Results from Industrial Size Biogas-Fed SOFC Plant (DEMOSOFC Project)

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The EU-funded DEMOSOFC project demonstrates the technical and economic feasibility of operating a 174 kW_e (+ 100 kW_{th}) SOFC system in a wastewater treatment plant, fed by biogas. The integrated biogas-SOFC plant includes three main units: 1) the biogas clean-up and compression section; 2) the SOFC power modules, and 3) the heat recovery loop.

The present work is related to the results of the operation of the SOFC system. More than 7000 hours of operation have been reached onsite.

Biogas raw composition is daily measured: starting form values of around 50 ppm (Sulphur equivalent) and 1.0-1.5 ppm (siloxanes equivalent) downstream the results show zero H_2S and zero siloxanes.

Measured SOFC efficiency from biogas to AC power has always been higher than 52-53%, with peaks of 56%.

A dedicated emissions measurements campaign shows NO_x < 20 mg/m^3, SO_2 < 8 mg/m^3 and particulate lower than ambient air values (0.01 mg/m^3).

Introduction

The DEMOSOFC plant (1) is the first European industrial-size Solid Oxide Fuel Cell (SOFC) system. The plant demonstrates the technical and economic feasibility of industrial-size SOFC systems, with focus on bio-based fuels feedings (biogas in this case). Industrial-size fuel cell systems, usually Molten Carbonate Fuel Cells (MCFCs) are already available outside Europe, especially in USA (2-3)], Japan and South Korea (4). In Europe, the first fuel cell power plant has been installed at the site of FRIATEC AG in Mannheim (Germany). The power plant went into operation in 2016. The fuel cell power plant was installed in only nine months as a joint project by E.ON Connecting Energies, E.ON's subsidiary for commercial and industrial energy solutions.

Key advantages of fuel cell based industrial systems in biogas plants have been deeply demonstrated in the authors' previous works (5-9) and include:

- High efficiency increase respect to traditional biogas-fed Internal Combustion Engines (ICEs), especially for low-medium size systems. ICEs usually show electrical efficiency ranging from 35-38% to 43% (10), when the plant size increases from tens of kW to MW size. SOFC systems can indeed provide values around 50-56% from few kW to MW size (11).

- Zero emissions to atmosphere in terms of NOx, SOx, VOC and PM, which are traditionally a criticality in standard combustion engine. In the last years, many traditional ICEs installed post-combustors to comply with the national-regional strict rules on emissions (12).

The scientific and research activity in the framework of the DEMOSOFC project has been related first to the biogas purification system (required to be more efficiency and robust than the one for traditional ICEs (13)) and then to overall system management (in terms of control algorithms and interface with the real WWTP) and analysis. Significant results are now available.

DEMOSOFC plant layout

The DEMOSOFC site WWTP is located in Collegno, in the Torino premises (IT). The Collegno plant has a nominal capacity of 250’000 Person Equivalent (P.E.) and it is currently serving around 180’000 P.E., both residential and industrial. The plant used to exploit biogas for heating-only purpose in a boiler, for pre-heating the sludge entering the anaerobic digester, and excess biogas – not sent to boilers – was simply flared.

The new integrated biogas-SOFC plant, installed in the framework of the DEMOSOFC project, is using the as-produced biogas for electrical and thermal energy production in a SOFC-based cogeneration system.

The DEMOSOFC plant includes three main sections: 1) the biogas cleaning and compression section, 2) the SOFC power modules, and 3) the heat recovery loop. Figure 1 shows a schematic layout of the WWTP process and its integration with the DEMOSOFC plant.

