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DEMOSOFC

Project n° 671470

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

Deliverable number 4.5

D4.2 Analysis of the thermal energy recovery from the DEMO: second part

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Abstract:

This document is related to the monitoring of the DEMOSOFC plant. In particular, the document focuses on the thermal energy recovery from the exhaust gas of the SOFC modules.

Keyword list: biogas, SOFC, WWTP, thermal recovery, heat, sludge heating

Summary

1. Thermal layout

The thermal recovery layout is shown in Figure 1. The drawing is showing 3 SOFC modules as planned in the design phase and as included in the control system layout, even if the project ended with only 2 SOFC modules in operation.

Every SOFC module includes a shell-and-tube heat exchanger (HEX), fed by an inlet cold water stream and an outlet hot water stream. Every SOFC module water loop includes a pump (2 pumps running alternatively to avoid stops during maintenance periods) and a three-way valve. The three-way valve is used to mix part of the hot stream coming from the SOFC with the inlet cold water, in order to control the temperature of the water entering the HEX, set at 45 °C and guaranteed through a PID controller. The pump speed can be varied to guarantee, on the other side, a fixed temperature change across the HEX, which also means a fixed outlet temperature at the outlet of the system. This PID objective in terms of temperature was set to 25 °C temperature change (equal to 70 °C outlet temperature). The water line is actually composed by water and glycol (30%, to avoid freezing problems). The different SOFC water loops are then collected together and sent to the secondary HEX (where the heat is transferred to the sludge line). Before reaching the secondary HEX, a hydraulic separator is installed, to avoid pressure problems in the line (which could be generated by having different pumps running in series in the primary and secondary loop). The dashed lines in Figure 1 represents the long (around 100 m) pipeline which is connecting the DEMOSOFC are with the sludge pumps area. Here, a pump is installed (again 2 pumps running in an automatic alternating mode): the pump speed is regulated, through another PID controller, to have – in the secondary loop after the hydraulic separator – the same flow rate as in the primary loop (calculated including the three-way valves positioning). This regulation is essential because, otherwise, the hydraulic separator – which is acting as a mixing heat exchanger – would mix the flow rates and change the temperatures.

The secondary HEX can be fed by either industrial water from the local SMAT line or sludge (through a dedicated sludge pump).

The same complete layout can be also seen in the control system pages (Figure 2 and Figure 3).

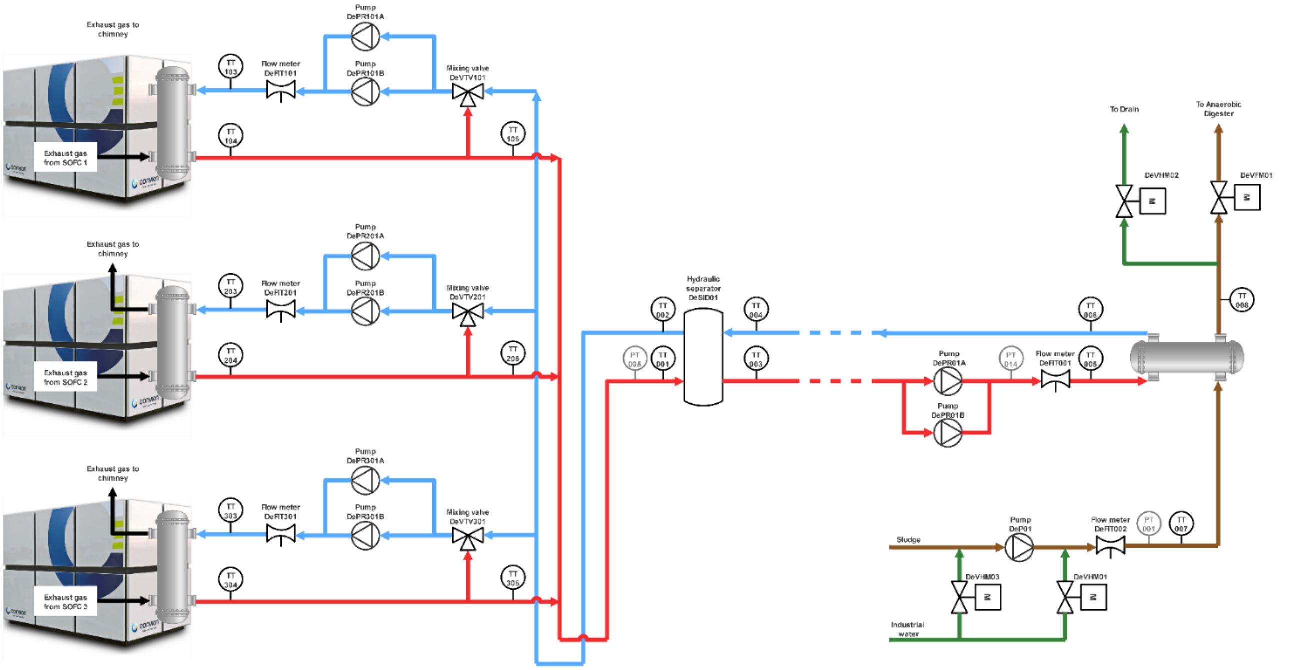

Figure 1. Thermal recovery layout.

