DEMOSOFC

Project n° 671470

"DEMOnstration of large SOFC system fed with biogas from WWTP"

Deliverable number 5.7

Report on the operation, management, control and maintenance of the DEMOSOFC system on the long run

Due Date of Delivery	M62
Actual Submission Date	08/02/2021
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Work package	WP5
Dissemination Level	PU
Nature	R
Version	1.0
Total number of pages	32

Abstract:

This document is the final report on the DEMOSOFC plant. It summarizes public information for what concerning the DEMOSOFC operation, management, control and maintenance activities.

Keyword list: biogas, SOFC, WWTP, management, control, operation, demo site

Summary

1. Analysis of the operation on the long run

The present chapter summarizes the results of the SOFC1 and SOFC2 operation during the entire DEMOSOFC project, focusing on the performance (electrical and thermal efficiency) and the influence of biogas quality. The methodology used for the evaluation is provide in Appendix A.

1.1 Overview

Two SOFC units manufactured by Convion were operated in the waste water treatment plant of SMAT in Collegno (Torino, IT) during the DEMOSOFC project (Figure 1 and Figure 2). The first unit started its operation in October 2017, while the second unit was started in October 2018. During the project, these units were operated for a total of 14166 hours on site at various operating points.

Figure 1. Collegno waste water treatment plant in Torino, Italy.

Figure 2. The two SOFC units of Convion installed on site.

1.2 The first SOFC unit performance

In Figure 3 the data analysis results of the first system with a nominal power output of 53 kWe are shown over the whole project. During the project, the first system was operated for a total of 7100 hours with an average power production of 39 kW_e and heat production of 23 kW_{th}. It should be noticed that these figures are not beginning-of-life figures, but averages over the whole operation period, containing all steady-state operation of at least 4 h. In Figure 3a) the total electric efficiency and the total efficiency vs the electric net power output from 0 to 55 kW are illustrated. The red squares in Figure 3a) represent the mean values of the electric efficiencies of the corresponding electric net power output segment during stable operation. The SOFC system was operated at an electric net power output range between 7 kW and 55 kW. In this range the electric efficiency stayed stable between 20% and 55%. The black crosses show the total efficiency mean values which were between 45% and 85% during stable operation. The larger deviation of the total efficiency in comparison to the electric efficiency was caused by heat recovery flow rates not being optimized in the beginning of the operation. The stable and high electric efficiencies over the operating net power output range illustrate an advantage of fuel cell technology in comparison to micro turbines and internal combustion engines. The results show that power modulation according to the site demand is possible while maintaining high efficiencies using SOFC systems.

In Figure 3b) and 3c) the distribution of the electric net power output is shown. For the majority (80%) of the operating time the system was at 45…55 kW of net electrical power output with electrical efficiency of 45…55% and total efficiency of 65…85%.

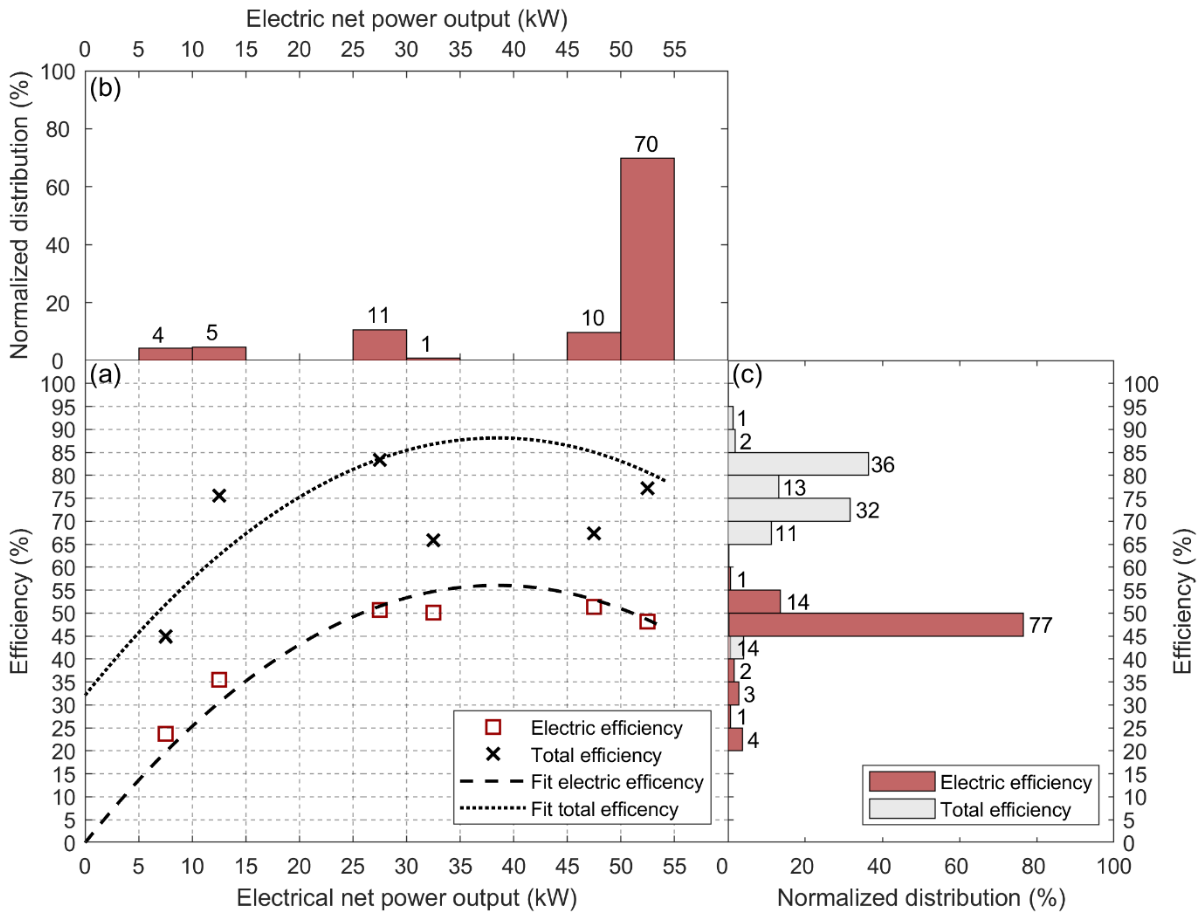

Figure 3. Performance of the 1st SOFC unit over the whole project. The combined standard uncertainty for electrical efficiency is ±3% and ±6% for the total efficiency.

1.3 The second SOFC unit performance

In Figure 4 the data analysis of the second system is illustrated over the whole project. The second unit was operated for 10200 hours during the project, with average power output of 37 kW_e and average thermal power of 26 kW_{th}. It should be noticed that these figures are not beginning-of-life figures, but averages over the whole operation period, containing all steady-state operation of at least 4 h. The net power output was mostly (~83%) at 35…45 kW with electrical efficiency of 45…55% (red squares Figure 4a)). The total efficiency at this power range was 80…90% (black crosses, Figure 4a)).

