DEMOSOFC

Project n° 671470

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

Deliverable number 2.1

Energy planning of the DEMO

Task T2.1: Energy planning of the DEMO

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Author(s):	Andrea Lanzini, Marta Gandiglio, Angelo Le Pera, Massimo Santarelli (POLITO), Eugenio Lorenzi (SMAT), Tuomas Hakala (CONVION), Adam Hawkes (IC)
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Abstract:

The main characteristics of the wastewater treatment plant in which the DEMOSOFC plant will be installed have been analysed and reviewed. Hourly biogas availability, type and amount of contaminants and thermal needs of the digester have been all determined.

A preliminary energy simulation of the integrated digester gas SOFC plant has been carried out in order to identify an operating strategy of the SOFC modules in view of the highly fluctuating biogas supply. Also, seasonal trends in biogas availability have been identified and quantified.

The main achievement has been eventually the development of an Energy Planner Tool (EPT), or Energy Simulation Tool, with a user-friendly graphical user interface (GUI) that is able to simulate the integrated plant energy performance. More in detail, EPT is time-resolved hourly-dense simulation tool that provides valuable information on the system energy performance according to user-defined input variables and system constraints. A PID regulator is also able to automatically control the SOFC power output based on the amount of biogas available in the gas holder. The Energy Planner Tool will serve as the simulation platform for a thorough techno-economic optimization of the integrated biogas SOFC plant.

The preliminary design of the DEMO plant is also presented, with a description of the main DEMO sections which includes the biogas clean-up unit, the SOFC modules and the heat-recovery loop.

Keyword list: biogas, SOFC, energy model, contaminants, siloxanes.

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1. Purpose of this document

The main characteristics of wastewater treatment plant (WWTP) will be reviewed in terms of:

- seasonal biogas availability;
- biogas composition;
- trace contaminants and their amount in the as received biogas (mostly H_2S and siloxanes will be monitored);
- seasonal heat duty of the digester.

The information above will contribute toward the definition of a detailed seasonal model of the digester material and energy streams.

Based on this knowledge, the SOFC installation is first designed, and then the optimal operation of the SOFC modules are assessed in term of electrical and thermal energy produced and their use within the WWTP.

A time-resolved Energy Planning Simulation Tool (based on daily data) will be developed (starting from models already available in POLITO) to study the performance in different scenarios of the integrated biogas SOFC system. The aim of the Energy Planner will be to evaluate real-life performance of the energy system taking into account the time availability of biogas, the necessity of thermal recovery, and the electrical load of the system.

Each technology present in the DEMO (WWT plant, biogas clean-up section, SOFC modules, thermal recovery system) is assessed and included in the Energy Planner, by taking into account their energy performance, investment and operating costs, off-design operability and dynamic response to load changes.

The aim of this activity is to define the preliminary design of the DEMO. Furthermore, the primary energy savings of the DEMO is evaluated.

2. WWTP characteristics

The core part of the DEMOSOFC installation is a 174 kW_e SOFC plant, which consists of three modules (each one rated 58 kW_e AC power). The site of the installation is the wastewater treatment plant (WWTP) of Collegno (Torino, IT) managed by project partner SMAT (see Figure 1).

The WWTP currently serves 270’000 equivalent inhabitants – that is only a portion of the overall municipality of Torino – collecting an overall of 59’000 m^3 of wastewater on a daily basis that corresponds to ~220 liter/day/capita. Digester gas is available from the anaerobic fermentation of pre-thickened sludge at this facility. The suspended solid volatile (SSV) fraction in the sludge results in 1.34 wt. % leading to a calculated biogas yield of 0.39 Nm^3 of biogas per kg of SSV.

Given these site-specific productivity facts, and by taking the biogas-to-electricity efficiency of 53% (LHV basis) for the SOFC generator in nominal operation conditions, the resulting electricity yield is ~1 W_e/capita. Further details are summarized Table 1.

Table 1. Site specific facts about the WWTP of SMAT in Torino

Number of equivalent inhabitants served		270’000
Wastewater feed	[m^3/day]	59’000
Daily wastewater feed per capita	[l/day/capita]	220
Biogas production rate	Yearly overall [Nm^3/y]	706’890
	Hourly overall [Nm^3/h]	80.7
	Yearly specific [Nm^3/year/capita]	2.62
	Daily specific [l/day/capita]	7.2
LHV (average vol. composition 60% CH_4 40% CO_2)	kJ/m^3	21’501
Average SSV (Suspended Solid Volatile) fraction	%	1.34
Average SST (Suspended Solid Total) fraction	%	1.91
Ratio SSV/SST	-	0.70
Sludge feed	Yearly [m^3/y]	135’465
	Hourly [m^3/h]	15.5
	Specific [m^3/ab]	0.50
SSV feed	kg/year	1’815’231
Specific biogas yield	**Nm^3 biogas / kg SSV**	**0.39**

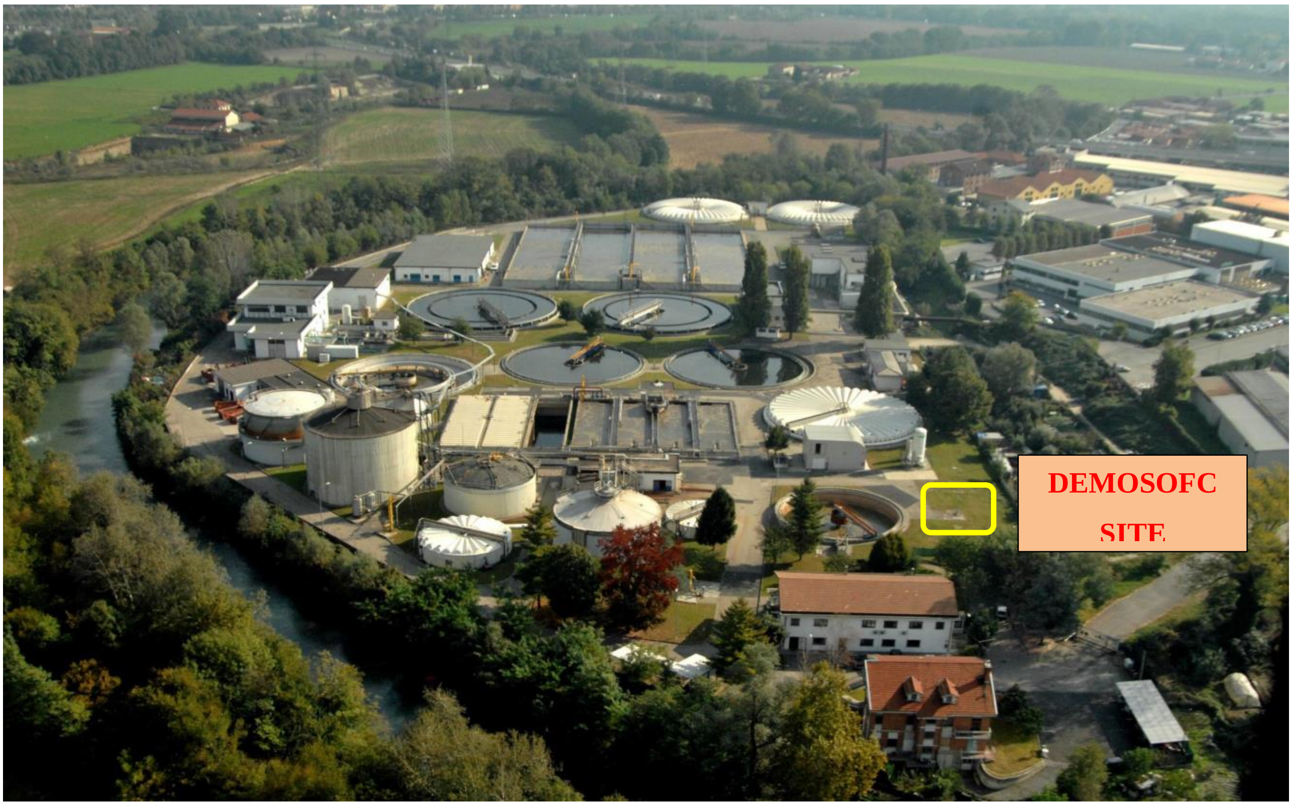

Figure 1. WWTP of SMAT Collegno (TO)

Biogas availability

A variable biogas supply to the SOFC is expected in the DEMOSOFC installation.

The hourly biogas production for 2014 and 2015 (till October) are given in Figure 2 and Figure 3.

The main observed features are:

- a widely fluctuating biogas production throughout the year;
- a seasonal pattern according to which less biogas is produced in summertime (June to September) due to lower incoming wastewater.

The average biogas production has been 63 Nm^3/hr in 2014, while for 2015 is about 70 Nm^3/hr (however data records are available only till October 11th, 2015).

A detailed understanding of the digester behaviour and regulation is outside the scope of DEMOSOFC project. Nonetheless, fluctuations in biogas production might affect the SOFC operation (this aspect is investigated in detailed in the following part of this Deliverable, when introducing the Energy Planner Tool). For this reason, during the project the main operating parameters of the anaerobic digester have also been analysed in order to better predict the conditions which might lead to biogas shortages.

The main variables able to affect biogas production rates are the incoming sludge flow rate (that is depending on the wastewater intake flow rate) and the digester temperature (that strongly impact on bacterial activity within the anaerobic vessel). The inlet chemical oxygen demand (COD) and biological oxygen demand (BOD) of treated wastewater are also important variables.

