DEMOSOFC

Project n° 671470

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

Deliverable number 2.2

Optimization of the DEMO

(Task leader: POLITO - Participants: CONVION, SMAT, IC - Start: M2 - End: M4)

Due Date of Delivery:	M4
Actual Submission Date:	January 27, 2016
Lead Beneficiary:	Politecnico di Torino
Author(s):	Andrea Lanzini, Marta Gandiglio, Davide Papurello, Massimo Santarelli (POLITO), Eugenio Lorenzi (SMAT), Tuomas Hakala (CONVION), Adam Hawkes (IC)
Approved by:	Massimo Santarelli (POLITO)
Work package:	WP2
Estimated PM:	7
Dissemination Level:	*CO (because the presence of confidential data from SOFC manufacturer)*
Nature:	*R*
Version:	3.0
Total number of pages:	29

Abstract:

The Energy Planner Tool (EPT) is here presented in its most up-to-date release, with results on the optimal sizing of the DEMOSOFC plant and related preliminary economic scenarios.

Furthermore, the roadmap for the second part of the work on techno-economic optimization of integrated biogas SOFC plants in wastewater treatment plants (WWTPs) is presented. Starting from the technical model of the integrated biogas SOFC system – developed through the EPT – a detailed economic model will be developed, comparing CAPEX and OPEX calculated through from conventional costing methodologies with real manufacturer's costs.

Keyword list: biogas, SOFC, energy model, system design, , techno-economic analysis, WWTP, optimization.

INDEX

1. Purpose of this document

The optimal design of the DEMOSOFC plant is assessed in this task. The Energy Planning Simulation Tool is used for the identification of the optimal configuration of the integrated biogas-SOFC plant to be installed in Collegno (IT) prior to finalizing the detailed plant engineering.

Furthermore, the control architecture of the whole DEMOSOFC system is preliminary designed. The plant control unit will enable the optimal management of the integrated plant.

Possible objective functions to target are the maximisation of the self-consumption of electricity, the minimization of operational costs, energy efficiency maximization, etc.

In the design of the control strategies, the computational efficiency of the real-time optimization process will be taken into account, so as to allow for system scalability and applicability of the approach also to scenarios for future applications in other sites.

2. DEMOSOFC Energy Planner Tool (EPT)

The Energy Planner Tool (EPT) is a simulation tool with user-friendly graphical user interface (GUI) that is able to simulate the integrated plant energy performance. More in details, EPT is a 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 Proportional – Integral – Derivative (PID) regulator has been implemented in order automatically control the SOFC power output based on the amount of biogas available in the gas holder. The focus in this report is only on the WWTP of Collegno (IT); however, the Energy Planner Tool may serve as a broader simulation platform for a thorough techno-economic optimization of integrated biogas SOFC plants. More details on the EPT can be found in Deliverable 2.1 (D2.1).

Optimal sizing of the DEMOSOFC plant

The first design variable is the number of SOFC modules to install (each module has a nominal net power rate of 58 kW AC; this value excludes electric consumption for biogas blower and compressor and chillers, whose overall consumption at full load is estimated below 5 kW for each module). As already highlighted in D2.1, the higher the number of modules installed, the lower the equivalent capacity factor gets for the overall installation (see Table 1).

It was originally decided to install three modules for DEMOSOFC when submitting the project proposal. Based on the results on Table 1, having three modules installed seems the best trade-off between having a sufficiently high biogas recovery in the SOFC while maintaining at the same time a high (i.e., ~95%) equivalent capacity factor (CF) (the term 'equivalent' indicates equivalent operating hours at full load). Having CF values higher than 95% results in a few added value as at least one ordinary maintenance event – of the duration of approx. 1 week – is expected for every year, which reduces already the theoretical maximum CF to 98%.

The biogas production of both 2014 and 2015 was used for all calculations presented in this section (see Figure 1), i.e., 2-years of full operation of the SOFC modules is simulated. Biogas production was slightly higher in 2015 than the previous year, however the daily and seasonal extent of fluctuations are remarkably similar in the two monitored years.

Simulations well show that there would be room for an additional module, which would result in almost full biogas utilisation and electrical valorisation in SOFC modules. However, the equivalent capacity factor would reduce by almost 6.6 percentage points when switching from 3 to 4 modules. Even more significant, having more electric capacity installed makes events as forced shut-downs more frequent. Figure 2 and Figure 3 show the SOFC production for 2014 and 2015 with 3 and 4 modules installed, respectively. There are now shut-down events with 3 modules running, whereas an overall of 5 shut-downs in the 2-year time frame occur when having 4 modules installed.

Table 1. 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.*

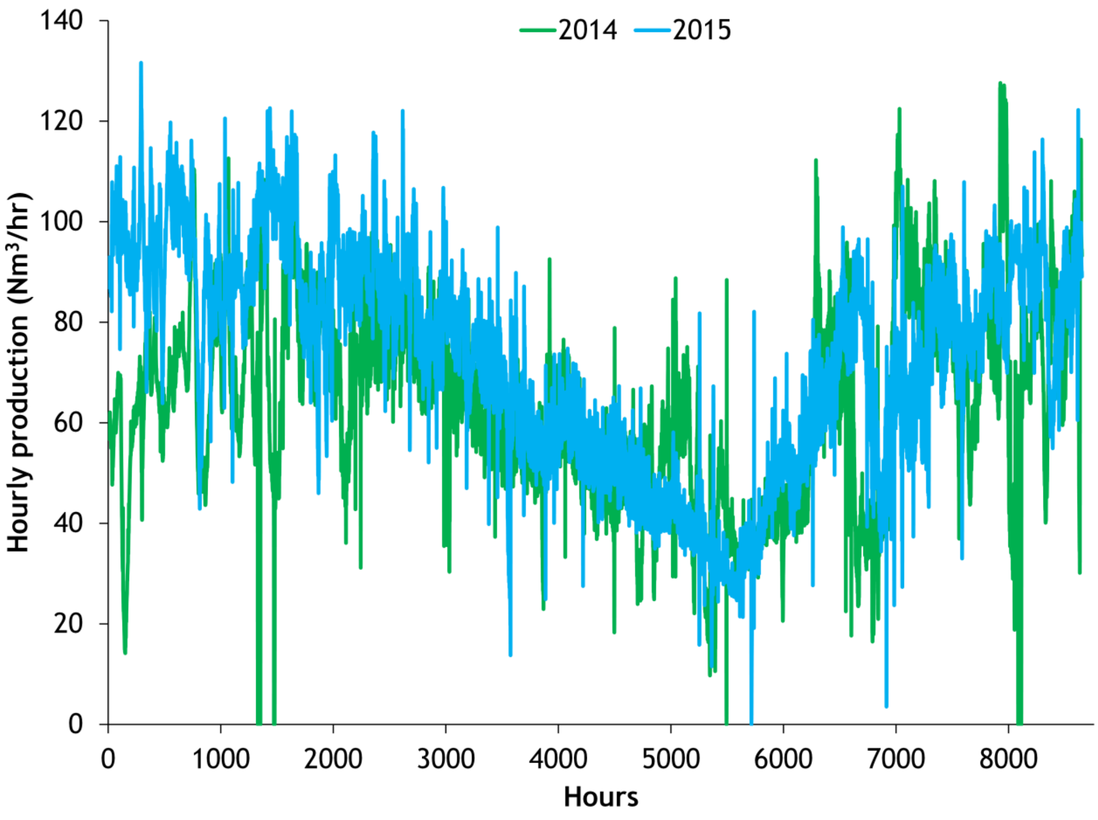

Figure 1. Biogas production for 2014 and 2015

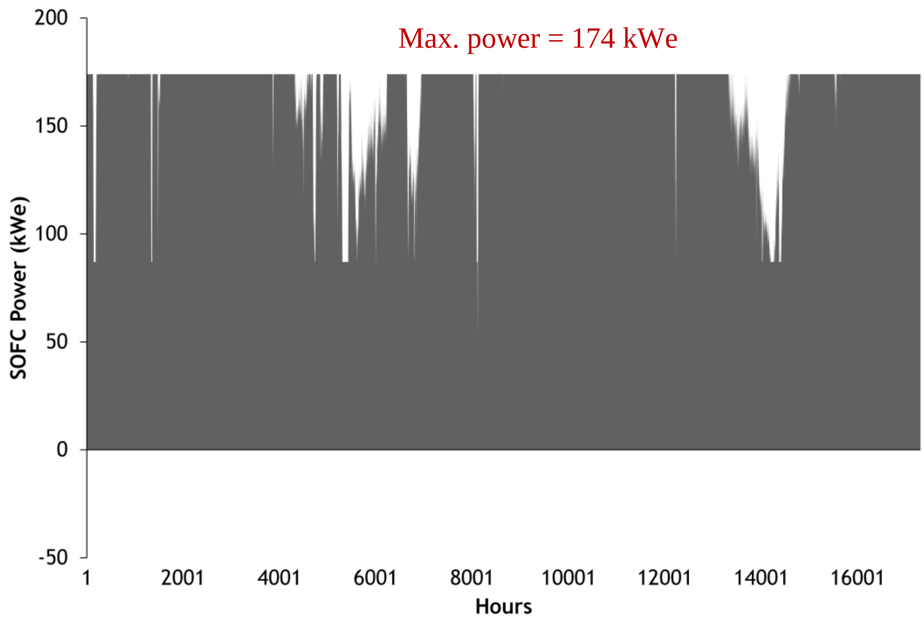

Figure 2. SOFC power production for 2014 and 2015 with 3 modules installed (64% vol. CH_4)