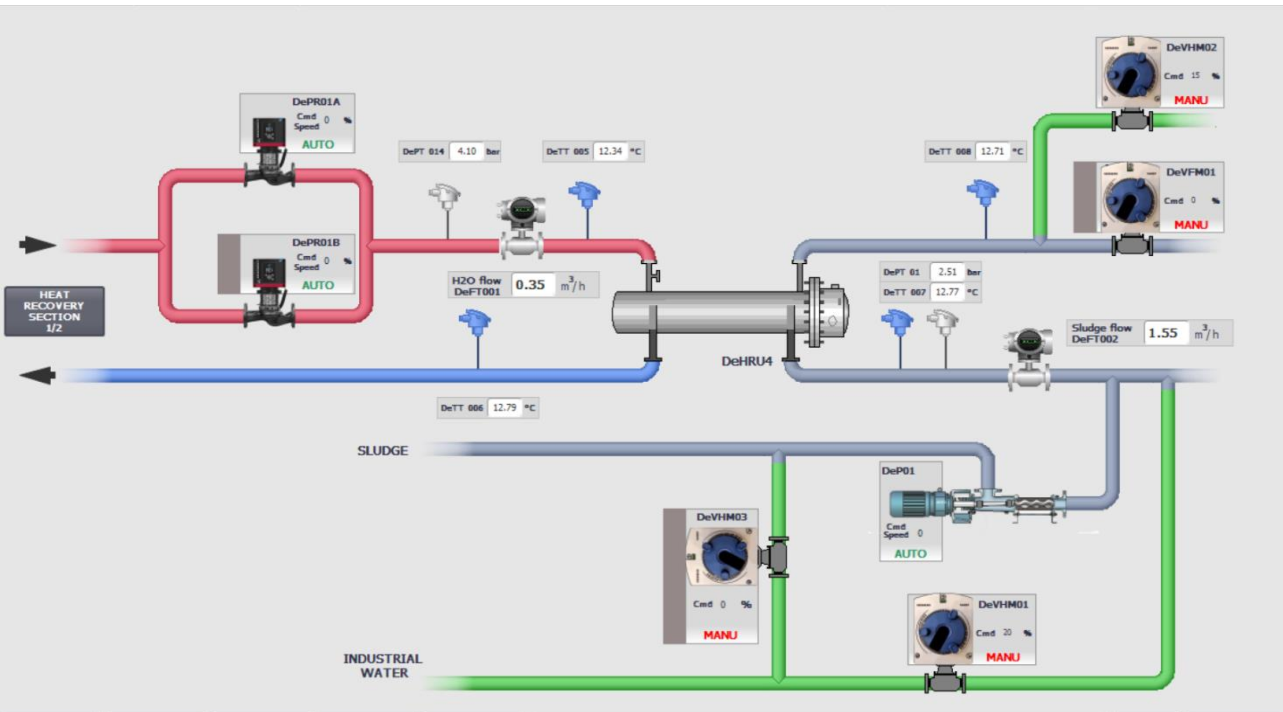

Figure 2. Thermal recovery section – page 1.