For instance, the recorded digester mean temperature for 2014 and 2015 is shown in Figure 4. A clear correlation between digester temperature and biogas production has been not established yet. The plant manager reported that the digester temperature has been gradually increased from the mesophilic condition (30-38 °C) to 40-45 °C starting from 2014 in order to maintain a high biogas yield. However, there is no clear understanding at the moment that justifies such shift outside the mesophilic range besides empirical experience. **POSSIAMO CORRELARE DATO DI TEMPERATURA E DATO DI PRODUZIONE?** Avevamo provato a farlo senza però trovare correlazioni chiare che si potessero spiegare in un deliverable. Ne abbiamo parlato con SMAT in più di un'occasione senza mai ricevere un feedback veramente chiarificatore. La gestione termica del digestore appare quanto mai empirica. Nicoletta Mesiano sostiene che nel tempo hanno gradualmente aumentato la temperatura del digestore ai fini di mantenere elevata la produttività di biogas. Non so davvero quanto si possa commentare nel deliverable senza uno sforzo diretto di SMAT nel cercare di capire come mai fanno lavorare il digestore a 42-43 °C, che è un range sopra il mesofilico.

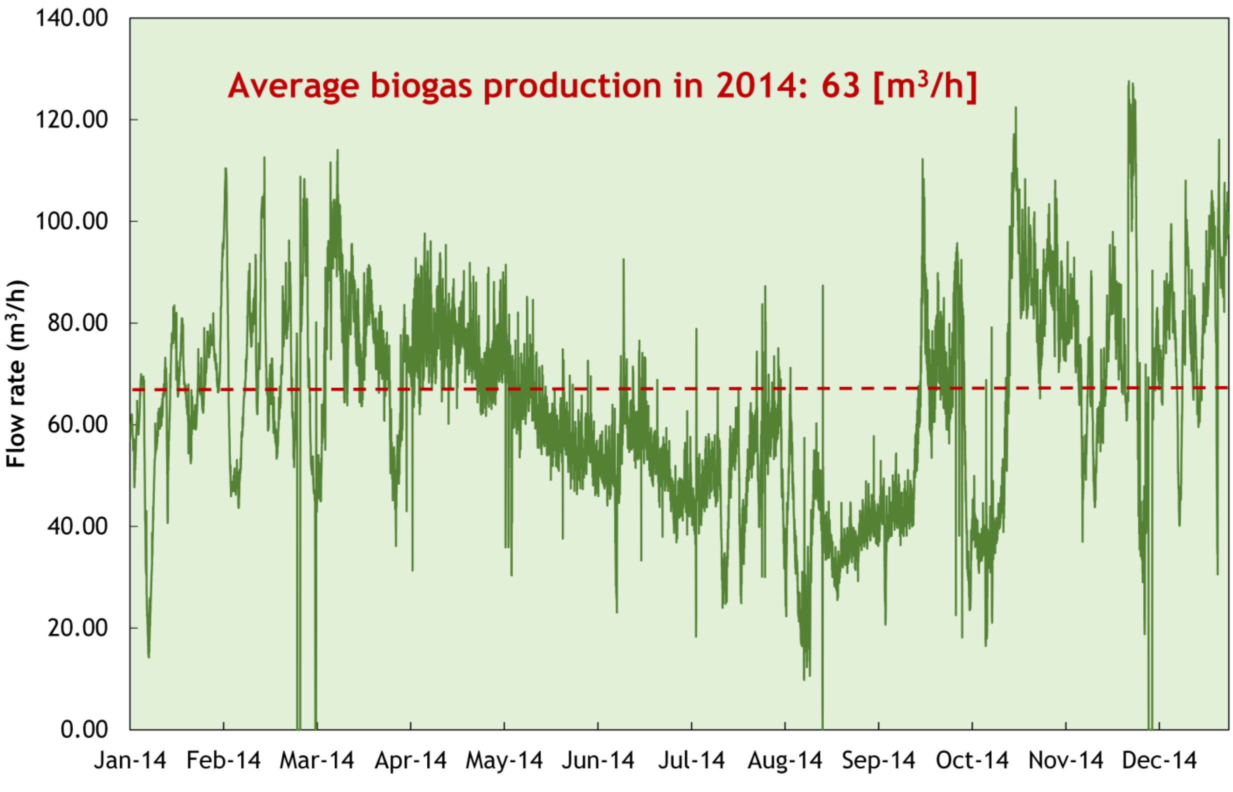

Figure 2. Biogas hourly production in 2014.

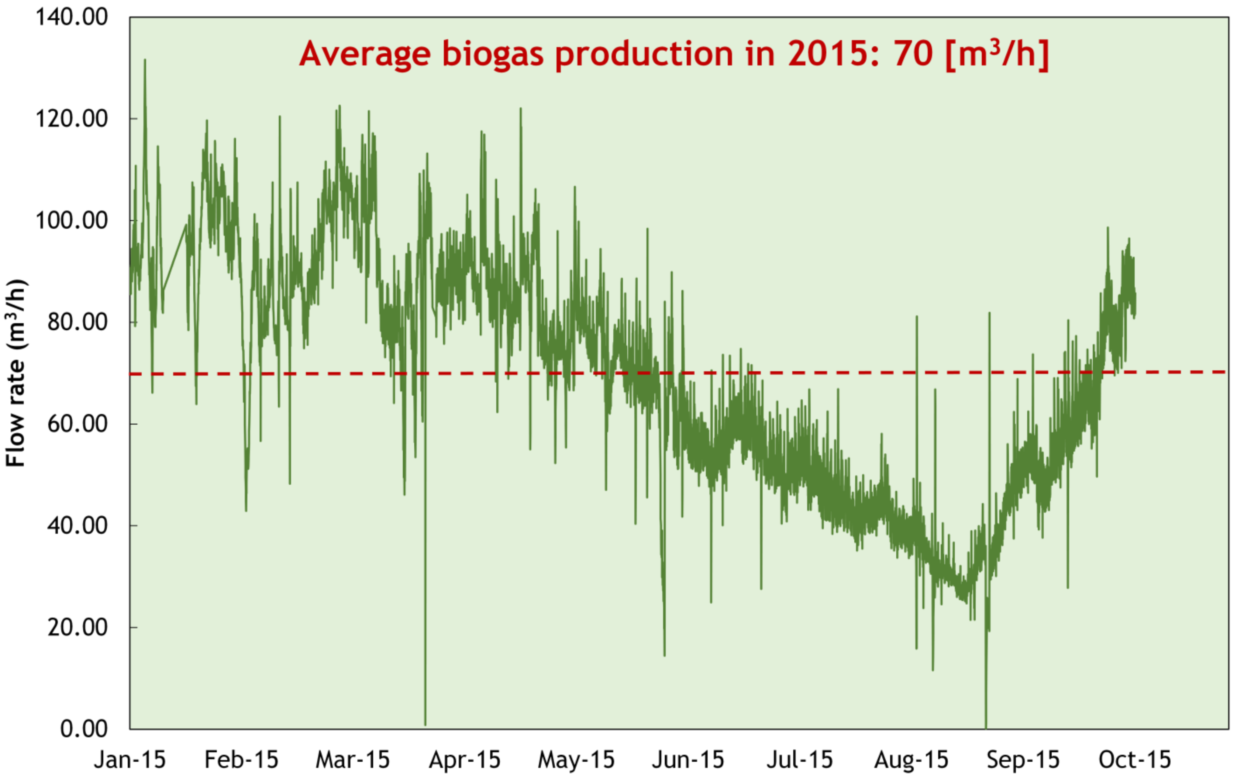

Figure 3. Biogas hourly production in 2015

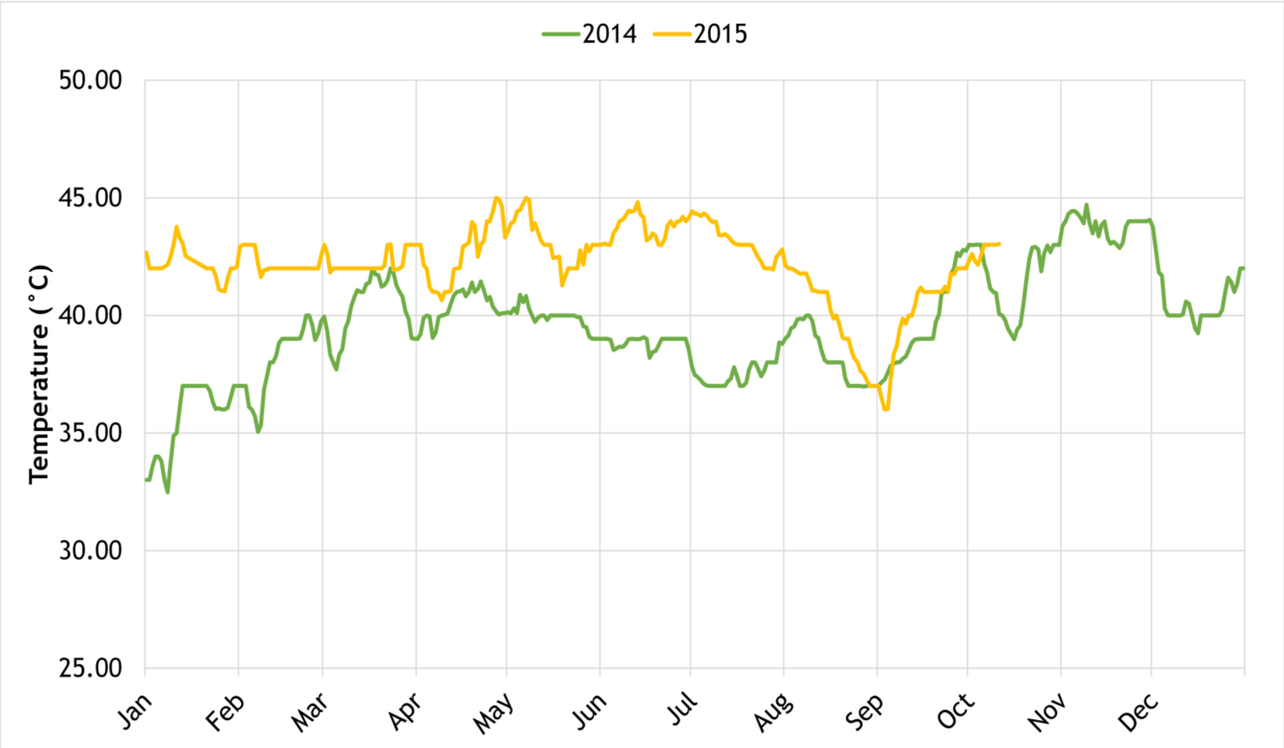

Figure 4. Digester mean temperature in 2014 and 2015

Biogas composition

The biogas composition in terms of CH_4 and CO_2 volumetric fractions is quite stable in the observed period (see Table 2). The average CH_4 content is about 64% vol.