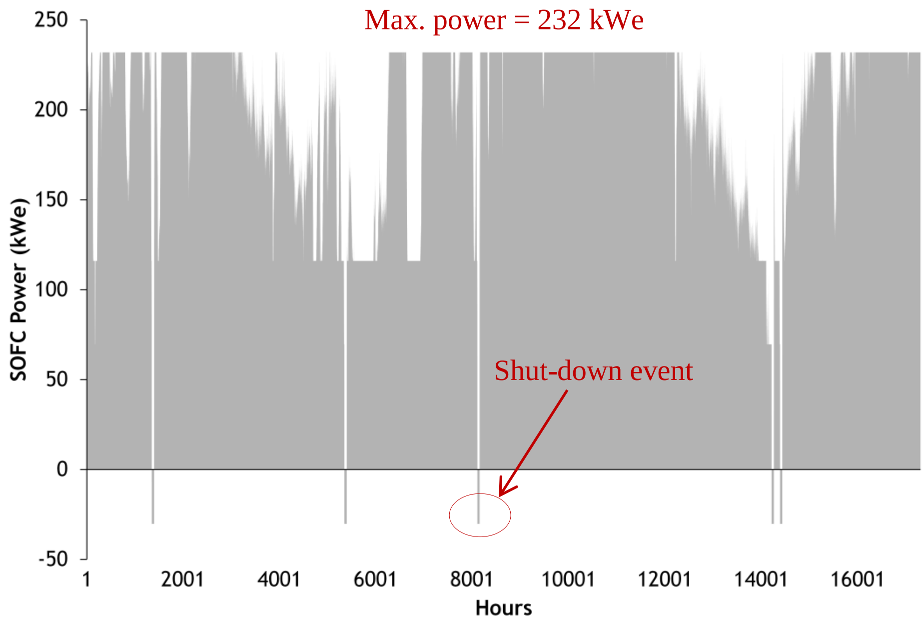

Figure 3. SOFC power production for 2014 and 2015 with 3 modules installed (64% vol. CH_4). Shut-down events are clearly marked by a negative SOFC power production since power is absorbed by the modules during the start-up phase.

Finally, Figure 4 shows the impact of biogas quality – in terms of CH_4 content in the biogas – on the plant capacity factor. So far, an average CH_4 content of 64% has been observed in the Collegno WWTP, with a minimum concentration of 63.1% and maximum of 65.5% (see D.21). According to results in Figure 4, a varying CH_4 content within the range 62-65% would lead to no forced shut-down events while achieving at the same time a high CF. However, as the CH_4 content decrease below 62% vol., forced shut-downs occur due to biogas shortage. These simulations stresses the fact that not only the overall biogas flow rate should be carefully monitored, but also its quality.

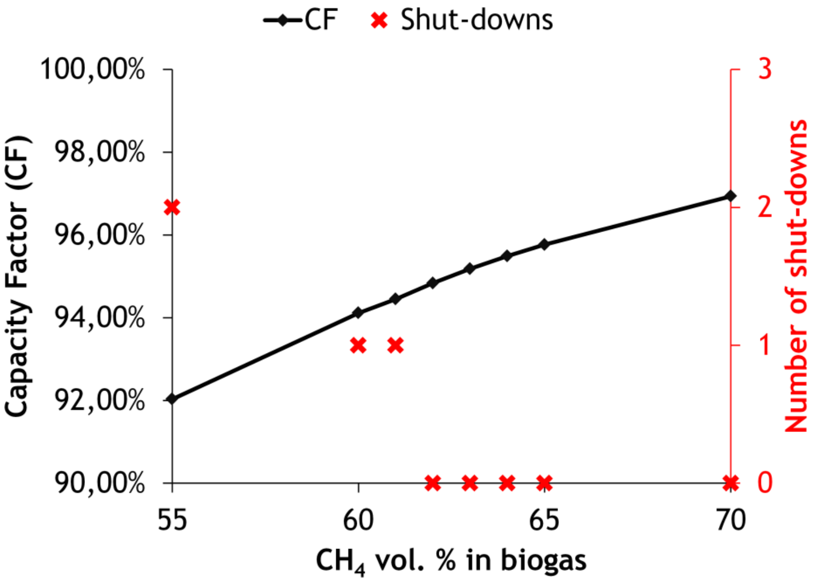

Figure 4. Impact of biogas quality in terms of CH_4 % vol. content on plant capacity factor (CF) and events of forced shut-down due to biogas shortage (scenario with 3 modules installed)

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

Economic performance of the DEMOSOFC plant

The economic performance for the plant configuration with three modules installed is presented in this section. Actual energy prices for electricity and NG from the grid are used (prices were directly provided by the SMAT energy manager and refer to 2016).

Both capital costs (CAPEX) and operating costs (OPEX) are considered for the integrated biogas SOFC plant of DEMOSOFC. The goal of this analysis is to identify for which SOFC total installed module cost (expressed in €/kW) the revenues from the CHP plant equal that of biogas burning in conventional boilers. At the moment, the WWTP in Collegno is characterized by a high thermal load to cover the digester thermal needs (mostly due for inlet sludge pre-heating). Therefore, there is a situation of potential competitive use of biogas between thermal production only in boilers (reference case) and combined heat and power (CHP) production in the SOFC. In the following of this report, we analyse the revenues generated in both cases in order to have a comparison between them. Data and assumptions on plant performance and costs (both

CAPEX and OPEX) are summarized in Table 2. Three different scenarios were modelled based on a gradual increase in the learning curve of both SOFC and biogas clean-up technology.

Figure 5 depicts the possible use of biogas in one of the two above mentioned scenarios. The option of NG feeding to the SOFC in a bi-fuel SOFC configuration is also shown: scenarios with NG feeding to the SOFC will be analysed in the final deliverable of WP2 entitled ‘Optimal Design and Management of Integrated Biogas SOFC plants in WWTPs’. Looking at Figure 5, the option of flaring biogas could be a free variable, however there should be no value in doing so. Therefore the biogas should be flared *only* in the peculiar condition under which it cannot be used neither in the SOFC (i.e., max. capacity has been achieved already) nor in the boiler (no need for thermal power for the digester) and the gas holder is full.

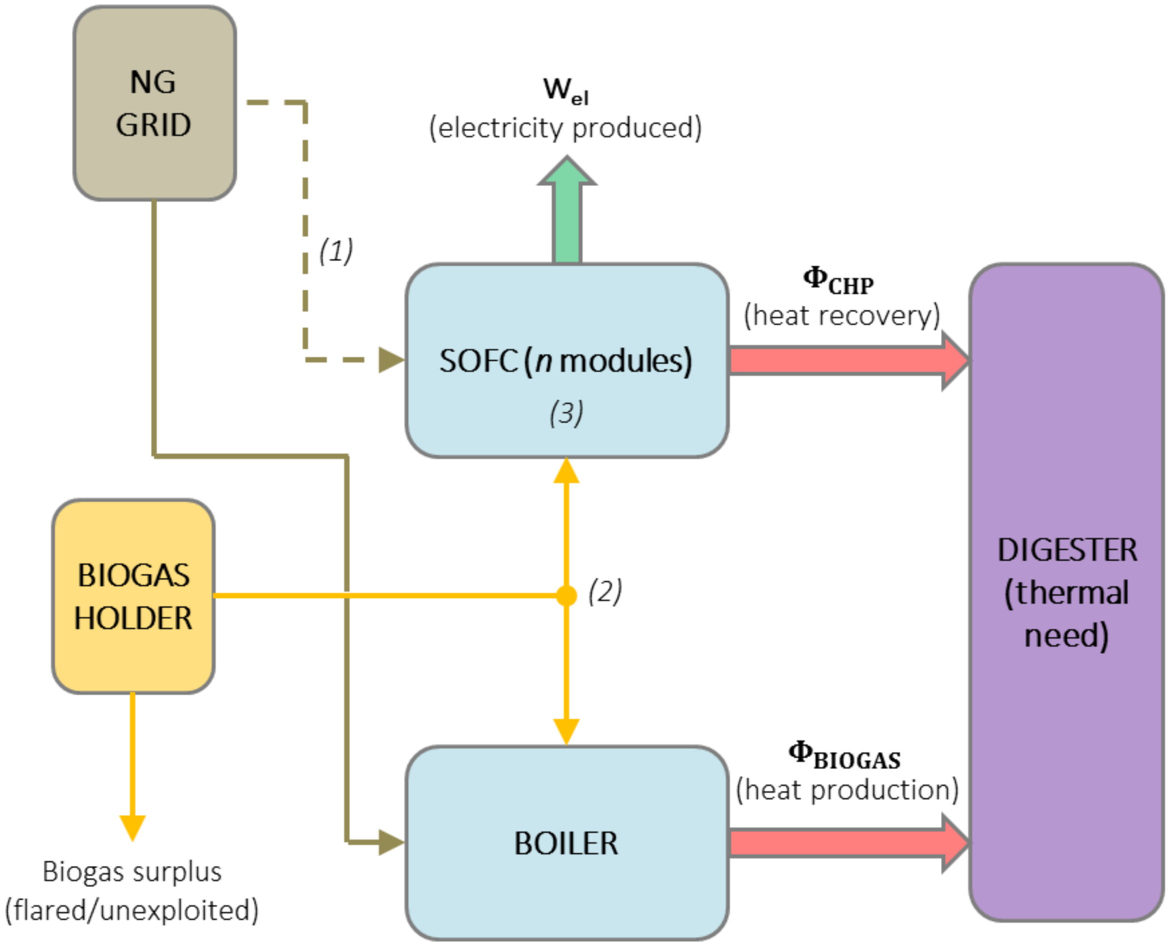

Figure 5. Integrated biogas SOFC plant: possible use of biogas and NG for thermal only and combined heat & electricity (CHP) production. (1): NG feeding to the CONVION is not foreseen for the actual DEMOSOFC installation, however the possibility to have a bi-fuel SOFC generator will be further investigated from a techno-economic point of view; (2): biogas use is competitive among SOFC and boilers; (3) the overall SOFC electric capacity installed is a further potential free variable of the integrated biogas SOFC plant (the choice for the DEMOSOFC installation is to have 3 modules; however the impact of different choices will be evaluated).

