Smart Ways for In-situ Totally Integrated and Continuous Multisource Generation of Hydrogen

D6.3: Report on the in-field testing of the SWITCH system under real conditions

WP6, T6.4

June 2024

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Technical References

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[1] PU = Public

PP = Restricted to other programme participants (including the Commission Services).

RE = Restricted to a group specified by the consortium (including the Commission Services).

CO = Confidential, only for members of the consortium (including the Commission Services).

Versions

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1 Introduction

The SWITCH project aims to develop an in-situ fully integrated and continuous multisource hydrogen production system, based on solid oxide cell technology.

Solid Oxide Cells (SOC) efficiently convert variable electricity from renewables and steam into green hydrogen in electrolysis mode. They can also be used in a reversed mode, as a fuel cell, to enable the use of other sources (e.g., methane, bio-methane) to match a variable electricity production with continuous and guaranteed production of hydrogen.

The SWITCH project focuses on the development of a system able to generate efficiently both hydrogen via water electrolysis (i.e. SOE) as well as reversibly operate in fuel cell mode (i.e. SOFC) to not only produce electricity from hydrogen, but also co-generate (simultaneously generate) electricity and hydrogen from methane-rich gas.

Core of the system is the reversible Solid Oxide module supported by an advanced fuel processing unit able to manage steam generation and methane reforming reactions and a purification unit to obtain hydrogen with a purity in compliance with the main industrial and automotive standards.

A system capable of producing up to 100 kg/day of H_2 and having a maximum power output of 50 kWel has been designed and realized. More details on the realized prototype are available in deliverable D6.1.

After the factory acceptance test (FAT) and the functional and operational check of the SWITCH system (for more information see D6.2), the testing campaign has been performed. Overall, the system has been tested under real conditions for more than 1 month.

The main testing results are described in this deliverable; showing the major goals /KPIs achieved.

1.1 Full SWITCH prototypal system realized

The Switch prototype system comprises two SOFC/SOE large stack modules (LSMs) that represent the core of the system. These stack modules can operate in fuel cell mode (SOFC-mode) or in electrolysis mode (SOE-mode): in SOFC mode the modules simultaneously generate electric power and hydrogen via steam reforming of methane-rich fuels, whereas in SOE mode the modules produce hydrogen via steam electrolysis. The prototype has a production capacity of up to 40 kg/d of H_2 plus 50 kW_{el} in SOFC-mode, and 100 kg/d of H_2 in SOE-mode; the latter requires the input of about 150 kW_{el} (which in a commercial system should come from renewable power sources).

The Balance of Plant (BoP) components of the system provide all the required feed streams to the LSM’s at the desired conditions and take care of the conditioning and purification of the product gases from the LSM’s.

From temperature level point of view cold and hot BoP units can be identified. Table 1 summarizes the units the BoPs mainly consist of.

Table 1Main cold and hot BoP units

Cold BoP	Hot BoP
Air supply	Steam pre-reforming reactor
NG cleaning and supply	Steam generator
Water treatment and supply	Burner
Gas conditioning	Water gas shift reactor
Gas purification	Large stack module (SOFC/SOE)
Coolant conditioning	Fuel and air heat exchangers

The realized prototype has been assembled inside two 40 ft containers; a schematic layout of both containers is shown in Figure 1; the two containers and a side view are shown in Figure 2.

One container is dedicated to the gas upgrading section, including the steam generation units and part of the gas train (fuel, air, nitrogen and forming gas interception valves); this container accommodates:

- two SOE/SOFC modules
- two Hot BoP modules
- one steam generation unit with the steam train
- Cooling and condensing system after the WGS units (HX-10 and water knock-out),
- the SPLC cabinet and the power electronics.

The second container accommodates most of the cold BoP section, including the control PLC. Specifically, it consists of:

- the utilities gas trains
- the PSA unit
- the two compressors (for hydrogen and syngas)
- the electrical cabinets and control PLC.

The containers are ventilated by means of roof blower that assure, in case of gas leakages, to avoid the creation of an explosive atmosphere inside the containers.

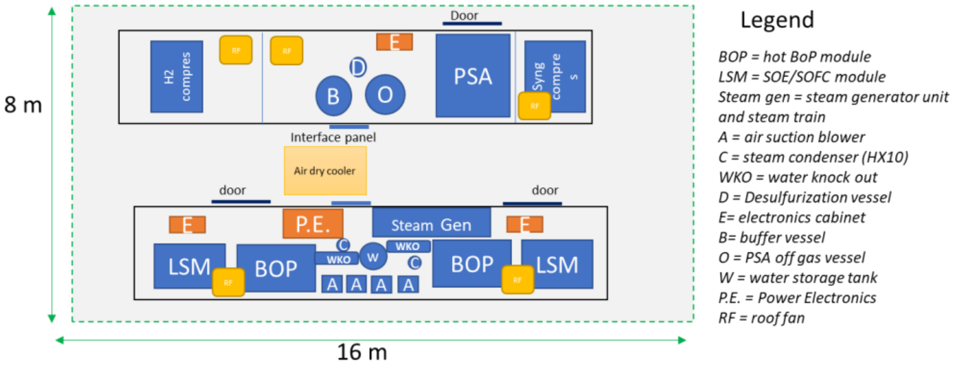

Figure 1 schematic layout of two containers A and B

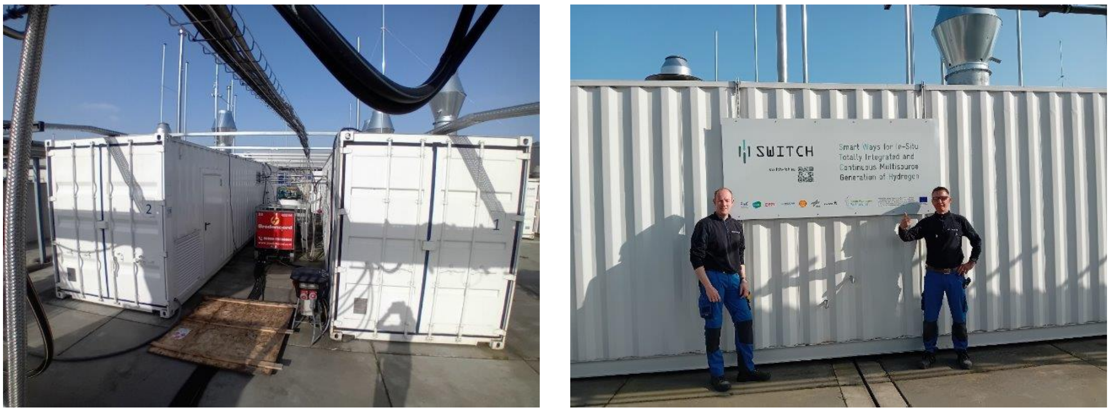

Figure 2 Overview of the two containers and side view of container

2 In field testing of the SWITCH system

The realized prototype consists of two units (2 x (LSM + BoP)) (named system A and system B), with a maximum combined production capacity up to 100 kg/day of H_2 in SOE mode.

Due to temporary electrical power limitation at the testing site, only one system has been tested in production mode. However, both systems have been debugged, tested and validated. Tests with a dummy LSM have been performed to validate the system A, while the test under real conditions have been performed with system B, with a real LSM module.

Hereafter the main results of the overall testing campaign, from pre validation tests to final tests are reported.

SOE and SOFC modes have been both tested; per each mode, an overview of the main test results of the hot BOP and LSM module as well as the post processing and PSA unit is provided.

2.1 Pre validation test

The SWITCH prototype is a quite complex system, consisting of many interconnected equipment, therefore several pre-validation tests have been performed to ensure proper system operation and to reduce the risk of conditions (e.g., pressure surge) that are potentially harmful for fragile components, such as those inside the LSM module.

Coupling and decoupling of the hot section with H_2 or syngas compressors have been extensively tested to identify the optimal procedures, in terms of controllability and pressure management.

The defined control logic has been tested and validated; the control parameters of control valves, like the coupling and decoupling ones, have been further tuned based on actual system behaviour.

The startup, shutdown and switching from syngas compressor to H_2 compressor have also been tested during the pre-validation testing phase.

Beside the coupling and decoupling tests, functional tests of equipment like the liquid/gas separator (WKO) and steam condenser (HX10) have been executed: they performed perfectly within design specs.

More details about FAT and the functional and operational check of the SWITCH system have been reported in deliverable D6.2.

2.2 Validation test

This testing phase has started with the heating up of the system B. Once the system reached a temperature above 600 C, it has been always kept hot: only few Emergency Shutdowns (ESDs) occurred, but most of time, it was possible to restart the system almost immediately.

