Solutions for improving the energy efficiency in wastewater treatment plants based on solid oxide fuel cell technology

Solutions for improving the energy efficiency in wastewater treatment plants based on solid oxide fuel cell technology

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Abstract

Polygeneration configurations for small power generation systems offer significant potential for energy saving and reducing carbon emissions in wastewater treatment facilities. In this work, a biogas-fed solid oxide fuel cell system operating in a wastewater treatment plant (located in Turin, Italy) is analyzed in terms of its potential improvements through novel polygeneration systems. In its present combined heat and power configuration, along with electrical power, thermal energy from the exhaust gas is recovered to provide required heat to the plant's anaerobic digester. The analysis is focusing on different energy efficiency solutions for this type of plant by using solar thermal collectors, microturbines, a trilateral Rankine cycle, and an absorption chiller. Results reveal that, despite of higher efficiency for the trigeneration case using both trilateral Rankine cycle and absorption chiller (up to 88.4 %), the solar integrated system results in the lowest natural gas consumption, which is 38.5 % lower than the baseline scenario. This same scenario is also the worst in economic terms due to the high capital costs of solar collectors. In a short-term cost trajectory of the solid oxide fuel cell technology, the most economically favorable scenario is the microturbine integrated case in which the calculated levelized cost of electricity is 0.11 €/kWh, lower than grid electricity price, and with payback time of 6.5 years. Long-term cost trajectory is indeed generating effective investments for all of the four scenarios with payback time between 3 and 5 years in all cases. The analysis has been developed to the entire European Union area: the most suitable market conditions are found in Germany, Denmark, Slovakia, and Italy.

Keywords: *solid oxide fuel cell, solar thermal system, microturbine, trilateral Rankine cycle, biogas, economic analysis.*

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Highlights

- Different polygeneration solutions for installation at WWTP are analyzed.
- Thermodynamic and techno-economic models are created for polygeneration systems.
- Integration of microturbines is the most economic solution with LCOE of 0.11 €/kWh.
- The techno-economic analysis is extended for the entire EU area.
- Suitable market conditions are found in Germany, Denmark, Slovakia, and Italy.

1. Introduction

Water is a natural asset, sometimes in scarce supply and fundamental to life on Earth. Just 3 % of the planet's water is freshwater, of which only one third is accessible for use in agriculture and diurnal human consumption. The rest is frozen in glaciers or hidden too deep underground. Nowadays, an enormous number of facilities are in service worldwide to make wastewater recycled. Similar to any other facilities, wastewater treatment plants (WWTPs) require a great amount of electrical and thermal energy in order to run the plant uninterruptedly. As shown in Figure 1, a typical wastewater treatment plant involves processes listed below (MosayebNezhad et al., 2019) :

- In the first stage, wastewater is transferred to the plant by gravity through the central sewer system. One could observe a variety of objects with different sizes and elements reaching the WWTPs.
- In the preliminary treatment or pre-treatment which is the first mechanical stage, in order to settle out the sand and grit, water flows through the gravel chamber. Then, gravel is disposed of. Further, the bar screens are used to remove large substances from the wastewater. Firstly, the coarse screens are implemented and then the fine screens are used to remove smaller elements such as plastic films and cigarette butts.
- Grit is supposed to be separated from the wastewater next to the removal of large objects. Like the gravel chamber, grit chamber allows the settlement of grit. Afterward, grit is taken out of the tank and disposed of at the dump. Due to the high contamination levels of both gravel and grit, neither of them can be reused.
- In the primary treatment known as "pre-settling basins", water is guided to the hopper in the tank base. At the velocity of about 4 cm/s, the hopper arm moves around the edge of the tank. Treated water is steered towards edges and higher sedimentation velocity than flowing fluid leads to settlement of particulates on the tank bottom. Here the primary pre-treatment finishes and secondary wastewater treatment begins. At the end of the primary treatment, the level of wastewater pollution cuts down to about 60 %.
- The biological stage which is the secondary treatment, is based on natural processes. WWTPs use bacteria digesting the contaminants including biodegradable organics, phosphorus and carbon. Subsequently, dead bacteria and organic residues convert to sludge.

- During the secondary treatment, the excess sludge is moved before the settling tanks by pumping it out. This is the point where the sludge settles and is guided to digestion tanks for next level of treatment.
- Sludge which is pumped out of the digestion tanks is then heated and mixed. During the digestion process, biogas is produced from the sludge. WWTPs can reuse the biogas for electrical and thermal energy production.
- The second digestion stage happens in storage tanks when sludge digestion comes at its optimal level. The water is separated from the semi-solid sludge, and sent back for next treatment while the residual semi-solid experiences mechanical dewatering.
- Finally, sludge and dewatered to the optimal degree are disposed of at the dump. About a month should pass so that the sludge is suitably dried out. However, it can be complied with agricultural standards to be utilized as fertilizer for industrial crops.
- The final step of wastewater treatment is the profound inspection of service water. The main purpose is to evaluate the contamination level and ensure that the highest standards are achieved.

Depending on the wastewater treatment plant, the electrical and thermal demand would be different. Accordingly, depending on the size of the WWTP and the person equivalent served the electrical demand of the WWTPs usually is in the range of 300kW to 1000kW which could be suitable for medium size movers (Guerrini et al., 2017; Wellinger et al., 2013). Considering the steps discussed above, there is a possible solution to supply the demand by means of the utilization of biogas produced in the plant itself. Utilization of biogas produced in the plant in order to supply the demand of the wastewater treatment plants has been investigated in the literature. Conventionally, the produced biogas was burnt in a boiler to supply only the thermal demand of the plant, a part of which were thermal demand of the digester itself. To produce electricity, some plants have used an internal combustion engine (ICE) or micro gas turbine (MGT) to utilize the biogas. In literature, other more sophisticated solutions are analyzed. For a target biogas plant in Busan, Republic of Korea, thermoeconomics of a biogas-fueled micro gas turbine (MGT) system combining with a bottoming organic Rankine cycle (ORC), is performed by Sung et al. (Sung et al., 2017). It is reported that where natural gas prices are high and electricity prices are low (such as in Korea), the competitiveness of selling directly the biogas is very high compared to a power generation system. The optimum size of MGT cogeneration in a sewage treatment plant in terms of its economic performance is analyzed by Basrawi et al. (Basrawi et al., 2017). One of the main results of their work is that the net present value could be obtained when the input fuel of MGT is equal to the biogas production of the sewage treatment plant. On the other hand, in the cases of heat demand fluctuation throughout the year, the smaller size of MGT would be preferable.