Table 2. Techno-economic performance of the DEMOSOFC plant under different CAPEX and OPEX assumptions.

Energy Prices		**Current scenario** *(2016)*	**Short-term scenario** *(by 2020)*	**Target scenario** *(after 2020)*
NG Price (IMPORT)	€/kWh	0.060	0.060	0.060
Electricity Price (IMPORT)	€/kWh	0.160	0.160	0.160
Grid levies (EXPORT, for electricity produced)	€/kWh	0.020	0.020	0.020
SOFC Module				
Capital cost Module	€/kW$_e$	7,000	5,000	3,000
Stack share of total module cost		50%	40%	30%
Capital cost Stack	€/kW$_e$	3,500	2,000	900
Module lifetime (stack ex.)	Yr	20	20	20
Stack lifetime	Yr	5	6	7
No. of modules installed	-	3	3	3
Full load equivalent CF	-	0.95	0.95	0.95
Full load power	kW$_e$	58.0	58.0	58.0
Ave. Thermal Eff.	-	27.0%	27.0%	27.0%
Ave. El. Eff.	-	53.0%	53.0%	53.0%
Total SOFC unit cost	***€/kWh$_e$***	***0.136***	***0.080***	***0.043***
Module(s) unit cost	€/kWh$_e$	0.042	0.030	0.018
Stack replacement unit cost	€/kWh$_e$	0.084	0.040	0.015
Other SOFC maintenance (air filter, mech. & elect. equipment)	€/kWh$_e$	0.010	0.010	0.010
Clean-up unit				
Clean-up unit capital cost	€/kW$_e$	1,000	500	200
Unit lifetime	Yr	20	20	20
Clean-up unit CAPEX	€/kWh$_e$	0.006	0.003	0.001
Clean-up unit OPEX	€/kWh$_e$	0.010	0.008	0.005
Other costs / revenues				
Heat revenue (CHP)	€/kWh$_e$	0.036	0.036	0.036
Other Plant Costs (Labour, Catalysts)	€/kW$_e$	0.014	0.014	0.014
Total				
Total Plant Revenue / Saving (before taxes)	€/kWh$_e$	0.010	0.071	0.112
	€/kWh$_{bg}$	0.005	0.038	0.059
Biogas burning, Reference Revenue / Saving	€/kWh$_{bg}$	0.060	0.060	0.060

Notes:
1) Grid levies apply to the electricity auto-produced and auto-consumed.
2) Except for energy prices (of NG and electricity), all other specific costs – expressed in €/kWh – refer to either the electricity output from the SOFC (kWh$_e$) or to biogas energy (kWh$_{bg}$).
3) 1 kWh of biogas energy can either displace 1 kWh of NG (when used in boilers) or, alternatively, it can displace 0.53 kWh of electricity and 0.27/η_{boiler} kWh of NG (when used in the SOFC).

Results in Table 2 show how, currently, the best use of biogas is to produce thermal energy that is required for the digester (wall heat losses and, most of all, sludge pre-heating). Given the high thermal load of the digester, biogas is best used if burnt in boilers in order to reduce energy bill of the plant thus reducing the import of NG. Biogas used in SOFC results in a very modest profit of only 1 €cent/kWh of electricity produced. Only the long.-term target scenario is able to almost breakeven with biogas burning. Note that the effect of taxes and time value of money through discount rates have not included in the present analysis. The revenue (saving) connected with biogas use in the SOFC, r_{CHP}, expressed in € per kWh of biogas, is calculated as following:

$$r_{CHP} = c_{SOFC} \times \eta_{el,SOFC}$$

where c_{SOFC} (€/kWh$_e$) is the unit cost for the whole SOFC installation, including the clean-up system, and $\eta_{el,SOFC}$ is the SOFC electrical efficiency. Basically, r_{CHP} is calculated considering that for each kWh of electricity produced by the SOFC, $1/\eta_{el,SOFC}$ kWh of biogas has been consumed, which could have alternatively displaced the same amount of NG, which is priced c_{NG}.

Additional techno-economic scenarios, to be analysed in the final deliverable, will be characterized by a lower thermal need of the digester by the effect of enhanced sludge pre-thickening prior the anaerobic digestion process. This plant modification/improvement would clearly affect the optimal operation of the DEMO plant.

Finally, it is important to highlight the impact of local market energy prices on the economic scenarios here presented. Our analysis show how the profitability of SOFC CHP plants benefit from markets characterized by a low price of NG and high one of electricity.

Economic optimization (free variables, constraints and objective functions)

For future and more systematic economic optimization of the DEMO plant, the following free variables (the same numbering is used in Figure 5) have been identified:

(1) Amount of NG feed to the SOFC (the lower bound is clearly when NG is not fed to the SOFC)

(2) Split fraction of biogas to SOFC and boiler (competitive use of biogas for CHP production or thermal energy production)

(3) Amount of SOFC power installed (this can be achieved either by having a continuous variation of the installed capacity or considering the discretization in modules each rated 58 kW).

System constraints are instead the gas holder maximum storage volume and operating range, SOFC dynamic behaviour and off-design operation and the full coverage of the digester thermal load.

The objective function is the maximization of economic profit (i.e., the total ownership cost) of the plant. Other objective functions might be identified (e.g., the maximization of primary energy savings).

The information provide in this paragraph are expressly intended as an input to activities to be performed in the framework of 'Costs/ benefits Analyses', of which Task 2.6 deals with.

Architecture of the control system

An overview of the DEMOSOFC control system is shown in Figure 6. A central Programmable Logic Unit (PLC) will be implemented which is able to exchange information (signals) with the different plant sections (e.g., clean-up unit, gas holder SOFC modules, etc.). The central PLC will be able also to launch start-up and shut-down procedures for the different units. Alarms will be also issued the PLC based on measured signals from the plant.

The list of signals shown in Figure 6 does not intend to be an exhaustive accounting of all plant I/O signals. A detailed list will be available at the end of the design phase (due at M6). Nonetheless, the main features of the control system architecture are highlighted.