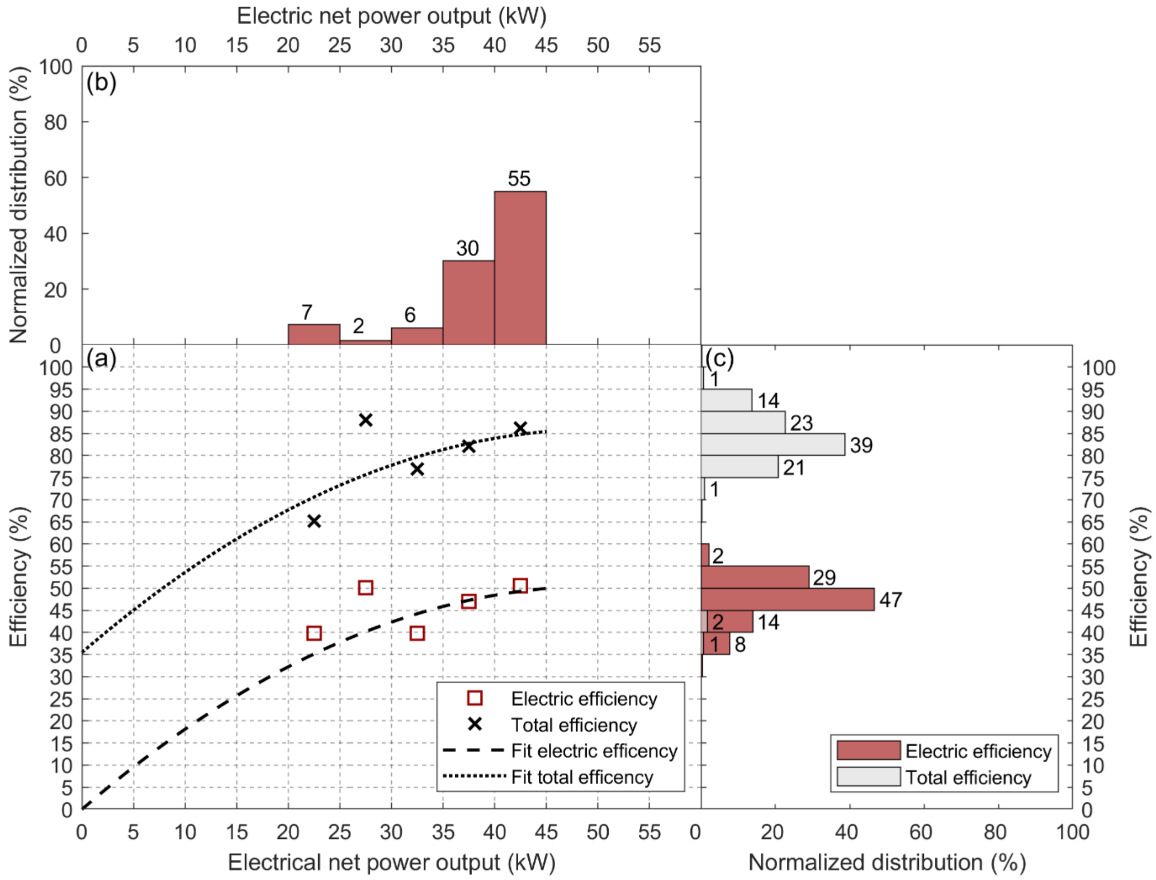

Figure 4. Performance of the 2nd SOFC unit over the project. The combined standard uncertainty for electrical efficiency is ±3% and ±6% for the total efficiency.

The lower electric net power output compared to unit #1 was caused by the fact that the systems had different stack technologies and therefore not identical amount of stack DC power. The dashed and dotted black lines which represent the electric efficiency and total efficiency as a function of the electrical net power output have a similar shape as the corresponding lines of the first system (compare Figure 3a)).

In general, the second system was operating more in the nominal power output range compared to the first system. This is mostly due to the increased site- and system maturity during the project. This caused also less interruptions and more optimized heat recovery loop control, which resulted in a more stable total efficiency of the second system in comparison to the first system. These are good indications for future installations.

1.4 Effect of biogas quality on SOFC efficiency

Figure 5 presents electrical efficiencies of both units plotted against methane concentration in the biogas. It can be noticed that the electrical efficiency is quite independent on biogas methane concentration. This is a very positive result for the SOFC technology as one of the key arguments has been the ability to utilize different fuels to produce power and heat.

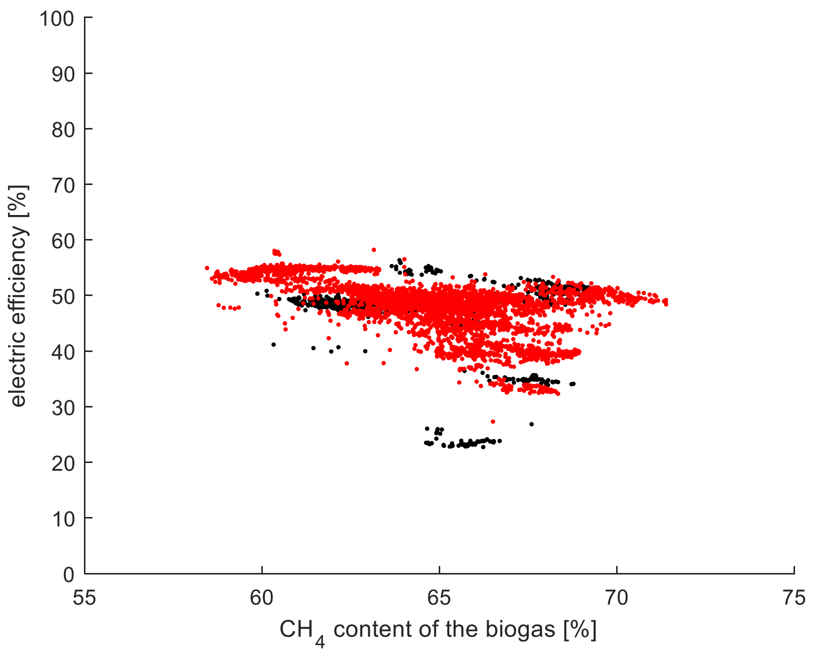

Figure 5. Electrical efficiency of both SOFC units (black: 1st unit, red: 2nd unit) as a function of methane content in biogas.

1.5 Discussion

Figure 6 contains a summary of the main performance figures over the DEMOSOFC project. The first SOFC unit was operated on site for over 7100 hours with average electrical efficiency of 52% and total efficiency of 81%. The second SOFC unit was operated on site for over 10200 hours with average electrical efficiency of 46% and total efficiency of 80%. The total number of hours for the DEMOSOFC plant (14166) is different from the sum of the 2 SOFC modules because, for a limited period in Spring 2020, the 2 modules were running in parallel and consequently the hours have been considered only one time in the DEMOSOFC plant operating hours.

The main conclusions from the data-analysis of the two DEMOSOFC systems operated during the project can be summarized as follows:

1. The systems reached average nominal point electrical efficiencies in excess of 50% and total efficiencies of over 80% which can be considered a good result for this first-of-a-kind installation.
2. Both units showed that the electrical and thermal efficiencies were independent of methane concentration in biogas. This result highlights the benefits of SOFC technology in utilizing lean fuel gases for power and heat production.
3. Both units have been operated at different power loads (partial loads) maintaining good values of efficiencies, and this is a good advantage compared to competitors such as thermal engines.
4. Installation site and auxiliary services such as grid connection and biogas cleaning and supply are very important in this kind of installations. In the beginning of the project these caused several incidents which probably caused additional degradation to the first system.
5. The two first-of-a-kind SOFC systems were successfully operated and maintained during the project and the operational data of the second system shows a marked improvement in reliability compared to the first system. This is a very positive sign for future installations.

		Hours ON - h	Fuel consumption - kWh	Electrical Energy - kWh	Thermal Energy - kWh	Electrical efficiency (%)	Power/Heat Ratio	Capacity factor
SOFC 1	Oct-Dec 2017	1 105	85 087	46 849	19 521	55 %	240 %	
	Feb-Mar 2018	336	24 742	12 371	8 247	50 %	150 %	
	Apr-Jun 2018	1 640	167 445	85 640	55 080	51 %	155 %	
	Aug 2018	63	5 698	2 849	2 295	50 %	124 %	
	Sep-Oct 2018	785	47 111	22 609	10 625	48 %	213 %	
	Feb-Ott 2020	3 214	229 514	106 623	70 884	46 %	150 %	
	Tot. SOFC1	**7 143**	**330 083**	**170 319**	**95 768**	**52 %**	**178 %**	**50 %**
SOFC 2	Oct-Dec 2018	1 291	101 104	55 601	35 995	55 %	154 %	
	Feb 2019 -Ott 2020	8 946	710 397	320 568	233 750	45 %	137 %	
	Tot. SOFC2	**10 237**	**811 501**	**376 170**	**269 745**	**46 %**	139 %	**58 %**
	Tot. DEMOSOFC	**14 166**	**1 141 585**	**546 488**	**365 512**	**48 %**	**150 %**	**49 %**

Figure 6. Main figures related to electrical and thermal power as well as efficiencies over the whole DEMOSOFC project.

2. Management of the DEMOSOFC plant

The DEMOSOFC plant (Figure 7) is located in the SMAT Collegno waste water treatment plant (WWTP), in via Don Lorenzo Milani 12, Collegno, in the Torino premises.

The plant is composed of three main sections:

- The biogas compression and purification system, purchased by SMAT (green container in the pictures)
- The SOFC modules, supplied by Convion during the project
- The heat recovery system, for transferring the heat from the SOFC modules to the sludge entering the anaerobic digester.

These 3 main sections are then operated through an overall control system and connected to the grid through a dedicated electrical system (see deliverable D2.4 – Detailed engineering of the DEMO – for details).

Figure 7. Aerial view of the DEMOSOFC plant.

The plant was managed – on a daily basis – by a group composed of the following partners:

- SMAT: technical operators of the Collegno WWTP and engineers from the internal SMAT engineering company (called Risorse Idriche);
- POLITO: researchers from the STEPS Polito research group;
- Convion: experts and technicians from Convion company.