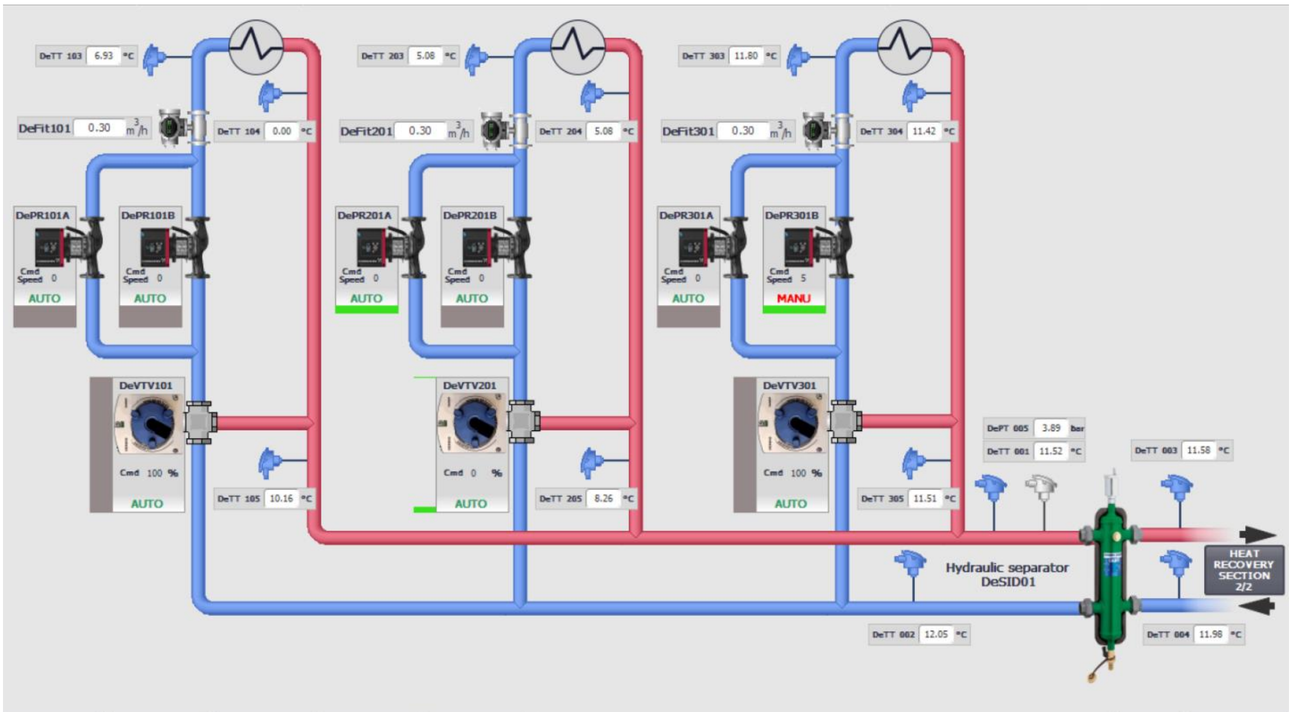

Figure 3. Thermal recovery section – page 2.

2. Operation timeline

The 2 SOFC modules have been operated always separately, except for some weeks in February-March 2020. This was not a decision, but a consequence of the different maintenance activities performed on the systems.

SOFC1 operated for the following operating periods:

- October-December 2017
- February-March 2018
- April-June 2018
- August 2018
- September-October 2018
- February-March 2020

During the complete year 2019 and part of year 2020 the SOFC module experienced some planned and unplanned maintenance activities as will be described in detail in D5.4 (Report on the Maintenance of the DEMO system).

SOFC2 operated for the following operating periods:

- October-December 2018
- February 2019-October 2020 (not continuous but with only short stops)

The operation of SOFC2 was more stable and with less interruptions, and the SOFC modules was also still running in October 2020, at the end of the project.

Figure 4 shows a summary of the plant operation described above. The data (especially the capacity factors) are calculated up to October 31st, 2020, the official project end.

		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	55.06%	2.40	
	Feb-Mar 2018	336	24,742	12,371	8,247	50.00%	1.50	
	Apr-Jun 2018	1,640	167,445	85,640	55,080	51.15%	1.55	
	Aug 2018	63	5,698	2,849	2,295	50.00%	1.24	
	Sep-Oct 2018	785	47,111	22,609	10,625	47.99%	2.13	
	Feb-Ott 2020	3,214	229,514	106,623	70,884	46.46%	1.50	
	Tot. SOFC1	**7,143**	**330,083**	**170,319**	**95,768**	**51.60%**	**1.78**	**50.11%**
SOFC 2	Oct-Dec 2018	1,291	101,104	55,601	35,995	54.99%	1.54	
	Feb 2019 -Ott 2020	8,946	710,397	320,568	233,750	45.13%	1.37	
	Tot. SOFC2	**10,237**	**811,501**	**376,170**	**269,745**	**46.35%**	1.39	**57.87%**
	Tot. DEMOSOFC	**14,166**	**1,141,585**	**546,488**	**365,512**	**47.87%**	**1.50**	**49.31%**

Figure 4. Summary of the DEMOSOFC plant operation.

3. Thermal production

The overall thermal production from the DEMOSOFC plant was 365.5 MWh, of which 269.7 MWh produced by SOFC2 (73.4%) and 95.8 MWh by SOFC1 (26.2%). As demonstrated for the electrical production, the contribution of SOFC2 is larger because of the higher number of stable operating hours reached with this system.