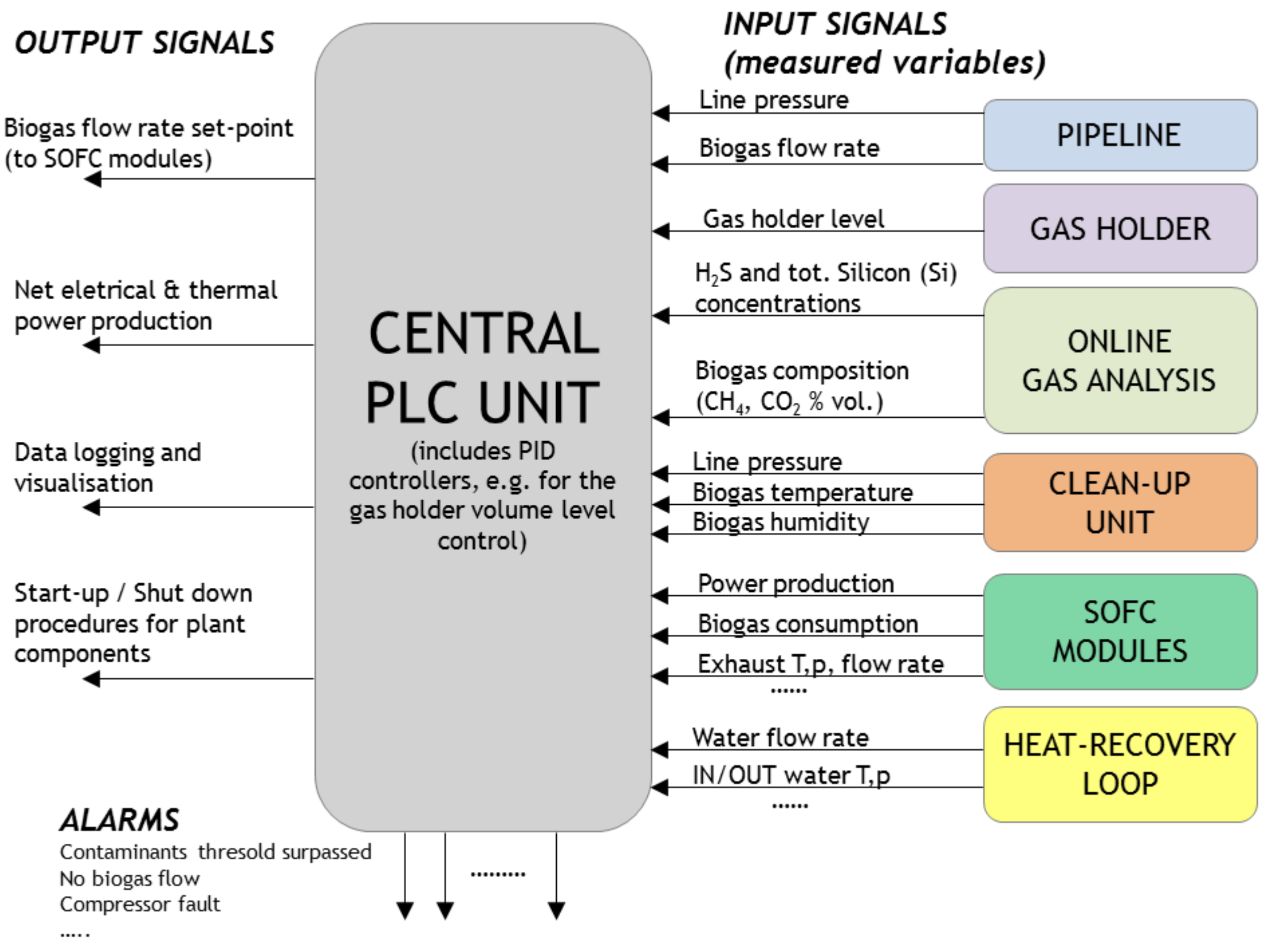

Figure 6. Overview of the control system architecture for the DEMOSOFC plant

Results on the system thermal integration

The SOFC modules will be equipped with an exhaust heat-recovery heat-exchanger, placed directly inside the SOFC module, that will recover thermal power from module's exhaust. Under nominal conditions, the exhaust gas is found at 218 °C with a flow rate of 620 kg/h. Data for the off-design point are available from CONVION and summarized in Table 3.

On other side of heat recovery loop, the requirement for the SMAT WWTP is the pre-heating of sludge feeding the digester, which needs to be heated up from 15 °C (average intake water temperature) to 45 °C (digester inlet temperature, considering also thermal losses).

Starting from the available heat source (gas exhaust) and the requested thermal energy (for sludge pre-heating), the heat recovery loop has been designed (in terms of HEX sizing) in order to satisfy the full load operation point. A water + glycol (50-50 %) stream is thus used to transfer thermal power from the exhaust gas to the sludge. The use of this secondary loop is justified in order to avoid the fouling of the SOFC-integrated waste heat exchangers due to the "dirty" sludge stream involved. Two separated heat-exchangers were thus preferred: the gas-water HEX will be a traditional shell and tube device, while the water-sludge HEX will be a spiral one (Alfa Laval, IT), specifically designed for applications with sludge.

Table 3. Exhaust conditions in different operating points for the three modules.

Stack current, %	**100**	**80**	**60**	**40**	**20**	**0**
Fuel inlet flow, kg/h	57.8	46.5	35.3	27.3	18.8	9.0
Hot Exhaust, kg/h	1859.5	1488.8	1116.8	938.6	938.0	939.3
Exhaust T, °C	218	196	195	197	195	186
c_p, mixture J/(kg K)	1070	1065	1065	1063	1055	1044

The design (i.e., SOFC at full load) operating temperatures and mass flow rates of the whole heat recovery loop are shown in the Figure 7. The amount of thermal power exchanged in each HEX is also given.

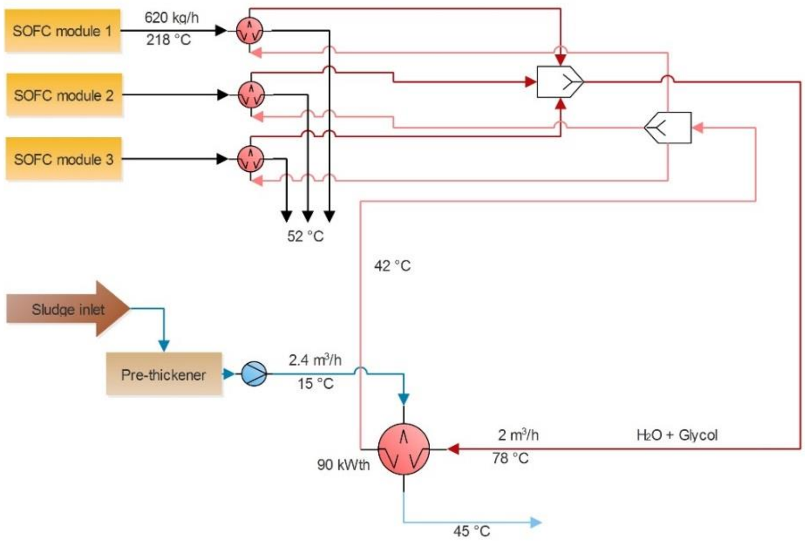

Figure 7. Thermal recovery system.

The SOFC exhaust gas is cooled down to 52 °C, while the water + glycol mixture is heated up from 42 to 78 °C (with an approach temperature of 10 °C). The water flow rate has been estimated as 2 m^3/h, while the sludge flow rate, that is heated from 15 to 45 °C, is 2.4 m^3/h, i.e., around 25% of the averrage sludge flow rate fed to the digester (9.7 m^3/h is the average value for 2015 according to SMAT data). The entire system has been then modeled with the AspenPlus® software in order to underline the technical performance of the system.

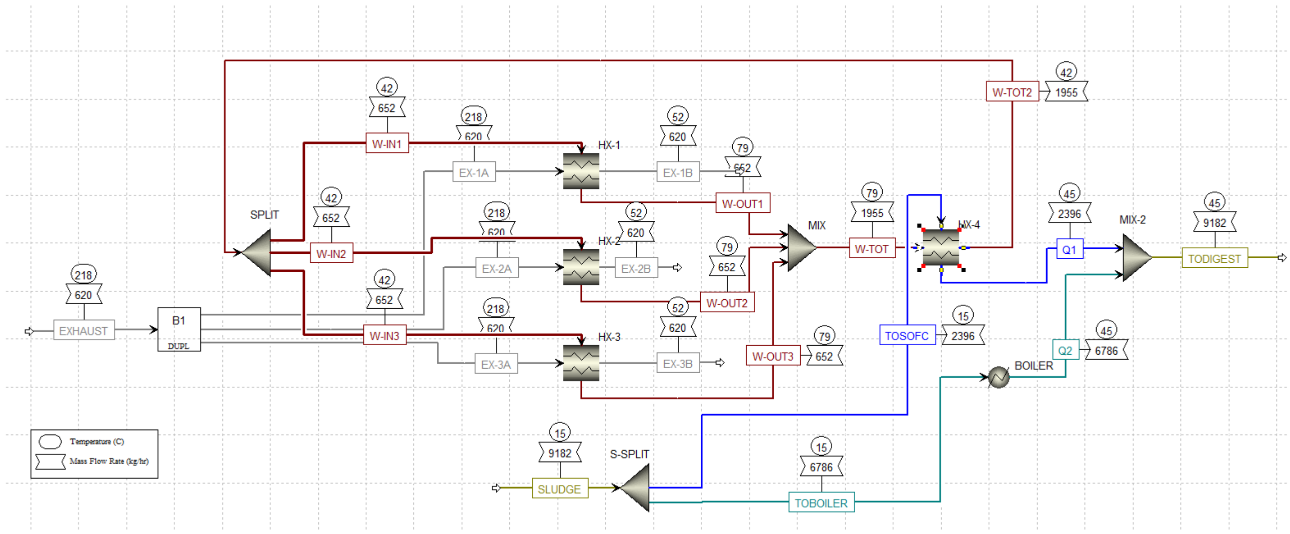

Figure 8. Aspen Plus model of the thermal recovery system.

As shown in Figure 9, the model needs as input parameters the total sludge flow rate and the exhaust flow rate and desired inlet/outlet temperatures of the exhaust gas from each SOFC module. Both primary and secondary loop temperatures are also required as input.

```
C       INPUT DATA
C       SLUDGE: TEMP IN °C, FLOW IN m3/h
        FLOW1=9.2
        TEMP1=15
        TEMP2=45
C       EXHAUST: TEMP IN °C, FLOW IN kg/h
        FLOW2=620
        TEMP3=218
        TEMP4=52

C       EXPORT TO THE MODEL
        MEX1=FLOW2
        TEX1B=TEMP3
        TEX1=TEMP4
        TEX2=TEMP4
        TEX3=TEMP4
        MSLU=FLOW1
        TSIN=TEMP1
        TSOUT=TEMP2
        TSOUT2=TEMP2
```

Figure 9. Model input parameters.