Having a relatively stable CH_4 content in the sewage biogas is beneficial for the SOFC as a variable LHV of the biogas supply feed would need a continuous adjustment of the fuel flow rate to the SOFC in order to maintain a fixed fuel utilization (FU) for a given current load. Nonetheless, daily or monthly fluctuations in CH_4 content might occur during the life-time of the project; therefore an online CH_4 sensor will be installed to provide information to the SOFC control system on the instantaneous CH_4 fraction in the biogas feed. In this way, a constant FU operation of the SOFC at a given current load can be always assured. Sudden fluctuations (i.e., within minutes or hours) in CH_4 content are not expected as a gas holder is placed downstream the digester. This buffer volume is large enough to smooth down possible, even though not likely, hourly variations in biogas production.

Biogas contaminants

The presence of contaminants in the biogas stream is another fundamental aspect to deal with for the integration of SOFC modules within a WWTP. The amount and type of biogas contaminants in the digester gas of the Collegno plant have been monitored in the period from July to October 2015.

As expected, the main contaminants are H_2S and siloxanes. Mercaptans and other organic sulfur compounds are also present at lower concentrations (see Table 2).

Table 2 (continued on next page). Biogas contaminants

Compound	**Chemical formula**	**M.W. (g/mol)**		**July 9, 2015**	**July, 24 2015**	**Aug 7, 2015**	**Sep. 16, 2015**	**Sep. 28, 2015**	**Oct. 20, 2015**
Methane	CH_4	16	[%]	65.5	64.7	63.4	63.8	63.1	64.4
Carbon dioxide	CO_2	28	[%]	32.2	30.39	30.15	31.6	33.3	35.1
Oxygen	O_2	32	[%]	0.33	0.22	0.17	0.11	0.06	0.02
Carbon monoxide	CO	44	[mg/m^3]	2.7	3.1	2.1	1.8	1.2	0.8
Hydrogen sulfide	H_2S	34	[mg/m^3]	25.2	27.2	25.9	25.5	22.7	32.9
Sulphur - Mercaptans	-	-	[mg/m^3]	2.7	2.9	2.4	2.3	2.1	2.6
Ammonia	NH_3	17	[mg/m^3]	0.132	0.112	0.039	0.091	0.052	0.032
Total siloxanes				0.82	5.67	17.4	43.8	13.4	12.8
(D6) Dodecamethylcyclohexasiloxane	$C_{12}H_{36}O_6Si_6$	445	[mg/m^3]	0.00	0.17	0.61	1.92	0.95	0.89
(D5) Decamethylcyclopentasiloxane	$C_{10}H_{30}O_5Si_5$	371	[mg/m^3]	0.75	4.08	13.57	33.15	9.80	9.34
(D4) Octamethylcyclotetrasiloxane	$C_8H_{24}O_4Si_4$	297	[mg/m^3]	0.07	1.42	2.87	8.10	2.21	2.25
(L3) Octamethyltrisiloxane	$C_8H_{24}O_2Si_3$	237	[mg/m^3]	0.00	0.00	0.35	0.63	0.44	0.32
Si tot (calculated)	-	-	[mg Si/m^3]	0.31	2.14	6.56	16.52	5.05	4.83

Table 3 (continued). Biogas contaminants

Compound	**Chemical formula**	**M.W. (g/mol)**		**July 9, 2015**	**July, 24 2015**	**Aug 7, 2015**	**Sep. 16, 2015**	**Sep. 28, 2015**	**Oct. 20, 2015**
Hexane	C_6H_{14}	86	[mg/m^3]	0.23	0.31	0.29	0.61	0.31	0.36
Heptane	C_7H_{16}	100	[mg/m^3]	0.2	0.26	0.19	0.58	0.12	0.35
Toluene	C_7H_8	92	[mg/m^3]	6.12	5.67	9.41	3.21	8.75	8.76
Xylene	C_8H_{10}	106	[mg/m^3]	0.48	0.77	0.4	0.55	0.17	0.21
Limonene	$C_{10}H_{16}$	136	[mg/m^3]	5.11	4.08	3.81	7.95	8.15	6.76
Aliphatic Hydrocarbons	-	-	[mg/m^3]	118.5	114.2	112.7	116	76.7	46
Aromatic hydrocarbons	-	-	[mg/m^3]	3.22	24.5	6.81	6.57	3.98	1.85
Alicyclic hydrocarbons	-	-	[mg/m^3]	21.4	0.5	22.7	16.3	11.7	9.13

Seasonal thermal load of the digester

A single digester dome is operating in the Collegno Plant. Both nominal and limiting operating conditions of the digester in terms of its thermal performance are summarized in Table 4. Additional geometric data are provided in Table 5.

Table 4. Digester thermal properties and design conditions

		Nominal conditions	**Limit conditions**	
Digestion temperature	T_d	42.17	42.17	°C
Sludge inlet temperature	T_f	15	10	°C
External temperature	T_e	2	-5	°C
Floor temperature	T_t	10	5	°C
Sludge flow rate in Collegno WWTP	Q_{sl}	248	248	$m^3\ d^{-1}$
Heat transfer coeff. through non-underground walls	U_1	0.8	0.8	kcal $h^{-1}\ m^{-2}\ °C^{-1}$
		0.9	0.9	$W\ m^{-2}\ °C^{-1}$
Heat transfer coeff. through underground walls	U_2	2	2	kcal $h^{-1}\ m^{-2}\ °C^{-1}$
		2.3	2.3	$W\ m^{-2}\ °C^{-1}$
Dispersions through pipes (hp.)		10%	10%	%

Non capisco perché l'unità di misura è segnata in rosso (?). A me sembra corretta! In ambito termotecnico si usa questa unità di misura, che tra l'altro ha un fattore di conversione molto vicino all'unità quando si usa il SI ($W/m^2/k$). 1 kcal/hr = 4182 J / 3600 s = 1.16 W. Il dato tra l'altro proviene direttamente dal progetto termotecnico del digestore.

Table 5. Digester geometrical dimensions

Digester dimensions			
Surface of the collar support of the dome	S_1	12.6	m^2
Above-ground side wall	S_{2a}	785.4	m^2
Inground side wall	S_{2b}	125.7	m^2
Flat top roof	S_3	3.1	m^2
Conical surface on top roof	S_5	331.0	m^2
Conical surface on bottom roof	S_6	322.0	m^2
Insulated external wall	S_e	1132.1	m^2
Inground surface	S_i	450.8	m^2

The thermal loads calculated, based on the digester thermal properties, design conditions and physical dimensions are given in Table 6.

Table 6. Digester thermal load

Yearly thermal balance	Nomimal	Max.	
Floor + Roof heat losses	42.3	49.7	kW
Bottom	33.7	39.0	kW
Thermal load for sludge pre-heating	326.3	386.4	kW
Dispersion through pipes	40.2	47.5	kW
Total thermal load	*442.6*	*522.5*	*kW*

Beacuse of varying external ambient temperature, and amount and temperature of as-received sludge during the year, it is worth referring to and calculting the seasonal thermal profile of the digester. The seasonal heat duty of the digester with a monthly resolution is shown in Figure 12.

The available equivalent biogas energy is not always able to guarantee the thermal self-sufficiency of the digester (the calculation of thermal energy in biogas assumes that *all* biogas is used for heat production). This is the case of the period spanning from December to March, during which the digester thermal load is higher than the thermal energy contained in biogas.

Clearly, the use of biogas for electricity production in the SOFC will further reduce the available thermal energy for the digester. In the DEMOSOFC installation, thermal energy will be recovered from surplus biogas that is not used for the electricity generation, and from the SOFC exhuast gas streams. Nonetheless, a lower internal thermal input will be available compared to the situation depicted in Figure 12. Questa frase non è chiara, e la figura penso sia una altra In realtà la figura sotto è proprio quella corretta. Anche rileggendo sopra non trovo particolari incongruenze. Provo a spiegare in italiano quanto intendo sopra: fig. 11 mostra il carico termico richiesto dal digestore, l'energia chimica e l'energia termica disponibile nel biogas. Si vede come in alcuni mesi c'e' un deficit di energia termica, da dic. a marzo. Se poi si usa il biogas per fare energia elettrica in SOFC, la situazione chiaramente peggiora ancora. Se produco elettricità, riduco necessariamente la quota termica. Questo rimane vero anche se prevedo un funzionamento cogenerativo della SOFC, e se uso il biogas non inviato in SOFC per produzione termica. Questo discorso appena fatto introduce l'utilità di avere un sistema di pre-inspessimento dei fanghi, in modo da ridurre il carico termico del digestore. Questo è scritto sotto.