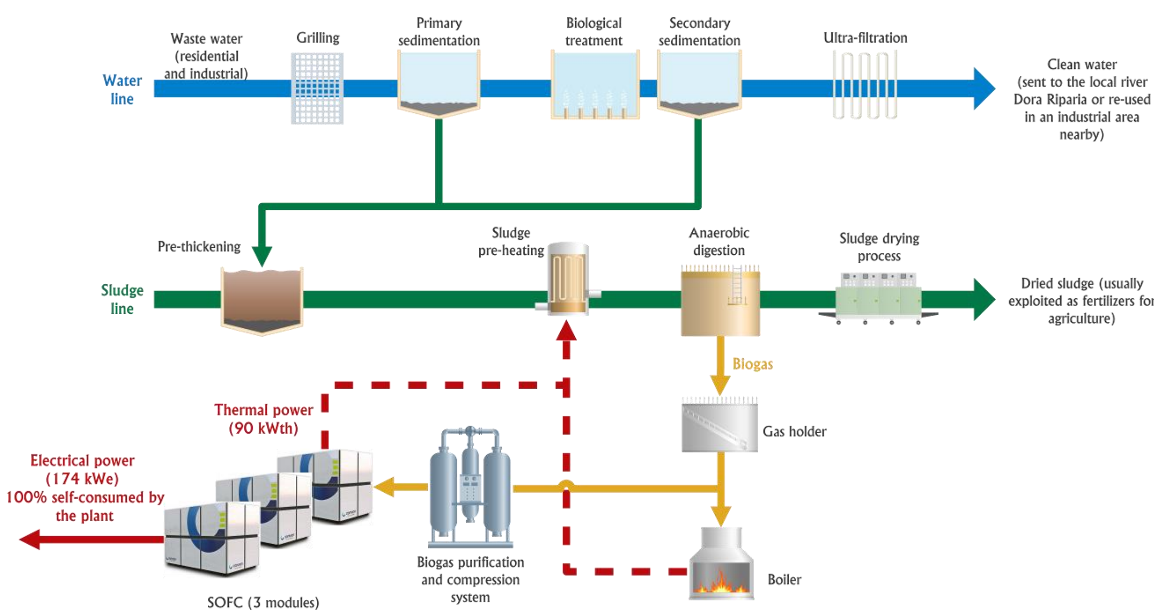

Figure 1. DEMOSOFC plant layout.

Biogas cleaning and compression section

The biogas cleaning system includes two sub-sections (Figure 2). The first part is located close to the anaerobic digester where biogas is produced and then stored in a gas holder (1 day of storage capacity - 1440 m3). Here biogas is slightly pressurized (from near-atmospheric pressure to 400 mbar(g)) to reach the DEMOSOFC area, located around 100-150 m from the biogas production area. After the blower, a first chiller (working at 8-10°C) is installed to remove water from the biogas line and avoid condensation on the pipeline. The biogas is then sent to the DEMOSOFC area through an insulated pipeline (aboveground). In the DEMOSOFC area, all pipelines are indeed underground.