Under nominal conditions, the ideal HEX thermal performance are shown in

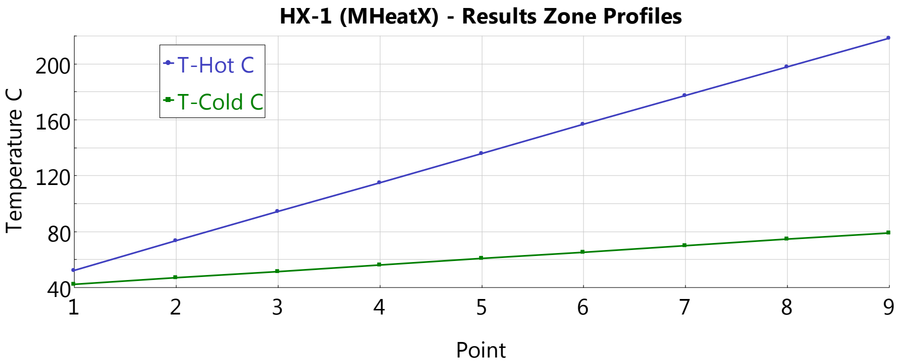

Figure 10 and Figure 11. Temperature trends are shown for both the heat-exchangers. At inlet section of the water-gas HEX the minimum temperature difference (pinch point) of 10 °C is reached. Based on the amount of heat recovery available, the sludge which can be pre-heated by the SOFC is calculated and the split fraction in the inlet sludge mixer is calculated accordingly. The remainder of the total sludge whose pre-heating is not covered by the SOFC, is heated through a hot-water looped fired by a NG (or biogas) boiler (the NG consumption is determined in a dedicated calculator block).

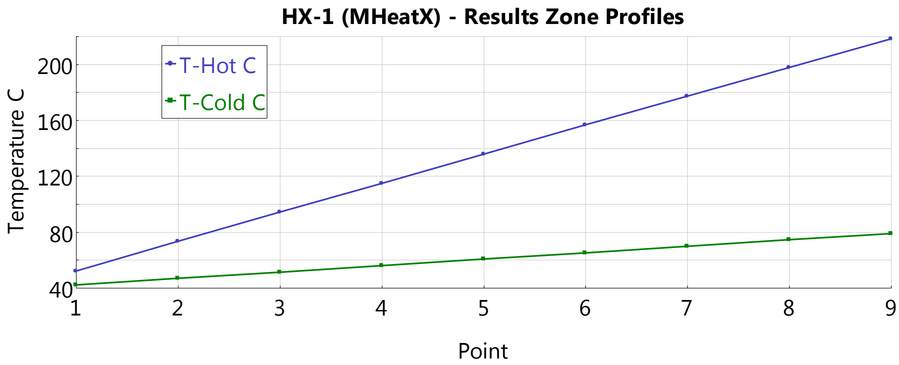

Figure 10. Gas-water HEX hot-cold curves.

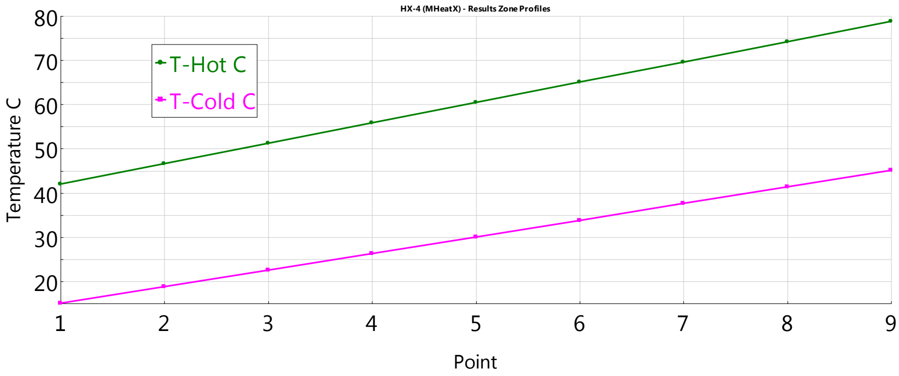

Figure 11. Water-sludge HEX hot-cold curves

The sludge flow which is sent to SOFC heat recovery system is automatically varied in the model to keep the outlet temperature to 45 °C. As previously mentioned, under nominal conditions, 26 % of inlet sludge is heated by the heat recovery, while 74% by the auxiliary boiler. As will be seen from dynamic analysis, the boiler can be fed either by extra-biogas that might available in the gas holder or by natural gas from the grid.

Table 4. Results for the sludge splitting.

Stream	Split fraction
TO SOFC	26,10%
TO BOILER	73,90%

In Figure 12 off-design conditions are given for the heat recovery loop. As can be seen from the results (Figure 13). For instance, when reducing the SOFC power from 100% to 60%, the thermal recovery decreases from 90 to 47 kWth. The thermal recovery rate tends to flatten as the SOFC power is reduced as a result of the rather inefficient (electrical) performance of the SOFC when the modulation rate goes below 50-60% of the nominal power.

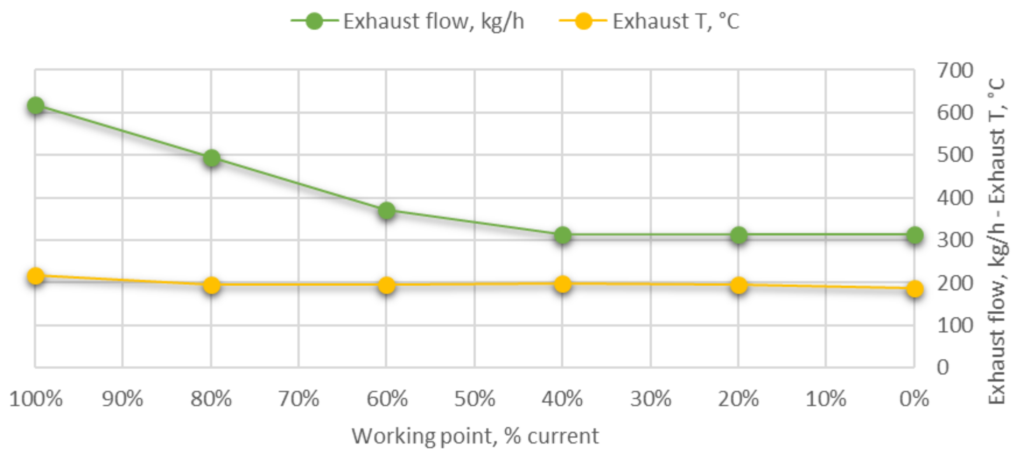

Figure 12. Exhaust flow and temperature in different operating points.

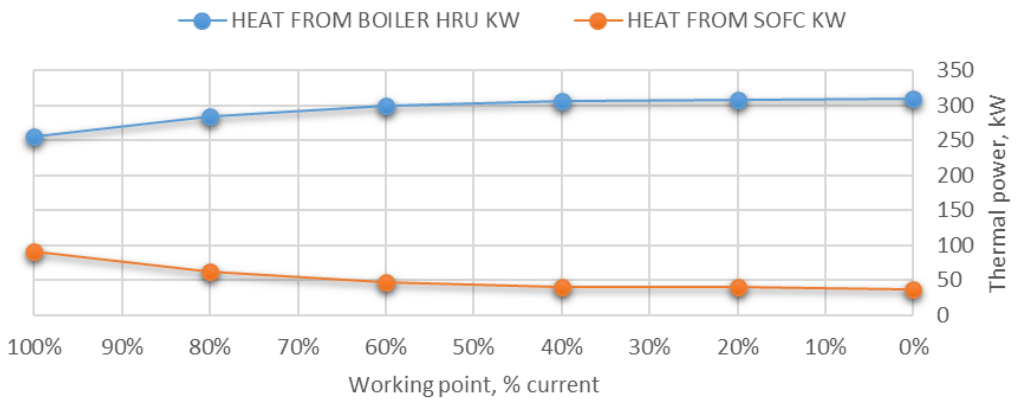

Figure 13. Thermal power obtained from SOFC HRU and external boiler in different operating points.

3. Roadmap for the techno-economic optimization

The future work within Work Package 2 (WP2) will be related to the optimization of the DEMOSOFC plant operation. Since the plant layout is fixed (size of the SOFC already defined), the first part of this work will investigate optimal plant operation strategies in order to maximize the economic revenues of the plant. Activities will focus not only on DEMOSOFC system itself, but will encompass also the biogas production line (sludge line), taking into account the thermal needs of the anaerobic digester. Site-specific electrical and thermal consumption of the WWTP will be also considered.

Starting from the current scenario in the SMAT Collegno plant, the second part of the work will evaluate design and plant improvements, which are: enhanced sludge pre-thickening to reduce the digester thermal load, the use of condensation heat-exchangers to increase the thermal recovery from the SOFC, the introduction of a fourth SOFC module (for better biogas resource exploitation), bi-fuel operation of SOFC modules (NG and biogas).

As previously mentioned, an even broader perspective – moving out from the Collegno WWTP and analyzing possible replications in different countries – will be exploited in the D2.6 “Cost/benefit analysis of the system”, with research activities led by Imperial College.

Scenarios

Starting from the base scenario presented before, more scenarios will be then analyzed, by varying both technical and economic variables.

- Technical variables: enhancement of sludge pre-thickening, enhancement of SOFC exhaust thermal recovery with a condensing heat exchanger, addition of an extra SOFC module, bi-fuel feeding)
- Economic variables: electricity price, natural gas price, SOFC and clean-up cost
- Operation variables: for a fixed system layout, the operational strategy will be also considered as an optimization variable.

<u>Enhanced sludge pre-thickening</u>

The use of pre-thickening is a well-known procedure to increase the solid content in the sludge streams. In SMAT Collegno WWTP, sludge is already pre-thickened by simple sedimentation. The system is able to reach an outlet Total Suspended Solid (TSS) of around 2%. Using centrifugal or dynamic systems, thanks to the aid of mechanical power and a flocculating agent (a polyelectrolyte), the TSS can reach values higher than 5%. Centrifugal pre-thickeners can reach instead SST up to 8%, but in this case higher electrical consumption for the sludge movement and mixing is required.