One of the promising technologies in producing power is Fuel Cell technology. Among different types of fuel cell systems, Solid oxide fuel cell (SOFC) is an interesting choice as it is modular, scalable, and more efficient. Compared to other fuel cells, the SOFCs are fuel-flexible and can reform methane internally, use even carbon monoxide as a possible fuel, and tolerate some degree of common fossil fuel impurities, such as ammonia and chlorides (Cui et al., 2014). The energy analysis of two CHP plants using internal combustion engines (ICE) and SOFC systems by feeding biogas is investigated by Santarelli et al. (Santarelli et al., 2012). The comparison showed that the CHP plant based on SOFC system would be better from the thermodynamics point of view. However, it is shown that the produced thermal energy is quite higher for the case of ICE. Williams et al. (Williams et al., 2001) proposed an indirect SOFC-GT hybrid system. They reported that the maximum achievable efficiency for their system is 45 %. In addition, it is shown that the system has lower efficiency value than that of the direct combination of the two systems. Cheddie et al. (Cheddie and Murray, 2010a) evaluated a combined system including an SOFC system and a 10 MW gas turbine plant. Considering to the developed thermo-economic model, it is reported that the proposed system could generate 20.6 MW power at the electrical efficiency of 49.9 %. In their following research (Cheddie and Murray, 2010b), an integration of SOFC and gas turbine in a semi-integrated configuration was investigated. It is revealed that an output power of 21.6 MW could be generated at the efficiency of 49.2 %. A new model for evaluation an SOFC-GT system is proposed by Zhang et al. (Zhang et al., 2014) where the SOFC stack and the combustion chamber exhaust gases are utilized to heat up the gas turbine inlet stream. Bicer and Dincer (Bicer and Dincer, 2015) introduced a scheme including underground coal gasification, steam-assisted gravity drainage, solid oxide fuel cell, integrated gasification combined cycle and an electrolyzer. Energy and exergy efficiencies of 19.6 % and 17.3 % are obtained for the combined system, respectively. Zhao et al. (Yan et al., 2013) investigated a coal syngas-fueled SOFC stack working in an atmospheric condition integrated indirectly with a Brayton cycle. The authors concluded that the system efficiency increases with decreasing current density and the value could be in a range of 48-56 %, depending on the operating temperature and current density. Inui et al. (Inui et al., 2005) proposed two configurations of carbon dioxide recovering systems using the integration of SOFC-GT. It is reported that applying the positive influence of the carbon dioxide recycle, the overall efficiency of 70.88 % (based on LHV) could be obtained. These values for the system with water vapor injection are 65.00 % (HHV) or 72.13 % (LHV), respectively. Eveloy et al. (Eveloy et al., 2016) investigated an indirect combination of an SOFC system and a gas turbine with an organic Rankine cycle. It is stated that the SOFC-GT-ORC system demonstrates an efficiency improvement of about 34 % compared to the gas turbine as a stand-alone system, and of 6 % compared to the hybrid SOFC-GT sub-system. It is stated that within three to six years depends on the working condition the profitability of the system is varying. Inui et al. (Inui et al., 2003) suggested a system combining of an SOFC and a magnetohydrodynamic (MHD)/noble gas turbine with a unit of carbon dioxide recovery. It is reported that the overall thermal efficiency of the system using methane as the fuel could be 63.66 % (HHV) or 70.64 % (LHV) (Safari et al., 2016). At full and part loads, performance of direct or indirect combination of SOFC and GT systems is analyzed and compared with the performance of regenerative gas turbine by Sànchez et al. (Sánchez et al., 2008). It is found that the direct hybrid system is superior to the indirect one as power and efficiency enhancements because of the higher pressure in the SOFC are not accessible in the indirect case. Results show that initial investment/installation cost of an integrated system is high in spite of low total cost of a fuel-cell-based configuration. A new approach to combine electrodeionization (EDI) and solid oxide fuel cells (SOFCs) is proposed by Xu et al. (Xu et al., 2017). This system is integrated with anaerobic digestion/landfills to capture energy from carbonaceous and nitrogenous pollutants. It is reported that under the optimal conditions, the system obtained a higher net energy output compared to the conventional systems. The effect of feeding SOFCs with biogas coming from anaerobic digestion is investigated by Lackey et al. (Lackey et al., 2017). It is demonstrated that a great reduction in greenhouse gas emissions could be achieved. Also, it is shown that higher humidification provides better performance as the water gas shifting reaction produced more H_2 with additional H_2O.

In 2015, a European project namely DEMOSOFC, considering SOFC power systems for a real wastewater treatment plant near Turin, Italy was proposed. The DEMOSOFC plant as shown in Figure 1 comprises the following systems (“DEMOSOFC project official website,” 2018):

1. In the first stage, the biogas processing unit comprising biogas dehumidification, disposing of contaminants, and compression is implemented. Biogas contains siloxanes and hydrogen sulfide both of which are detrimental for the fuel cell performance. An adsorption-based system using impregnated activated carbons is

considered for disposing of these contaminants. To this end, biogas should be cooled beforehand in order to ensure the carbon optimal operating parameters. At the inlet and outlet of the clean-up system, an online gas analyzer to detect both siloxanes and H_2S is set.

2. The electricity producing unit is composed of three SOFC modules, which generate about 58 kW_e per each unit.

3. Proposing a new heat recovery unit is to utilize the hot exhaust from the SOFC modules while a conventional water loop that is heated up by an existing boiler is being used in the plant.

4. To control the plant from both on-site and remotely a supervisory, control and data acquisition (SCADA) system is used.