SMAT technical operators were trained through a 2 days training events managed by POLITO (M. Gandiglio):

- Training of SMAT personnel @ Collegno: December 12th, 2017
- Training of SMAT personnel @ Collegno: February 14th, 2018

The communication flow through the three entities were performed through email exchange and through a dedicated DEMOSOFC WhatsApp group which were used for urgent matters and to exchange pictures and data related to day-by-day problems and maintenance activities.

2.1 Feedback from the companies

At the end of the project, a questionnaire was shared with the SMAT and Convion technicians to understand their opinion on the project and get feedback and lesson learnt. The same questionnaire was also answered by POLITO. The questionnaire was including 5 different questions. An overview on the answers received is provided below.

What were the most critical points and difficulties related to the management of the SOFC modules and the system?

- Optimization of the layout and control of the biogas line, including the cleaning and compression system (which was strongly influenced by the safety analysis which requested major changes during the design phase).
- Addition of the new DEMOSOFC section in the management, maintenance and availability (outside working hours) structure of the SMAT WWTP.
- Companies were not used and prepared to the experimental nature of the project, especially at the beginning. Despite the support of the Politecnico in the planning phase, SMAT lacked experience in this type of work.

- The control (in terms of set point) of the SOFC modules was the done always by Convion remotely while the management of the inlet and outlet sections (respect to the SOFC) was carried out by SMAT.
- Language barrier between SMAT onsite technician and Convion technicians (partially solve through the use of the WhatsApp group were written instructions could be translated).
- Lack of a suitable training activity for the whole group from Convion personnel, in terms of physical training course and user manual/ documentation related to the operation and maintenance of the SOFC modules (this difficulty was also enhanced by the language barrier).
- Too long maintenance time, from Convion side for what concerning the SOFC modules.

Have you seen any criticalities in the management of the SOFC module and in the relationship with SMAT/Convion (taking into account that here we were within a collaborative project)?

- Some critical issues arose due to the geographical distance between the CONVION and SMAT offices, difficulties that have been accentuated in the last year as a result of the COVID pandemic, and which have led to delays in interventions and an extension of downtime of the SOFC modules.
- Relations with Convion staff have been more than excellent despite the language difficulties. A trust was established on their part that allowed remote maintenance overcoming great difficulties in the continuity of operation, a delicate point on the life of the stacks.

Which were, based on your experience, the most critical components of the system (SOFC modules, Biokomp, heat recovery, sludge, etc.) and why?

- The SOFC modules, especially SOFC1, due to their sensitivity to the numerous stops due to the upstream components, which occurred at the beginning of the management of the system and resulting from the necessary set-up of the system (due to the innovative nature of the project).
- The rest of the plant has been critical in the first months of operation, when the different equipment and the control system were tested and optimized (learning by doing). After this

initial period, the biogas compression and purification system, the heat recovery and the control system worked quite fine.

In creating a similar system from scratch (replication of the DEMOSOFC concept) what could be done better / differently?

- An aspect to improve is the sizing of the biogas clean-up plant, which in the DEMOSOFC project proved to be oversized, increasing the costs of building the plant.
- The initial budget available did not allow SMAT to refine some control aspects during and after the design which in normal operation, not research, must certainly be implemented.
- An increased and improved control system.
- Correct scheduling of ordinary maintenance and good storage and rapid supply of spare parts and raw materials.
- Reduce the distances between the SOFC units and the uses (electrical connection and heat recovery) as much as possible.
- Reduced cost of the pipeline (currently underground with a carriageable coverage)
- More involvement, from the beginning, of all the technicians, in the project and technology details. Training course with the company and high level of detail user manuals are essential.

How do you evaluate the control system implemented for DEMOSOFC and what were the main criticalities?

- The control system of the plant was not integrated with the remote control system of the Collegno WWTP plant since the latter was being replaced and updated during the same years.
- The control system requested different months to be optimized compared to the initial logics developed by SMAT and POLITO. After the first year, the control system was behaving in a more stable way and it was not generating any troubles in the operation of the DEMOSOFC system.
- The control system was designed by POLITO staff and implemented by an external company. SMAT personnel was involved probably late in the management of this control

system and the structure and the logics were really different from the standard one available in the Collegno WWTP control system.

- The management of the SOFC units which were – for more than 90% of the operation time – remotely controlled (in terms of set point) by Convion.

3. Control of the DEMOSOFC plant

3.1 Control system description

Different sensors along the whole plant allow measuring 91 operative parameters and 29 electric parameters, which are automatically logged by the DEMOSOFC software every ~10 minutes.

A numbered list of measured data is available in Appendix 1.

Data are collected in different ways by the DEMOSOFC Programmable Logic Controller, directly connected with the different field sensors and with CONVION PLC in Finland. The structure of the local PLC is represented in Figure 8. In particular:

- Parameters about fluids and equipment controlled by SMAT are measured by 35 sensors disposed along the DEMOSOFC plant.
- Convion Programmable Logic Controller in Finland directly receives complete data from the module and forward 42 unclassified measures to the DEMOSOFC PLC. These data are labelled as ETH.
- The two electrical cabinets of DEMOSOFC plant and WWTP submit a total of 30 measures to the PLC.

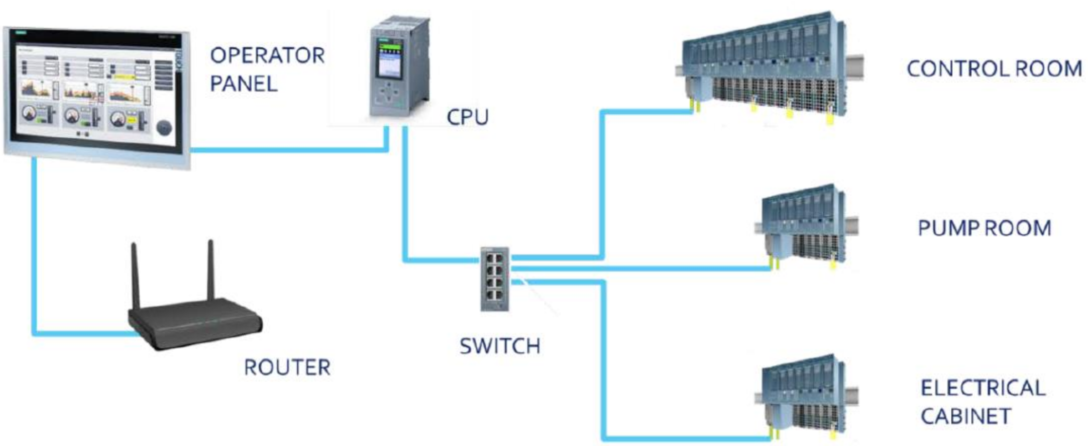

Figure 8. DEMOSOFC Programmable Logic Controller.

Globally the operator panel provides:

- 38 electrical measures, including active and reactive power, power factor, voltage, current and frequency.
- 38 temperature measures of the module, the fuel line and the different heat exchangers.

- 17 flow rates including fuel, air, technical gas, sludge and water-glycol mix.
- 11 pressure measurements of fuel, air and water-glycol.
- 8 set points of the couples of pumps associated with each heat exchanger.
- 3 timers, measuring the loading hours of each module.
- 2 measurements of the CH4 content in the fuel.
- Biogas holder level, ambient air humidity, and speed of Bio-komp compressor

In addition to this, the biogas is analysed by a Qualvista online monitoring system, based on NDIR method, which logs the concentrations of methane and pollutants in the biogas as received, in the middle and at the end of the clean-up unit. Data are logged daily about the raw biogas and every 40 minutes for the other two sampling points. This way it is possible to check when a part of the unit needs maintenance. Measures concern biogas flow (m3) and the concentrations of CO2 (%), H2S (ppm), CH4 (%), O2 (%) and siloxanes (mgSi/m³).

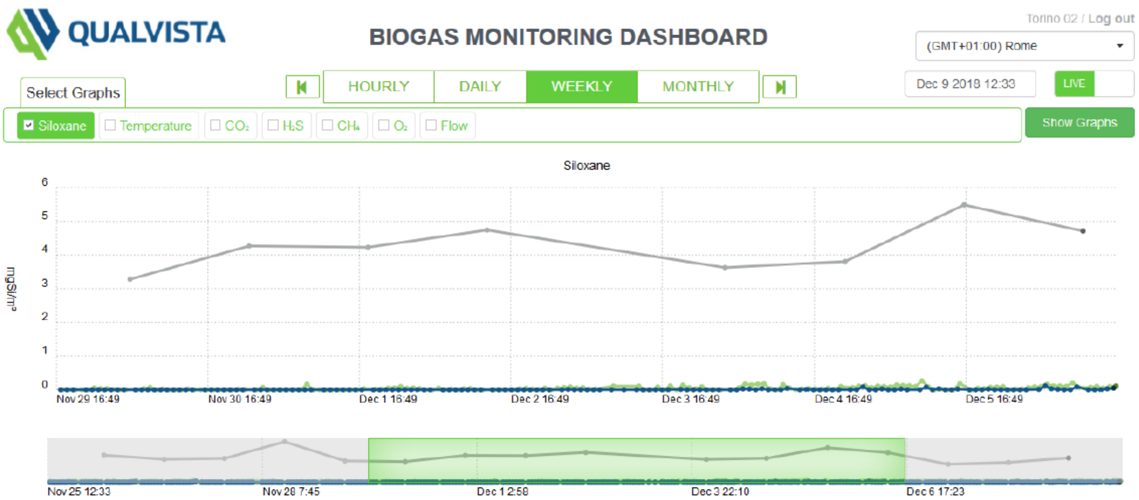

Figure 9. The Qualvista online tool.