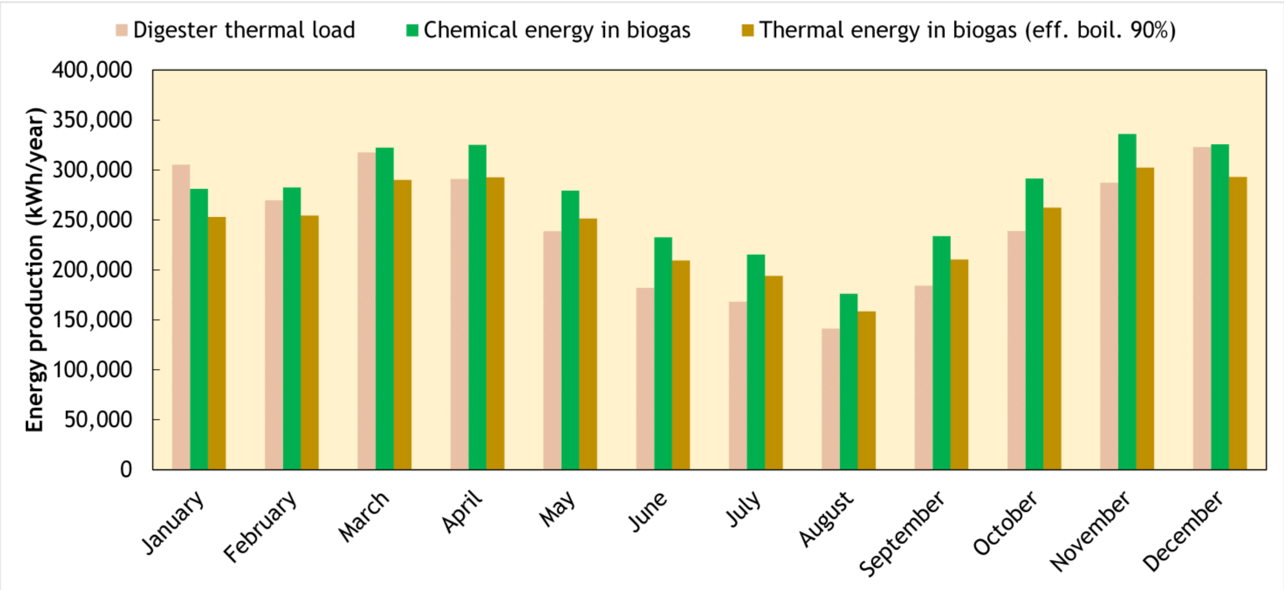

Figure 5. Digester thermal load vs. available biogas energy.

A shown in Table 6, the digester thermal load is dominated by incoming sludge pre-heating. Measures to reduce the thermal load of the digester foresee treatments for enhanced pre-thickening of the sludge that feeds the digester. In this way, the organic matter results less diluted in water and significant reductions in the overall digester load can be achieved. Both dynamic and centrifugal sludge pre-thickening might be successfully applied in the Collegno WWPT. The impact of such practices within the DEMOSOFC installation will explored in detail in Task 2.2 'Optimization of the DEMO'. But these modifications are not planned in the first phase of the DEMOSOFC project, and they will be discussed with the Company hosting the DEMO (SMAT, partner of the project) during the evolution of the project itself.

3. **Preliminary energy modeling of the DEMOSOFC plant**

A preliminary energy modeling of the DEMOSOFC plant has been carried out taking into account the variability of biogas production and its physical storage capability in a gas holder already installed within the Collegno plant premises.

A regulation of the SOFC power output according to the monitoring of the gas holder level has been identified as the key strategy to avoid fuel shortages and SOFC shut down during the year. Details on the gas holder volume and preliminary calcuations showing the effectivennes of SOFC power regulation based on biogas contained in the storage volume are presented in the next section.

Gas holder volume for digester gas

The gas holder volume is 1,470 m^3. Currently, the gas holder level in the SMAT Collegno WWTP is monitored through different alarm signals. The list of alarms currently in use in the SMAT plant is:

- Low-Low (**LL**): level below 570 m^3;
- Low (**L**): level below 620 m^3;
- High (**H**): level above 670 m^3;
- High-High (**HH**): above 1,440 m^3.

When the level of the gas falls below LL, biogas extraction is stopped from the gas holder. Instead, if the level is above HH, biogas is flared.

For the scope of DEMOSOFC project, SMAT foresees to install a radar sensor that will be able to monitor continuously and with a high level of accuracy the gas volume level within the gas holder. Based on the output signal of this new sensor, revised operating thresholds of the gas holder can be programmed to better match biogas availability to SOFC operational needs. A second option, even more robust from a control strategy point of view, would be the implementation of a Proportional-Integral-Derivative (PID) controller that is programmed to maintain the gas holder level to a given set value, thus reducing the risk of a sudden fuel shortage to the SOFC modules due to a bad management of the available biogas resource. This second scenario is the option that is currently supported and under further investigation for the DEMOSOFC installation. Secondo me questa frase non è chiara, meglio riscriverla con più chiarezza, in particolare non mi è chiaro cosa significhi "to maintain the gas holder value to set value". Ho provato a riscrivere con maggiore chiarezza. Il PID prevede di regolare su un dato set-point. La nostra idea di controllo, se infine basata su un PID, prevederà che noi inseriamo nel sistema di controllo un set-point di livello (volume) del gasometro, e il PID cercherà di mantenere costante questo livello, o volume, di gas. Con riferimento al tool EPT che abbiamo sviluppato (nella presentazione che avevo mandato a Tuomas), si vede proprio come il volume del gas holder è mantenuto costante in riferimento al set-point indicato tra i valori di input del tool (ad es., posso inserire un set-point di 1000 m^3). E' chiaro che se poi il flusso di biogas dal digestore è troppo, nel senso che è più di quanto la SOFC possa consumare a 100% del carico, oppure è meno di quanto la SOFC possa consumare al al 30% del carico (minimo valore possibile di modulazione), allora il PID non può più 'fisicamente' mantenere un valore costante, e il livello del gas holder si scosterà rispetto al valore di set-point.

SOFC power regulation

A first attempt to simulate the temporal performance of the gas holder level depending on an adjustable SOFC power output is proposed below (i.e., gas holder volume regulation without PID controller). Anche questa frase secondo me non è chiara The simulation is carried out using the hourly biogas rate profile for 2014. The new gas holder levels are the following:

- Low-Low (**LL**): level below 300 m^3;
- Low (**L**): level below 500 m^3;
- High (**H**): level above 700 m^3;
- High-High (**HH**): above 1,400 m^3.

The corresponding SOFC modulation ranges are:

- Level < LL: SOFC module stop operation;
- LL ≤ Level < L: 50% SOFC power rate;
- L ≤ Level < H: 75% SOFC power rate;
- H ≤ Level < HH: 100% SOFC power rate;
- Level > HH: 100% SOFC power rate.

The assumptions of an SOFC able to operate at constant electrical efficiency all over the power modulation range (from 50 to 100% of the nominal power) and a constant biogas composition of 60% vol. CH_4 and 40% vol. CO_2 were done.

Modulation ranges of the SOFC according to the amount of biogas available in the gas holder are depicted in Figure 6.

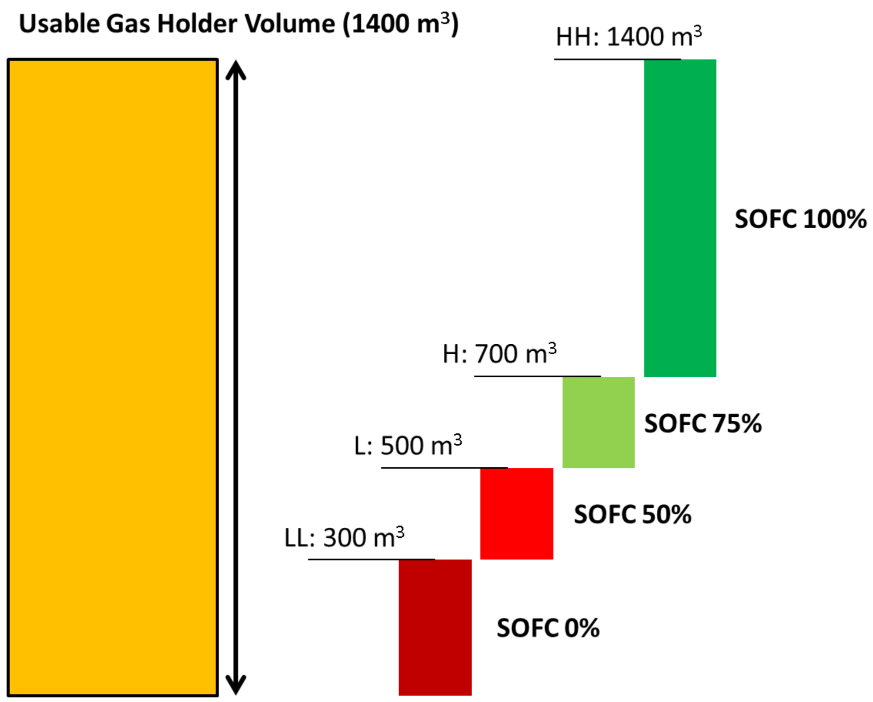

Figure 6. SOFC modulation range according to biogas availability in the gas holder tank

The results of the simulation are given in Figure 7.