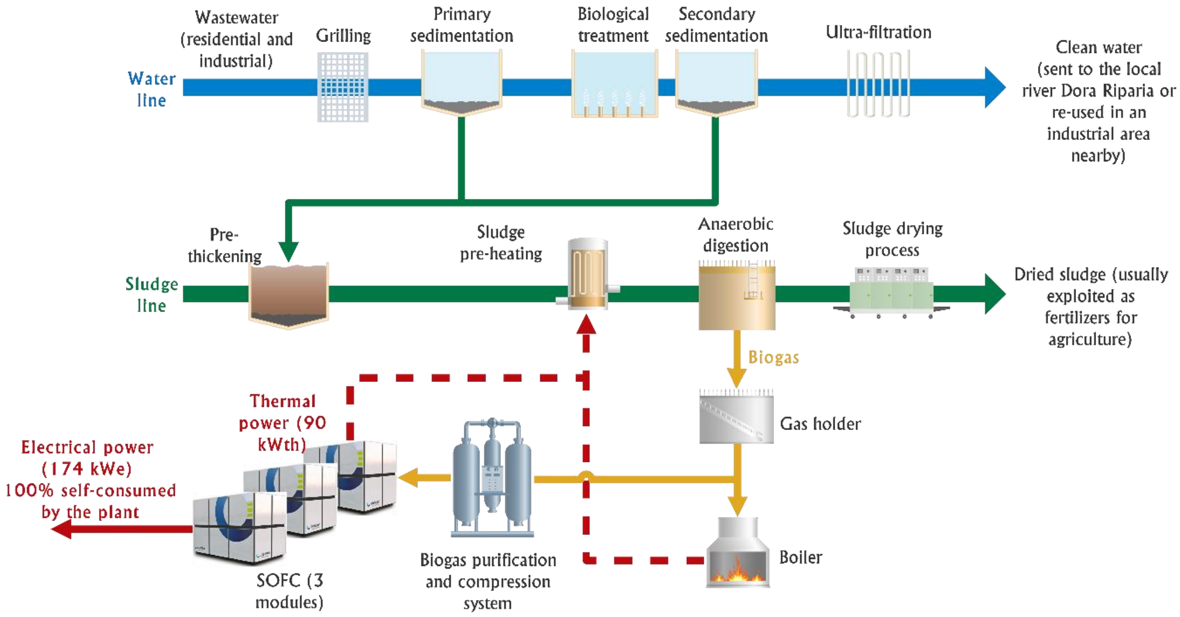

Figure 1. Concept diagram of the DEMOSOFC plant ("DEMOSOFC project official website," 2018).

Currently, the project is in the final phase and SOFC units are being deployed in the plant as shown in Figure 2.

Figure 2. The DEMOSOFC plant after commissioning of the second SOFC unit (“SMAT, Società Metropolitana Acque Torino S.p.A., Turin, IT.,” 2019).

Previously, supplying the electrical and thermal demands of WWTPs by means of ICE (Santarelli et al., 2012), MGT (MosayebNezhad et al., 2018) and SOFC (Mehr et al., 2017) were investigated in several works. However, a comprehensively comparative study revealing which configuration could be promising was carried out. In addition, most of the systems presented before did not consider the process of digester thermal load which plays a central role in producing biogas in the plant.

In the present work, four different scenarios, using SOFC unit as the primary electric power generator, and evolving to a poly-generative configuration are proposed. A comprehensive thermo-economic analysis is performed, and the performance of the proposed systems is compared with each other. In order to provide a meaningful comparison, the DEMOSOFC project is considered as the base case so that the proposed scenarios can be compared with a real life ongoing project. Finally, based on the results, the best possible solution from the energetic and techno-economic points of view for the WWTP is explained.

2. Description of the systems

In this section different configurations of the proposed and investigated systems are explained.

1.1 SOFC system

Figure 3 demonstrates the SOFC system configuration which has been analyzed in the present study. A mixture of the natural gas from the grid and biogas produced in the wastewater treatment plant is the fuel which is sent to the anode of the SOFC unit in order to produce electricity. The mixture is first sent to the pre-reformer before which the fuel is mixed with high temperature anode recycle gases. Through reforming and shifting reactions in the pre-reformer, complex and heavy chains of hydrocarbons are cracked, and a fraction of fuel (CH_4) is transferred into carbon monoxide and hydrogen. In order to obtain a determined fuel temperature before sending it to the anode for the electrochemical reaction, the fuel is heated through the fuel heat exchanger. As it can be observed, anode recycle gases are used to heat up the fuel. A suitable separator is equipped to divide the anode recycle gases into two streams. A part of gases is sent to the mixing unit while the rest is utilized in the after-burner. On the other side, the air is preheated through an air heat exchanger by receiving the thermal energy from the after-burner exhaust gases. Notice that, two blowers are used to increase the pressure of the fuel and air before sending them into the system. The blowers are just equipped in order to compensate the pressure drops within the system and not to increase the pressure of the SOFC system. So the SOFC system is operated at nearly the atmospheric pressure.

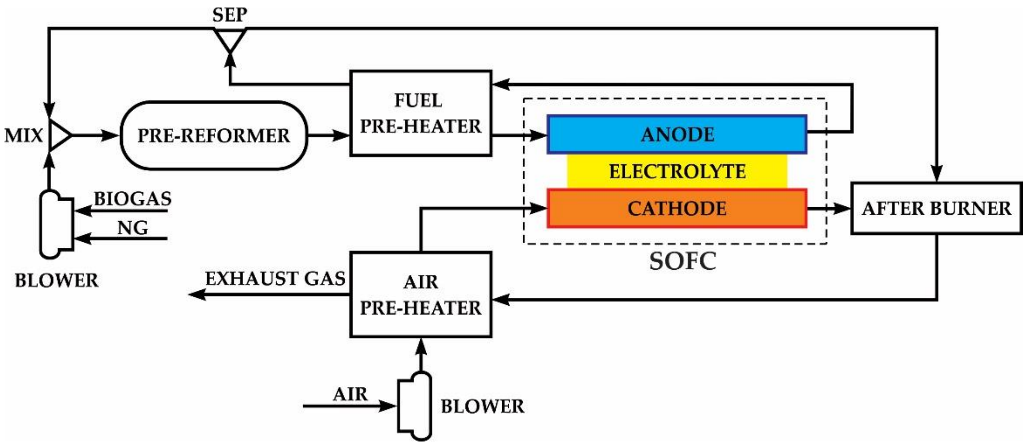

Figure 3. Proposed SOFC system layout.

1.2 Scenarios

There is a notable potential of the available biogas in the SMAT Collegno for electricity generation. Considering the SOFC units to generate power as a base scenario, which was supposed to be realized in DEMOSOFC project, base case layout is defined. Here, to provide the digester heat the available biogas from the plant is just to be fed to the SOFC units.

In the second scenario, solar collectors are used in parallel to the boiler in order to supply a part of the thermal load of the digester.

As an upgraded layout, the MGT case including a new integration of SOFC and micro gas turbines in the WWTP is introduced as the third scenario. In this case, a micro gas turbine is used to compensate a part of digester thermal energy demand. In addition, the whole system could produce extra electricity.

The last scenario which is called Trigen case is defined as a combined cooling and heating power (CCHP) system integrating SOFC units with trilateral Rankine cycle (TLC) system and an absorption chiller. The exhaust gas from SOFC systems is first sent to the TLC evaporator to run the system, and then the gases are utilized in an absorption chiller to produce cooling effects. In this case, the thermal demand of digester will be supplied by both the TLC condenser and the main boiler.