PID controllers on the SOFC HEX were operating fine during the whole project: inlet temperature was stable at 45 °C and outlet temperature at 70 °C. The exhaust flow rate, used for this evaluation, was calculated as the sum (in mass terms) of the inlet streams entering the SOFC module (biogas and air), because no direct exhaust flow rate measurement was available. Deliverable D5.1 (Report on the

Operation of the DEMO system in the long run) provides details on the thermal efficiency values during the whole project duration.

Figure 5 shows the thermal production from SOFC1, during the period in which the system operated at nominal point (April-June 2018). Thermal production was quite stable and varying between 30 and 35 kW (measured at the exhaust side).

Figure 6 shows the thermal production from SOFC2, between February 2019 and October 2020. In this period, the electrical production decreased from 42 to around 20 kW: in the first (and longer) operation time, the thermal production – initially equal to 25 kW - increased during time up to around 30 kW. At the same time, electrical production was decreasing. We can state that total efficiency and total energy production was kept constant during this period. From the restart in April 2020, the thermal production was indeed reduced, together with the electrical one. The set point, in this second operating period, was reduced compared to the first one, and this is the reason for the reduced total power production.

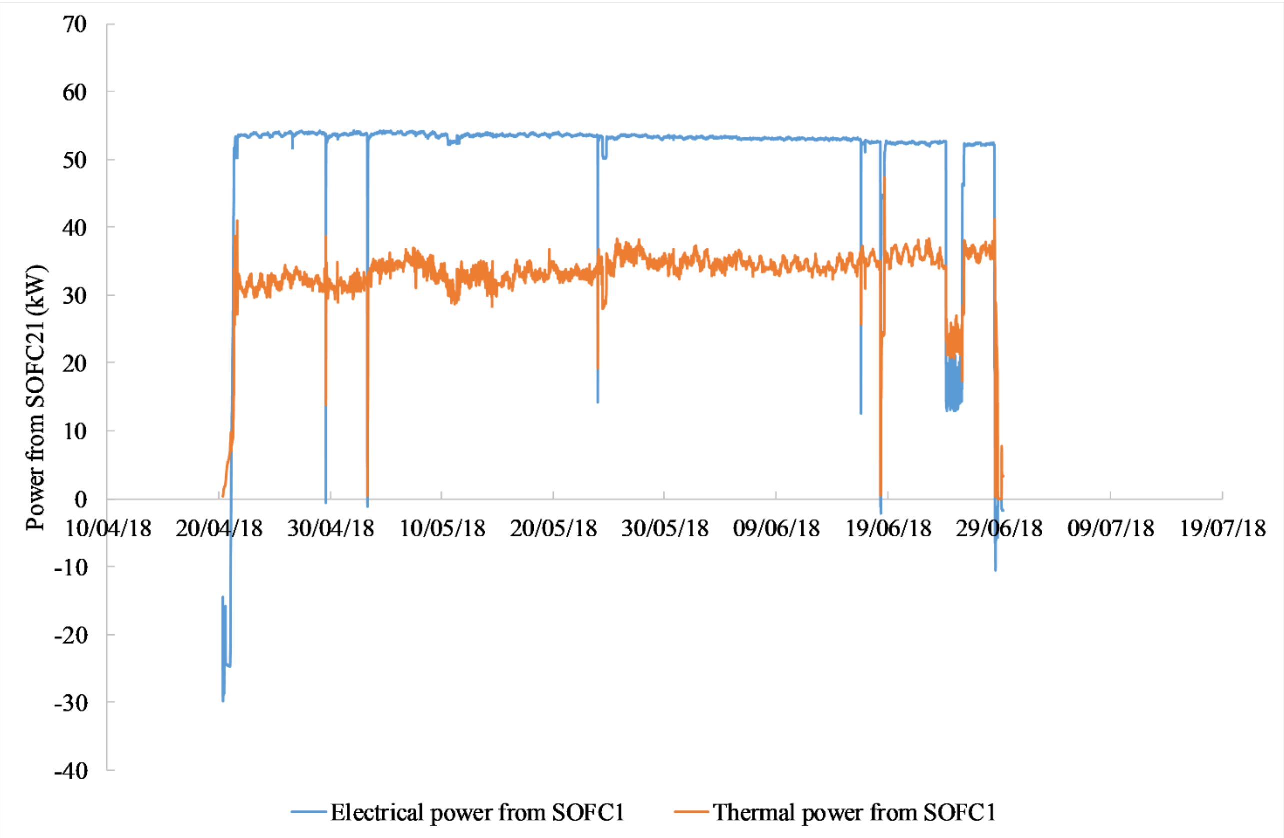

Figure 5. Electrical and thermal production from SOFC1 in April-June 2018.