Together with the table of data, Qualvista provides plots of the concentration of contaminants in different points of the clean-up unit with different time scales, as can be seen in Figure 9. Details on Qualvista analyzer are provided in Appendix 2.

In addition to the measures carried out within the DEMOSOFC project, SMAT provides monthly data about the quantities of natural gas and electricity purchased by the plant, together with relative prices, to compute the coverage of the SOFC plant over the WWTP balance.

The SCADA software by SMAT hourly logs many data regarding the entire WWTP, such as the rate of biogas produced, the total amount of water in the plant, the sewer sludge flow rate and its temperature.

The operators manually log the daily consumption of biogas of the two boilers, measured by one unique flow meter, and sometimes measure the composition of the biogas, of the flue gas and the auxiliary consumptions.

The complete control system layout is shown below. The complete description of the control system is available in D3.4 (Installation of the control system (hardware + software) of the complete DEMO (both electrical and thermal sections)).

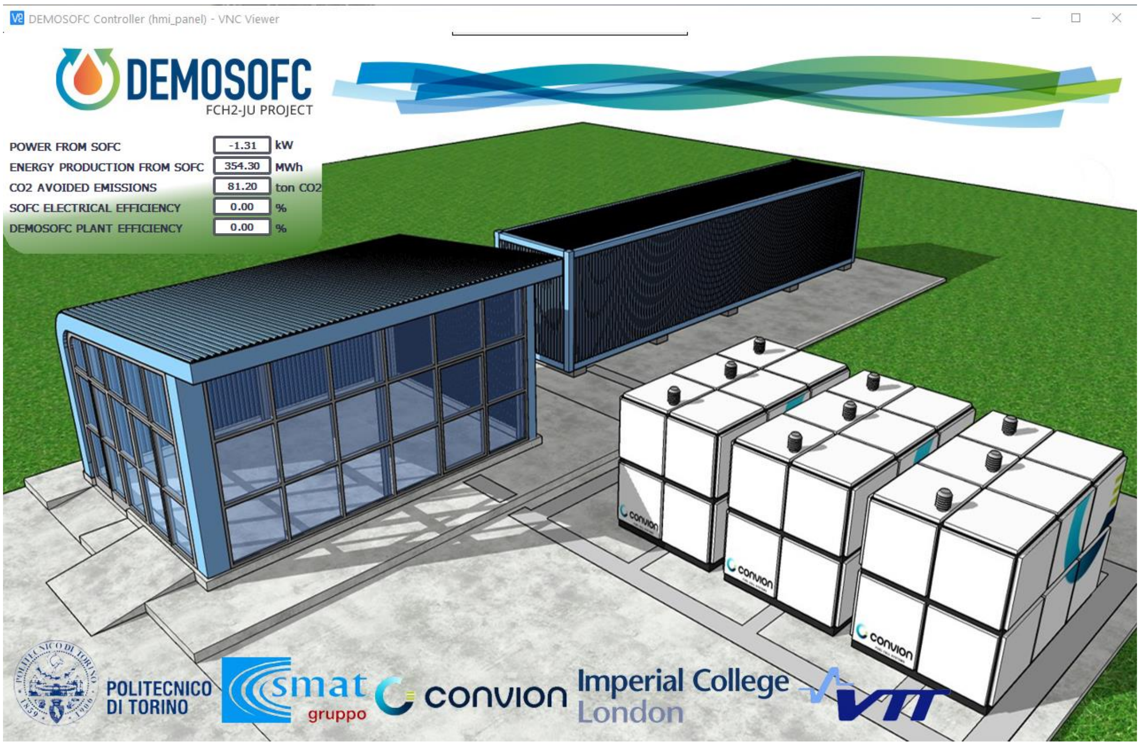

Figure 10. Screensaver.

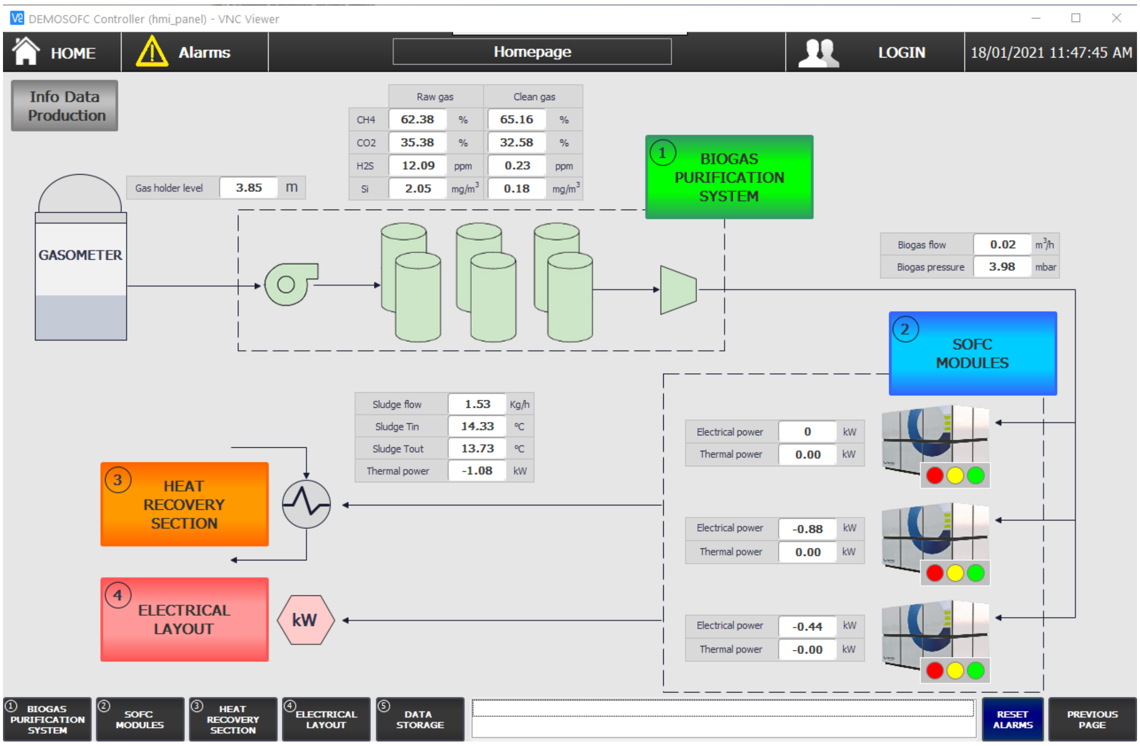

Figure 11. Homepage.