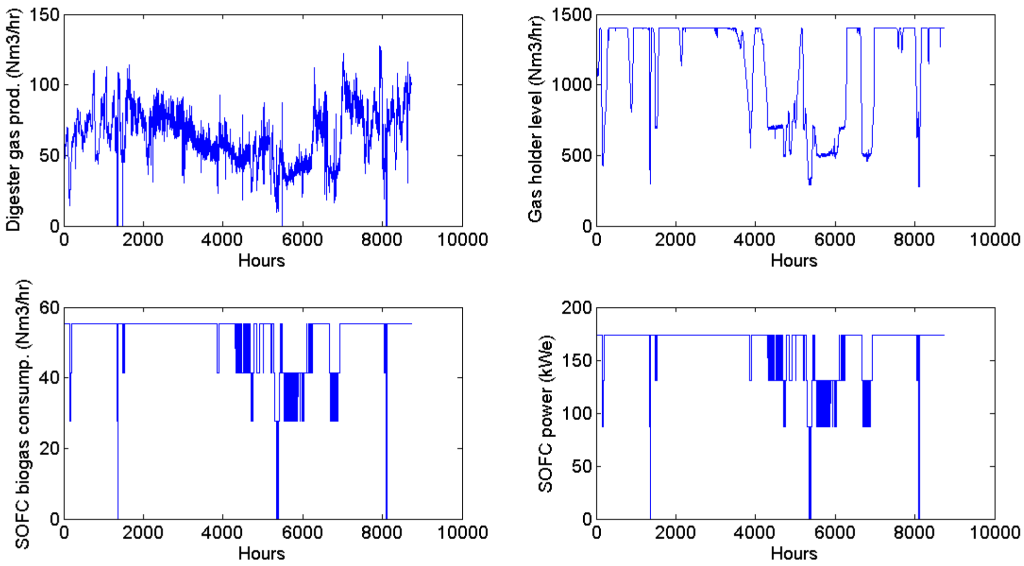

Figure 7. Simulated profile of the gas holder level and SOFC power based on 2014 hourly biogas production rates

According to the results shown in Figure 7, the SOFC reaches the full stop condition 29 times (of the order of 1 h length) in 1-year time frame. Other relevant date are summarized in Table 7.

Table 7. SOFC power production according to biogas availability in 2014 and modulation ranges in Figure 6

SOFC power rate (%)	**Hourly occurences (frequency)**
0	29
50	390
75	1365
100	6938
Average SOFC power (kWe)	162.7
% of biogas flared	18.1%
Eq. SOFC capacity factor at full load	93.5%

In order to avoid forced stops of the SOFC due to biogas shortage (especially considering that they are stops of 1 h that do not make sense in a large SOFC generator) the gas holder threshold levels have been changed while keeping the SOFC modulation within the same range as before. The new gas holder alarm levels are given in Table 8. Results for the SOFC operation are summarized Table 9.

Table 8. New gas holder alarm levels

Alarm level	**Gas holder (m^3)**	**SOFC power rate (%)**
LL	300	0
L	900	50
H	1200	75
HH	1400	100

Table 9. SOFC usage data according to biogas data from 2014 and modulation ranges in Table 8

SOFC power rate (%)	Occurences
0	0
50	455
75	1662
100	6605
Average SOFC power (kWe)	161.2
% of biogas flared	18.9%
Eq. SOFC capacity factor at full load	92.6%

The new gas holder alarm values enable to minimize, or even to avoid at all, forced stops (i.e., shut-downs) of the modules. The trade-off is a lower equivalent capacity factor of three modules with a slightly lower average SOFC power output throughout the year compared to the previous case in which several stops were required.

4. **Energy Planner Tool (EPT)**

Based on the preliminary energy modelling of the DEMOSOFC installation, a more detailed modelling has been carried out to investigate more in detail the needed SOFC load cycling to cope with a fluctuating biogas supply.

An Energy Planner Tool (EPT) has been eventually developed to predict the SOFC modules behavior based on the following data input or desing constraints:

(i) hourly-dense input data of biogas production from the digester;

(ii) average biogas compositon;

(iii) constraints on maximum and mininum gas holder levels (defined by the WWTP manager);

(iv) a PID-controlled set-point for the gas holder volume;

(v) a constraint on the SOFC rampining up/down capability;

(vi) SOFC off-design performance in the range 20-100% of nominal power;

(vii) duration of start-up and shut-down procedures;

(viii) the number of modules to be installed.

Hence, EPT is time-resolved hourly-dense simulation tool that provides valuable information on the system energy performance according to user-defined input variables and system constraints. A PID regulator is also used to automatically control the SOFC power output based on the amount of biogas available in the gas holder.

An additional feature of EPT is the possibility of having the user-defined setting of a intermediate gas holder volume level below which the SOFC power output is reduced at 30% of the nominal power, in order to save biogas and reduce the risk of a forced shut-down.

A screenshot of the Graphical User Interface (GUI) of the Matlab code built-in the Energy Planner Tool is shown below (Figure 8).

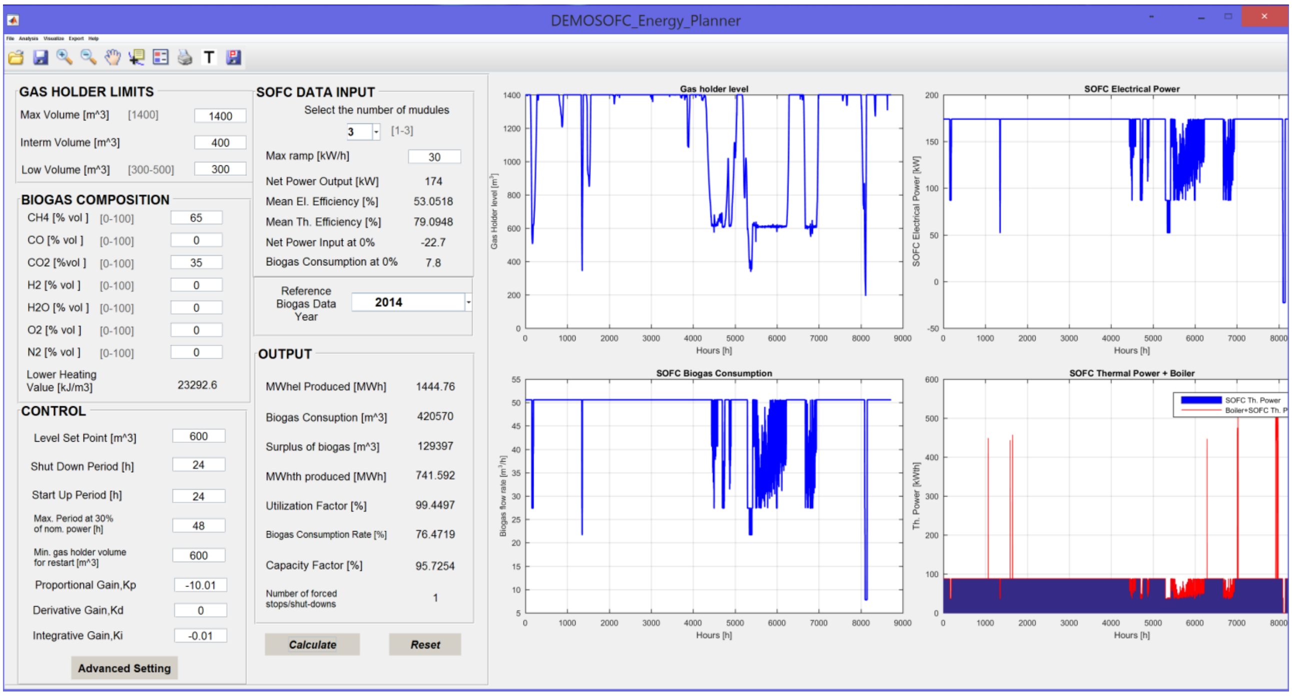

Figure 8. Graphical User Interface (GUI) of the Energy Planner Tool

The output of the EPT are the amounts of electricity ad thermal power recovered during a reference year operation. The surplus biogas that is not used for the SOFC is also calculated. The overall biogas consumption rate in the SOFC modules is also an output of the simulation tool. The most important output results are finally the number of forced shut-downs (or stops) of the modules due to a low volume of biogas in the gas holder and equivalent capacity factor at full load, that is the equivalent number of hours in which all modules run at 100% load with regard to the overall number of hours in a year (i.e., 8760 hours).

The ETP also provides graphical visualizations of the main variables of the DEMOSOFC installation as they vary hourly.

The EPT takes into account the off-design performance of the SOFC module. In Figure 9 power production (or consumption) and LHV electrical efficiency are shown for a modulation range in the interval 0-100% of the nominal power.

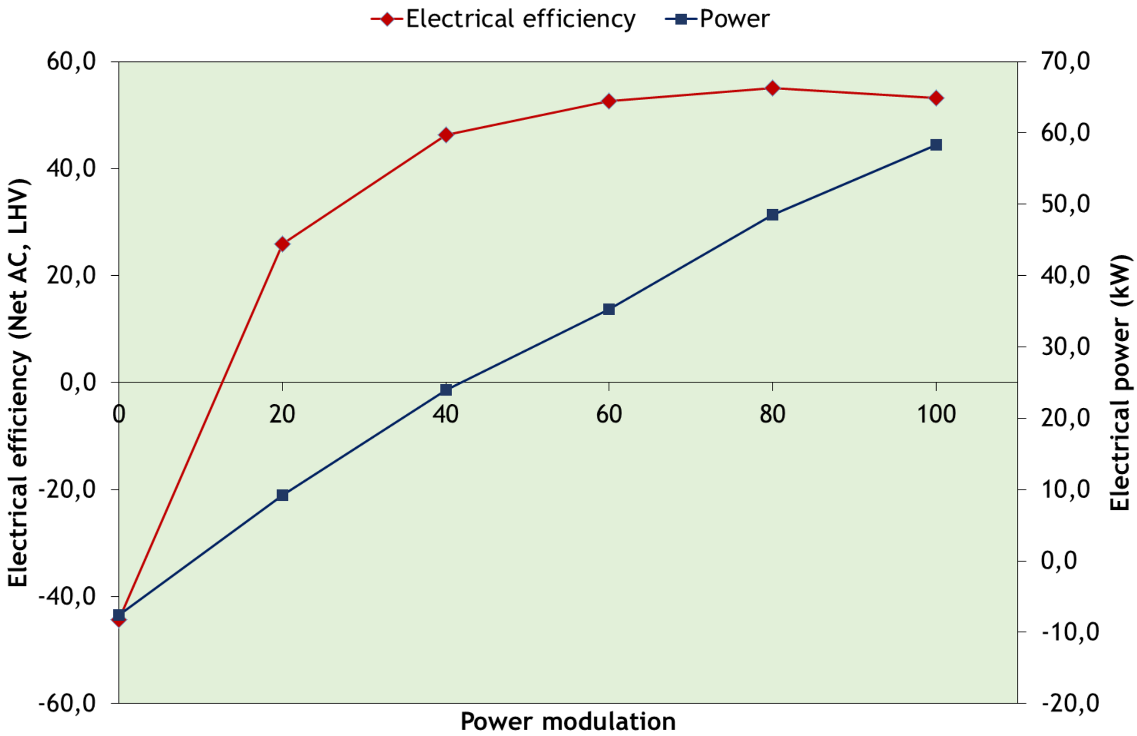

Figure 9. SOFC off-design performance

Results from sensitivity analyses

The EPT has been used to analyse the impact of some design choices/variables/constraints on the energy performance of the integrated biogas SOFC plant.