The system B has been tested in SOE and SOFC modes, with a particular focus on the operation in SOE mode, that was specifically targeted by the SWITCH project.

Figure 3 shows the overall validation testing phase window: from April 16th, when the system B reached its operating temperature, to May 16th, when the cooling down was completed.

The air and fuel temperature at the LSM inlet are shown in Figure 3 (respectively dark grey and yellow lines): these profiles show quite stable temperatures during all the testing phases, with an inversion of the temperature differences as the module passes from isothermal SOE operation to exothermal SOFC operation and the whole BoP adapts to the new operation conditions; more details are provided in further chapters.

The LSM electrical power input is shown with a black dotted line: for operation in SOE mode the power input is positive, where a max value of ca. 70 kW has been achieved. In SOFC mode, electrical power is produced by the LSM, thus the power input term is negative (<0).

The light blue solid line in Figure 3 is representative of the steam mass flow rate (kg/h) sent towards the LSM: H_2 was produced by the prototype whenever the steam was fed and the stacks were polarized (i.e., voltage imposed by the electrical power supply). This can be observed as for operation in SOE mode, the steam flow rate profile follows the power input profile.

The pressure difference, inside the stack, between fuel and air side (DP LSM) is also reported in Figure 3 with the green line: it must be highlighted since it represents a great challenge in terms of process control. Remarkably, the DP was quite constant and stable during the entire test campaign; it was kept within a small window even when coupling and decoupling the LSM+BOP subsystem and the purification + compression subsystem. This represents a key achievement for the prototype, since quite stringent constraints were in place for the pressure control.

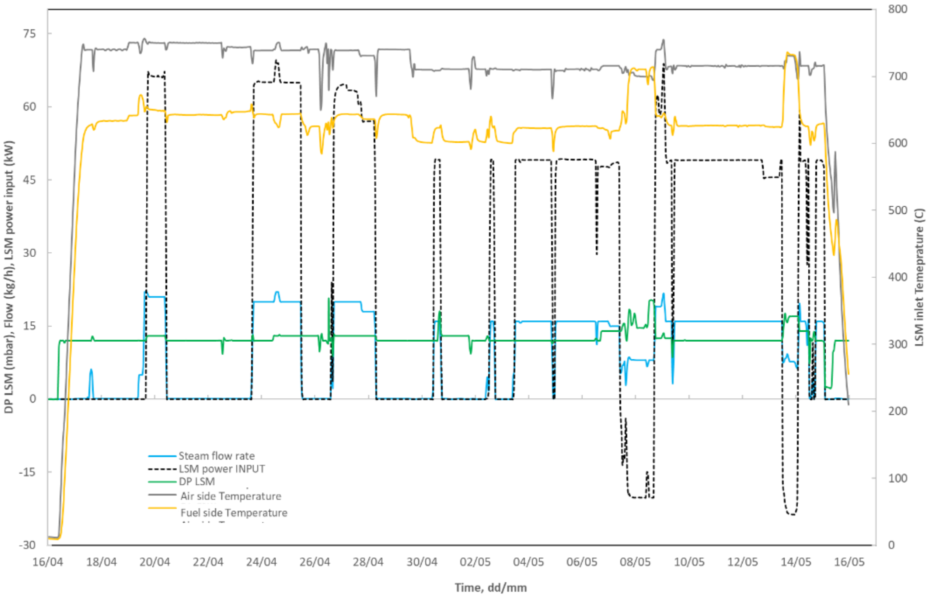

Figure 3 Overview of the testing phase: running hours (>700 h) in operation (SOE or SOFC mode

Figure 4 gives an overview of the time spent in each of the operating modes during the month of testing at HyGear's premises, cumulating more than 28 days in hot state. Most of the time was devoted to hydrogen production in electrolysis mode (320h), yielding ~300kg of H_2. The time dedicated to SOFC mode was comparatively shorter (42h) but however enabled to produce ~7.5kg of hydrogen from the co-generation mode. During the remaining time (315h), the system was maintained at OCV. This includes the idling and hot standby. As observed in Figure 4, the time spent at OCV was mainly at the beginning of the test, as bugs had to be corrected and control parameters adjusted. However, with time these OCV episodes became shorter and scarcer as we progressed along the learning curve: from the 3rd of May on, we were able to operate continuously in both production modes, including during nights.

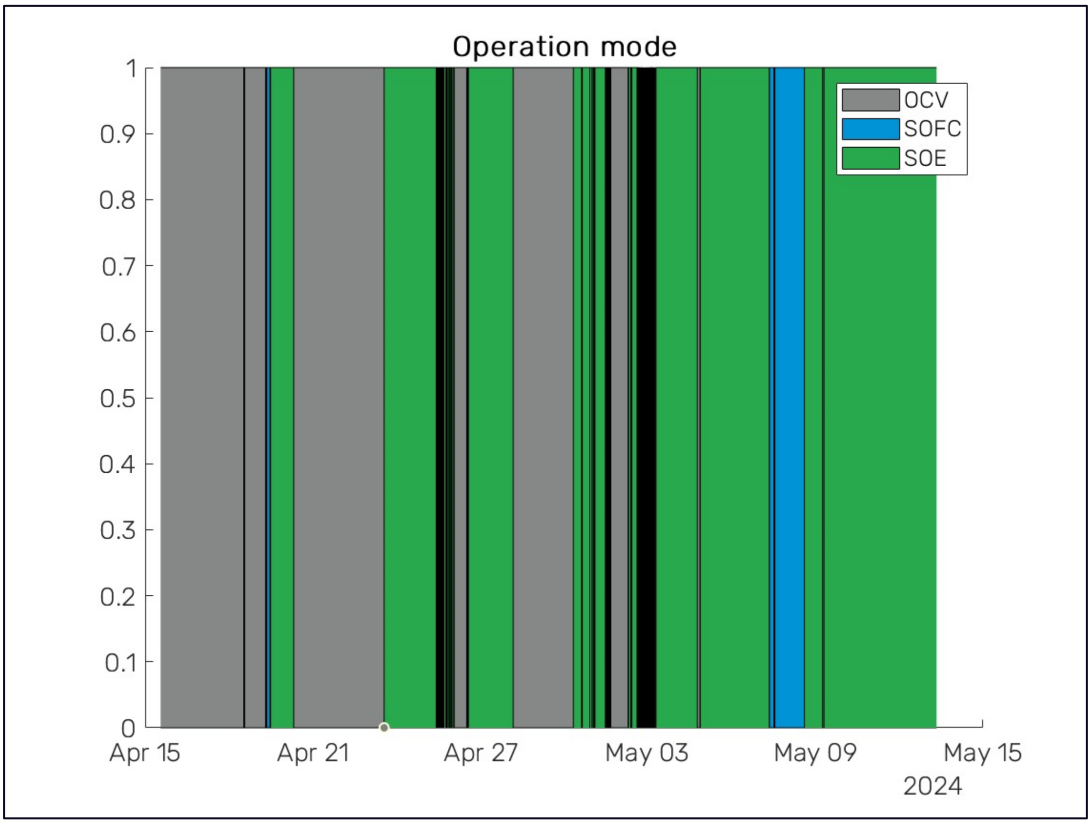

Figure 4: time distribution of the different operating modes: OCV includes hot stand-by and idling; SOE corresponds to hydrogen production in electrolysis mode and SOFC to co-generation of hydrogen and power from NG.

Figure 5 shows the hydrogen production levels throughout the testing campaign. As per Figure 4, the hydrogen produced through SOE is represented by the green area, and the blue area represents hydrogen that was co-generated in SOFC.

What stands out at first is the white region where no hydrogen was produced, and which corresponds to the aforementioned periods of time during which the system was idling at high temperature (i.e., hot idling). There, most actions involved solving small issues that could be identified only once the system was hot and operating for several days, and to better tune some of the control parameters. Among these, a few safety parameter thresholds capable of triggering emergency shutdowns had to be relaxed because of their originally too conservative values that ended up throwing spurious activations.

Then, looking at the production via SOE (in green), we see that more and more time was spent producing hydrogen as the campaign progressed.

The first production spike lasted 35 minutes and was intended to verify the response of the control system to a change of the operative conditions. It is followed by a second period at the beginning of which the system punctually produced more than 50 kg of hydrogen per day, which is the nominal output the system is designed for. However, it was not possible to work for long at nominal output due to the limited availability of electrical power on the testing site, and necessary adjustments of the ventilation flowrate and modification of the placement of a set of temperature sensors. Afterwards, the production rate was lowered to 45 kg/day, then 43 kg/day on the third production period, and finally down to 39 kg/day at the end of the fourth period.