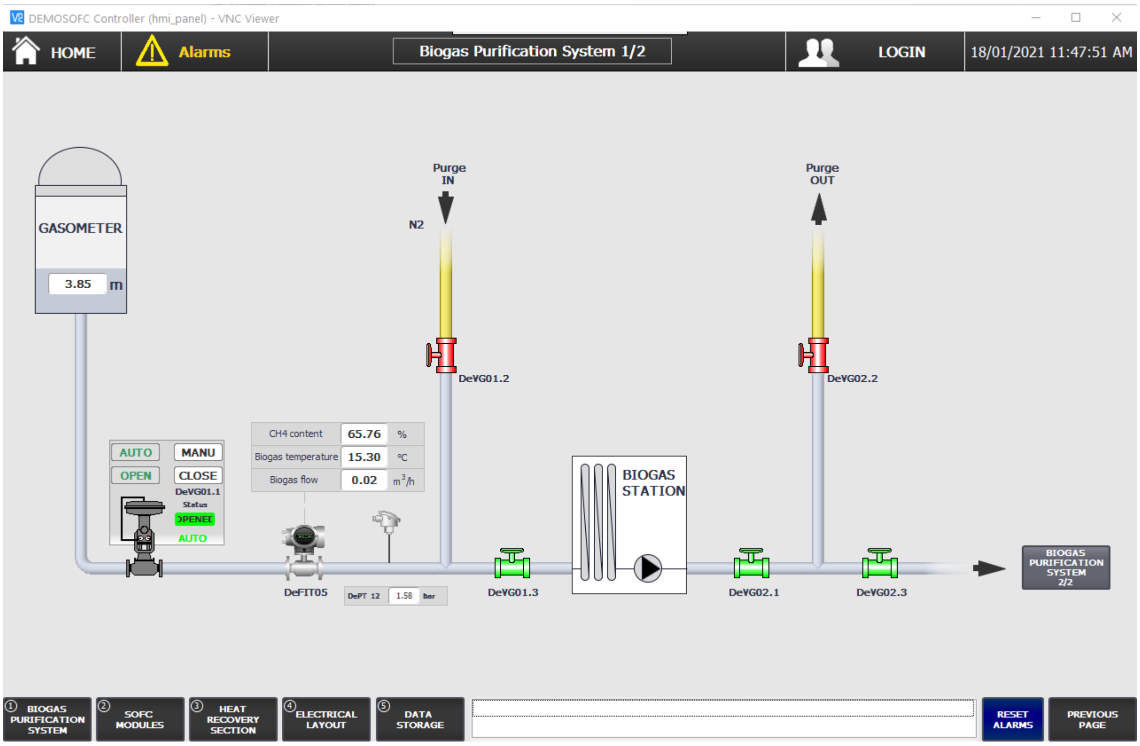

Figure 12. Biogas line – page 1/2.

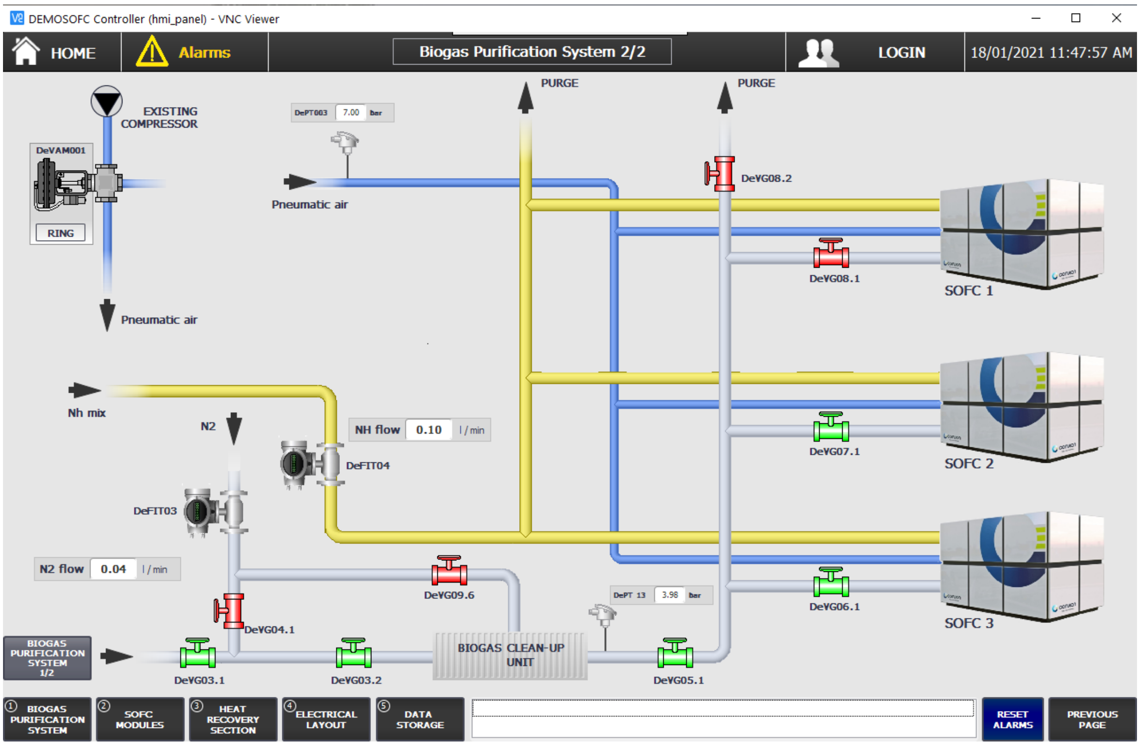

Figure 13. Biogas line – page 2/2.

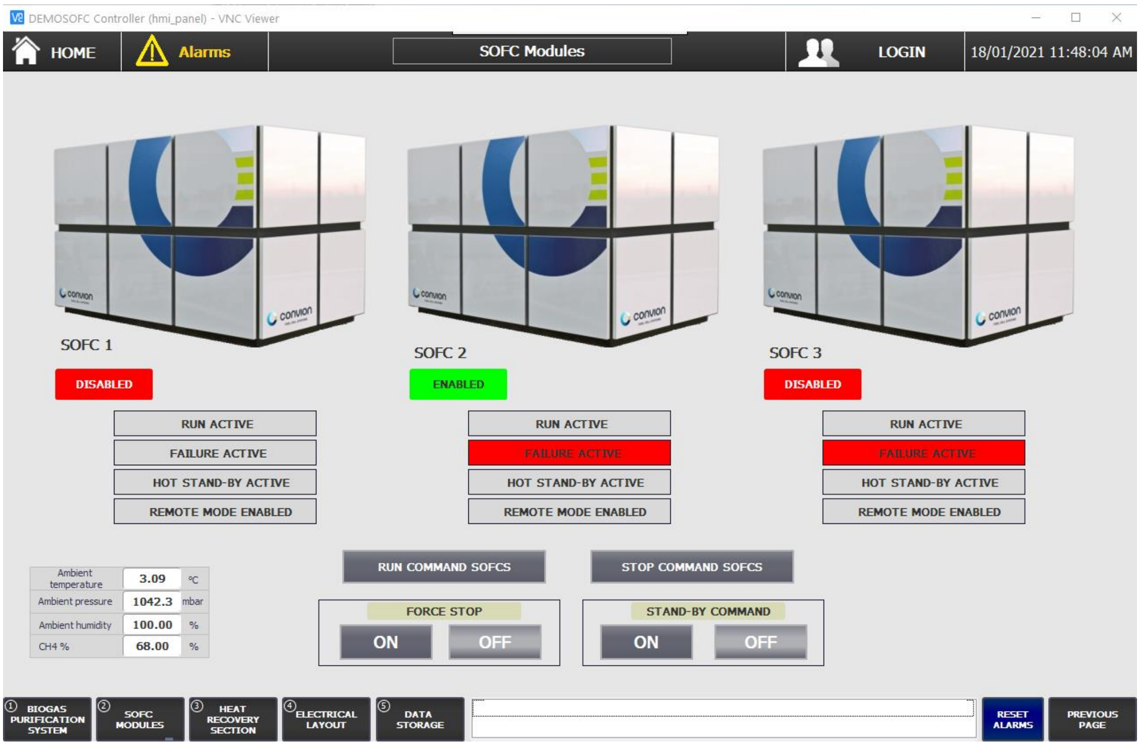

Figure 14. SOFC modules overview.

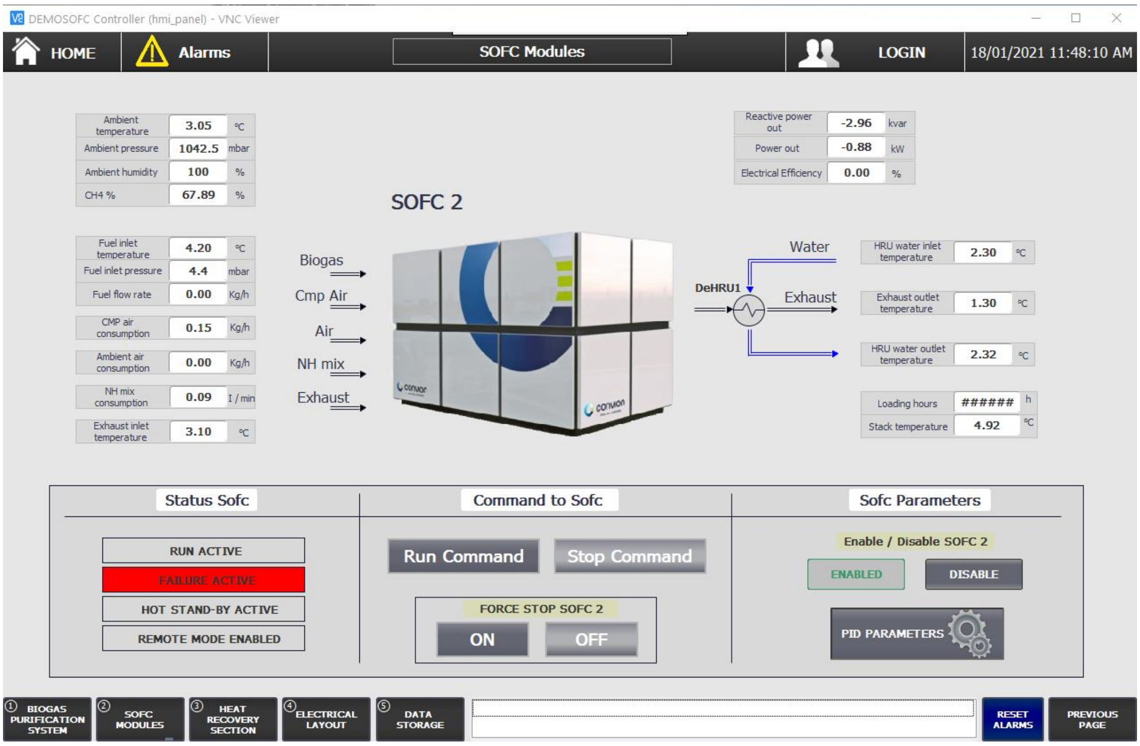

Figure 15. SOFC module detailed page (one page for every module).