The first design choice analysed is the impact of the number of SOFC modules installed on the overall energy performance of the Collegno Plant. The project foresees the installation of three modules. Nonetheless, it is worth to explore the impact that a different number of modules would have. Results are summarized in Table 10.

Simulations shows that there would be room for an additional module, which would actually result in almost full biogas utilisation and electrical valorisation in SOFC modules. However, the equivalent capacity factor reduces by almost 6.6 percentage points when switching from 3 to 4 modules.

At this stage an economic optimization of the plant has not been carried out. However, capacity factor is always expected to have a large impact on plant profitability. So a reduction of it should be carefully analysed in the broader context of a techno-economic optimization (which is the direction for future simulation efforts).

Table 10. Impact of the number of SOFC modules installed on the plant energy performance (biogas production according to historical records of year 2014)

Number of modules	**1**	**2**	**3***	**4**
Biogas share for electricity production	26.7%	53.4%	76.5%	97.8%
Equivalent capacity factor at full load	100.0%	99.8%	95.7%	87.3%
Number of forced shut-downs (during reference period)	0	0	1	4
Average electrical efficiency	53.16%	53.15%	53.05%	52.66%
Average thermal efficiency	80.00%	79.96%	79.09%	77.35%

*Actual choice for the DEMOSOFC installation.

A further sensitivity analysis has been carried out, related to the allowed ramp up/down of the SOFC module in term of power ouput. Results are shown in Table 11. In principle, a fast modulation of the SOFC is feasible from an electrical point of view, with a ramp-up/ramp-down modulation much above 40 kW/hr. CONVION indicates a modulation ramp of 4% of the nominal power per minute (that would correspond to almost 140 kW hr^{-1}). However, a practical limiting factor to the dynamic behavior of the SOFC is posed by thermal gradients within the solid stack structure. Realistic limits for ramp-up and ramp-down capability of the module are not avaialble yet and should be assessed within the next future. Faster ramp-down capability is expected more than ramp-up because the risk of over-heating is inhrently avoided when reducing the current load of the module.

Table 11. Impact of SOFC modulation ramp on the number of forced shut-down due to biogas shortage in the gas holder (reference year 2014)

Modulation ramp (kW hr^{-1})	**40**	**30**	**20**	**10**
Number of forced shut-downs (during reference period)	1	1	1	2

Quale è il dato nominale dell’impianto? Ad oggi ancora non lo sappiamo (vedi commento sopra che ho aggiunto). CONVION inzialmente aveva detto 4%/min della potenza nominale, che vorrebbe dire 140 kW/hr. A me è sembrato sempre improbabile questo valore, durante l’ultimo skype call Tuomas ha in effetti detto che il vero limite è la temperatura interna dello stack. Quindi idealmente sarebbe 4%/min della potenza nominale, in pratica il fattore limitante è il gradiente termico dello stack. In conclusione, limiti precisi ancora non sono noti.

The SOFC power output modulation during a 1-year operation is shown in Figure 10. Non è figura 9, e poi la figura indicata rappresenta un caso particolare, forse meglio dirlo; inoltre, non è chiaro perchè in due occasioni la potenza vada sotto il valore 0 I riferimenti alle figure non erano in effetti aggiornati da qui in poi, ma comunque erano linkati correttamente (tramite riferimento incrociato). Basta cliccare ‚CTRL+A e poi premere F9' per vederli aggiornati, ricapitasse il problema. La Figura 11 rappresenta sì un caso particolare, tuttavia abbastanza saliente. Si tratta infatti del caso con 3 moduli, e produzione biogas 2014. Quindi non è un caso poi così particolare. E' forse il più rappresentativo che abbiamo. Comunque in legenda di Fig. 10 specifico che ci si riferisce al 2014 e con rampa 10 kW/hr (valore conservativo). La potenza scende sotto zero perchè quando il modulo si spegne consuma potenza. Vedi curva in Fig. 9.

In Figure 11 the focus in a portion of the graph Figure 10 characterized by a highly fluctuating biogas production. The SOFC load cycling is also large to adjust for the variable biogas supply.

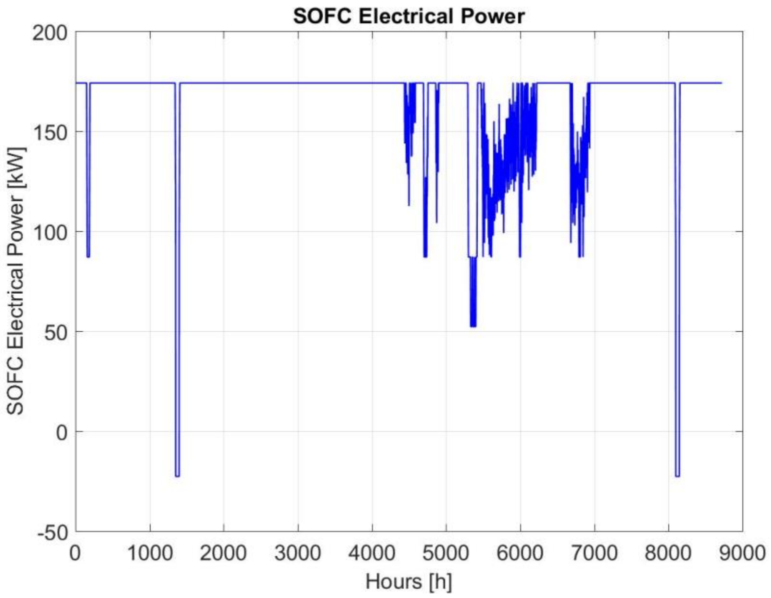

Figure 10. SOFC hourly load profile with ramp maximum capability of 10 kW hr^{-1} (reference year: 2014)

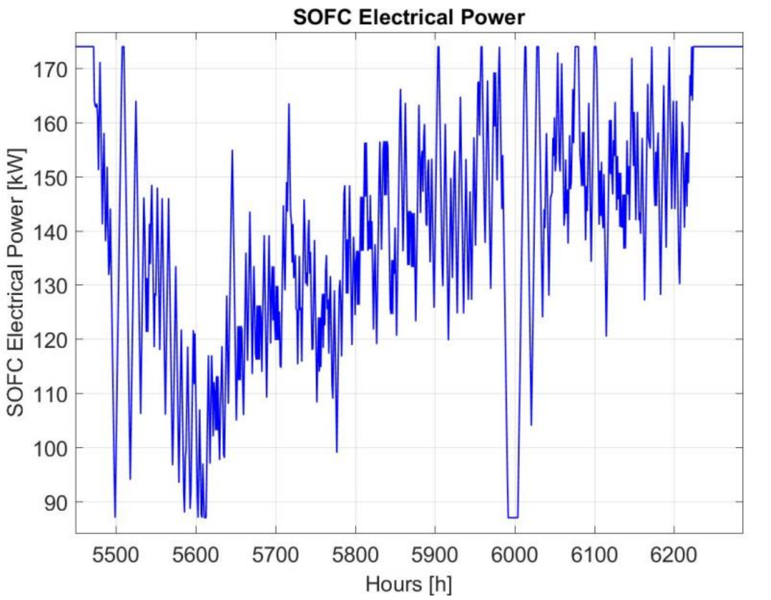

Figure 11. SOFC modules power modulation during a period of highly fluctuating biogas production.

5. Preliminary design of the demo plant

Questo paragrafo non sarebbe meglio metterlo all'inizio?

Questa sezione è trattata qui in fondo perchè la struttura originale del task lo prevedeva. La logica è analizziamo le caratteristiche dell'impianto (da un punto di vista di disponibilità del biogas, presenza di contaminanti, carichi termici, comportamento della SOFC, ecc.) e poi sulla base di queste informazioni si passa al design dell'impianto. Secondo me questa impostazione continua ad avere un senso. Detto questo, per me va benissimo anche invertire se si ritiene sia più efficace.

The DEMOSOFC project foresees the installation of a 174 kWe fuel cell system in a wastewater treatment plant (WWTP). Three Solid Oxide Fuel Cell (SOFC) modules, each one rated 58 kW AC power, will be installed in the WWTP of Collegno (TO). The modules will run on locally available digester gas that is produced from sludge.

Biogas is fed through a gas holder which collects the biogas production from anaerobic digester.

The DEMOSOFC project includes the following 4 main sections:

- moisture removal and compression unit: chillers will remove moisture before and after the compression stage up to 4 bar(g).
- clean-up unit: before feeding the biogas to the SOFC modules micro-contaminants (sulfur and siloxanes) shall be removed at ppb(v) levels.
- SOFC power generation: 3 SOFC modules, each of them able to produce 58 kWe AC.
- Heat recovery system: a heat-recovery loop will be installed for each SOFC module in order to recover waste heat from the hot exhaust gas. The heat will be transferred to a hot water loop that will pre-heat the sludge inflow to the digester.