As shown in Figure 14, pre-thickening up to 5% TSS would strongly reduce the digester thermal load, leading to more similar values among the SOFC thermal recovery and the thermal load.

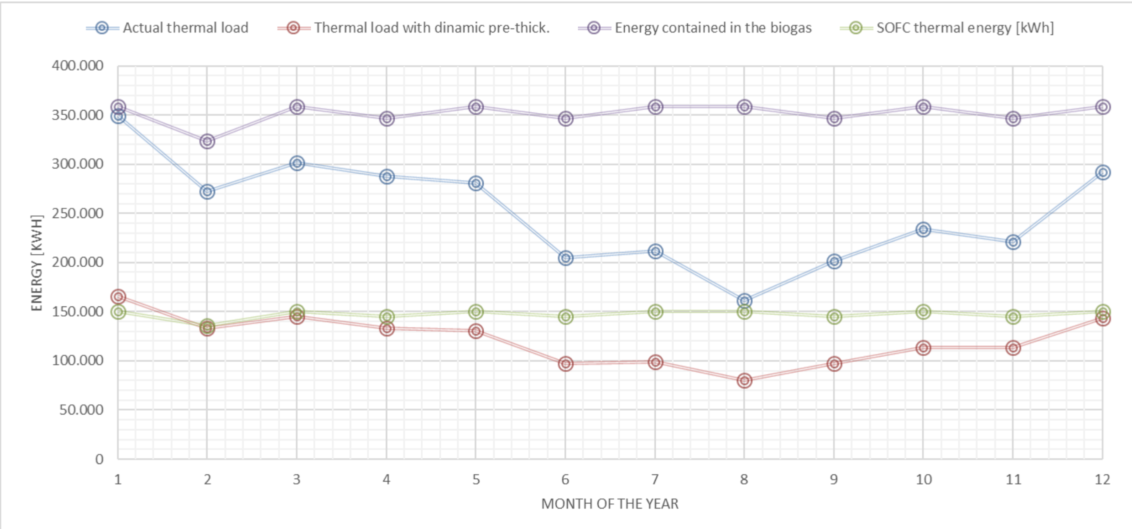

Figure 14. Influence of pre-thickening on digester thermal load.

Condensing heat exchanger

The condensing heat recovery HEX will lead to higher thermal power recovered from the SOFC modules, since the latent heat of condensation is also available. The main problem in this scenario is the exhaust is outlet temperature required to achieve exhaust gas condensation (currently the exhaust dew point is around 36 °C) always taking into account the thermal need of the plant (pre- heating sludge to 45 °C).

SOFC modules

Even if has been demonstrated that, with the available biogas flow, three modules is the optimal number in order to maximise the plant capacity factor, a future fourth module installation will be analysed, not fed with only biogas but with the possibility of a bi-fuelling scenario in order to maximise the electrical production.

Electricity and natural gas prices

Energy prices are currently strongly influencing the economic scenario and future variations of the same will be analyzed in the WP2.

SOFC and clean-up costs

Besides the cost of energy, the high investment cost is due to the still noncompetitive SOFC and cleaning costs. Thus, future scenarios will be analyzed with target values from literature.

Operation strategy

In Figure 15 all the possible operation paths are shown. Two fuels are available in the site: biogas, which is available “for free” and natural gas, which price is related to the plant contract. Both biogas and natural gas can be exploited in the fuel cell, producing both electricity and heat but with high investment and maintenance cost, or in the boiler, with thermal only production but reduced related costs. The available products can be then used for the WWTP itself: electricity is anyway required in the plant since the electrical load is around 550 kW, while the thermal production can be all required, in the current scenario, but could be also wasted in some periods in case of pre-thickening introduction.

All these possible pathways, with constraints and valid variation ranges, will be included in the operational optimization of the system, in order to define the best way to manage the plant in order to maximize the economic outcomes.

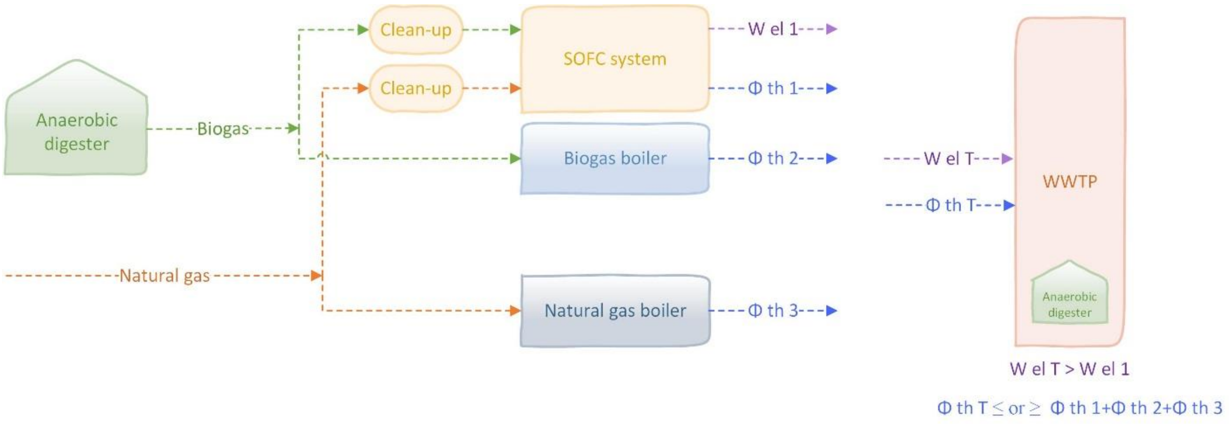

Figure 15. Layout of all possible operational pathways.

Cost-benefit analysis of SOFC systems in WWTP

The last part of the work, due in D2.6 "Cost/benefit analysis of the system" from Imperial College at M6, will be devoted to the cost analysis of a general SOFC installation in WWTP. This task will aim not only to study and optimize the costs occurring during the lifetime of the Collegno plant (Italy), but it will extend results to other the generic WWTP.

In order to optimize the plant profitability, a model is implemented and run in GAMS - a software dedicated to solve linear, nonlinear and mixed-integer optimization problems.

The model will provide the Minimum Lifetime Cost according to different scenarios that are analyzed.

The scenarios will be run from simplest to more sophisticated, going through different levels (adding different features and variables).

- Basic scenario: 3 modules, fixed size of the module (58.3 kW);
- Basic scenario plus sludge pre-thickening;
- Optimization of the size (SOFC electrical power installed);
- Sensitivity analysis on the cost of energy out of Italy (studying and comparing the energy market of e.g. UK and Finland);
- Possibility of plant scale-up.

The formulation of the mathematical model is based on the techno-economic analysis of Hawkes et al. (*Hawkes, A. D., D. J. L. Brett, and N. P. Brandon. "Fuel cell micro-CHP techno-economics: part 1–model concept and formulation." International Journal of Hydrogen Energy 34.23 (2009): 9545-9557.*). The model has been changed and adapted to the case of study.

4. Conclusions and future work

Techno-economic optimization activities are being carried out at different levels. This is the first report on the topic which attempts to summarize both present and future efforts.

The techno-economic optimization of the DEMOSOFC installation is first intended to look at the optimal operating strategy of the DEMO plant when looking just at OPEX. In this limiting case, in which CAPEX for SOFC module and clean-up are not included (also the stack replacement cost is excluded), the DEMOSOFC installation generates a revenue of 14.2 €/kWh (the same calculation spreadsheet used for results shown in Table 1 has been used, by setting to zero the CAPEX of SOFC and clean-up system). Therefore, biogas use in SOFC is more profitable than biogas morning (which generates instead 11.4 €/kWh).

Scenarios in which CAPEX are included as well, show how long-term target costs for both CAPEX and OPEX of the SOFC module and the clean-up unit are required to make biogas use in the SOFC as competitive as biogas burning.

All scenarios described so far refer to specific installation of DEMOSOFC, which is located in the WWPT of Collegno (IT). Economic results are thus widely influenced by market energy prices of both electricity and gas. The economic performances of integrated biogas SOFC plants in different WWPT sites should be recalculated by updating / revising energy prices. The daily availability of biogas is also important in determining a realistic plant capacity factor, which also strongly influences revenues.

After analysing the baseline DEMOSOFC plant configuration , we define a roadmap to study in the future possible design improvements. A techno-economic optimization of different plant layouts will be carried out in finale Deliverable of WP2 entitled ‘Optimal Design and Management of Integrated Biogas SOFC plants in WWTPs’.

5. References

[1] DOE NETL, "The Impact of Scale-Up and Production Volume on SOFC Manufacturing Cost," 2007.

[2] R. Turton, R. C. Bailie, W. B. Wniting, A. Shaeiwitz, and T. Eclition, *Analysis, Synthesis and Design of Chemical Processes*. .

6. Appendix – Techno-economic analysis and costing methodology

The methodology for the techno-economic optimization is presented here.

The general structure of the analysis is shown in Figure 166: a technical and an economical model are developed and coupled to perform an optimization of the entire model.