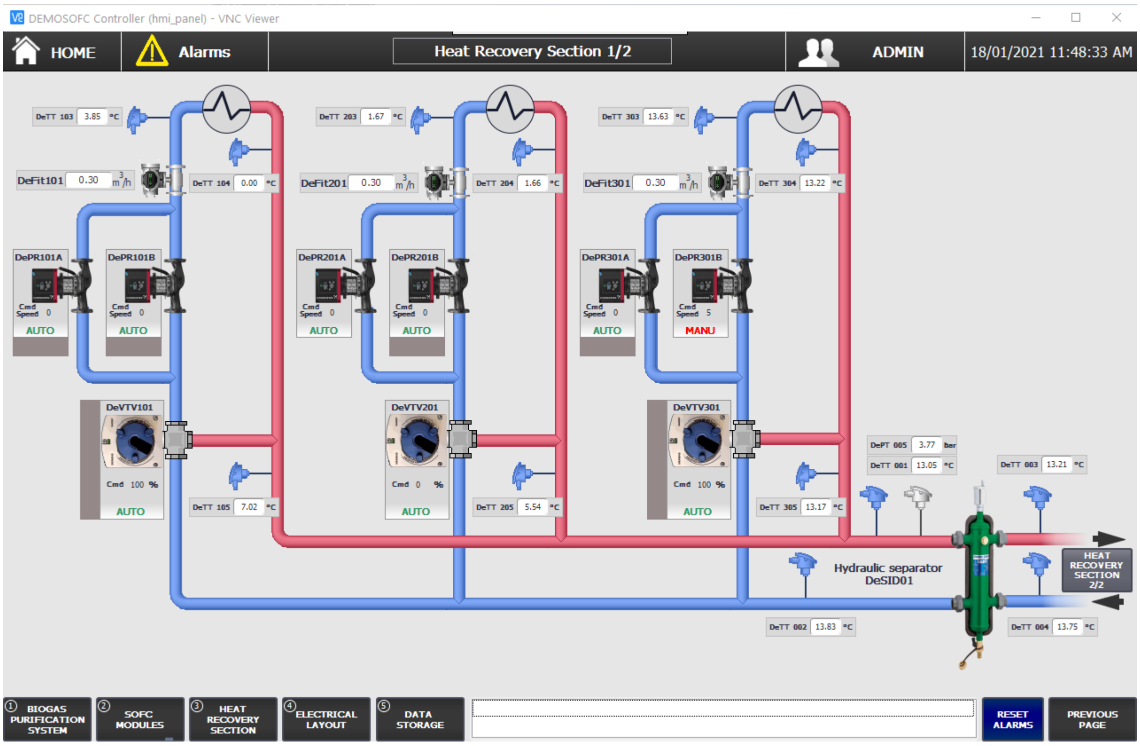

Figure 16. Heat recovery section page 1/2.

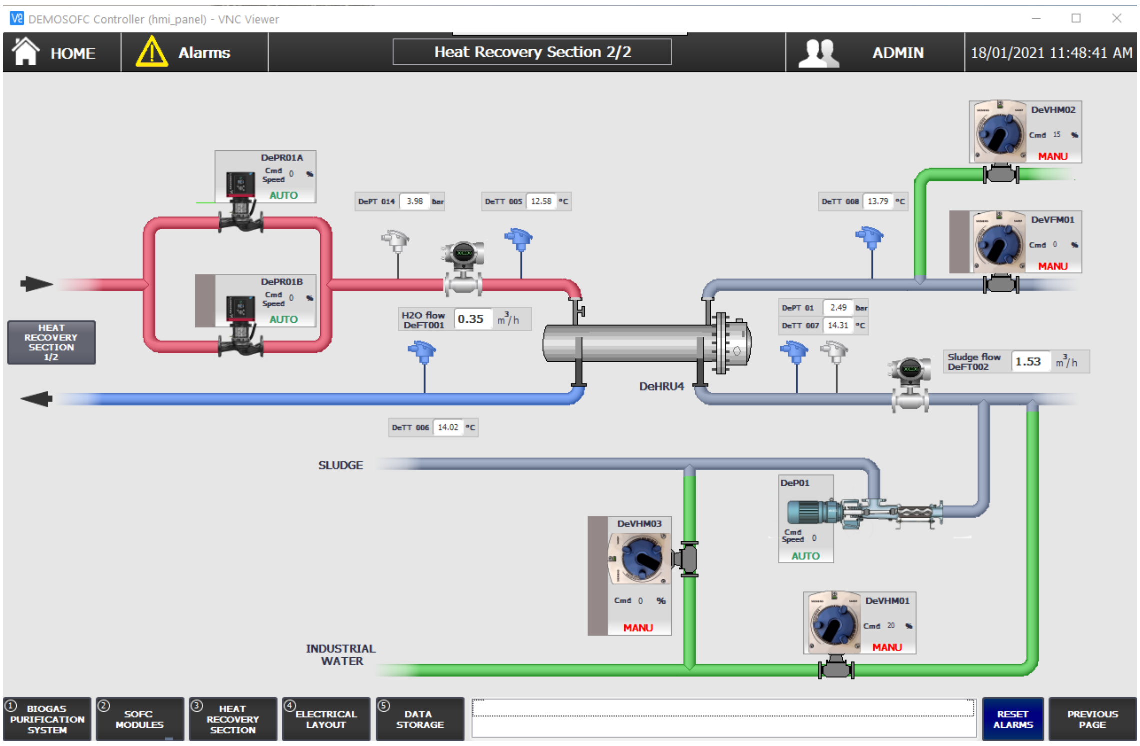

Figure 17. Heat recovery section page 2/2.

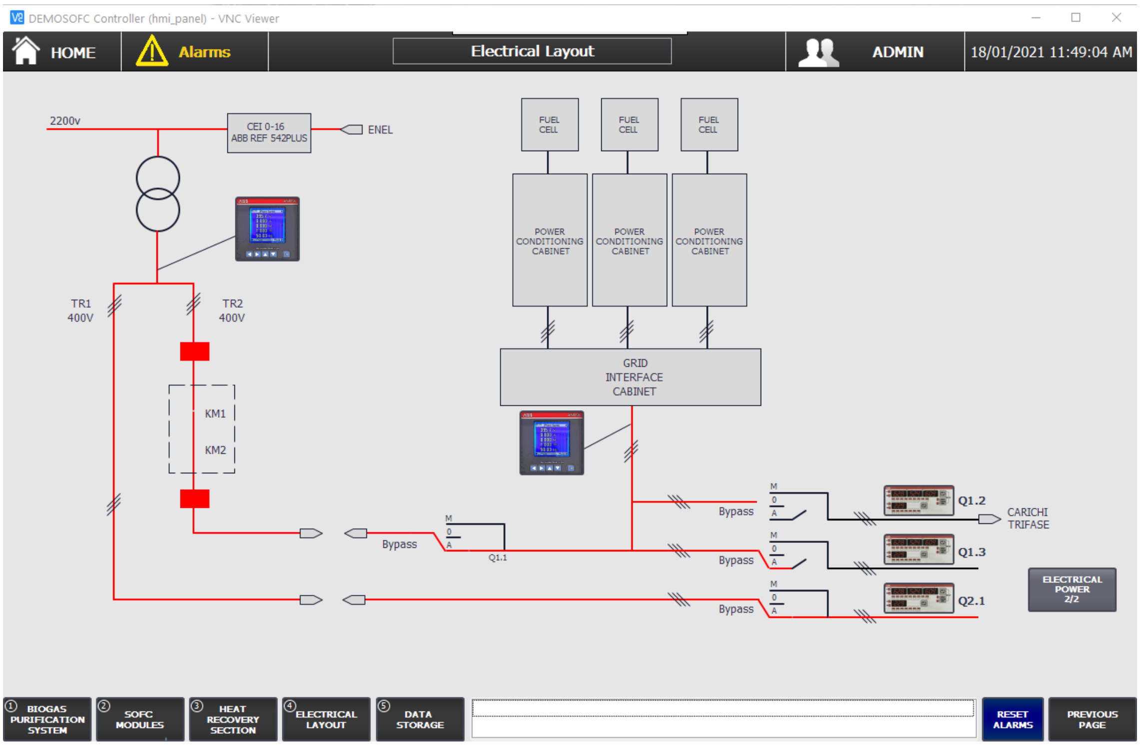

Figure 18. Electrical layout page1/2.