Working at different production outputs was extremely instructive to understand the behaviour of the system in more detail and to identify the most sensitive control levers. All the while, we were able to refine control strategies to increase overall system efficiency at these various production levels. More information about the evolution of the system efficiency is given in Section 2.2.1.

The rest of the production periods were done at a fixed output of 33 kg/day, which corresponds to 2/3 of the nominal production output of the unit. Working at this partial load was interesting in the sense that the operative space widens and offers more room for experimentations as the system moves further away from its constraints.

On May 9, there was sufficient electrical power on the site to use the electrical heating in the system instead of the auxiliary burner, which would allow for stepping up the efficiency at the system level. Hence, the power output was raised again to 40 kg/day and the control parameters were tuned to reach the highest efficiency point within the test campaign at 39.6 kWh per kg of hydrogen produced.

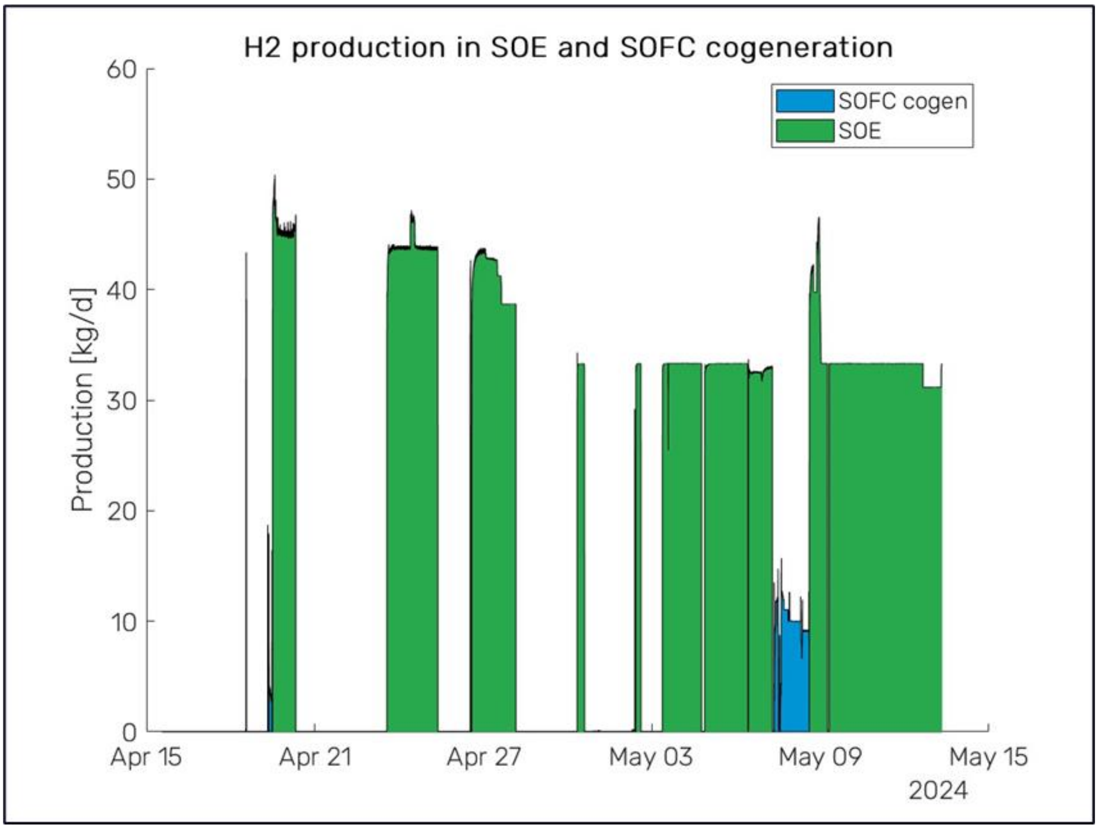

Figure 5: Hydrogen produced by the system in SOE and in SOFC cogeneration throughout the testing campaign.

Finally, on May 7 to 8 the operation was switched to SOFC co-generation and outputs of hydrogen in the range 9 to 12.5 kg per day were successfully demonstrated.

2.2.1 Test in SOE mode: overview of hot section and LSM module testing results (contribution from SolydEra)

The points covered during the test campaign are shown in Figure 6. SOE operation was demonstrated in the green region, with hydrogen outputs up to 50kg/day and a net LHV system electrical DC efficiency of more than 84.5% (< 39.7kWh/kgH_2), excluding the power required for the hydrogen compression and for generating the steam (considering steam obtained from the waste heat of a nearby process). These preliminary, not yet optimized results are fully in line with the expectations for a generation-1 LSM (limited to 75kW) and with the power limitations of the test site (resulting in limited operation time at full capacity).

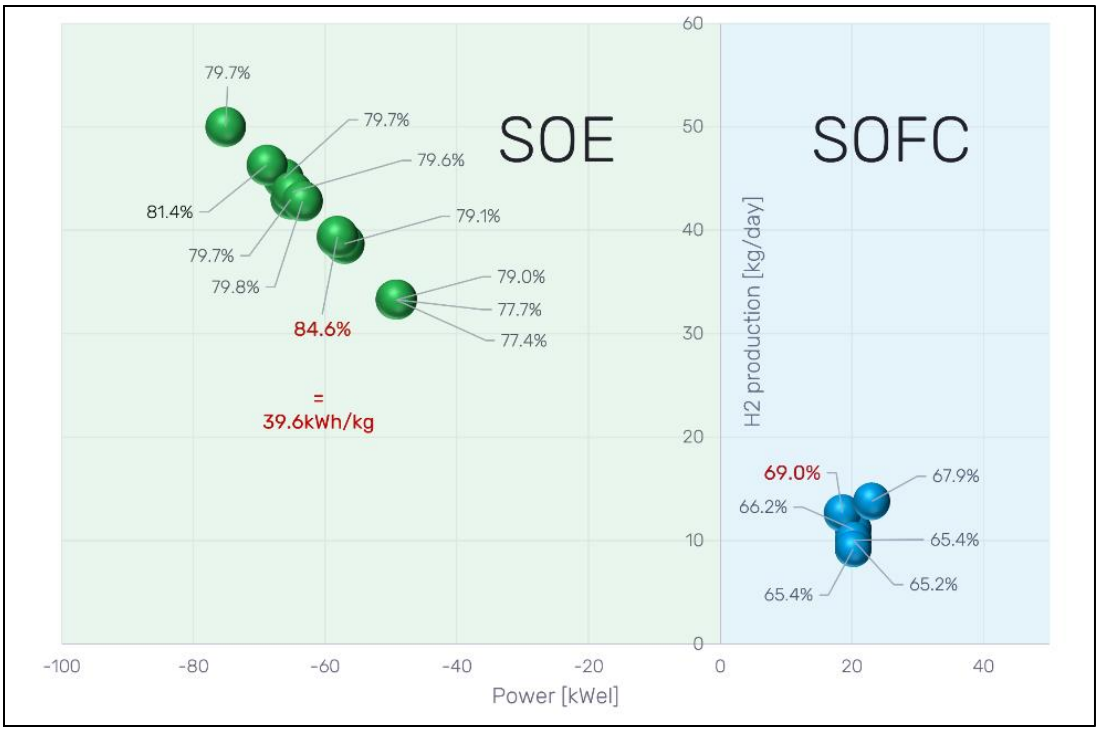

Figure 6: Operational domain and efficiencies recorded at the rSOC module level.

For SOE, the terms included in the calculation of the electrical efficiencies are the following:

$$\eta_{el_{LHV_{SOE}}} = \frac{\dot{m}_{H2_{OUT}} \cdot LHV_{H2}}{\dot{W}_{SOE_{IN}} + \dot{W}_{auxiliaries}}$$

where:

$$\dot{W}_{auxiliaries} = \dot{W}_{blower} + \dot{W}_{PLC} + \dot{W}_{electrical\ heater}$$

Modulation strategies – Fast modulation

Fast modulation strategies in SOE mode were investigated to check the capacity of the system to respond to rapidly fluctuating renewable power sources. In a multi-module plant, this would be done by switching modules from on to standby and vice versa.

In Figure 7, the hydrogen production goes from nominal to zero in approximately 5 minutes. This is first done by lowering the steam feed from 16 to 5kg/h at thermoneutral voltage. The current adapts automatically due to steam limitations before the power is finally switched off.