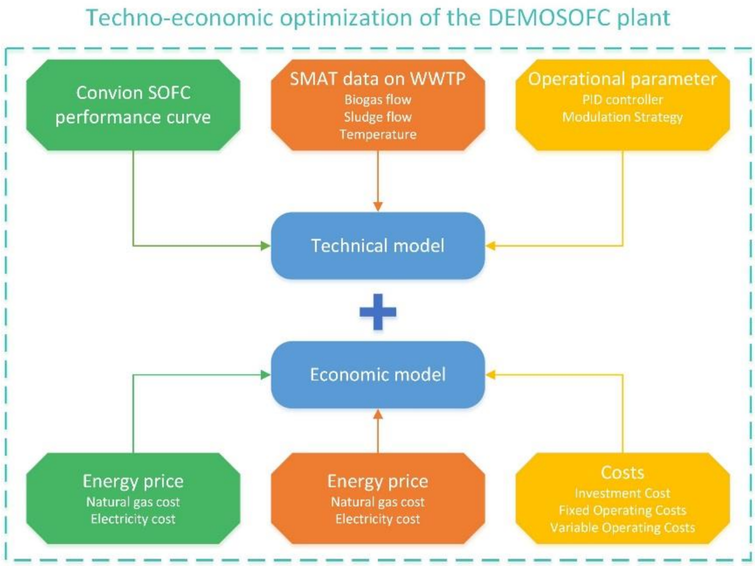

Figure 16. Layout of the techno-economic analysis and optimization

Technical model

As discussed for the DEMOSOFC Energy Planner in D2.1 and in the previous chapter, a first technical model has been developed to simulate the SOFC operation.

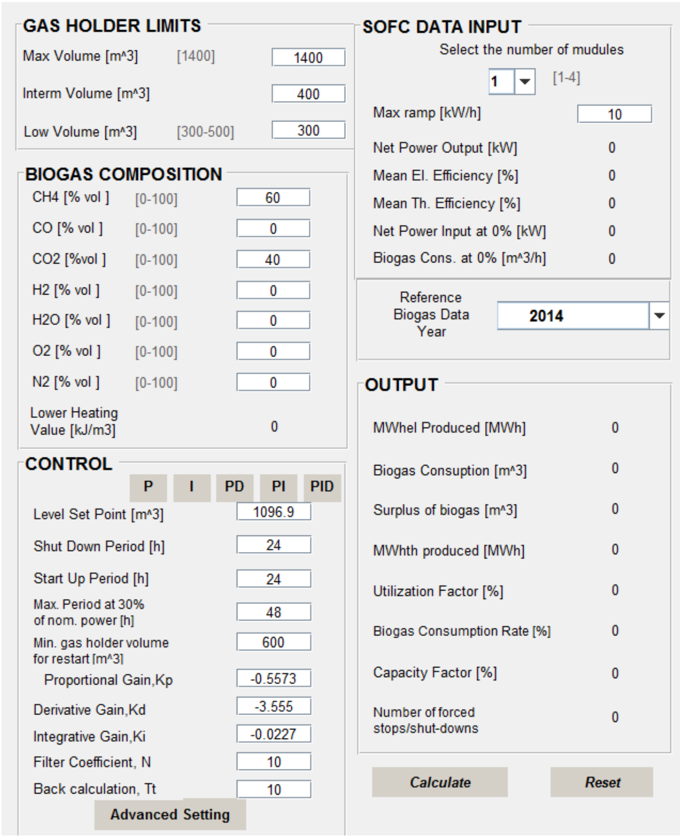

Figure 17. Technical model – input parameters.

Input parameters for the technical model are:

- Gas holder levels: minimum and maximum level are structural limits for the gas holder components and have been defined in accordance with SMAT. The intermediate level is the point for re-starting the system after shut-down and thus should be optimized during the analysis.
- The biogas composition is now standard but will be varied according to SMAT data. As shown in Deliverable D2.1, biogas composition is stable during the year with a methane fraction varying between 62 and 65%. Further analysis will be used to find a medium value for the technical model.
- The control section lets the user choose the type of control (proportional, derivative, integrative in different configurations) and requires a set point for the gas holder level (which will be another optimization variable). Start-up and shut-down periods, together with the maximum time at 30% of power have been defined together with CONVION in accordance with the SOFC module specifications.
- The SOFC data input is only related to the number of modules which can be installed and the maximum ramp rate.

From the technical point of view, optimizations will be developed in order to maximize the capacity factor (as shown in chapter 1) or the electrical production while varying not only the number of modules but also the gas holder set point, the intermediate volumes and the PID parameters.

Economic model

The second part of the work will be related to the economic analysis of the system. The economic model will require as input the effective yearly electrical and thermal production, derived from the technical model.

In order to calculate real costs, including all possible contingencies and risks, the NETL cost methodology has been followed. Multiplication factors have been assumed in accordance with the current scenario with a low penetration of the fuel cell technology in the market and a related medium-high risk.

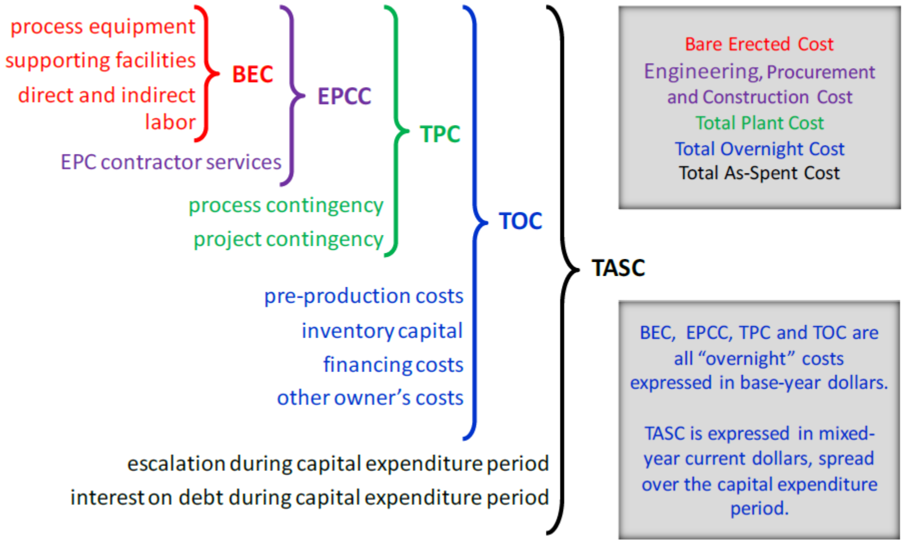

Figure 18. NETL methodology for plant cost assessment.

<u>Investment cost evaluation - CAPEX</u>

The analysis starts with the evaluation of the investment costs for the three main units:

- Clean-up system
- SOFC module
- Thermal recovery
- Other costs

For what concerning the clean-up system, the cost from the DEMOSOFC supplier will be used and compared with literature costs, in order to develop a reliable cost function for the system. The cost will include: vessels, catalysts for sulfur and siloxanes, piping and valves, compressor, blower and chillers. Furthermore, engineering and installation costs will be included, together with the online gas analyzer cost.

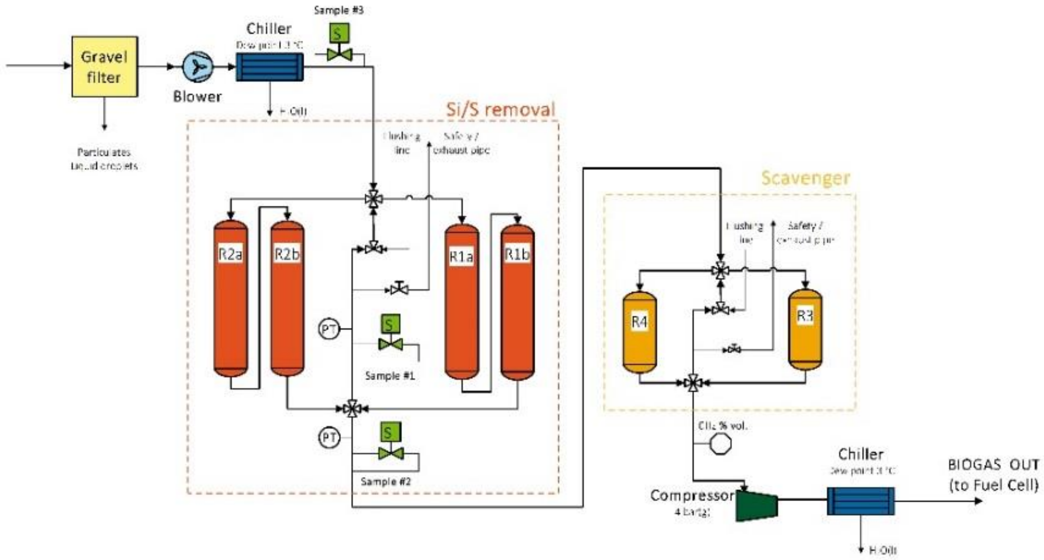

Figure 19. Clean-up system layout.

An example of costs comparison between literature works and DEMOSOFC purchase is shown on the figure below.