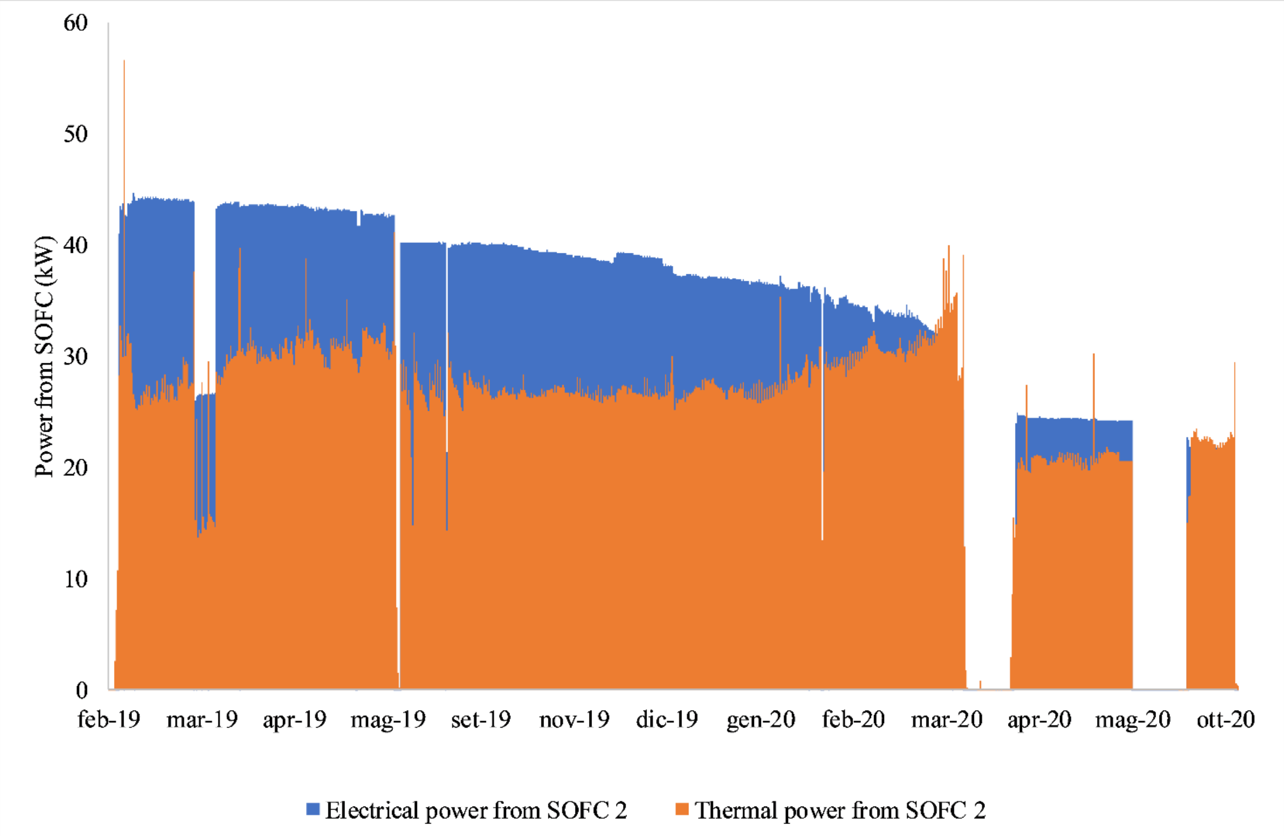

Figure 6. Electrical and thermal production from SOFC2 in February 2019 - October 2020.

All the data here presented are measured on the exhaust side of the SOFC module. The reason for this is linked with the uncertainties raised during the evaluation of the thermal production on water and sludge side. The main reasons were:

- Glycol percentage was fixed (30%) at the beginning of the DEMOSOFC plant operation. The system is anyway equipped with an automatic refilling system in case the pressure of the circuit drops below a fixed value and the refill is done with water only. For this reason, during the long operation time, the glycol percentage was reduced of an unknown percentage which leads to an unknown specific heat of the water-glycol mixture.
- The second unknow factor on the water side was the behaviour of the hydraulic separator. As mentioned above, this component is acting as a mixing heat exchanger (see Figure 7): if primary and secondary loop flow rates are exactly the same, the vessel is perfectly stratified (from a thermal point of view) and inlet/outlet flows and temperatures are kept constant (T1=T3 and T2=T4). This is the ideal scenario, and the PID on the secondary loop pump was in fact designed to have the same flow rate as in the first one (calculated by the single primary

loop flow meters values and the mixing valve positioning values). Anyway, if the primary loop flow rate happens to be lower than the secondary one, the HEX is recirculating back part of the secondary loop flow and so T3<T1 (the hot streams temperature will decrease across the HEX). On the contrary, if the primary loop flow rate is higher than the secondary one, the recirculation will be performed on the primary circuit, and so T2>T4. Beside the temperature changes across the separator, in case scenarios 2) and 3) happened, the flow rates were also modified and thus the total thermal power.