Conversely, the voltage is ramped up to thermoneutral in less than 1 minute while starting the ramp-up of steam flow back to 15kg/h. Having quickly reached thermoneutral voltage at approximately 100A, the current increases further as function of the increasing steam supply, reaching again the initial production level in less than 4 minutes.

As shown in the insert, the voltage of all four stacks could be ramped up rapidly (<1min.) The time lag of less than 20 seconds between each stack was done on purpose to allow for the testing team to observe their behaviour. However, the same ramp-up speed can be achieved simultaneously with a single power supply.

It has to be noted here that the ramp rate was kept moderate to allow for downstream equipment to adapt for the flow variations.

These results demonstrate that both the stacks and the modules can be operated dynamically to cope with the constraints of operation from renewable sources.

Figure 7: time response of the rSOC module to a fast modulation of hydrogen production in SOE mode

2.2.2 Test in SOE mode: overview of post processing and PSA section testing results

The post processing section mainly includes the conditioning, like steam condensation and water separation, the compression and purification of the product gases from the LSMs.

To cool down the gas and condensate the steam, a shell and coil heat exchanger - with max duty up to 10 kW - was selected.

The unit has shown good performance: the constraint on max allowed DP (< 10 mbar) was always achieved (even lower), the specifications on the outlet temperatures have been fulfilled, too.

Figure 8 shows the profiles of the cold and hot streams at the inlet and outlet of the heat exchanger.

The hot stream inlet temperature (dark blue solid line, TEC14), as expected, follows the profile of the power input (see red dotted line in Figure 8): when the LSM was operating in electrolysis mode, the produced H_2 plus the unconverted steam stream were entering the heat exchanger at a temperature level of ca 110-120 C.

The hot stream outlet temperature (dark orange solid line, TEC16) was always approaching the cooling medium inlet temperature (light blue dotted line, TEC06).

The measured DP (light green solid line) across the heat exchanger is also shown in Figure 8: the value, always below 10 mbar, was, on average, around 5 mbar.

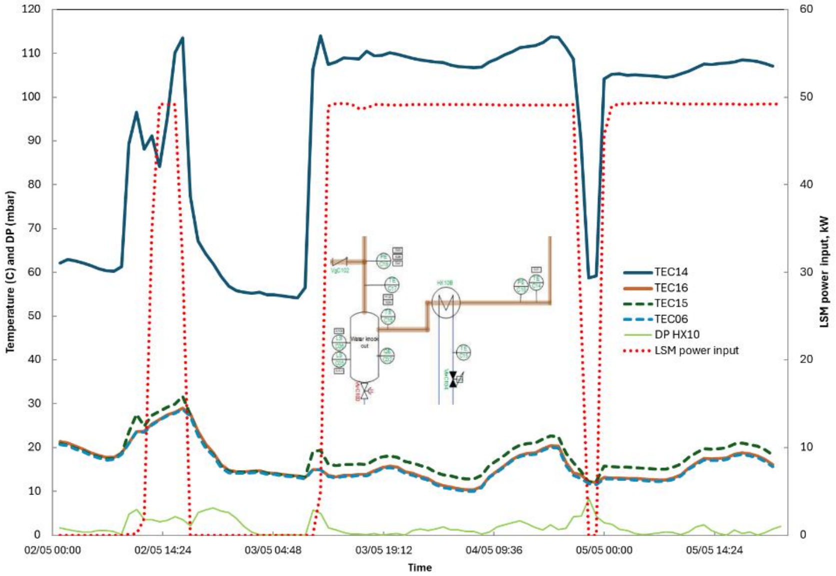

Figure 8 Steam condenser performance: temperature and pressure drop profiles

As mentioned above, the strict control of the pressure at the LSM level has been implemented downstream the gas liquid separator (WKO) by using proportional control valves.

A valve was controlling the coupling with the compressor and unit downstream, and another one was controlling the decoupling; a schematic view is shown in Figure 9.

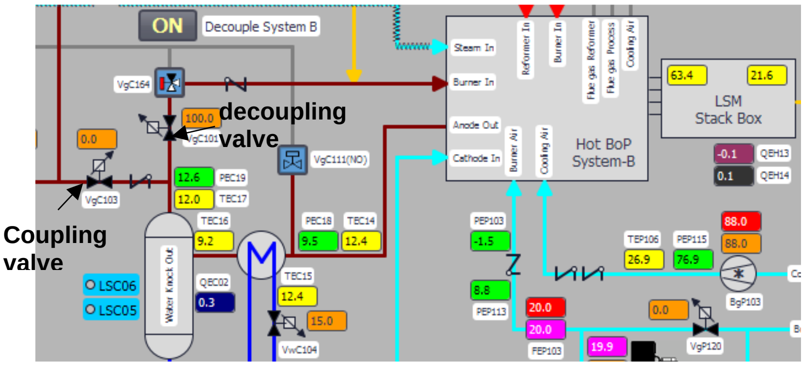

Figure 9 Schematic view of the coupling and decoupling valves at the WKO level.

The valves opening was adjusted to keep the DP between fuel and air side in the LSM module in the range of 5-30 mbar.

Figure 10 shows the pressure profiles during operation in SOE mode, both when the LSM module was coupled with the compression and PSA unit and in decoupled condition.

The pressure control was very smooth: even during H_2 production modulation, by increasing or decreasing the power input and steam flow rate toward the LSM, no significant pressure variations were observed. The LSM DP (grey solid line) was almost constant, at ca. 12 mbar, while the pressure at the WKO level (yellow solid line) was kept in the range 10-30 mbarg.

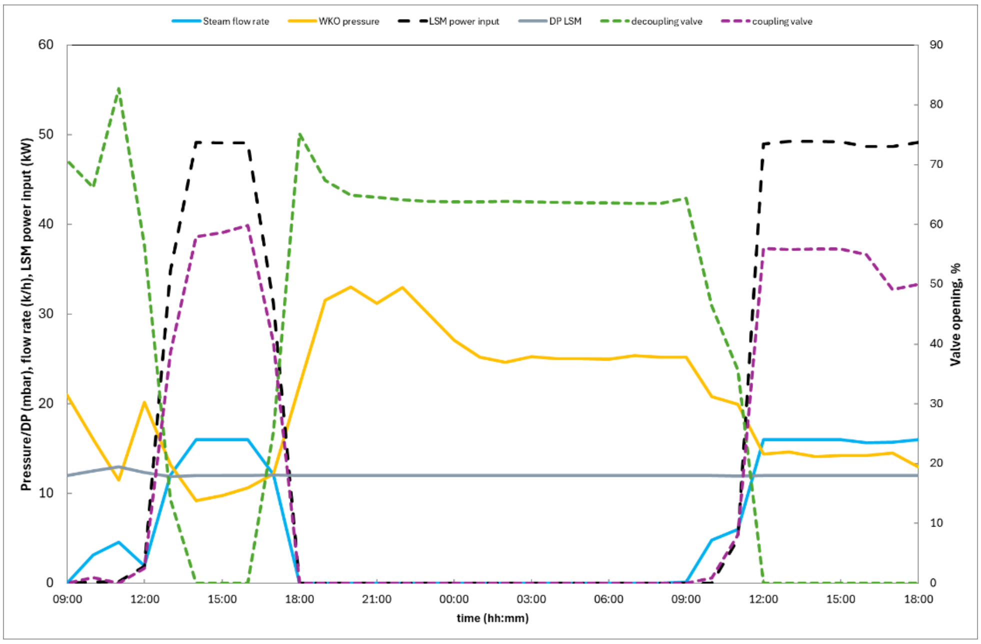

Figure 10 Overview of pressure profiles during operation in SOE mode

As already mentioned, a particular attention was paid to the coupling and decoupling of the LSM module with the compressor. Figure 11 shows a detailed overview of the profiles of pressure and valve opening during coupling and decoupling with the H_2 compressor.

Each valve has its own PID control and if the state is changed, for instance, coupling is launched then the controls are programmed so that the decoupling valve (green dotted line) starts to close with a constant ramp, while the pressure control (PID) of coupling valve (purple dotted line) is activated. For the decoupling phase, the approach is vice versa. This has led to a quite smooth pressure control, with minor pressure fluctuation in the water knock out and very little differential pressure deviations in the LSM.

The opening of the compressor recycling valve (light blue dotted line) is shown in Figure 11, too. This valve controls the compressor suction pressure: it can be noticed as it basically follows the pressure profile at the WKO.