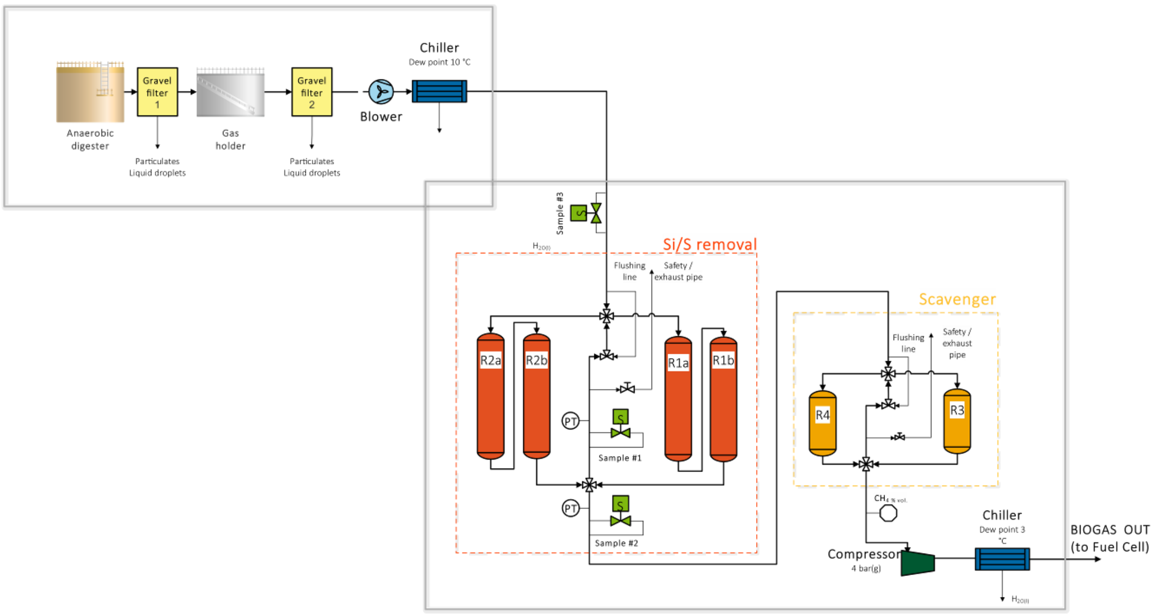

Figure 2. Biogas cleaning and compression section layout.

The second section is located inside a container and includes adsorption vessels for biogas contaminants removal, and a compressor. Commercial impregnated activated carbons, specific for sulphur and siloxanes compounds, are chosen as media for biogas cleaning. A lead-and-lag layout is used for the first four vessels connection (see Figure 2): the four reactors can work in series during nominal operation (with the first two lead reactors and the second two lag reactors). When contaminants breakthrough is detected after the lead reactors, the system is switched – thanks to a series of valves – into parallel mode to avoid the stop of the SOFC units during the maintenance. While the lag reactors are kept working, the lead ones are replaced. Lead and lag are then switched to guarantee the cleanest reactor to be always the last one in the sequence. A second scavenger section (made of two reactors) is also available as guard bed.

The second part of the container is the screw compressor, which increase biogas pressure up to 4 bar(g), as requested at the SOFC module inlet. The biogas cleaning and compression section has been supplied by Biokomp (14).

The biogas cleaning system has been designed after a one-year monitoring of biogas composition in Collegno, where H2S (average 20 ppm) and siloxanes (average 1 ppm) have been detected as the most harmful components to be removed. An in-line and real-time gas analysis (supplied by Qualvista LTD (15)) is installed to monitor the removal efficiency of the biogas clean-up unit. The online gas sensor can detect continuously both macro-composition (CH_4, CO_2, O_2) and contaminants (H_2S and total Silicon).

SOFC modules

The core of the DEMOSOFC plant are the three SOFC units supplied by Convion, partner of the DEMOSOFC project. The modules provide up to 56% electrical efficiency and 30% thermal efficiency (16). The three SOFC modules produce 174 kWe, which cover around 25-30% of the WWTP electrical consumption (7). Currently the first two modules are running at the DEMOSOFC site, which is also ready to host the third and last module. The SOFC units, as shown in Figure 3, are fed by biogas during nominal operation and are connected to the heat recovery system (water-glycol loop). Compressed air is required during start-up and an N-H mixture (95% N_2, 5% H_2) is available for standby operation (maximum 24 hours maintenance on the biogas line – e.g. compressor maintenance – with the SOFC system hot, thus avoiding thermal cycles).