Figure 12 shows a conceptual scheme of the overall WWTP and the DEMOSOFC plant with highlight on both water and sludge lines.

The main sections of the DEMOSOFC installation are shown in Figure 13.

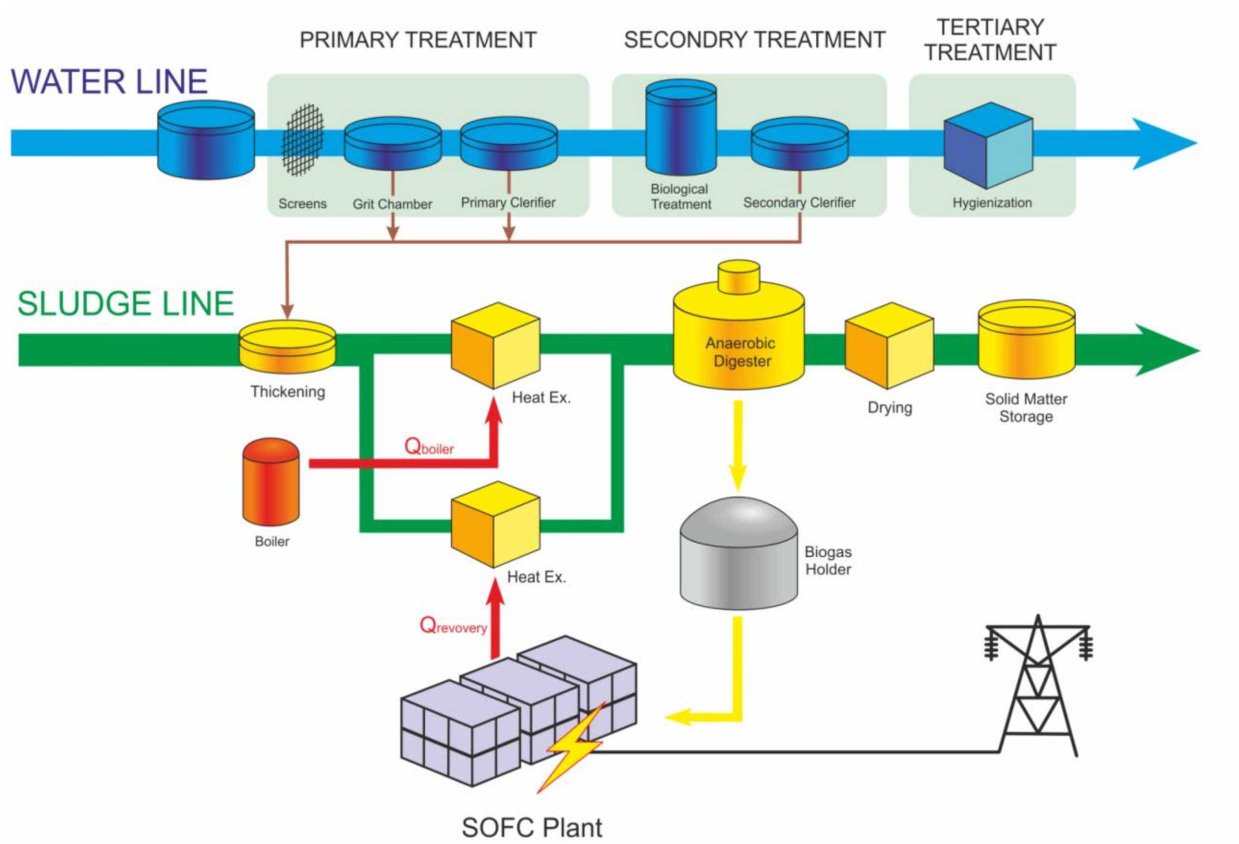

Figure 12. General layout of the WWTP with SOFC modules for CHP production

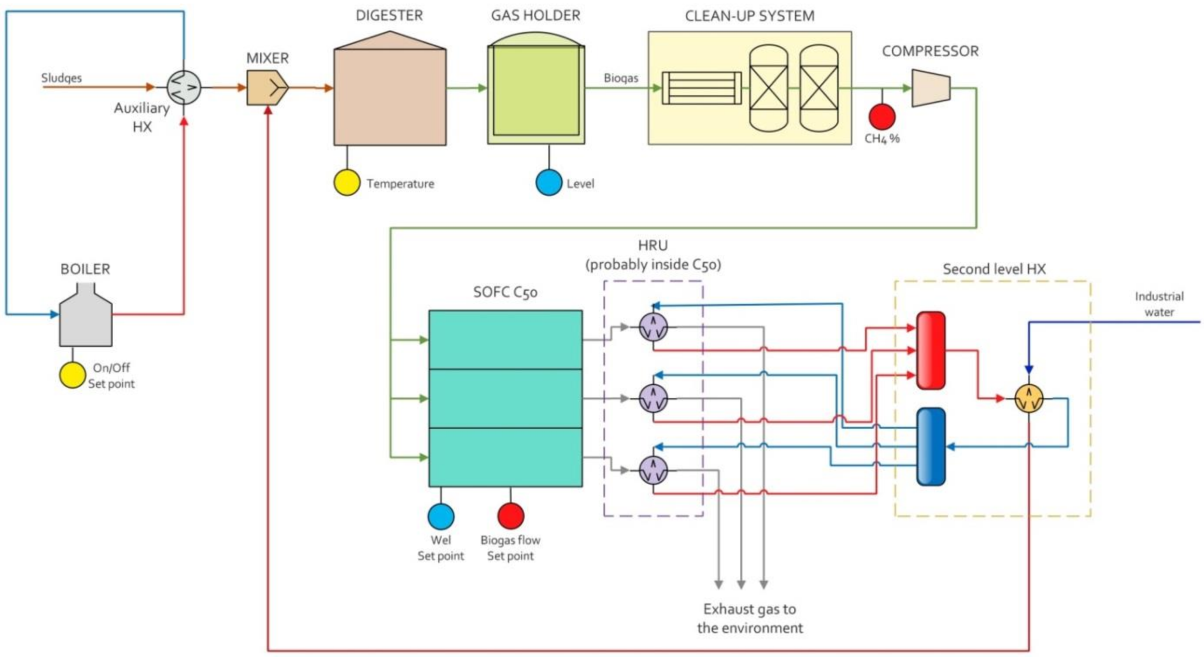

Figure 13. Main sections of the DEMOSOFC installation

Clean-up technical specifications

A high-purity level is required for the fuel gas of a fuel cell generator. The gas purity requirements for the SOFC modules is <30 ppb(v) for total sulfur (corresponding to < 0.045 mg tot. S / Nm^3), and <10 ppb(v) for siloxanes compounds (corresponding to < 0.06 mg tot. Si / Nm^3). The biogas is also required at a pressure of 4 bar(g).

The nominal biogas flow rate is 51 Nm^3/hr (assuming 65% vol. CH_4). The min./max. flow rates are 2/60 Nm^3/hr. The biogas is available from a gas holder where it is stored at a pressure of about 40 mbar. The minimum period of continuous operation between each catalyst(s) change should be between 6 and 12 months. A stop of the fuel cell system is expected once per year. So a redundancy of the clean-up vessels (i.e., the installation of spare vessels) depends on the lifetime of the catalyst. **Vessels should be changeable without affecting fuel cell operation regardless of the vessel lifetime.**

The biogas contains on average 60% vol. CH_4 and 40% CO_2. The type and amount of micro-contaminants found in the raw gas are discussed in the next section.

The clean-up reactors' configuration foreseen for the DEMOSOFC installation in based on adsorption vessels with activated carbons. A schematic of the clean-up section is shown in Figure 14.

Either reactors R1 ('a' and 'b') or R2 are the lead ones, while the other are the lag reactors. The lead reactors are responsible for removing the most of the contaminants. The lag reactor, instead, act as guard beds in case of temporary high loads of contaminants that reach the clean-up section. Once the breakthrough concentration is measured in SAMPLE PORT #1, the current lag reactors become the new lead vessels (the switch is realized by changing the positon of the 4-way valves) . The catalyst is then replaced in the original lead reactors in order to restore their full functionality. A flushing line is also included to purge vessels in which the adsorbent catalyst has been replaced.

Two different adsorbent materials for each leg of the clean-up section are used. One material should be specific for the removal of siloxanes (i.e., the catalyst for reactors R1a and R1b), while the second one should be specific for H_2S removal (reactors R1b and R2b).