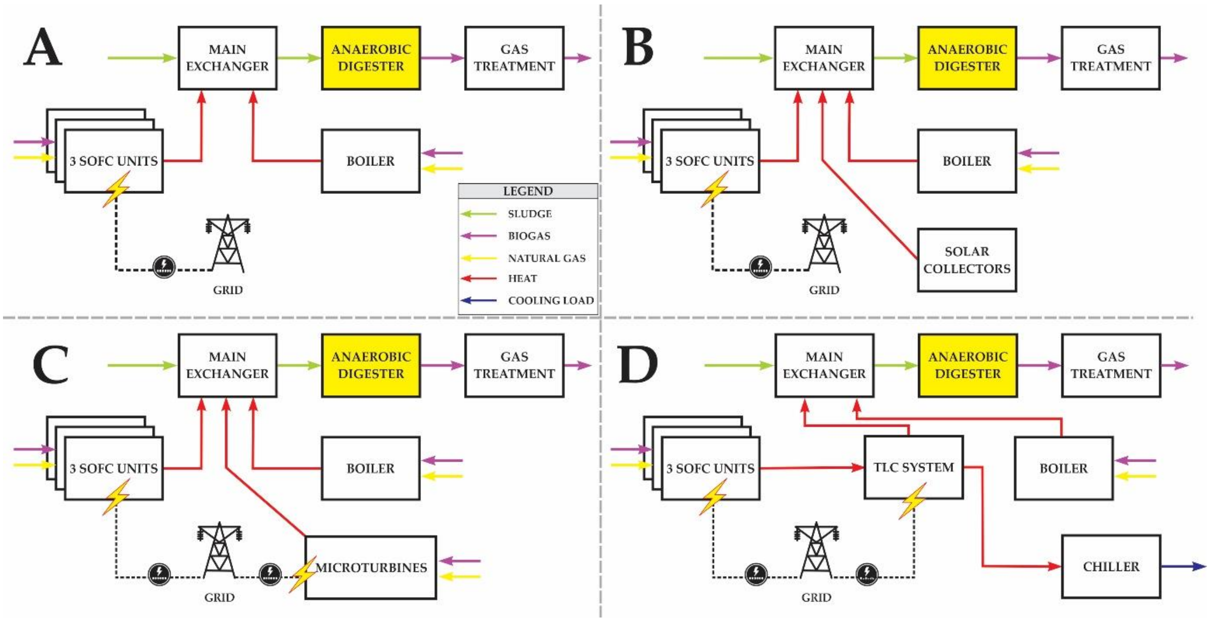

Figure 4. Proposed configurations: A) Base case, B) Solar case, C) MGT case, and D) Trigen case.

The detailed energy modeling of the proposed systems in the previous section has been performed in the authors' works (Gandiglio et al., 2016; Mehr et al., 2018, 2017; Yari et al., 2016). However, comparative techno-economic analysis for all proposed systems, particularly the Trigen case, has not been carried out yet. Therefore, in the present work, it is tried to provide full economic investigation, as well as extending the economic analysis for the entire EU area.

2. Energetic investigation

The energy modeling of the proposed systems is described in this section in detail.

2.1 Assumptions

Some meaningful assumptions were used in the present simulation:

- Air is considered to contain 79 % N_2 and 21 % O_2 neglecting other tiny components.

- Gas leakage from the components and pipelines is neglected.
- Cathode and anode temperatures are assumed to be identical.
- Accordingly (Gandiglio et al., 2016), the available biogas in the plant containing 65% CH_4 and 35 % CO_2 on a volume basis.
- The priority is to utilize the available biogas produced in the plant as much as possible.
- The type of digester is mesophilic.

2.2 Solid oxide fuel cell modeling

By means of an electrochemical process occurred in SOFC stack, DC power can be produced. The fuel (biogas) containing methane gas is reformed inside the anode side in order to finally produce H_2 which is oxidized in the SOFC. DC power is produced as;

$$\dot{W}_{FC,stack} = N_{FC} \cdot j \cdot A_a \cdot V_c \tag{1}$$

Where NFC is the number of the cells, j is the current density, Aa is the active area of cells and Vc is the actual cell voltage. The key point in calculating the SOFC power is to determine the actual cell voltage. It is defined as:

$$V_c = V_N - V_{loss} \tag{2}$$

Here, V_N is the Nernst voltage expressing as;

$$V_N = -\frac{\Delta \bar{g}^o}{2F} + \frac{\bar{R} T_{FC,e}}{2F} \ln\left(\frac{a_{H_2}^{Anode,exit} \sqrt{a_{O_2}^{Cathode,exit}}}{a_{H_2O}^{Anode,exit}} \right) \tag{3}$$

V_{loss} the voltage loss, which is the sum of ohmic, activation and concentration voltage losses:

$$V_{loss} = V_{ohm} + V_{act} + V_{conc} \tag{4}$$

Ohmic loss is formulated as (See also Table 1):

$$V_{ohm} = (R_{Int} + \rho_{an} L_{an} + \rho_{cat} L_{cat} + \rho_{ely} L_{ely})\, j \tag{5}$$

Table 1. Material features for estimating the Ohmic voltage loss (Wongchanapai et al., 2012).

Component	Material type	Thickness (mm)	Resistivity
Anode	Ni/YSZ cermet	0.5	$\rho_{an}=2.98\times10^{-5}\exp(\frac{-1392}{T_{FC,e}})$
Electrolyte	YSZ	0.01	$\rho_{ely}=2.94\times10^{-5}\exp(\frac{10350}{T_{FC,e}})$
Cathode	LSM-YSZ	0.05	$\rho_{cat}=8.114\exp(\frac{600}{T_{FC,e}})$
Interconnection	Doped $LaCrO_3$	-	0.0003215

The activation voltage loss is the sum of losses for both the anode and cathode sides;

$$V_{act}=V_{act,a}+V_{act,c} \tag{6}$$

$$V_{act,a}=\frac{\bar{R}T_{FC,e}}{F}(\sinh^{-1}(\frac{j}{2j_{oa}})) \tag{7}$$

$$V_{act,c}=\frac{\bar{R}T_{FC,e}}{F}(\sinh^{-1}(\frac{j}{2j_{oc}})) \tag{8}$$

Where j_o is the exchange current density and it can be calculated for the anode and cathode sides using the following equations;

$$j_{0,a}=\gamma_{an}\ (\frac{RT}{2F})\ e^{\left(-\frac{E_{a,an}}{\bar{R}T}\right)} \tag{9}$$

$$j_{0,c}=\gamma_{cat}\ (\frac{RT}{2F})\ e^{\left(-\frac{E_{a,cat}}{\bar{R}T}\right)} \tag{10}$$

Notice that pre-exponential and active energy values for anode are 6.54×10^{11} A/m^2 and 140 kJ/mol while these parameters for the cathode are 2.35×10^{11} A/m^2 and 137 kJ/mol (Wongchanapai et al., 2012; Yari et al., 2016). Anode electrochemical semi-reaction results in the hydrogen consumption at the electrode-electrolyte interface. Since the fresh fuel could not readily replace the hydrogen, its partial pressure drops resulting in a reduction of the cell voltage. Meanwhile, a similar phenomenon happens at the cathode compartment where oxygen is consumed in the cathode electrode. This overvoltage can be calculated taking into account transportation phenomena occurring in the fuel cell. It is usually negligible for low current density while for high current densities it becomes a major issue in producing power by the fuel cell. Concentration is usually simulated neglecting heat convection and taking into account only diffusion phenomena, introducing binary and Knudsen diffusion models.