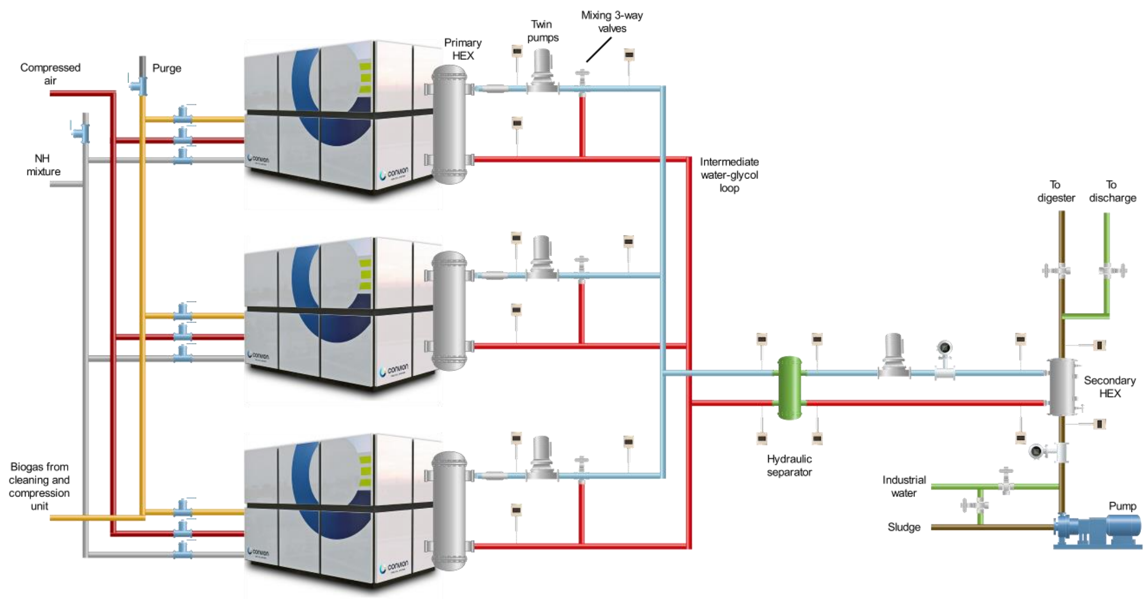

Figure 3. SOFC module and heat recovery section P&ID.

Heat recovery section

Heat recovered from the SOFC units is completely transferred to the sludge entering the anaerobic digester through an intermediate water-glycol loop (30% glycol in water). Circulation pumps (twin pumps to avoid stops during maintenance) and three-way valves for regulation have been installed (Figure 3) and a new sludge-water heat exchanger is supporting the existing one.

The regulation of the DEMOSOFC system is performed by an automatic control system (no ordinary human intervention required, except visual inspection by plant operators) and is based on PID controllers. SOFC module set point is varied in accordance with the gas holder level, while water temperatures in the heat recovery section are controlled by varying the pumps speed and the mixing valves opening ratios. Automatic procedures are also available to guarantee the safety shutdown of the system in case of emergencies in the plant (biogas shortages, heat recovery system overheating, etc.).

Results

Figure 4 shows a view of the DEMOSOFC plant with the first two SOFC modules installed. The DEMOSOFC system has started its operation, with the first module start-up, at the end of October 2017. The system has worked continuously until end of December 2017. After a maintenance break in the Winter, the system has been restarted first in February-March and then definitively in April 20th, 2018 until September 2018. In October 2018 the secondo SOFC module has been started and it is currently running. The first SOFC module was stopped at the end of 2018 for a maintenance at the producer’s facility and it is currently in the phase of restart. From June 2019, two modules running in parallel will be available on site. More than 7200 hours of operation have been reached onsite. Planned and unplanned maintenance activities were devoted to optimizing the biogas feeding line, to install a mandatory power meter on the power production line, and for some SOFC module maintenance and for authorization approvals. More than 1990 hours of operation have been now collected.

Figure 4. DEMOSOFC plant view. On the left, the technical building where the control room and the electrical cabinet room are located. On the right, the 2 SOFC modules. Between the control room and the modules, part of the biogas cleaning and compression container is also visible.

SOFC start-up procedure from cold state to full load lasted around 48 hours. First tests were devoted to verifying the functionality of all internal equipment after the transport of the first C50 module to Italy and to set the regulation parameters. The cleaning system was previously tested from the early Summer 2017 to verify the effectiveness of the contaminants removal and check measurements from the online gas analyzer.

Biogas raw composition is measured once per day by the online Qualvista analyzer (sample #3 in Figure 2). Clean biogas (both between and after the lead-and-lag reactors, respectively sample#1 and sample #2 in Figure 2) is indeed measured continuously for the other hours of the day. Each measurement (performed in batch mode) takes 40 minutes and N2 is flushed after raw gas analysis. Results on the raw biogas composition (in terms of contaminants) are shown in Figure 5. As it can be seen, H2S contents has been in line with historical trends with an average value of 31.56 ppm (min 1.8 ppm – max 71.05 ppm). Siloxanes are also varying in a limited rage with an average value in the analyzed period of 4.07 mg/m3 (min 0 mg/m3 – max 9.24 mg/m3). An increase in both sulphur and siloxanes compounds can be detected ins some periods: for H2S this is probably due to a reduction in the iron oxide chloride dosing in the water line (iron oxide is used to precipitate phosphor but also reduce the sulphur content in the water) and SMAT is trying to correlate the two parameters. Siloxane increase is indeed probably due to seasonal variations: seasonal effect on silicon was already registered in previous experiences in WWTP biogas analysis (17–19). Average methane content in the same period has been 62.49% (min 56.04% - max 68.11%). Methane content is stable on an hourly basis while weekly-monthly variation has been detected.