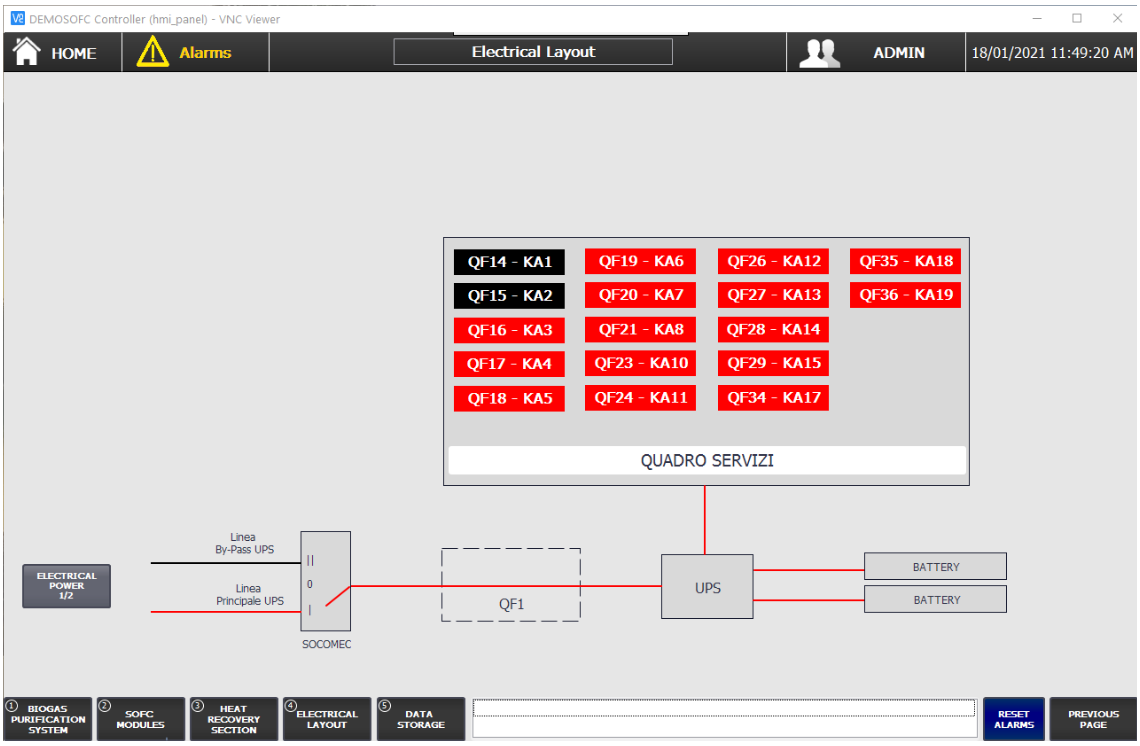

Figure 19. Electrical layout page 2/2.

3.2 Management of the DEMOSOFC control system

The DEMOSOFC control system was developed, based on specification from Politecnico di Torino (in agreement with SMAT), by the company BD Automation[1], to which SMAT assigned the PLC and control system supply.

The control system was designed for the complete installation (3 SOFC modules) and was optimized in the first 6 months of the plant operation to better suit for the specific applications. Convion was involved in the optimization process, especially for what concerns the variables and the controllers which could influence the interface parameters (biogas line, water line, etc.).

POLITO organized 2 training sessions for SMAT personnel to introduce them to the DEMOSOFC plant and show them how the system was operating.

The control system was then operating quite autonomously, except for what concerns the datalog management. Data were registered inside the operator panel which is anyway not acting like a

[1] http://www.bdautomation.it/

personal computer and so it was not possible, from the operator panel, to access and view historical trends (except for the last hour). If some problem has occurred, or if a data analysis on the long period was requested (like the one shown by VTT in Deliverable D5.1) the data were downloaded by SMAT operators on a USB pen drive. The .xls files where then sent to POLITO and from POLITO to VTT.

This process was not optimized for different reasons. In order to partially solve these issues, especially the reduced SMAT personnel involvement (in terms of overall personnel, some technicians were strongly involved because of their personal interest in the activity) in the plant control (SMAT was indeed very active to perform maintenance activities upon ordinary planning or Convion request), POLITO developed an automatic Excel-based toolkit to directly analyze the datalog files downloaded by the operator panel. The toolkit aimed to automatically produce a simplified table of data starting from the .xls file downloaded, by only using Excel software. The toolkit was developed using a dedicated macro written in VBA (Visual Basic for Applications) environment. The tool was ready at the end of 2019 but was unfortunately not implemented because of the COVID-19 pandemic which started in early 2020. The initial plan was to perform a training activity by POLITO to SMAT personnel to teach them how to use the toolkit and try to increase their involvement. The tool was indeed only shared with them. Anyway, a problem still not solved even with the toolkit was the language issue (a part of the SMAT technicians were not able to read/speak English).

4. Maintenance of the DEMOSOFC system

Different maintenance activities – planned (ordinary) and unexpected (extra-ordinary) – were performed at the DEMOSOFC site during the DEMO commissioning and operation (from 2017 to 2020). The maintenance activities on the SOFC modules have been performed by Convion experts, both onsite at the DEMOSOFC plant and at Convion headquarter in Finland (in this case the stacks or the entire module were shipped back to Finland). A good cooperation was established between Convion and SMAT experts, the latter providing support and tools to the first ones. During the 2020 COVID-19 pandemic, they were able to perform some maintenance activities on the SOFC systems based on remote indications by Convion experts (which were unable to travel because of travelling restrictions). Other maintenance activities were performed by SMAT only concerning the biogas and heat recovery (water-sludge line). Anyway, in case of problems/alarms on the DEMOSOFC plant, the WhatsApp group was used to discuss, between POLITO, Convion and SMAT, about the problem and share datalog images and thoughts before planning the maintenance.
The table below lists a summary of the maintenance activities performed on the DEMO site during the project. SMAT and Convion were contacted to ask feedback and details on the activities.

Date	Issue
Summer 2017	Problem with the SOFC1 air pre-heater during the shutdown at Convion facilities. SOFC1 air pre-heater replaced onsite by Convion technicians.
	SOFC1 started on 31/10/2017.
December 2017	Maintenance on the Biokomp container condensate discharge lines, which were freezing outside the container.
March 2018	Maintenance on the control system to update the tool with optimized logics which were understood during the first months of operation.
June 2018	System forced stop due to a delay in the renewal of the local municipality authorization. Maintenance on the biogas sampling lines layout (due to condensate problems in the biogas online analyzer – no stop of the entire system).
July 2018	Scheduled maintenance on SOFC1 module air filters (replaced by SMAT and POLITO personnel).
August 2018	SOFC2 air pre-heater replaced onsite by Convion technicians. Problems with the Ethernet cables communication. An external certified company came to site to make and certify all the connections.
	SOFC2 started on 25/10/2018.
December 2018	SOFC1 module stack scheduled disassembly. The stack was shipped back to Convion for repair activity. Planned maintenance on the Biokomp section (blower, chillers and compressor). Planned maintenance on the biogas analyzer (NDIR sensor for siloxanes replacement)
January 2019	Maintenance on a broken SOFC2 electrical resistance by Convion personnel.
March 2019	Replacement of NH-mix cylinder (used for SOFC standby operation).
March 2019	Scheduled tests of the island mode switch for SOFC2 inverter to understand the reason for the malfunctioning (problem solved thanks to Danfoss intervention on the inverter).