Concentration loss is also can be expressed as;

$$V_{conc} = V_{conc,a} + V_{conc,c} \qquad (11)$$

where

$$V_{conc,an} = \frac{RT}{2F} \ln\left(\frac{P_{H_2} \times P_{H_2O,TPB}}{P_{H_2O} \times P_{H_2,TPB}}\right) \qquad (12)$$

And

$$V_{conc,cat} = \frac{RT}{4F} \log\left(\frac{P_{O_2}}{P_{O_2,TPB}}\right) \qquad (13)$$

where the subscript TPB denotes the three-phase boundary. To calculate the pressure at the reaction sites, the following equations are used:

$$P_{H_2O,TPB} = P_{H_2O,an} + j\,\frac{R\,T_{FC}\,L_{an}}{2\,F\,D^{eff}_{an,H_2}} \qquad (14)$$

$$P_{H_2,TPB} = P_{H_2,an} - j\,\frac{R\,T_{FC}\,L_{an}}{2\,F\,D^{eff}_{an,H_2O}} \qquad (15)$$

$$P_{O_2,TPB} = P_{cat} - (P_{cat} - P_{O_2,cat})\,\exp\left(j\,\frac{RT_{FC}\,L_{cat}}{4F\,D^{eff}_{O_2}\,p_{cat}}\right) \qquad (16)$$

where, $D^{eff}_{H_2}$, $D^{eff}_{H_2O}$ and $D^{eff}_{O_2}$ are the effective gaseous diffusivity through the anode (for H2), anode (for H_2O) and the cathode (for O_2), respectively. The effective gaseous diffusivity can be calculated as:

$$\frac{1}{D^{eff}_{an,H_2}} = \frac{\varepsilon_{an}}{\tau_{an}}\left(\frac{1}{D_{H_2,K}} + \frac{1}{D_{H_2,H_2O}}\right) \qquad (17)$$

$$\frac{1}{D_{an,H_2O}^{eff}} = \frac{\varepsilon_{an}}{\tau_{an}}\left(\frac{1}{D_{H_2O,K}} + \frac{1}{D_{H_2O,H_2}}\right) \quad (18)$$

$$\frac{1}{D_{cat,O_2}^{eff}} = \frac{\varepsilon_{cat}}{\tau_{cat}}\left(\frac{1}{D_{O_2,K}} + \frac{1}{D_{O_2,N_2}}\right) \quad (19)$$

Where the porosity (ε) and tortuosity (τ) of electrode materials are estimated to be 0.48 and 5.4, respectively. To calculate the effective gaseous diffusivity, combined ordinary and Knudsen diffusion should be defined and calculated using the following equations;

$$D_{H_2,K} = 97\ r_{pore,an}\sqrt{\frac{T_{FC}}{M_{H_2}}} \quad (20)$$

$$D_{H_2O,K} = 97\ r_{pore,an}\sqrt{\frac{T_{FC}}{M_{H_2O}}} \quad (21)$$

$$D_{O_2,K} = 97\ r_{pore,cat}\sqrt{\frac{T_{FC}}{M_{O_2}}} \quad (22)$$

$$D_{H_2,H_2O} = \frac{1.43\times10^{-7}{T_{FC}}^{1.75}}{\sqrt{M_{H_2,H_2O}}\,(V_{H_2}^{1/3} + V_{H_2O}^{1/3})^2 P} \quad (23)$$

$$D_{O_2,N_2} = \frac{1.43\times10^{-7}{T_{FC}}^{1.75}}{\sqrt{M_{O_2,N_2}}\,(V_{O_2}^{1/3} + V_{N_2}^{1/3})^2 P} \quad (24)$$

Where M is the molecular weight of species, V represents diffusion volume of species. Meanwhile, pore radius value (rpore) is estimated to be 0.5 μm.

2.3 Thermal and electrical demand of the WWTP

For the comparison purpose, the real wastewater treatment plant in Torino, Italy is considered in this study as a reference plant (the SMAT Collegno WWTP, site of the DEMOSOFC plant). For the considered plant, thermal and electrical demand are shown in Figure 5. As it can be observed, the average electrical power and thermal power required in the plant is about 720 kW and 280 kW respectively. Notice that the electrical demand is provided by onsite measurements at the SMAT site, while the thermal load needed for maintaining the digester temperature in a suitable range is calculated according to the digester design procedure, as follows.

On a monthly basis, the digester thermal load ($\dot{Q}_{digester}$) is calculated as the sum of the following terms:

- the thermal power required for the sludge heating up: from a variable inlet temperature (14-23°C depending on the season) to the digester temperature (38-47°C, taken from real hourly WWTP measurements), $\dot{Q}_{sludge}$
- $\dot{Q}_{loss}$ which is accounted as for the heat losses through the digester walls;

$$\dot{Q}_{digester} = \dot{Q}_{sludge} + \dot{Q}_{loss} \tag{25}$$

The first term in (Eq. 14) is calculated assuming the followings:

- The sludge mass flow rate $\dot{m}_{sludge}$ (the average monthly value is used as calculated from the SMAT hourly measurements)
- The sludge inlet temperature $T_{sludge,in}$ (Mazzini, 2014; Pizza, 2015)
- The digester constant temperature $T_{digester}$
- The specific heat capacity c_p is the same as to that of water because the solid content in sludge is lower than 2 % (weight).

The sludge pre-heating term is calculated as:

$$\dot{Q}_{sludge} = \dot{m}_{sludge} \cdot c_p \cdot \left(T_{digester} - T_{sludge,in}\right) \tag{26}$$

The heat losses can be expressed as;

$$\dot{Q}_{loss} = \dot{Q}_{underground} + \dot{Q}_{external} + \dot{Q}_{piping} \tag{27}$$

Where:

$$\dot{Q}_{underground} = U_{underground} \cdot A_{underground} \cdot \left(T_{digester} - T_{ground}\right) \tag{28}$$

$$\dot{Q}_{external} = U_{external} \cdot A_{external} \cdot \left(T_{digester} - T_{external}\right) \tag{29}$$

$$\dot{Q}_{pipes} = 0.05 \cdot \left(\dot{Q}_{sludge} + \dot{Q}_{underground} + \dot{Q}_{external}\right) \tag{30}$$

$\dot{Q}_{underground}$ is the contribution for heat losses from the underground surface and $\dot{Q}_{external}$ accounts for heat losses through the external surface (walls and roof). The calculated values of thermal energy for digester is illustrated in Figure 5. As the figure indicates, the needed thermal and electrical demands in summer are less than those in other seasons because of the lower wastewater inflow during the summer time.