When the LSM module and the PSA unit are decoupled and the compressor is running, the recycling valve is used to recycle all the gas back to the compressor inlet. When the coupling is launched, the compressor receives the fresh make up gas from the LSM module and thus the recycling valve starts to close. However, since the compressor is designed for a larger flow rate (based on the H_2 production from two LSM modules), the recycling valve always stayed partially open, to keep the suction pressure at the desired set point value (ca. 5 mbar).

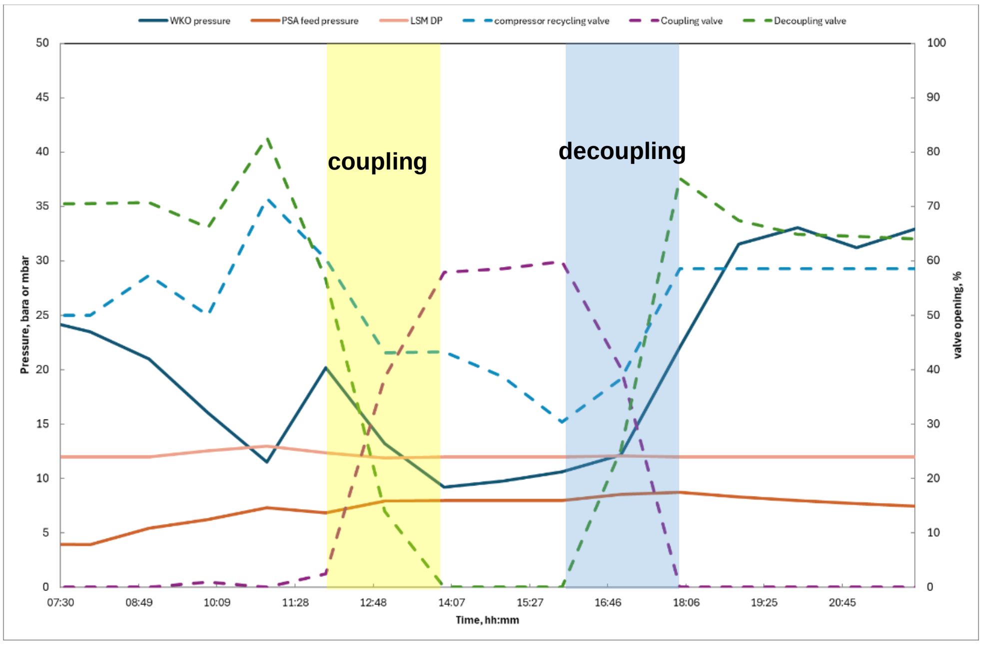

Figure 11 Coupling and decoupling with H_2 compressor: pressure and valve opening profiles

The results of the testing of the PSA unit during operation in SOE mode are shown in Figure 12 to Figure 14.

A detailed view of the pressure profiles inside the 4 PSA vessels is shown in Figure 13.

The main operating parameter for a PSA unit is the cycle time: the latter is defined as the time that the stream to be purified spends in the vessel during adsorption phase.

Test with different cycle times were performed to investigate the impact on the achievable purity. Typically, by reducing the cycle time, the H_2 production decreases, as well as the yield, while the purity increases.

As reported in Figure 13, the cycle time was reduced from 4 minutes to ca. 2 minutes and samples of the produced H_2 were taken during this phase. The achieved purity was in line with the target: the water content was below the detection limit and the N_2 was < 100 ppm_v.

During the testing phase, different PSA operating pressures have been also tested: in particular, as shown in Figure 13, the absorption pressure was increased from 8 to 9 bar_a.

In principle, by increasing the ratio between absorption and desorption pressure the yield can be increased. No significant changes were observed in the investigated pressure range, likely because there were no further adjustments on the PSA operational scheme that could have actually make effective the pressure increase (e.g., adjust the purge pressure).

The overall pressure profiles in the PSA vessels during a complete one day of testing are shown in Figure 14: it can be observed as the PSA operated stationary, in stable condition.

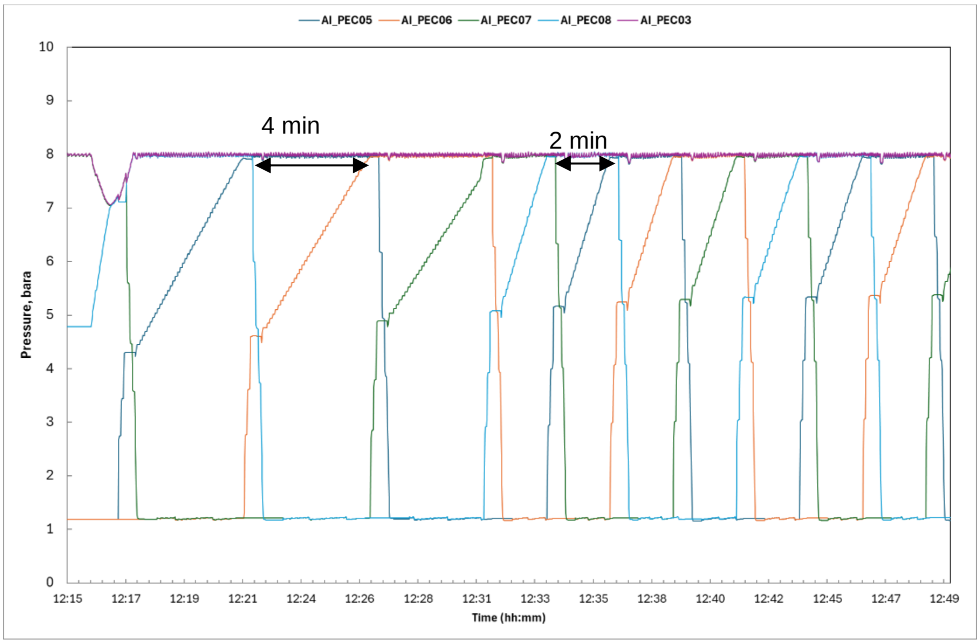

Figure 12 Detailed overview of the pressure profiles in the PSA vessels at different cycle time

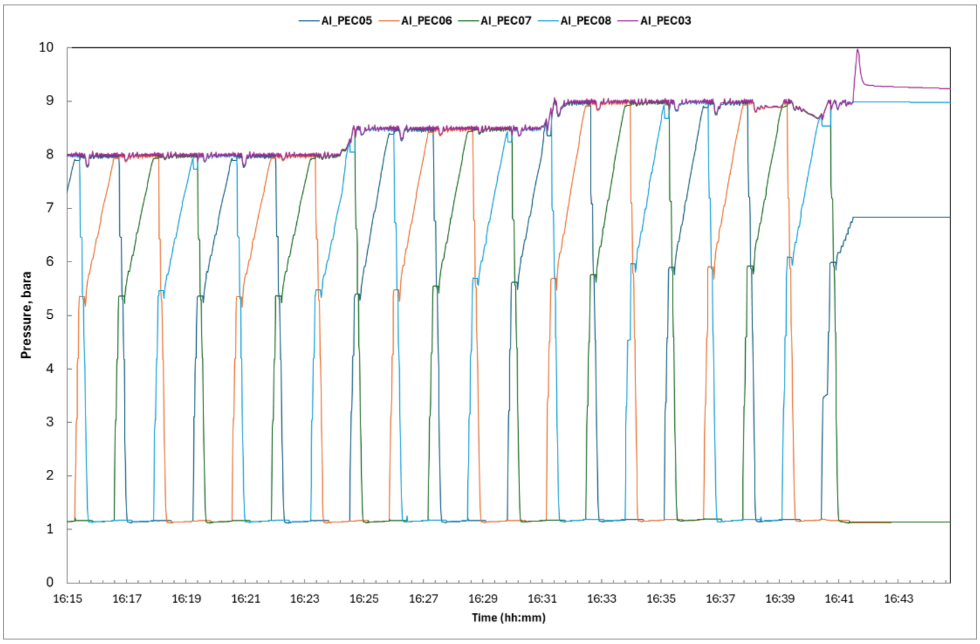

Figure 13: Pressure profiles in the PSA vessels operated at different adsorption pressures