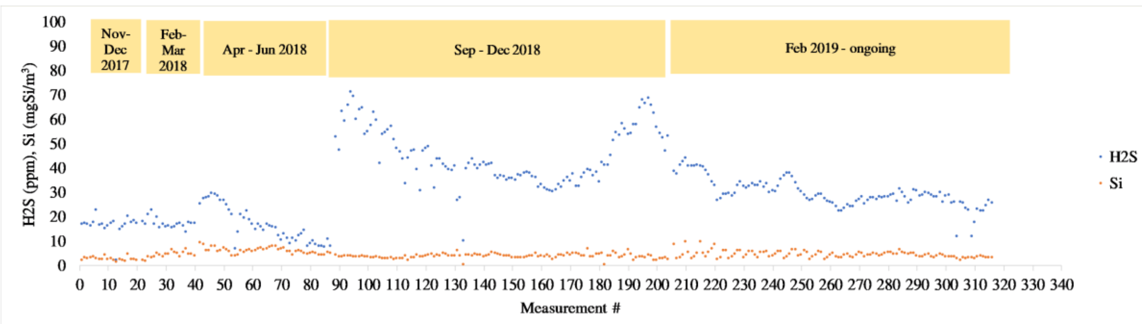

Figure 5. Raw biogas composition.

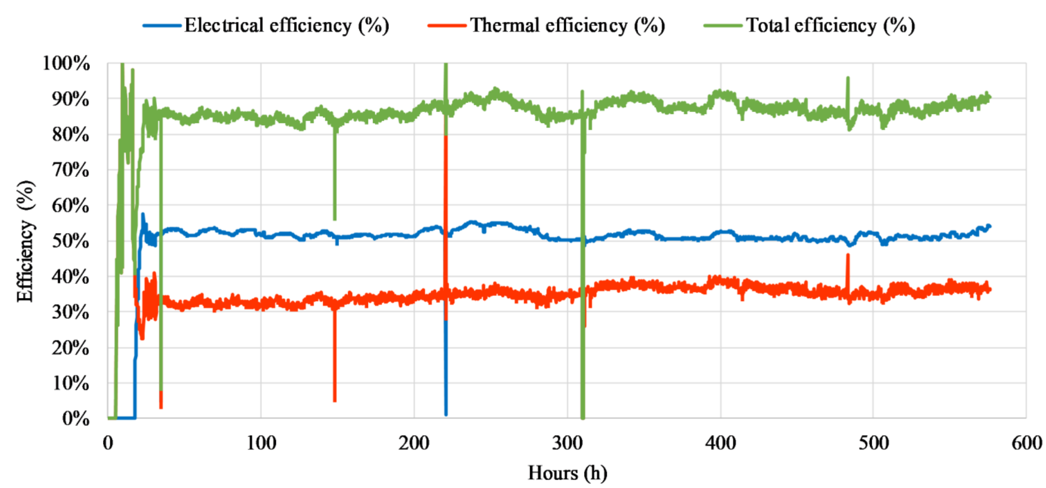

Figure 6. Efficiency plot for a 600-hours operation period, referred to the first SOFC module.

For what concerns the SOFC module operation and performance, Figure 6 shows the results of the last 600 hours of operation (from April-May 2018). The first SOFC module, controlled by the local operator panel, is set to 90% and is continuously producing 53 kWe. Electrical efficiency has always been stable and with values higher than 50% (range 50-53% at 53 kWe). An efficiency peak of 56% has been reached at 40 kWe power output. No degradation effect is visible yet.

Thermal efficiency (in Figure 6 showed at the water side of the heat exchanger installed inside the SOFC module) showed an average value of 31.4% (average total efficiency 82%). Temperature losses between the SOFC module and the secondary sludge-water HEX are always lower than 3°C on the hot side. Heat recovery temperature (hot water side) is set to 75°C, in line with the sludge set point heating temperature of 40°C.