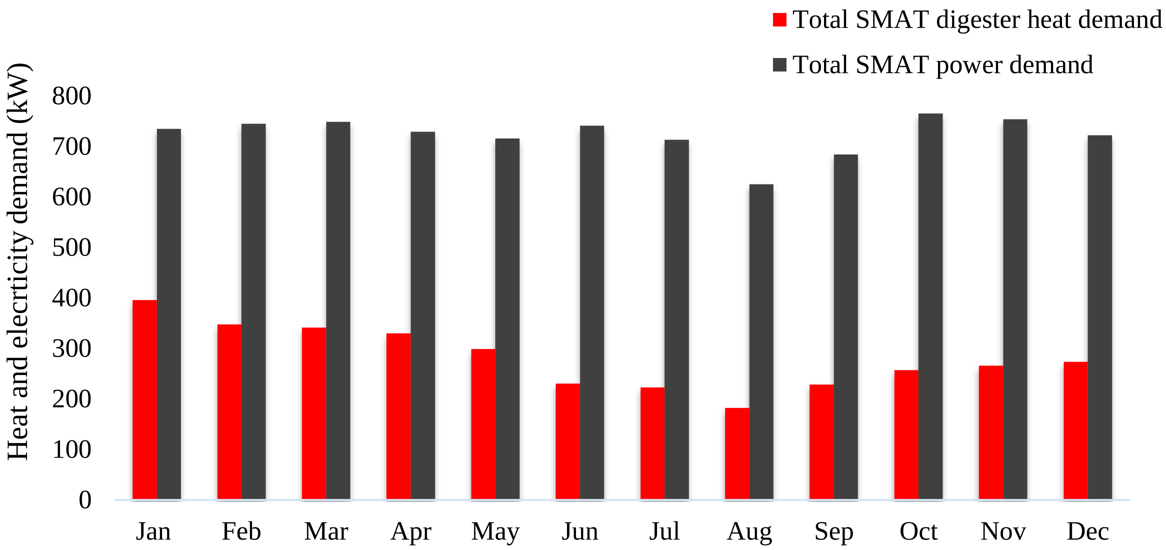

Figure 5. Required thermal energy for digester and electrical demand in SMAT Collegno reported for 2015.

Table 2. Factors for calculations of digester thermal load (all data are retrieved from the SMAT Collegno anaerobic digester sizing report, (FISIA, 2018).

Parameter	Unit	Value
for underground walls $\boldsymbol{U_{underground}}$	W/m^2°C	2.326
for non-underground walls $\boldsymbol{U_{external}}$	W/m^2°C	0.930
floor and partial side walls $\boldsymbol{A_{underground}}$	m^2	450.8
partial side walls and roof $\boldsymbol{A_{external}}$	m^2	1132.1

As discussed before, for each scenario the coverage of the thermal load would be different. For the base case, the boiler and the heat recovery from the SOFC exhaust gases would supply the digester thermal load. However, for the solar case, in addition to the boiler and SOFC systems, a parabolic solar system will be responsible for supplying the thermal demand. For the MGT case, the exhaust gas from MGT could partially supply the thermal energy. Supplying the thermal demand in the trigeneration case is somehow different. In this case, the SOFC exhaust gases will be utilized in TLC and absorption chiller, and the thermal demand of digester will be recovered by using the boiler and heat recovery system of TLC.

2.4 Proposed integrated systems

2.4.1 Solar Case

Parabolic trough collectors are located in the plant to receive the solar energy. It is basically composed of a parabolic-trough-shaped concentrator which reflects direct solar radiation onto a receiver or absorber tube located in the focal line of the parabola. The Parabolic Trough Collectors (PTC) efficiency is not fix and depends on the heat losses as well as on the useful heat carried by working fluid. The heat losses at air side are varied by environmental temperature, cover temperature, and wind velocity.

The temperature difference between working fluid and surface determines the useful heat at the working fluid side. To decrease the heat losses, an evacuated concentric glass tube is employed around the receiver. The collector *IND300*, one of the smaller models of PTC family is chosen. The IND 300 PTC's efficiency is reported as;

$$\eta_{IND300} = 0.733 - 0.238 \cdot \left(\frac{\bar{T}_{wf} - \bar{T}_0}{G}\right) - 0.0013\left(\frac{\bar{T}_{wf} - \bar{T}_0}{G}\right)^2 \quad (31)$$

Where, $\bar{T}_{wf}$ and G are the average collector working fluid temperature and direct (or beam) normal irradiance (BNI), respectively, and $\bar{T}_0$ is the ambient temperature. The beam and diffuse irradiances for the Turin city are available in ("National Renewable Energy Laboratory (NREL). System advisor model (SAM).," 2018) on a monthly basis

2.4.2 MGT Case

The MGT system fed by biogas and natural gas is modeled though using each component of the system as a control volume and applying the mass balance, and energy balance equations.

Some meaningful parameters at ISO conditions are considered for MGT system and listed in Table 3.

Table 3. Parameters used for the components of the MGT system.

Parameter	Unit	Value
Turbine inlet temperature	°C	951
Exhaust temperature	°C	290
Compression ratio (CR)	-	4.6
Turbine isentropic efficiency (η_{GT})	%	85
Compressor isentropic efficiency (η_C)	%	85
Combustion efficiency (η_{CC})	%	99
Mechanical efficiency (η_M)	%	95
Generator efficiency (η_{EL})	%	94

Regeneration effectiveness (ε_{REG})	%	80

In this project, two commercially available microturbines (C30 and C65) from Capstone Turbines Corporation are chosen since their thermal heat recovery potentials could bring the required digester thermal demand ("Capstone Microturbine Products," 2017). As for some months there is a need to operate the MGT systems in partial load (PL), the partial load analysis is also formulated as in Ref. (Firdaus et al., 2012).

$$\dot{W}_{MGT-30,PL} = \dot{W}_{MGT-30,FL} \times PL \quad (32)$$

$$\dot{Q}_{ehr,PL_{MGT-30}} = (0.1718 + 0.6529PL + 0.1706PL^2)\dot{Q}_{ehr,FL_{MGT-30}} \quad (33)$$

$$\dot{Q}_{fuel,PL_{MGT-30}} = (0.1513 + 0.7824PL + 0.06004PL^2)\dot{Q}_{fuel,FL_{MGT-30}} \quad (34)$$

$$\dot{W}_{MGT-65,PL} = \dot{W}_{MGT-65,FL} \times PL \quad (35)$$

$$\dot{Q}_{ehr,PL_{MGT-65}} = (0.1240 + 0.9707PL - 0.1706PL^2)\dot{Q}_{ehr,FL_{MGT-65}} \quad (36)$$

$$\dot{Q}_{fuel,PL_{MGT-65}} = (0.1228 + 0.9766PL - 0.1131PL^2)\dot{Q}_{fuel,FL_{MGT-65}} \quad (37)$$

It has been reported in the authors' previous research, implementing one C65 unit with one C30 unit will be suitable for the plant (MosayebNezhad et al., 2018).