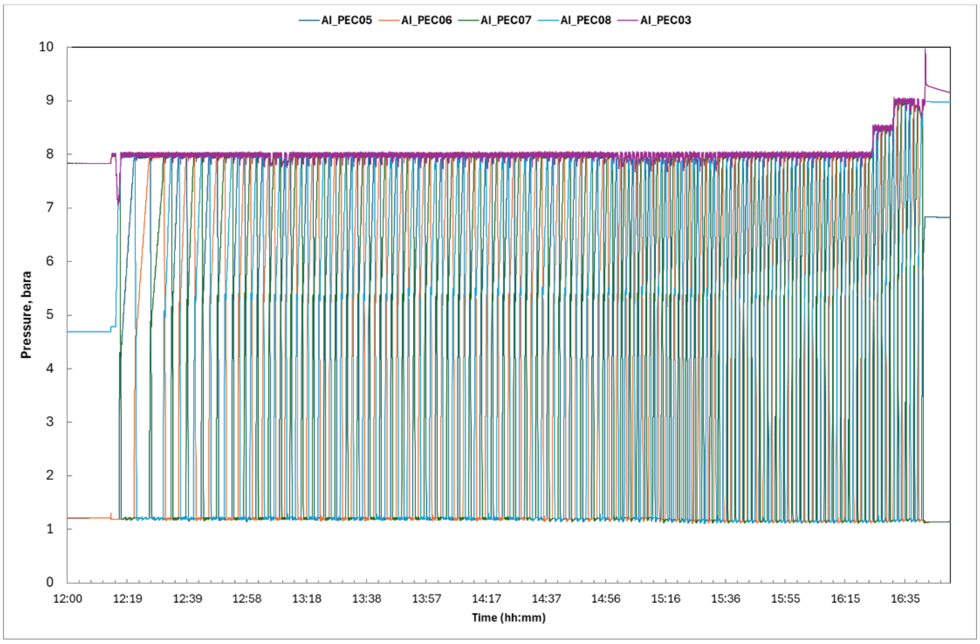

Figure 14 Overall pressure profiles in the PSA vessels during one day of testing

The performances of the purification and recovery section have been evaluated in terms of PSA yield and purity of the produced hydrogen.

The PSA yield (purple solid line in Figure 15) is defined as the ratio between the flow rate of the recovered H_2 (green solid line in Figure 15) and the H_2 in the PSA feed flow rate.

As predicted by the PSA modelling results, the overall PSA yield increases by recycling the PSA off gas stream. In SOE operation, the PSA off gas stream mainly consists of unrecovered wet hydrogen: by recycling that stream back to the PSA feed is possible to further increase the net H_2 recovery. The PSA off gas recycle is done by opening a recycle valve implemented downstream the PSA off gas vessel.

Figure 15 clearly shows the overall PSA yield increase when the recycling valve starts to open (see light blue dotted line), although the actual production from the LSM module was kept constant (see dark dotted line).

The yield increased from 45% to ca. 85%, confirming the relevant impact of the recycle implementation on the system performance. It is expected that the yield can go above 90% by means of further tuning of the cycle time and of the amount of recycled off gas stream.

For what concerns the quality of the produced H_2, the results of the gas sampling and analysis confirmed the capability of the designed PSA unit to produce H_2 at the required purity: the water content was below the detection limit and the nitrogen was < 100 ppm_v. The requirement on max allowed nitrogen content for fuel cell applications is eve higher (300 ppm_v), so by increasing the cycle time the yield could be further improved.

Typically, the N_2 can come from possible small leaks from the units in the hot BoP or LSM modules.

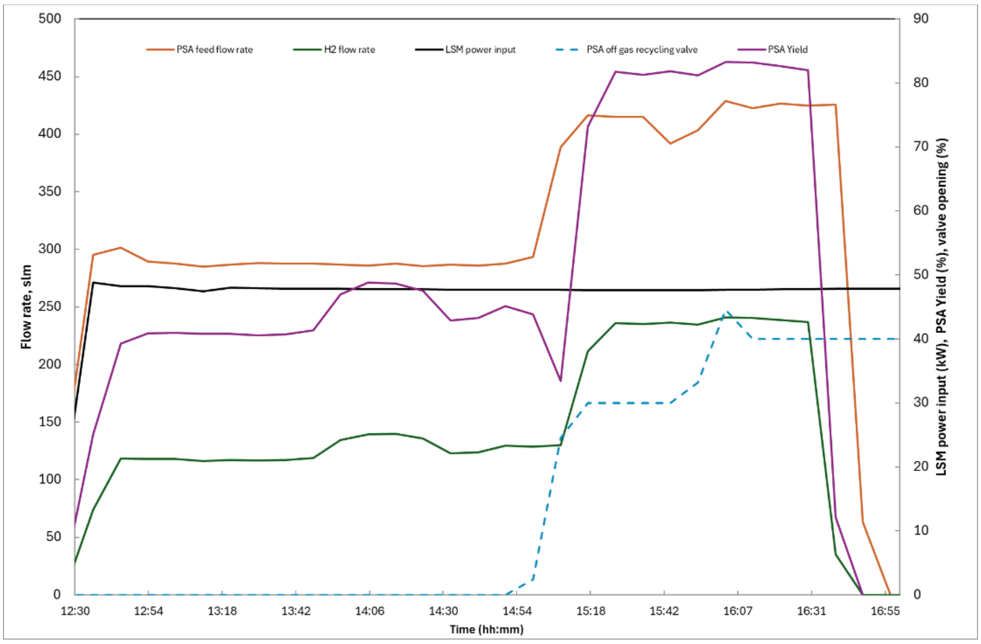

Figure 15 Overview of PSA performance during testing in SOE mode.

2.2.3 Test in SOFC mode: overview of hot section and LSM module testing results (contribution from SolydEra)

SOFC with co-generation of power and hydrogen from natural gas was demonstrated in the blue region of Figure 6. The system could deliver a combination of 23kW and 14kg per day of hydrogen and showed an LHV electrical efficiency up to 69%. For co-generation, efficiency was calculated as follows:

$$\eta_{el_{LHV\,COGEN}} = \frac{\dot{W}_{SOFC_{OUT}} + \dot{m}_{H2_{OUT}} \cdot LHV_{H2}}{\dot{m}_{NG_{IN}} \cdot LHV_{NG} + \dot{W}_{auxiliaries}}$$

where:

$$\dot{W}_{auxiliaries} = \dot{W}_{blower} + \dot{W}_{PLC}$$

2.2.4 Test in SOFC mode: overview of post processing and PSA section testing results

Although the focus of SWITCH project was on electrolysis operation, the developed system is actually able to both efficiently generate hydrogen via water electrolysis (i.e. SOE) as well as reversibly operate in fuel cell mode (i.e. SOFC).

Tests in fuel cell mode have been performed to prove the capacity of the system to use other sources (e.g., methane, bio-methane) to produce hydrogen.

In this chapter no extra details on the performance of the steam condenser and the gas water separator are reported for the operation in SOFC mode: they performed in line with the design specifications and profiles of temperature and pressure drop very similar with the ones already shown for the SOE mode (see Figure 8) were obtained.

During the testing phase in SOFC mode, as for the SOE mode, special attention has been paid to the coupling/ decoupling with the syngas compressor and to the PSA performance.

Figure 16 shows a detailed overview of the profiles of pressure and valve opening during coupling and decoupling with the syngas compressor.

The same control and coupling strategy as the ones used for the operation in SOE mode have been applied.

A quite smooth coupling and decoupling, with minor pressure fluctuation in the water knock out (blue solid line in Figure 16) and very little differential pressure deviations in the LSM (pink solid line in Figure 16) has been achieved also with the syngas compressor.

The latter, as well as the H_2 compressor, is equipped with an internal recycle loop and a control valve in that loop is used to control the compressor suction pressure.

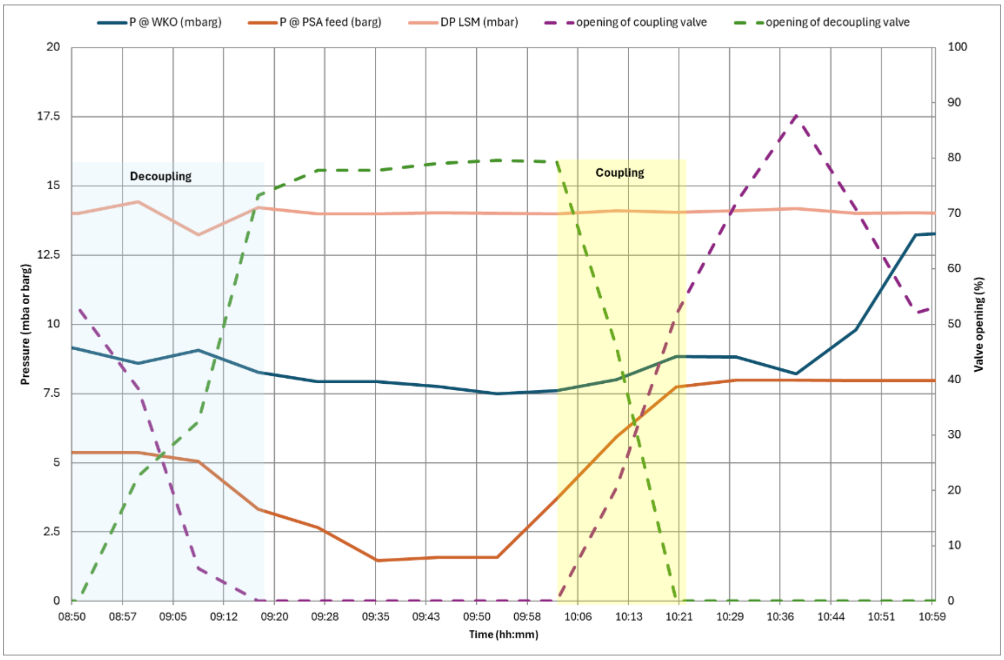

Figure 16 Coupling and decoupling with syngas compressor: pressure and valve opening profiles

The results of the testing of the PSA unit are shown in Figure 17 to Figure 19.