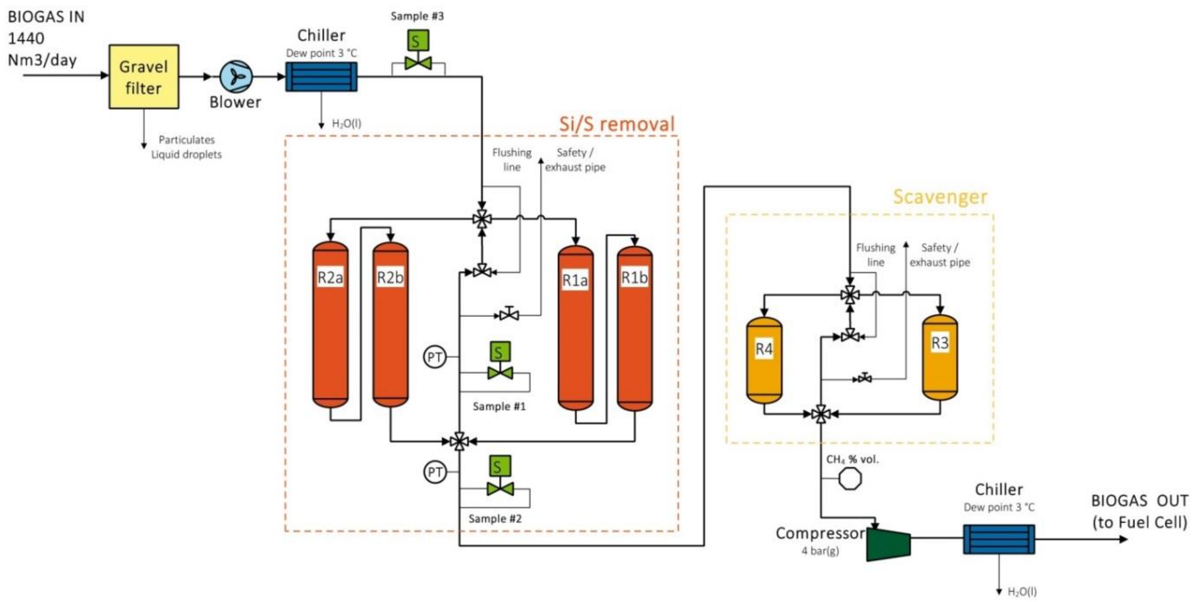

Figure 14. Layout of the clean-up section

<u>Biogas moisture removal and compression:</u> biogas is compressed and dried before feeding the SOFC. The clean-up unit is ideally placed before the biogas compressor to increase the lifetime of this component.

SOFC power generation

The layout of the SOFC installation is shown in Figure 15. Electric cabinets included DC/DC converters and DC/AC inverters for grid connection.

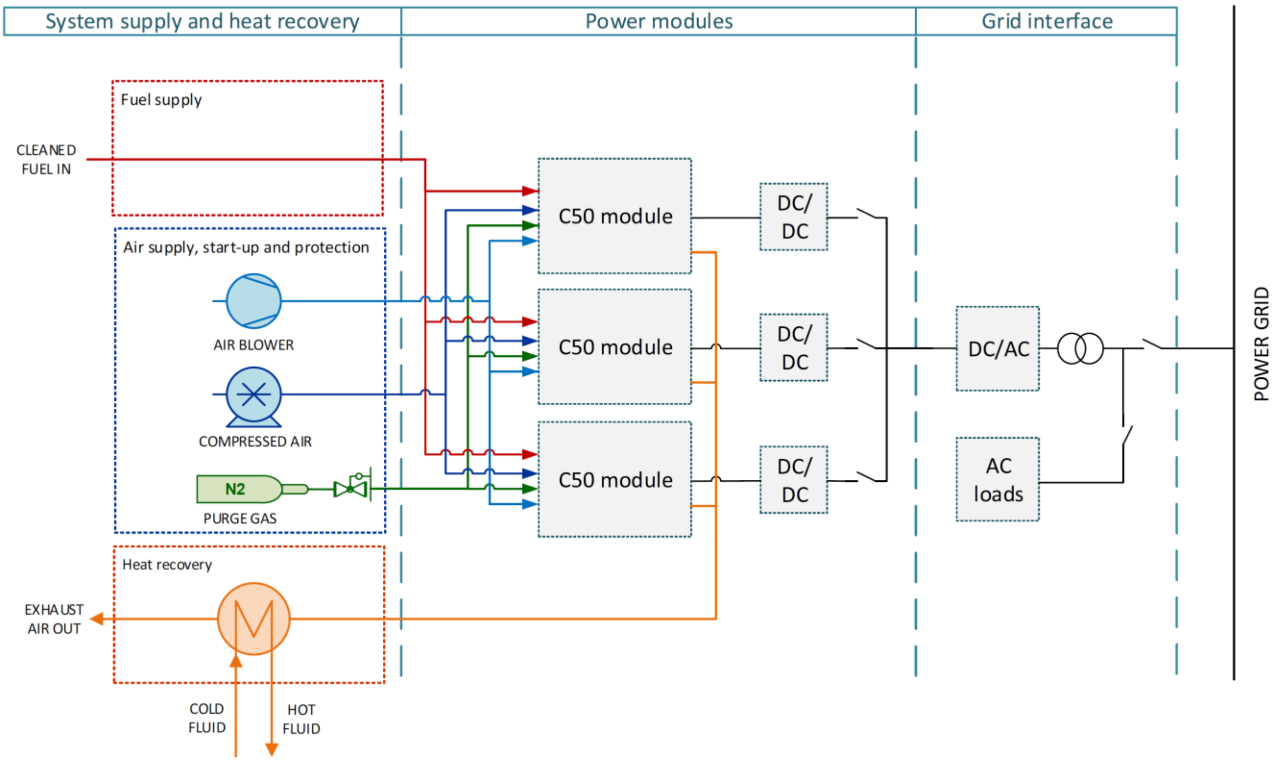

Figure 15. Layout of the SOFC installation

Heat recovery loop

The heat recovery loop is show in Figure 16. A secondary heat recovery loop takes heat from the exhaust of each module. A mixture of water/glycole circulates in the cold side of this loop. A heat-exchanger is the used to transfer heat to a primary heat loop whose cold side can include either industrial water or cold sludge that has to pre-heated prior to feeding the digester. The nominal operating condition foresees sludge preheating. However, in case sludge is not available, heat can be dumped to industrial water.

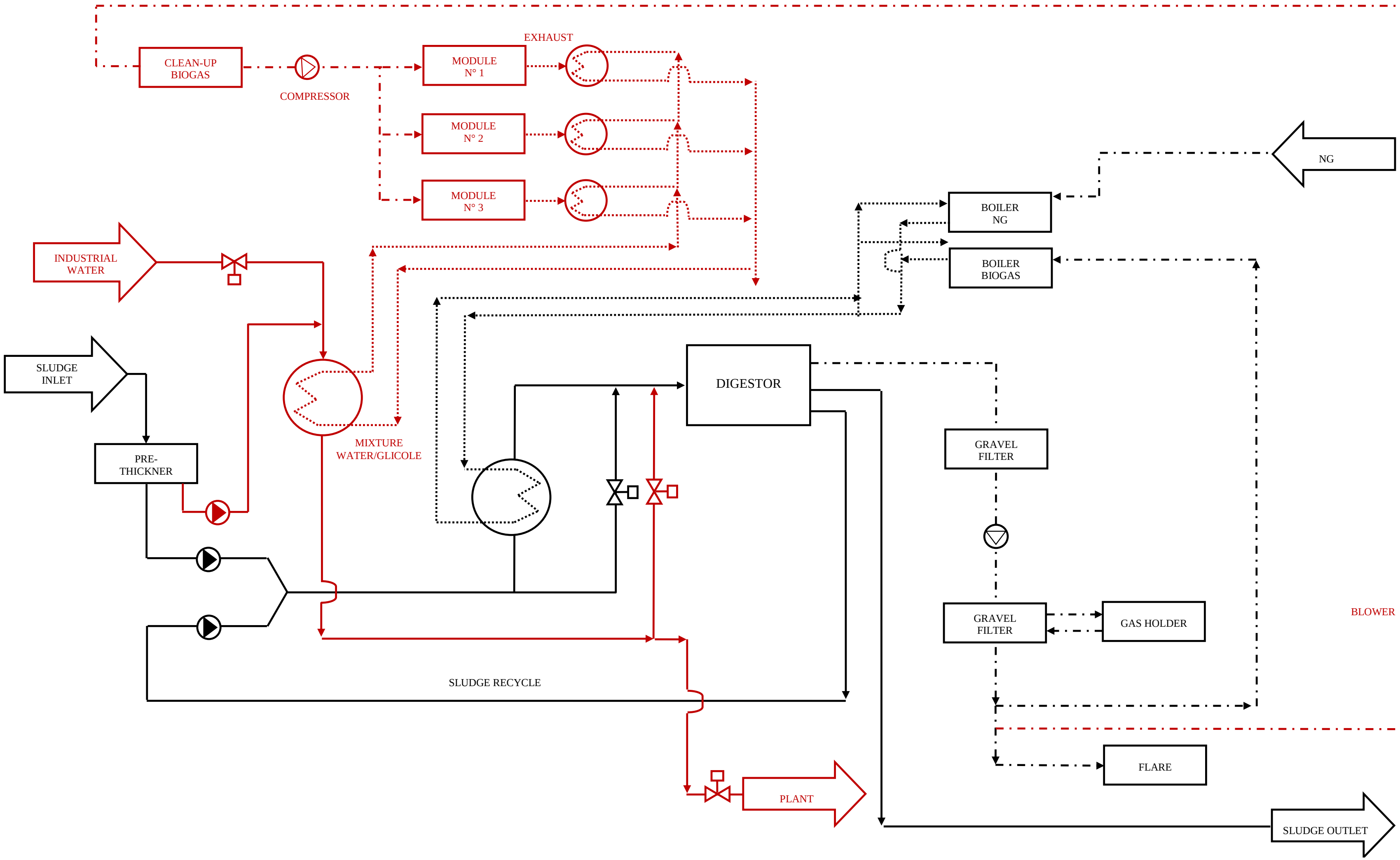

Figure 16. Layout of the heat recovery loop

6. Conclusions and future work

The WWTP plant of Collegno (TO) has been characterized in terms of biogas availability, the type and amount of contaminants in it and thermal needs of the digester.

An Energy Planner Tool has been developed in order to predict the performance of he integrated biogas SOFC plant.

Future work will focus on the optimization of the integrated plant (D2.2 Optimization of the DEMO, M4), on ist detailed engineering (D2.4 Detailed engineering of the DEMO, M6) and on ist techno-economic performance evaluation (D2.5 Cost/benefit analysis of the system, M6). The optimal tuning of PID controller fort he gas holder volume mangement will be also carried out.