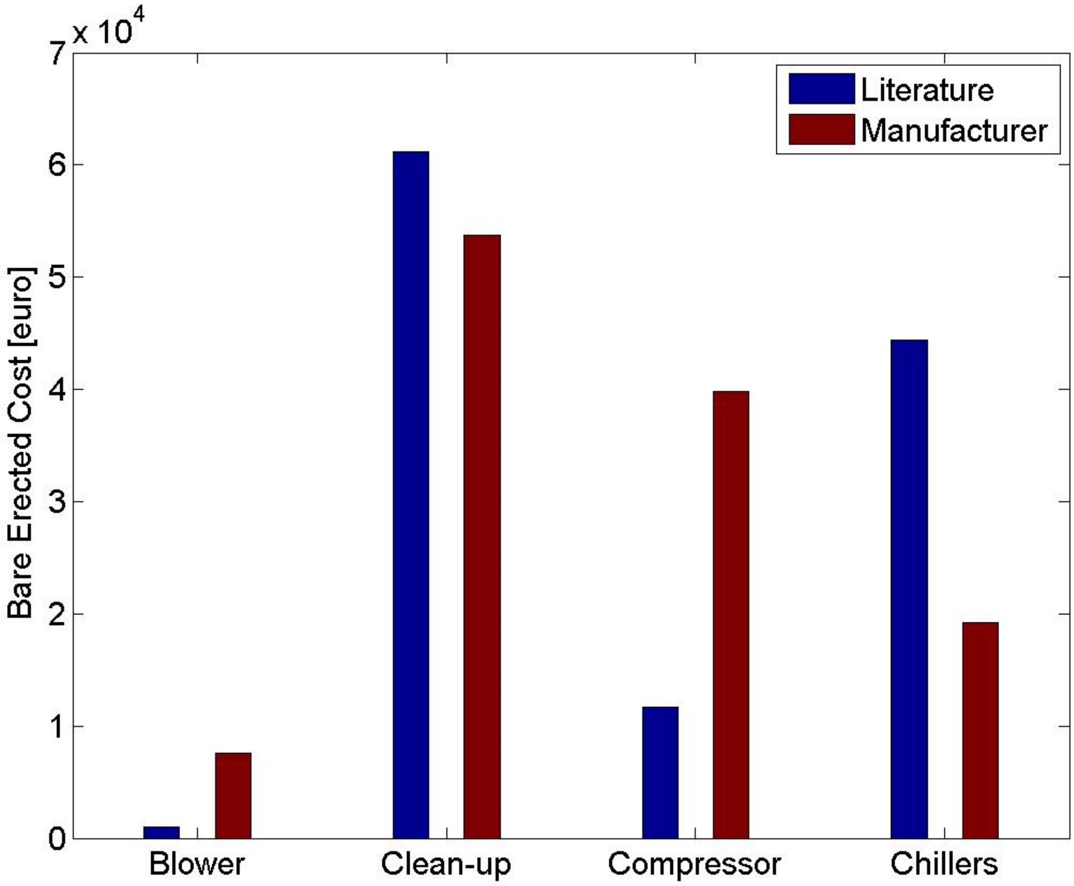

Figure 20. Comparison between Bare Erected Cost of the Fuel Supply System (clean-up, chillers and compressors)with literature analysis and direct manufacturer costs in DEMOSOFC system.

For what concerning the SOFC module, a literature research has already been developed in order to compare reference cost functions with current costs from manufacturers. The DOE cost trend (Figure 21) for varying production volumes has been chosen, with an annual production lower than 5 for the current scenario [1]. The cost will be then compared with CONVION cost ranges shown in the DEMOSOFC proposal (Table 5).

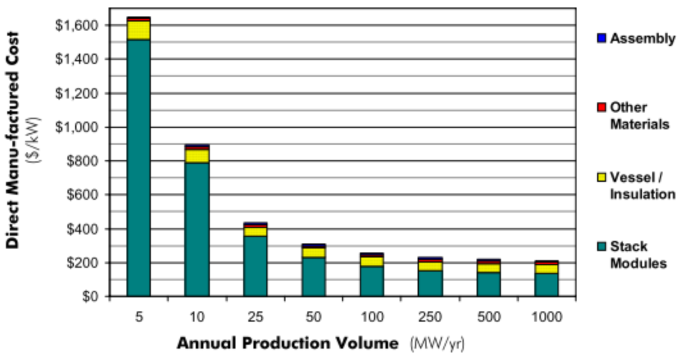

Figure 21. Stack cost share for different yearly production volumes [1]

Table 5. Expected trend for SOFC modules CAPEX as in the DEMOSOFC proposal

		SoA 2014	KPI 2017	KPI 2020	KPI 2023
CAPEX	€/kW	6'000 – 10'000	5'000 – 8'500	4'500 – 7'000	3'500 – 6'500

Finally, the cost for the heat recovery unit will be both estimated from literature (summing the costs of pumps – redundant in the water line to guarantee continuous operation – piping and heat-exchangers from [2]) and compared with real costs from SMAT, in order to validate the system cost.

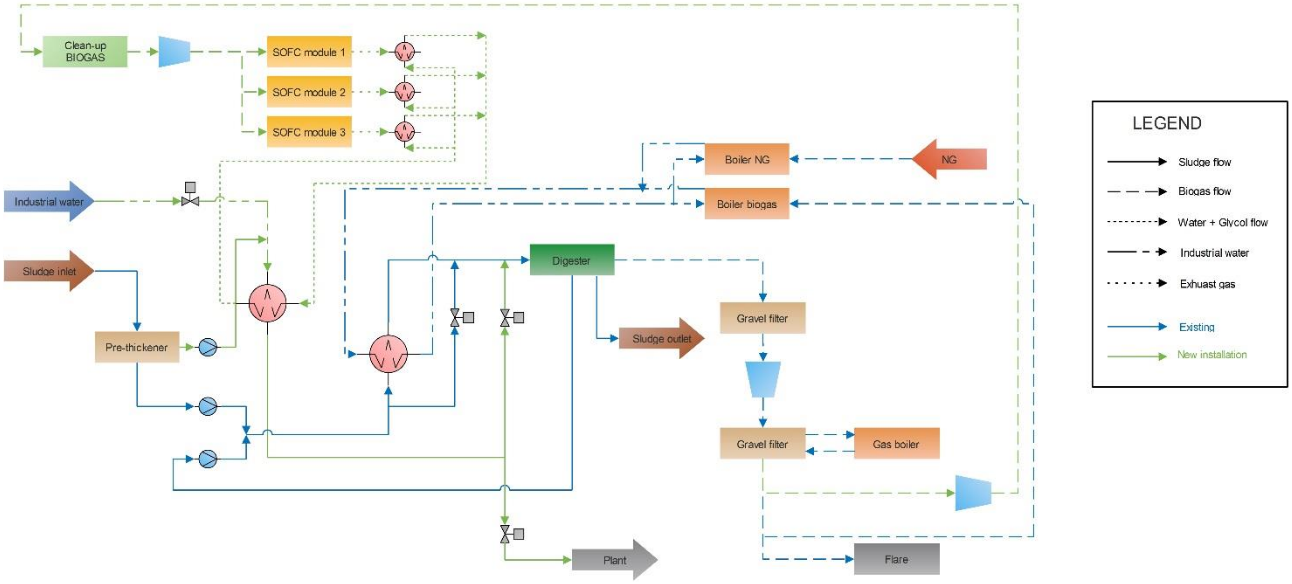

Figure 22. Thermal recovery system (existing + modifications related to DEMOSOFC)

The total investment cost will also include other costs as: development of the control system, plant preparation since all the required services (electricity, compressed air, heat) should reach the DEMOSOFC plan boundaries, control room, safety system.

The total plant cost (TPC) will thus be the sum that the plant owner needs to pay the first year of the system lifetime.

<u>Operating costs evaluation - OPEX</u>

From the second year of lifetime (supposing one year of design and construction), the plant will start operating and thus operating costs will be associated.

Operating costs can be divided into:

- Fixed operating costs, which are expressed in €/y and are not depending on the fact that the plant is producing more or less.
- Variable operating costs, which are depending on the production, usually expressed ad €/kWh.

The operating costs which will be considered for the economic evaluation are:

- Clean-up system maintenance, since catalyst will be replaced every 6 months (twice per year) and so a cost is associated with this activity. This value will be directly taken from the clean-up manufacturer offer.
- SOFC module maintenance cost, which will be assumed in accordance with CONVION, related to the general maintenance of all components included in the module. Furthermore, every 3-5 years depending on the stack lifetime, the SOFC stack substitution needs to be considered with a related cost (expressed as % of the initial investment cost).
- Thermal recovery systems maintenance, mainly related to the heat exchanger fooling and pumps maintenance.
- Labor costs: if operators are needed for the plant operation, their costs will be included in the analysis. Operators will especially require during maintenance time and not during nominal operation.
- Energy cost: as discussed in Deliverable D2.1, natural gas will be required to supply part of the thermal power for the digester heating, in case the one from SOFC recovery is not enough. Furthermore, depending on the system control volume, electricity costs will be included.

<u>Revenues</u>

Revenues from the fuel cell installation are related to the system two products:

- Electrical production. Because of the high efficiency SOFC system, electrical power is produced and self-consumed in the waste water treatment plant, which consumption is higher (around 600 Kw). From the electrical self-consumption a saving is generated. This value is the price paid for the electricity minus the taxes which could be applied also on the self-production.
- Thermal production. The heat generated is accounted as consumption of natural gas to be sent in a boiler in order to get the same amount of heat.

The analysis has been then compared with the current scenario in which the amount of biogas – feeding in the future the SOFC – is burnt in a boiler, generating only some maintenance costs and a earning for the natural gas saving.

The technical and economic model will them be collected in a unique model, which will be optimized. The optimization will be performed on different chosen indicators for the plant:

- Life Cycle Cost (LCC)
- Primary Energy Saving (PES)
- Yearly net revenues