- The heat recovery system was designed for 3 modules working at full power (174 kWe). For this reason, the system was operating strongly off-design with one module only, and especially with one module at reduced power. In these conditions, even if PID controllers were working, sometimes happened that the requested flow rates (very low) cannot be achieved with the available pumps, even if working at their minimum level.

For this reason, the evaluation of the thermal power exchanged on the water-glycol side before and after the hydraulic separator, often brought to non-realistic values and for the same reason, these values have not been included in this analysis. A more detailed analysis of this problem is available in Appendix A.

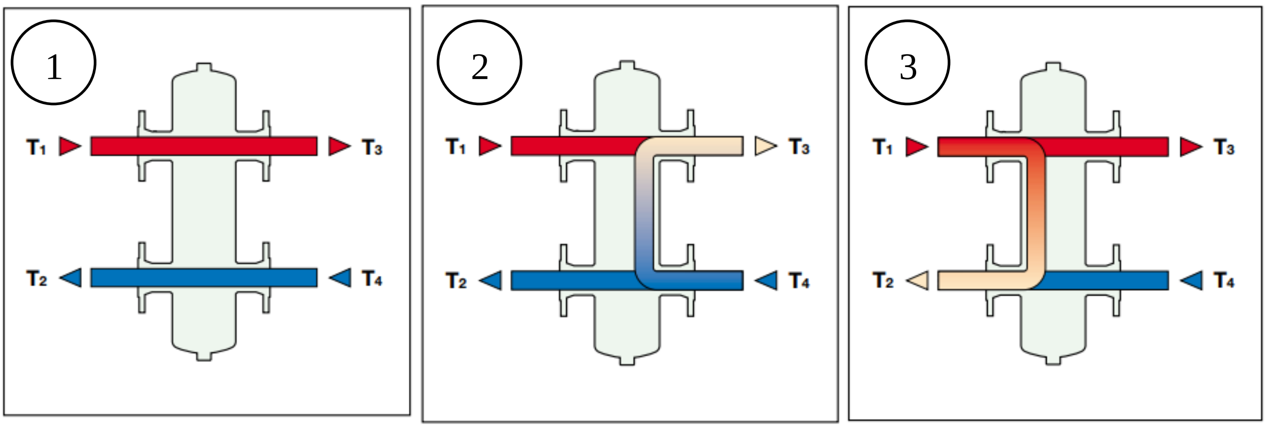

Figure 7. Hydraulic separator behaviour. 1) Equal flow rates in the primary and in the secondary loop. 2) primary loop flow is lower than secondary loop. 3) primary loop flow is higher than secondary loop.

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4. Appendix A[1].

This analysis is referred to the following operating periods:

- Period A: 20th April – 28th June 2018. SOFC1 set at 90%.
- Period B: 12th September – 16th October 2018. SOFC1 set at 50%.
- Period C: 25th October – 19th December 2018, SOFC2 set at 100%, SOFC1 OFF.

Figure 8 represents the thermal power carried by the exhaust, the water-glycol mix (after the first heat exchanger and before the second) and the sludge. Data in this section of the plant clearly have problems, as each of the two heat recovery units seems to increase the thermal power of the relative fluids.