The Finnish research center VTT (20), partner of the DEMOSOFC project, has performed onsite emissions analysis at the DEMOSOFC plant on December 7th, 2017. Results are shown in Figure 7. Gas emissions have been measured with Fourier Transform Infrared Spectroscopy (FTIR) (Gasmet Dx4000N). Particulate matters are measured with Electronic Low Pressure Impactor (ELPI). Results show that NOx, SO2, HCl, HF and organic compounds are all below the instrumentation detection limits. Particulate matter (on right size of Figure 7) shows that particulate concentration in the surrounding ambient air is higher than the one in the SOFC module exhaust gases: the system is indeed filtering inlet ambient air and adding zero particulate during the process. These numbers underline the real ‘zero-emission’ concept within the fuel cell-based installations.

Species	Unit	Measured value
H_2O	Vol-%	4.7
CO_2	Vol-%	3.4
CO	mg/m³	<9
CH_4	mg/m³	<2
N_2O	mg/m³	<8
NO	mg/m³	<20
NO_x (as NO_2)	mg/m³	<20
SO_2	mg/m³	<8
C_2H_6	mg/m³	<14
HCHO	mg/m³	<7
HF	mg/m³	<10
HCl	mg/m³	<10
SO_2	mg/m³	<10
O_2	Vol-%	18.3
Particulate	mg/m3	0.01

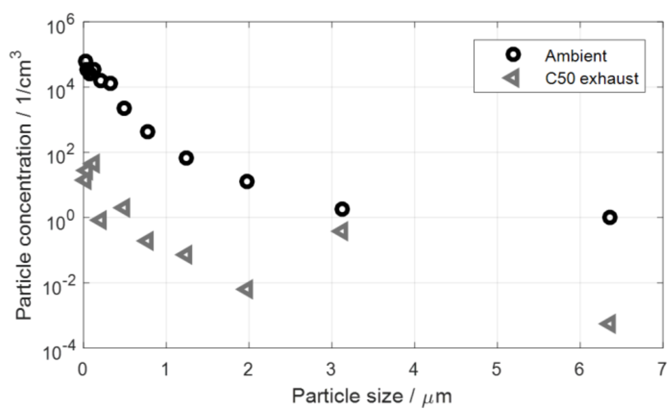

Figure 7. Results of the emissions analysis (performed on December 7th) at the DEMOSOFC site (courtesy of VTT (18)).

Figure 8 shows the electrical layout of the DEMOSOFC system. The SOFC module is designed to be installed parallel to power grid but is capable of island mode, thus securing critical power loads within a micro grid. The following phases can be observed, by looking at Figure 8:

- During the START-UP of the system, auxiliaries (green line) are supplied by the dedicated line from the grid (green line), and the SOFC modules also take power from the grid for the heating phase (blue line) (4);
- During NOMINAL OPERATION the SOFC modules are producing power to the grid (blue line, reverse flow respect to start-up) and auxiliaries can either be fed from the grid (green line) or the SOFC modules (through the purple line) (4);
- During ISLAND MODE operation – i.e., the grid (grey line) is off either due to a grid failure or a grid disconnection by the grid protection device – both blue and green lines are no longer active. The SOFC thus reduces its power output until the auxiliaries load requirement is reached, and guarantees, through the purple and yellow lines, power supply to its auxiliaries. The SOFC can also secure additional loads that are critical for the overall site operation. Such critical loads can be

connected to the three-phase load line (red line), which is already available at the plant site. In the presented configuration, the presence of the UPS protects critical loads during the 'switch' time (0.5 - 1 second) required by the SOFC inverter to go into island mode. This switching time could be avoided by having the SOFC + battery + critical loads working always and continuously in a micro-grid mode (4).

Figure 9 shows the SOFC power output trend during a dedicated island mode testing at DEMOSOFC site. As it can be seen, after a first 'transition' phase (managed by the UPS), the SOFC is able to power the loads. Island mode was tested for a full working day. Re-connection to the grid was also tested and power output went back to the set-point (47 kWe on that day).