A detailed view of the pressure profiles inside the 4 PSA vessels is shown in Figure 17. For operation in SOFC mode a cycle time of ca. 4 minutes was initially used, based on modelling results. Similarly to the operation in SOE mode, an optimal operating point can be found by tuning the cycle time. Typically, the optimal operating condition of a PSA unit compromises among the achievable purity and yield.

During the testing phase in SOFC mode, different desorption pressure values have been tested: in particular, as shown in Figure 18, by activating a vacuum pump the desorption pressure has been reduced below 1 bar_a (ca. 100 $mbar_a$).

As mentioned above, by increasing the ratio between absorption and desorption pressure the yield can be increased. Results confirmed an increase of ca. 10% on the yield value.

Finally, the overall pressure profiles in the PSA vessels during a complete one day of testing are shown in Figure 19: it can be noticed as the PSA operated stationary, in stable condition also in SOFC mode. A system shutdown occurred, at ca. 2:30 p.m., triggered by a fault error, but within less than 30 minutes it was possible to recover the system and run in production mode again.

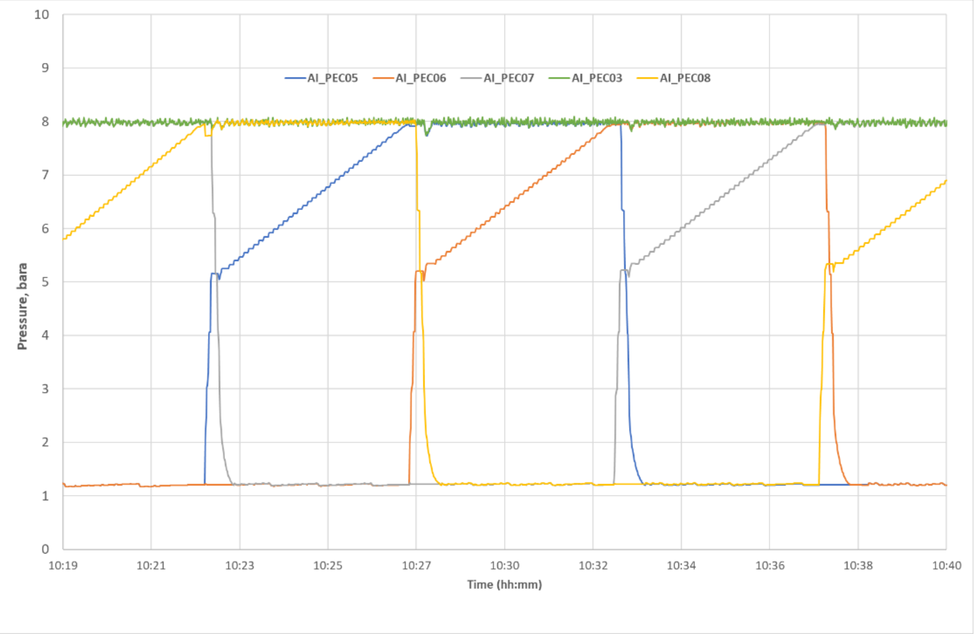

Figure 17 Detailed overview of the pressure profiles in the PSA vessels

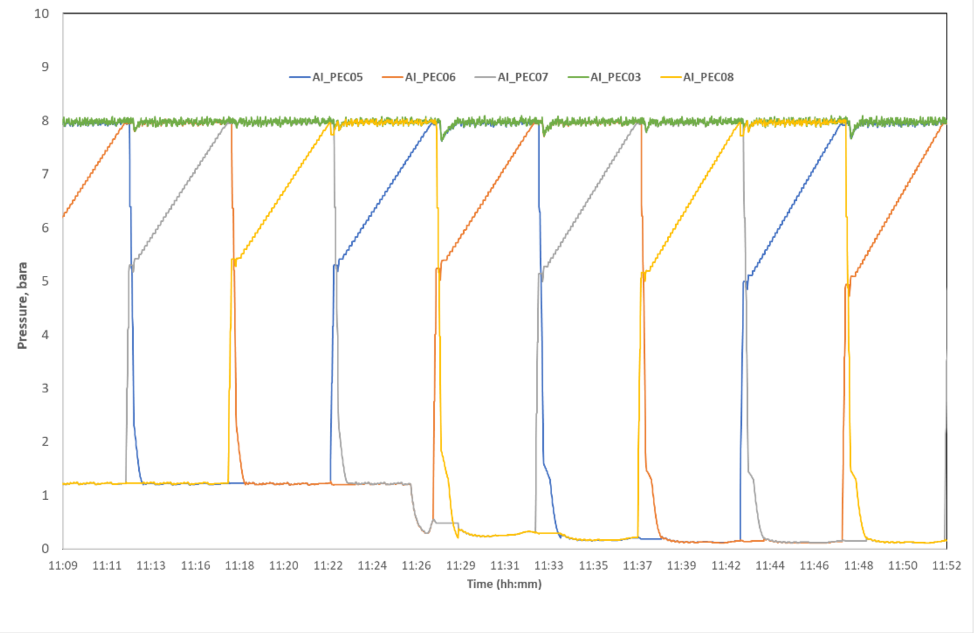

Figure 18 Pressure profiles in the PSA vessels operated at different desorption pressures

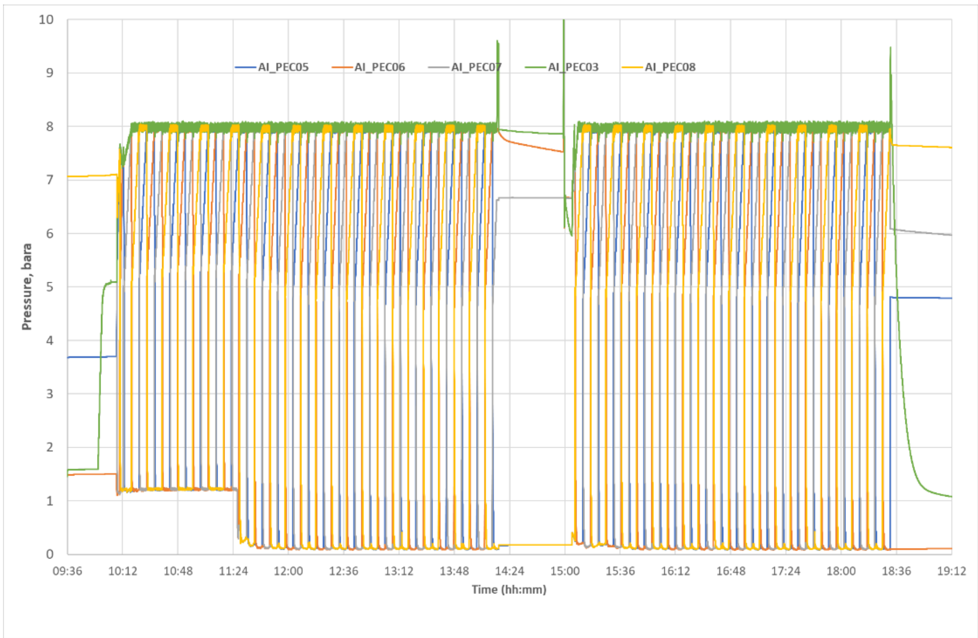

Figure 19 Overall pressure profiles in the PSA vessels during one day of testing

The performances of the PSA unit during SOFC operation have been also evaluated. A PSA yield (purple solid line in Figure 20) up to 45% has been estimated, based on an H_2 inlet concentration of ca. 60%.