2.4.3 Trigeneration Case

Trilateral Rankine cycle generates the electrical power via its two-phase expander for which a reasonable isentropic efficiency of 75 % (Yari et al., 2015) could be assumed.

$$\eta_{\text{expander}} = \frac{\dot{W}_{\text{a, expander}}}{\dot{W}_{s,\text{expander}}} \quad (38)$$

The modeling of the single effect LiBr-H_2O absorption refrigeration is based on the authors' previous work (Yari et al., 2013).

2.5 Energy efficiency

One can define the overall energy efficiency for the plant as:

$$\eta_I = \frac{\sum \dot{W}_{produced} - \sum \dot{W}_{consumed} + \dot{Q}_{heating} + \dot{Q}_{cooling}}{\dot{m}_{biogas} \cdot LHV_{biogas} + \dot{m}_{NG} \cdot LHV_{NG}} \quad (39)$$

Where $\dot{W}_{produced}$ is the electrical power produced in the system by means of SOFC and/or MGT and/or TLC's expander. $\dot{W}_{consumed}$ is the electrical power consumed in the pumps and/or compressors and/or blowers. $\dot{Q}_{heating}$ is the total heat recovered in the system and $\dot{Q}_{cooling}$ is only defined for the trigeneration case where it is equipped with an absorption chiller. In the denominator, overall consumption of NG and biogas is given.

2.6 Economic evaluation

Starting from the results of the energy analysis, an economic evaluation of the investment has been performed for the four analyzed scenarios.

2.6.1 Input data and cost functions

Input data from the energy to the economic model are:

- Natural Gas (NG) consumption of the plant, used for the boiler feeding (for supplying heat when biogas from CHP is not enough).
- Electrical energy production from the available electrical generators depending on the scenarios (SOFC, MGT and TLC system)
- Heating and cooling energy production, where heat production is available only in the CHP case studies (solar, MGT and Trigen) and cooling only in the Trigen one.

Economic analysis has been calculated by evaluating investment costs spent during the year of construction (Capital Expenditure, CAPEX), operating costs required to run the plant on a yearly basis (Operating Expenditure, OPEX) and savings generated from the self-consumption of electricity, heating and cooling.

The CAPEX cost item is including:

- The cost of the Anaerobic Digester (AD), which is kept constant among the 4 scenarios since the biogas available is considered as stable. The cost function for the anaerobic digestion section has been retrieved from (Mehr et al., 2017), where it was discussed in detail. The cost was scaled down, starting from a literature source, with an exponential factor of 0.75.
- The costs of the cleaning system, again constant for the 4 scenarios, which was used in both (Mehr et al., 2017; MosayebNezhad et al., 2018) and was derived from a

dedicated workshop on cleaning systems for fuel cell applications (Argonne National Laboratory et al., 2014). The cost will be analyzed in a current/short-term scenario (500 \$/kWe) and in a long-term scenario (200 \$/kWe).

- The cost of the three SOFC modules, constant in all the scenarios, derived from the Roland Berger's Consultancy report for the FHC-JU funding agency (Roland Berger Strategy Consultants, 2015). As for the cleaning system, because of the innovative nature of the technology, a short-term cost (equal to 5,656 €/kWe) and a long-term cost (equal to 2,326 €/kWe) have been analyzed. Both the data are derived from the reference document and referred to different cost production volumes, as discussed in detail in (MosayebNezhad et al., 2018). Current costs from the mentioned reference (17,908 €/kW) are not analyzed since, as shown in the authors' previous works, no economic convenience is achievable with these cost levels. Short term costs can be considered as 'future' cost due to an increase of production volumes or current costs with an incentive on the investment, supplied by local governments (as happens in the U.S.) or by dedicated projects.
- The cost of the Heat Recovery Unit, which has been assumed constant and equal to the one designed in (MosayebNezhad et al., 2018).
- The cost of the solar system for scenario B, taken from (Cavalcanti and Motta, 2015; Mehr et al., 2017) and equal to 2710 \$/m^2 (with a reference solar collector area of 500 m^2).
- The cost of the MGT for scenario C, taken from (MosayebNezhad et al., 2018; Pierce, 2005) and equal to 1,000 €/kWe.
- The cost of the Trigeneration section for the scenario D, which includes the cost of the TLC system (taken from (Fischer, 2011; Mehr et al., 2018; Yari et al., 2015)and expressed as a function of the expander power) and the cost of the chiller unit (expressed as a function of the cooling power produced and retrieved from (Berliner Energieagentur GmbH (Project coordinator), 2009)).

For what concerning the Operating Expenditure, they have been evaluated as the sum of:

- Cleaning system operating costs, due to the cleaning sorbents yearly substitution, taken from (Argonne National Laboratory et al., 2014) and equal to 1 c\$/kWh in the short-term scenario and 0.5 c\$/kWh in the long-term scenario.

- SOFC modules general yearly maintenance, retrieved from (Roland Berger Strategy Consultants, 2015) and equal to a fixed value of 3,000 € in the short-term scenario and 2,350€ in the long-term scenario.
- SOFC stack substitution, occurring every 5 years in the short-term scenario (with a cost equal to 712 €/kWe) and every 7 years in the long-term scenario (with a cost equal to 482 €/kWe) (Roland Berger Strategy Consultants, 2015).
- Anaerobic Digester maintenance and Solar Collectors maintenance, expressed as 5 % of the relative CAPEX (Mehr et al., 2017), while Trigeneration section maintenance expressed as 4 % of the CAPEX.
- MGT section maintenance, equal to 1 c€/kWh from (MosayebNezhad et al., 2018).
- Cost of NG from the grid, when heat produced from the plant is not enough to supply the plant thermal load (digester heating). The price of energy streams (electricity and heat) has been first set as the one in the SMAT Collegno case study and then varied to analyze possible installation throughout all the EU area.