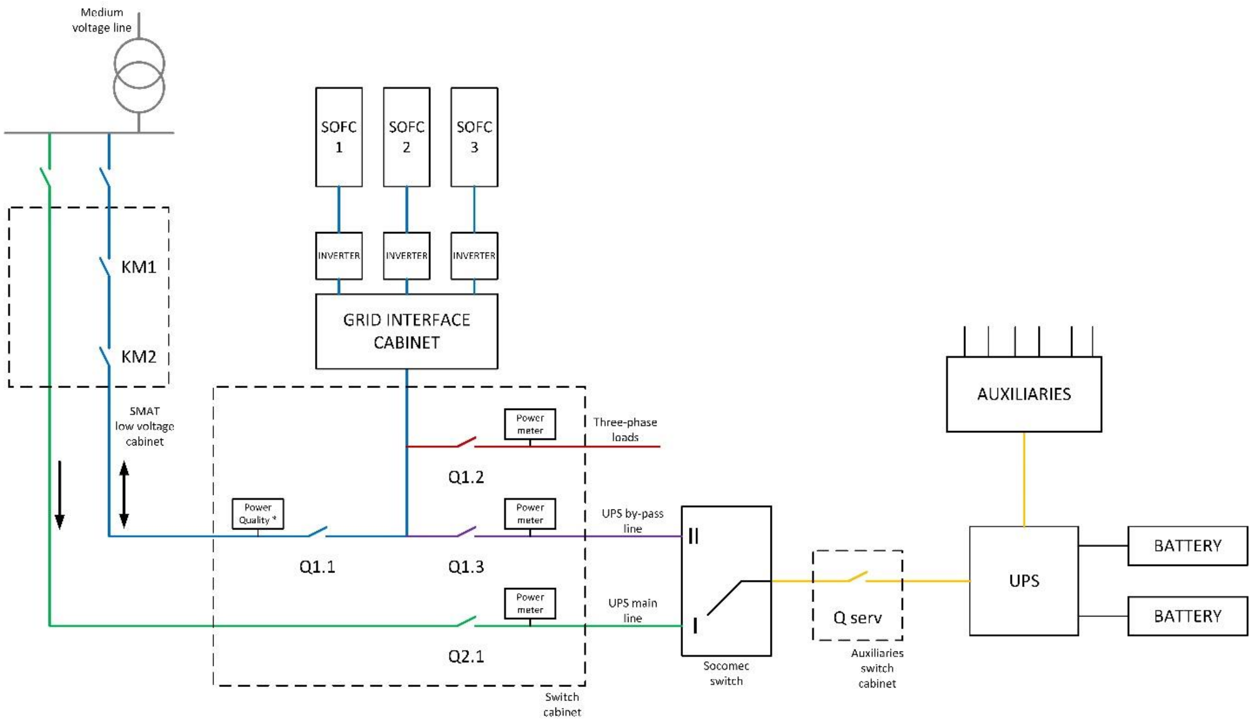

Figure 8. Electrical layout.

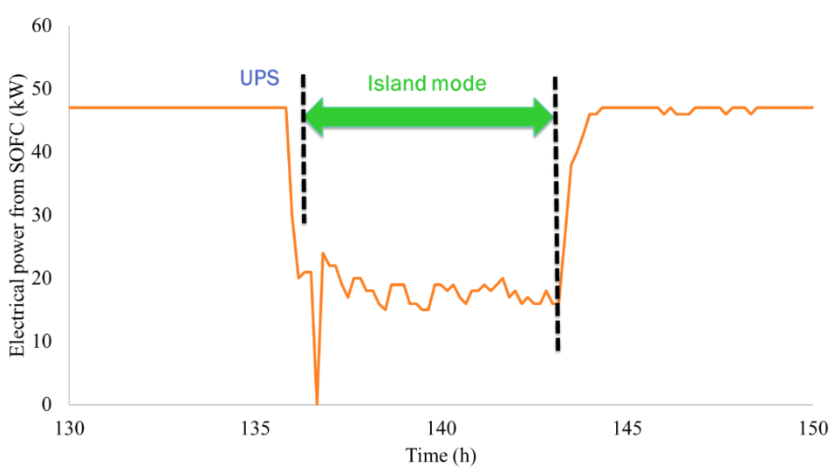

Figure 9. Island mode testing.