The yield achieved in SOFC mode is lower than the one obtained in SOE mode but it must be highlighted that the testing in SOFC mode was less extensively investigated than the one in SOE. Practically, much higher yield could be achieved even in SOFC mode (modelling results showed value > 80%) by a proper tuning of the operating parameters (e.g., cycling time). Moreover, it is expected that a larger error from the flow measuring devices have affected the measured values in SOFC mode.

During operation in SOFC mode the PSA offgas stream is meant to be fed to the burner as lean fuel, reducing the overall NG make up.

For what concern the quality of the produced H_2, the results of the gas sampling and analysis confirmed the capability of the designed PSA unit to produce hydrogen at the required purity.

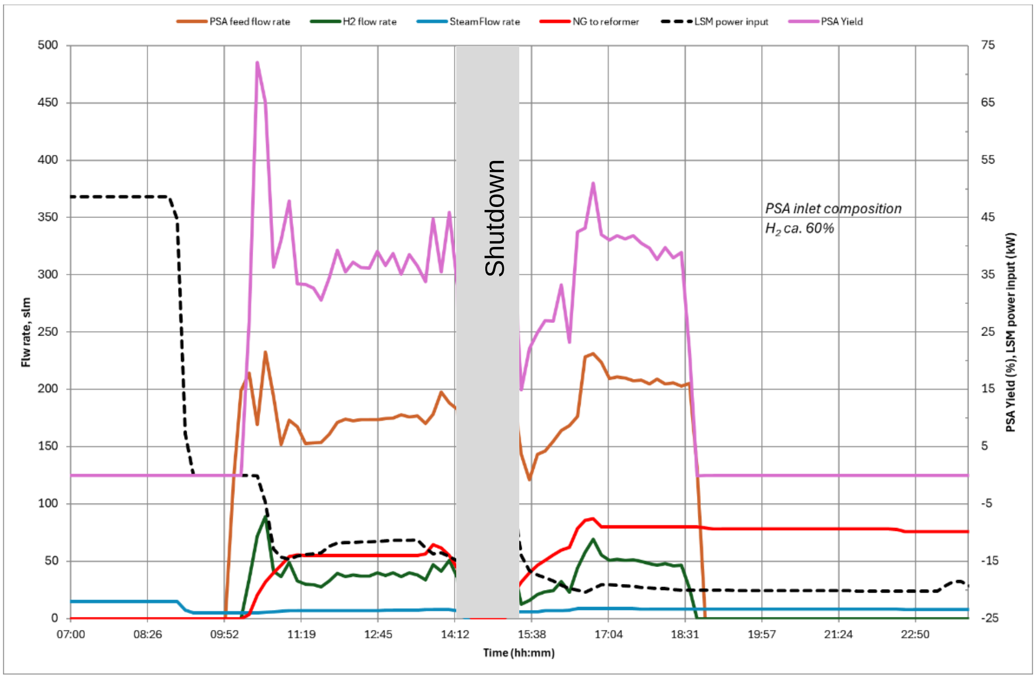

Figure 20 Overview of PSA performance during testing in SOFC mode.

2.2.5 Switching from SOFC to SOE: overview of hot section and LSM module testing results (contribution from SolydEra)

Fast switching tests – SOFC to SOE

The system showed good transition performance when going from one production mode to the other. Figure 21 shows how the system underwent a transition from SOFC co-generation – represented by the blue area – to SOE – represented by the orange area.

The module initiated a transition at 1:24am by ramping down its SOFC power production to zero, reached OCV 9 minutes later, performed a safety purge and switched the feed gases for SOE operation in 4 minutes, and went from OCV to thermoneutral voltage in 1 minute. All in all, the switch took 14 minutes.

The evolution of the inlet and outlet stack temperatures is also shown in Figure 21: the transition from a highly exothermic case in SOFC mode - which is typical for operation with hydrogen as fuel (dT~100°C) - to thermoneutral (dT~20°C) in SOE mode proceeds smoothly thanks to the thermal inertia of the stacks and the rapid switching to thermal neutral conditions in SOE mode, which minimizes operation in endothermic mode.

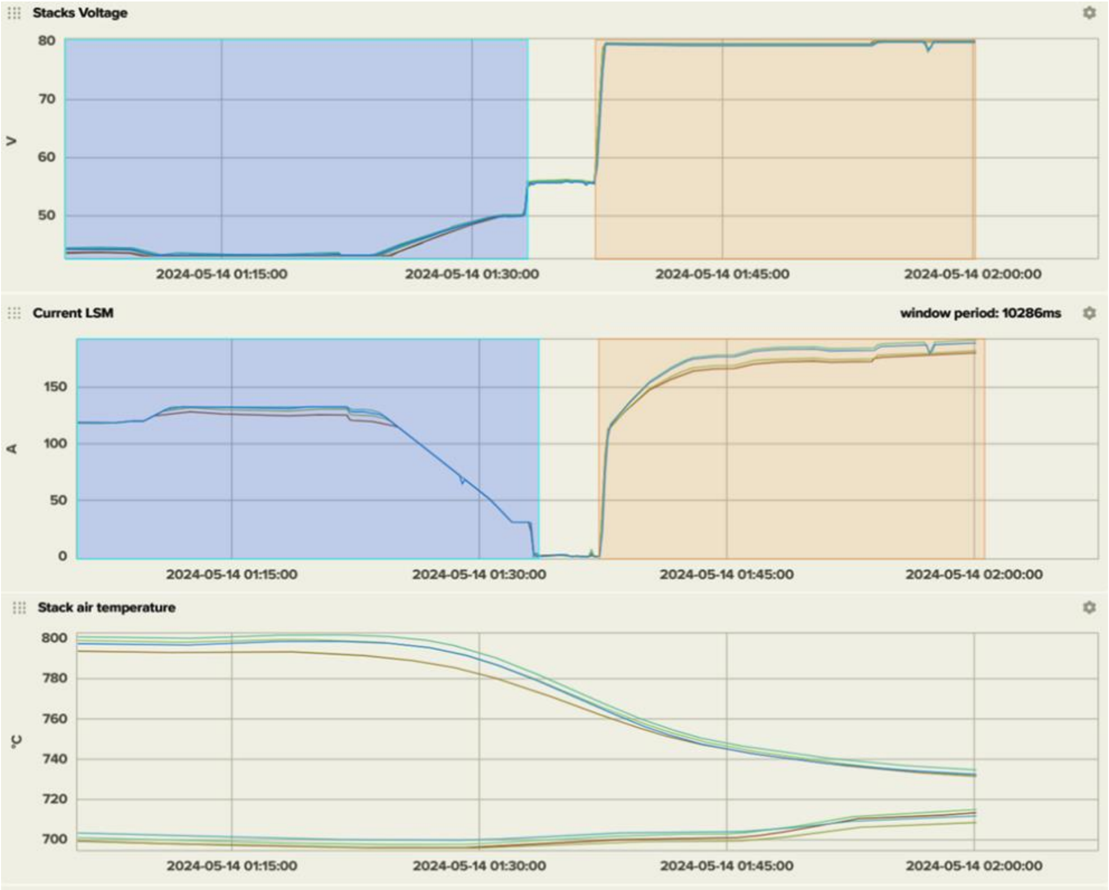

Figure 21: rSOC module fast switching between power production and steam electrolysis modes: individual stack voltages, current and temperatures versus time.

3 Conclusions

The SWITCH prototype system has been extensively tested and the results of the testing phase have been reported in this deliverable.

The realized prototype consists of two LSM and hot BoP modules (named system A and system B), with a maximum production capacity up to 100 kg/day of H_2, in SOE mode.

Due to temporary electrical power limitation at the testing site, only one system has been tested in production mode but both systems have been debugged, pre-tested and pre validated.

Including the pre validation testing phase more than 1000 hours of testing have been achieved.

During the validation testing phase, all the tests have been performed with the real LSM.

SOE and SOFC modes have been both tested; per each mode, an overview of the main test results of the hot BOP and LSM module as well as the post processing and PSA unit has been reported.

A PSA yield up to 85% has been achieved in SOE mode, with a H_2 purity in line with the target, confirming the capability of the developed prototype to produce pressurized hydrogen at the required purity via steam electrolysis.

Due to the particular power distribution of the SWITCH prototype, partially coming from the grid and partially from an extra power generator, it was not possible to measure the total power consumption. However, excluding the steam generation and compression, a power consumption of ca. 52 kWh/kg of produced H_2 has been estimated.

Beside the achieved production and system efficiency, other two key exploitable results to be mentioned are:

- very smooth control of the pressure in the SLM
- easy and very functional control of the coupling/decoupling procedures of the LSM with the compressor and PSA unit downstream.