June 2019	Planned maintenance on the biogas blower (with the DEMO off) because of leakages problems. Planned maintenance on SOFC2 by Convion technicians (software maintenance and air filter change). SOFC1 was back from Finland but some problems were present on the voltage measurements cables. A new maintenance was required (back at Convion facility).
February 2020	SOFC1 repaired stack are back onsite and the SOFC1 module is restarted.
March 2020	Planned thermal cycle on SOFC2 (which could have a positive effect on the degradation of the system).
August 2020	Replacement of the biogas chiller and ordinary maintenance on the Biokomp section (blower, chillers and compressor). Maintenance activity on the PLC of SOFC2.

This project has received funding from the Fuel Cells and Hydrogen 2 Joint Undertaking under grant agreement No 671470. This Joint Undertaking receives support from the European Union's Horizon 2020 research and innovation programme, Hydrogen Europe and Hydrogen Europe research.

Appendix A

Measurement devices

Table 1 contains information of the measurement devices used for the analysis in this document.

Table 1Maximum measurement errors declared by equipment manufacturers

Parameter	Equipment	Max. measured error	Standard
Methane (%-Vol)	Proline Prosonic Flow B 200	±2 % o.f.s. = ±2 % abs.	ISO/DIS 11631
Volume flow (3-30 m/s)	Proline Prosonic Flow B 200	±1.5 % o.r.	ISO/DIS 11631
Volume flow (1-3 m/s)	Proline Prosonic Flow B 200	±3 % o.r.	ISO/DIS 11631
Temperature	Endress+Hauser Proline Prosonic Flow B 200	±0.6 % ± 0.005· T ˚C	ISO/DIS 11631
Temperature	Endress+Hauser (Pt-100 Sensor)	0.15 + 0.002 · |T ˚C|	IEC 60751
Voltage	ANR96	< 0.5 %	EN 62053-21
Current	ANR96	< 0.5 %	EN 62053-21
Active power	ANR96	< 1 %	EN 62053-21
Mass flow (10-100% o.f.s.)	Endress+Hauser Proline t-mass 65	±1.5 % o.r.	ISO/IEC17025
Sludge flow	Endress+Hauser Proline Promag L400	±0.5 % o.r.	DIN EN 29104
Water-glycol flow	Grundfos VFI+T/0.3-6m/1/C/M5.00-X/VG6/S	±1.5 % o.f.s (in water 0-100 ˚C)	IEC 68-2-14, EN61010, EN61326

Water-glycol temperature	Grundfos VFI+T/0.3-6m/1/C/M5.00-X/VG6/S	± 0.5K	IEC 68-2-14, EN61010, EN61326

Calculation of results

Performance values of SOFC system were calculated from delivered measurement data according to IEC 62282-3-200 standard (Fuel cell technologies Part 3-200: Stationary fuel cell power systems - Performance test methods).

Electrical efficiency ηel

Electrical efficiency η_{el} was calculated according to following equation:

$$\eta_{el} = \frac{P_n}{P_{in}} \times 100\ \% = \frac{W_{el}}{LHV \cdot \dot{m}_{bio}} \times 100\ \% \qquad (1)$$

where

η_{el} is the electrical efficiency (%)

P_n is the net electric power output (kW)

P_{in} is the total power input (kJ/s)

W_{el} is the net electric power production (kW)

LHV is methane lower heating value (802.69 kJ/mol)

$\dot{m}_{bio}$ is methane molar flow (mol/s)

Heat recovery efficiency η_{th}

Heat recovery efficiency η_{th} was calculated according to following equation:

$$\eta_{th} = \frac{P_{HR}}{P_{in}} \times 100\ \% = \frac{W_{th}}{LHV \cdot \dot{m}_{bio}} \times 100\ \% \qquad (2)$$

where

η_{th} is the heat recovery efficiency (%)

P_{HR} is the recovered thermal power output (kJ/s)

P_{in} is the total power input (kJ/s)

W_{th} is the net thermal power production (kW)

LHV is methane lower heating value (802.69 kJ/mol)

$\dot{m}_{bio}$ is methane molar flow (mol/s)

The net thermal power production W_{th} was calculated from the heat recovery fluid (water/glycol mixture) according to following equation:

$$W_{th} = \sum [(T_{HR1} - T_{HR2}) \cdot q_{VHR} \cdot \rho_{HR} \cdot c_{HR}] \quad (3)$$

where

W_{th} is the net thermal power production (kW)

T_{HR1} is the temperature of heat recovery fluid output (K)

T_{HR2} is the temperature of heat recovery fluid input (K)

q_{VHR} is volumetric flow rate of heat recovery fluid (m^3/s)

ρ_{HR} is the heat recovery fluid density (kg/m^3)

c_{HR} is the specific heat capacity of heat recovery fluid (kJ/(kg·K))

Overall energy efficiency η_{total}

The overall energy efficiency η_{total} was calculated according to following equation:

$$\eta_{total} = \eta_{el} + \eta_{th} = \frac{W_{el} + W_{th}}{LHV \cdot \dot{m}_{bio}} \times 100\ \% \quad (4)$$

where

η_{total} is overall energy efficiency (%)

η_{el} is the electrical efficiency (%)

η_{th} is the heat recovery efficiency (%)

W_{el} is the net electric power production (kW)

W_{th} is the net thermal power production (kW)

LHV is methane lower heating value (802.69 kJ/mol)

$\dot{m}_{bio}$ is methane molar flow (mol/s)

Uncertainty analysis of results

Uncertainty analysis was carried out according to IEC 62282-3-200 standard (Fuel cell technologies Part 3-200: Stationary fuel cell power systems - Performance test methods) and ISO/IEC GUIDE 98-3 Uncertainty of measurement Part3: Guide to the expression of uncertainty in measurements. This document contains a brief overview of the procedure but for more details please refer to the standard.

Combined standard uncertainty U_{95} is defined according to following equation:

$$U_{R95} = \sqrt{(B_R)^2 + (2S_R)^2} \tag{5}$$

where

U_{95} is combined standard uncertainty

B_R is the systematic uncertainty component of a result

$2S_R$ is the random uncertainty component of a result

For function f $(x_1,x_2,\ldots x_n)$ with independent variables $x_1,x_2,\ldots,x_n$ having each corresponding uncertainties $(\Delta x_1, \Delta x_2, \ldots,\Delta x_n)$ can combined uncertainty Δf calculated according to following equation:

$$\Delta f = \sqrt{\sum_{i=1}^{n}\left(\frac{\partial f}{\partial x_i}\cdot \Delta x_i\right)^2} \tag{6}$$

As a first approximation, we can assume maximum error for measurement to be a combined uncertainty of measurement errors presented in Table1.

The electrical efficiency error $\Delta\eta_{el}$:

$$\Delta\eta_{el} = \eta_{el}\cdot\sqrt{\left(\frac{\Delta W_e}{W_e}\right)^2 + \left(\frac{\Delta\dot{m}_{bio}}{\dot{m}_{bio}}\right)^2 + \left(\frac{\Delta(vol\%)_{CH4}}{(vol\%)_{CH4}}\right)^2} \tag{7}$$

The heat recovery efficiency error $\Delta\eta_{th}$:

$$\Delta\eta_{th} = \eta_{th} \cdot \sqrt{\left(\frac{\Delta q_{VHR}}{q_{VHR}}\right)^2 + 2 \cdot \left(\frac{\Delta \mathrm{T}_{HR}}{\mathrm{T}_{HR1} - \mathrm{T}_{HR2}}\right)^2 + \left(\frac{\Delta\dot{m}_{bio}}{\dot{m}_{bio}}\right)^2 + \left(\frac{\Delta(vol\%)_{CH4}}{(vol\%)_{CH4}}\right)^2} \quad (8)$$

The overall energy efficiency error $\Delta\eta_{total}$:

$$\Delta\eta_{total} =$$

$$\eta_{tot}\left(\sqrt{\left(\frac{\Delta \mathrm{W}_e}{\mathrm{W}_e+W_{th}}\right)^2 + \left(\frac{\mathrm{C}_{HR}\cdot(\mathrm{T}_{HR1}-\mathrm{T}_{HR2})\cdot\Delta q_{VHR}}{\mathrm{W}_e+W_{th}}\right)^2} + \sqrt{2 \cdot \left(\frac{\mathrm{C}_{HR}\cdot\Delta q_{VHR}\cdot\Delta \mathrm{T}_{HR}}{\mathrm{W}_e+W_{th}}\right)^2 + \left(\frac{\Delta\dot{m}_{bio}}{\dot{m}_{bio}}\right)^2 + \left(\frac{\Delta(vol\%)_{CH4}}{(vol\%)_{CH4}}\right)^2}\right)$$

(9)

The combined standard uncertainty for electrical efficiency is ±3%. The uncertainty for the total efficiency is ±9%. For further details please refer to *D4.2 Analysis of the thermal energy recovery from the DEMO: second part / Appendix 1*.