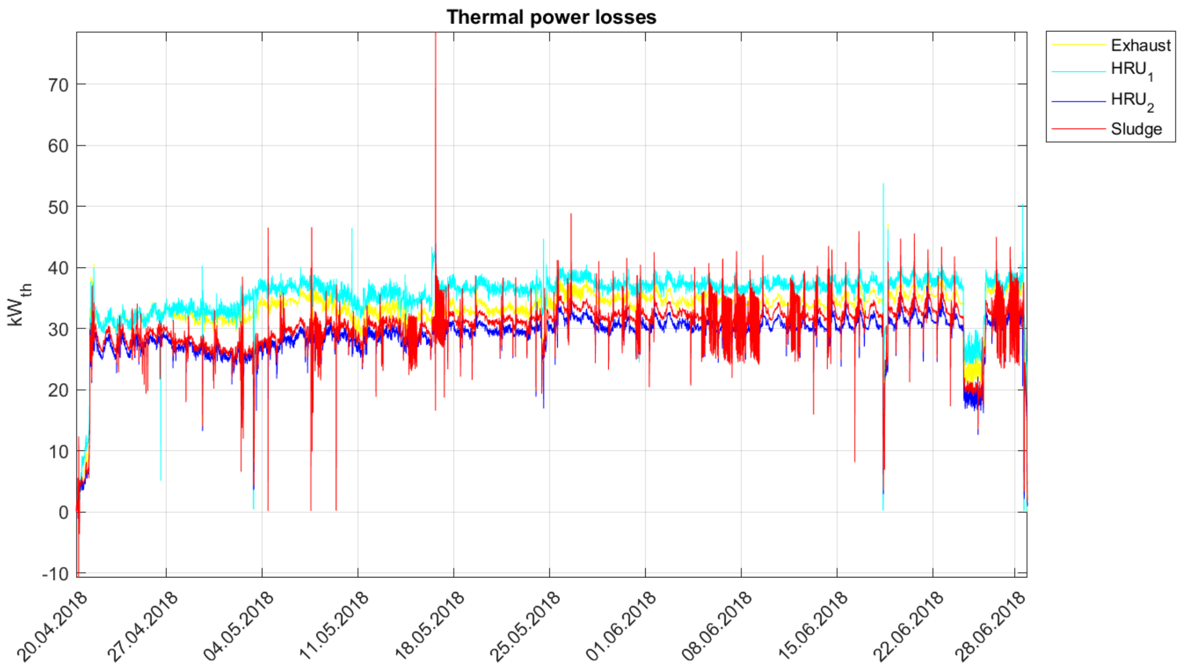

Figure 8. Thermal power related to the different fluids before and after each heat exchanger.

In particular, in the first heat exchanger, the water seems to get more power than the one got by the flue gas. In the sludge heat exchanger, again the sludge seems to receive more energy than how much is contained on the other side of the heat exchanger. This incongruence is not linked to a bad choice of the constant as the thermal capacity or the density, since data about the heat transfer fluid, a water-

[1] M. Capello, "Analysis of the performance of the first biogas-fed SOFC plant in Europe (the DEMOSOFC project) - Webthesis," Master thesis, 2019. [Online]. Available: https://webthesis.biblio.polito.it/11313/. [Accessed: 08-Jan-2021].

glycol 30% mix, are provided by the supplier, and the sludge heat exchanger is heating up simple water, since during the analysed operations the macerator was out of service. However, a variation of those parameters would only reduce the problem in one heat exchanger and increase it in the other one. Further analysis has to be conducted about this problem.

The error could be linked to a bad measuring of the water-glycol flow meters, or to an erroneous setting of the different pumps. Errors in the flow rate measurements were already observed about the sensor DeFIT005, which measures the flow of biogas extracted by the gasometer.

An error in the pumps PID could be highlighted by the behaviour of the flow rate measured by the sensors. The water-glycol line contains many pumps, since the sludge heat exchanger is located in a different building and the pipes are quite long: a couple of pumps for every heat exchanger in the modules and a fourth couple near the sludge heat exchanger. Between the first three heat exchangers and the fourth is interposed a hydraulic separator, with the task to smooth out potential difference between the two flow rates.

As depicted in Figure 9, which resumes the flow rate measured in the first three periods (A, B and C), the sum of the flow rates of the first three HRU, represented in dark green, and the flow rate of fluid through the sludge HRU, in blue, are very different, with the first being much higher than the second. Part of the flows before the hydraulic separator is recirculated through the mixing valves, even if the amount of fluid deviated is not certain.

