price is set here at 0.038€/kWh

Because of the CHP mode, higher gas prices, leading to reduced price difference with power prices, has a negative impact on rSOC competitiveness. Nevertheless, this impact remains quite limited.

Conclusion

In order to reach high power-to-power (P2P) round-trip efficiency, improved flexibility and durability in dynamic operation, the key components of the rSOC based Smart Energy Hub system have been optimised. Cells, stacks, and power electronics have been improved and targets set by the project achieved. The performance of cells have been increased by 20% as compared to reference cells, reaching -1.2 A/cm^2 at 1.3V in SOEC mode and 0.6 A/cm^2 at 0.8V in SOFC mode at 700°C at single cell level. The cells have been successfully integrated into stacks, which were tested in SOEC, SOFC in H_2 and SOFC in CH_4 to evaluate the operating window, which in terms of power covers the range 58-100, 23-100 and 13-100% respectively. Nearly double active area cells have been successfully integrated into stacks, with the same level of performance achieved as with standard size cells.

With the support of modelling activities, the rSOC based system, made of three modules of four stacks each, coupled with a battery storage has been designed. Several options for the insulated hotbox have been simulated in order to choose the best design to reach the overall performance. The optimum operating window has been defined. The site where the system will be installed has been prepared.

Furthermore, techno-economic simulations have been carried out to evaluate market driven requirements on system sizing and costs to be competitive with other storage solutions.

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