Conclusions

The DEMOSOFC plant is the first and largest industrial-size biogas-fed SOFC system installed in EU. It is composed at present of two SOFC modules, rated 58 + 45 kW_e. The plant is running since end of October 2017 (with the first SOFC module), with some planned stops for maintenance activities (on the biogas feeding line and on the electrical system). The SOFC module has always worked in a stable operation point (usually 90% of the full power) producing electric power and recovered heat for the WWTP.

Efficiency has always been higher than 50% (from compressed biogas to AC power) with a peak at 56%. The consumption of the compressor machine only is on average 1.9 kW_e. Other auxiliaries' consumption is under evaluation since the number and the type of components strongly depends on the design of the entire system: already existing chillers in the plant, location of the system respect to the biogas production area, heat recovery system layout, etc.

The emissions of local contaminants are close to zero (NO_x < 20 mg/m^3, SO_2 < 8 mg/m^3 and PM lower than ambient air values 0.01 mg/m^3), while the CO2 emitted is low (thanks to the high efficiency of the FC system) and neutral (because of the biogas fuel).

Through a dedicated plant optimization (included in the exploitation activity coordinated by Imperial College of London) a realistic business case for this typology of energy solutions (distributed SOFC-based CHP fed by biogas produced by waste water treatment plants) in under evaluation in all EU economies.

Acknowledgments

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References

1. "DEMOSOFC project official website," 2016. [Online]. Available: www.demosofc.eu.
2. P. Margalef, T. Brown, J. Brouwer, and S. Samuelsen, *Int. J. Hydrogen Energy*, vol. 36, no. 16, pp. 10044–10056 (2011).
3. Fuel Cell Energy, *DOE-NREL Workshop* (2012).
4. M. Gandiglio, A. Lanzini, and M. Santarelli, *Springer*, *Cham*, pp. 233–261 (2018)
5. M. Gandiglio, D. Drago, and M. Santarelli, *Energy Procedia*, vol. 101, no. September, pp. 1002–1009 (2016).
6. E. Rillo, M. Gandiglio, A. Lanzini, S. Bobba, M. Santarelli, and G. Blengini, *Energy*, vol. 126, pp. 585–602 (2017).
7. M. Gandiglio, A. Lanzini, A. Soto, P. Leone, and M. Santarelli, *Front. Environ. Sci.*, vol. 5, p. 70 (2017).

8. M. Santarelli et al., *J. CO2 Util.*, vol. 18, pp. 206–221 (2017).
9. M. Sorace, M. Gandiglio, and M. Santarelli, *Energy* (2016).
10. B. Tjaden, M. Gandiglio, A. Lanzini, M. Santarelli, M. Jarvinen, *Energy and Fuels*, vol. 28, no. 6, pp. 4216–4232 (2014).
11. S. Giarola, O. Forte, A. Lanzini, M. Gandiglio, M. Santarelli, A. Hawkes, *Appl. Energy*, vol. 211, pp. 689–704 (2018).
12. M. Gandiglio, F. De Sario, A. Lanzini, S. Bobba, M. Santarelli, G. A. Blengini, *Energies*, vol. 12, p. 1611 (2019).
13. Argonne National Laboratory, U.S. Department of Energy, and Fuel Cell Technologies Office, *Gas Clean-Up for Fuel Cell Applications Workshop* (2014).
14. "Home Page | Bio-komp.com - official website." [Online]. Available: http://www.bio-komp.com/index.php.
15. "Qualvista Ltd - official website." [Online]. Available: http://www.qualvista.com/.
16. "Convion fuel cell - official website," 2017. [Online]. Available: http://convion.fi/.
17. M. Gandiglio, A. Lanzini, M. Santarelli, and P. Leone, *J. Fuel Cell Sci. Technol.*, vol. 11, no. June, p. 14 (2013).
18. A. Lanzini et al., *Prog. Energy Combust. Sci.*, vol. 61, pp. 150–188 (2017).
19. D. D. Papadias, S. Ahmed, and R. Kumar, *Energy*, vol. 44, no. 1, pp. 257–277 (2012).
20. "VTT | VTT Technical Research Centre of Finland Ltd Technology for business." [Online]. Available: https://www.vttresearch.com/.