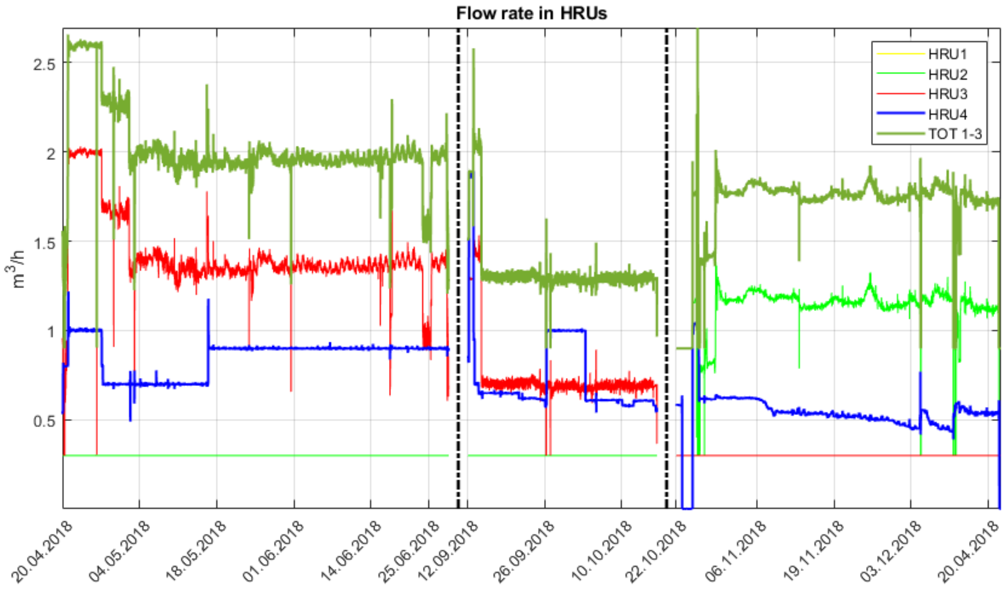

Figure 9. Water-glycol flow rate in different HRUs.

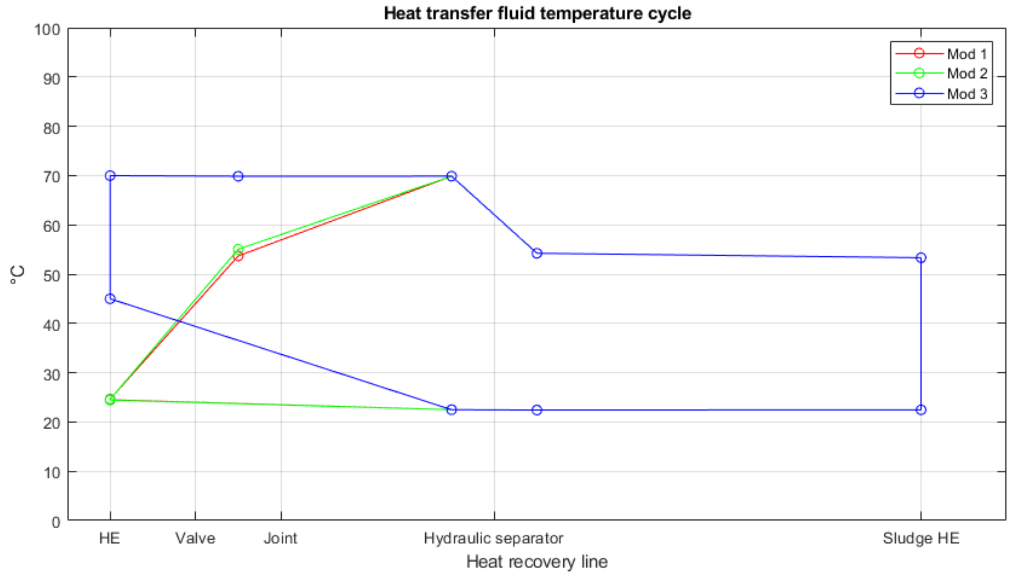

Figure 10. Heat recovery system, temperature cycle (for periods A and B).

Even looking at the temperature cycle, represented in Figure 10, is evident a drop in the temperature over the hydraulic separator.

If the measures are correct this differences could lead to a huge loss of thermal power in the hydraulic separator, even if it would not explain the strange behaviour of the thermal power represented in Figure 8**Errore. L'origine riferimento non è stata trovata.**.

Ignoring the data of the heat exchanger fluid, but considering only the difference between the thermal power of the flue gas and the one received by the sludge, the heat recovery system seems to have an almost constant dispersion: 6.68 kW_{th}, 8.20 kW_{th} and 7.44 kW_{th} in the three different analyzed periods.

Table 1 resumes the amount of thermal energy monthly produced and received by the sludge. The data are compatible with the net efficiency of the heat recovery system for SOFC1, respectively of 85.37%, 62.07% and 78.31% (in periods A, B and C). The net efficiency evaluated about period A and C as to be considered as the most reliable since in those periods the modules were working at nominal conditions. Similarly, the most accurate measures on a monthly basis are those of May and November, as the modules worked for the entire month without any stop at nominal conditions.

The percentage of energy loss in period C is higher since the second module showed a lower production of thermal energy, added to a slightly higher loss in the pipes due to the lower winter temperatures.

	kWh_{th} SOFC	**kWh_{th} sludge**	**Loss**
Apr	7 512.49	6 551.39	12.79%
May	26 976.74	22 600.25	16.22%
Jun	24 339.61	21 047.91	13.52%
Sep	8 903.57	5 797.88	34.88%
Oct	6 728.36	3 853.10	42.73%
Oct	3 446.25	2 624.20	23.85%
Nov	23 111.77	18 531.12	19.82%
Dec	13 823.83	11 002.97	20.41%

Table 1 - Thermal energy dispersion on a monthly basis