The third cost item which is included in the analysis is the quota related to the savings, which in the 4 analyzed scenarios are accounting for:

- Savings for electricity, equal (in all Scenarios) to the total yearly electrical production (kWh), available from the energy model, multiplied by the price of electricity (€/kWh).
- Savings for heating, accounted (in Scenario 2, 3 and 4) as natural gas saved for producing the same amount of thermal power. The calculation has been performed with a boiler efficiency of 95 % and a NG LHV of 47 MJ/kg.
- Savings for cooling accounted (in Scenario 4) as electricity saved for the production of the same amount of cooling thermal power. The calculation was performed with a Coefficient of Performance (COP) equal to 3.5.

All the analysis is based on the assumption the WWTP is self-consuming all the energy produced (electricity, heating and cooling) because, as deeply discussed in one of the authors' previous work (Gandiglio et al., 2017), WWTPs are energy intensive plants which require a high amount of energy to reach their goal (clean the inlet wastewater). Furthermore, especially for the Italian case, self-consumption is also the most convenient choice because there is no incentive available for electricity sold to the grid which would be paid in a range between 0.04 and 0.06 €/kWh (strongly lower than the price paid for electricity).

2.6.2 Baseline case study analysis

The first baseline analysis has been performed with energy price related to the SMAT Collegno case study, which is equal to 0.141 €/kWh and 0.526 €/Sm^3, available as average 2017-2018 values for the site ("SMAT, Società Metropolitana Acque Torino S.p.A., Turin, IT.," 2019). A summary of the CAPEX, OPEX and savings values for the four different scenarios in short-term view with baseline energy cost is available in Appendix A.

Starting from the input data discussed above, a complete cash flow analysis has been performed for the baseline case study (the Collegno WWTP), following the methodology discussed in (Mehr et al., 2017; MosayebNezhad et al., 2018) with an interest rate of 5 % and performing the analysis on a system lifetime of 15 years.

Pay Back Time (PBT) – expressed as the first year in which the cash flow turns to positive – has been used as a first economic performance indicator, and has been calculated as:

$$PBT(y) = (1 + n_y - {}^{n}/_{p}) \tag{40}$$

Where:

- n_y is the number of years after the initial investment at which the last negative value of cumulative cashflow occurs.
- n is the value of cumulative cashflow at which the last negative value occurs.
- p is the value of the present cashflow at which the first positive value of cumulative cash flow occurs.

The second economic indicator used it the Levelized Cost of Electricity, which has been calculated as:

$$LCOE\left({}^{€}/_{kWh}\right) = \frac{\sum_{t=1}^{n} \frac{CAPEX_t + OPEX_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}} \tag{41}$$

Where:

- $CAPEX_t$ is the investment cost in year t
- $OPEX_t$ is the operating and maintenance cost in year t
- E_t is the electricity generation in year t
- r is the discount rate

- n is the lifetime of the system.

2.6.3 EU area economic analysis

The second phase of the economic evaluation has been the analysis of the investment considering different EU countries and thus different energy and NG prices. The energy prices for the different countries analyzed are referred to the second semester of 2018 and have been taken from the Eurostat online database for electricity (Eurostat - Data Explorer, 2019a) and NG (Eurostat - Data Explorer, 2019b) for non-household (industrial) consumers (take as full price, '*including all taxes and levels*'). Since the energy price is varying with the annual energy consumption according to defined ranges, yearly data have been derived from the baseline scenario. The electrical yearly consumption of the overall WWTP has been assumed equal to the one of SMAT Collegno (~ 5,500 MWh/y) and the related range of 2,000-20,000 MWh/y has been selected. The range allows also for a variation in the real plant consumption without varying the energy prices. The NG yearly consumption has been indeed taken from the energy model, because the thermal balance of the anaerobic digester (which is usually the highest and most relevant NG consumption within the WWTP) was included in the model. According to the different scenarios, yearly NG consumption was varying between ~ 2,100 and 3,300 GJ/y and so the Eurostat range between 1,000 and 10,000 GJ/y has been chosen.

Starting for these data, and focusing especially on the spark spread, defined as the difference between the national electricity price (c_{El}) and the NG price (c_{NG}):

$$Spark\ Spread = c_{El}\left(€/_{kWh}\right) - c_{NG}\left(€/_{kWh}\right) \tag{42}$$

A summary of energy prices is available in Figure 6.

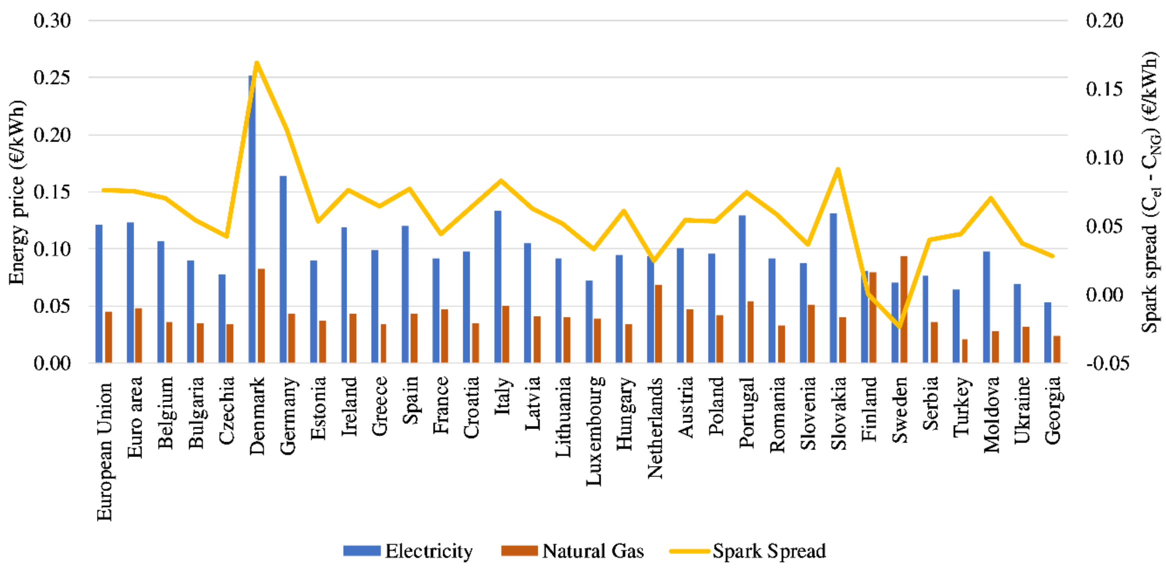

Figure 6. Price of electricity and natural gas in different EU countries. Authors' own elaboration of data from (Eurostat - Data Explorer, 2019a, 2019b).

In order to analyze all the countries included in the EU area with a simple approach, a new definition of the economic performance evaluators has been also formulated. The interest rate effect has been neglected since the goal is to analyze the relative difference among the different countries. Furthermore, in the baseline scenario analysis, it has been evaluated that the effect of the interest rate (set as 5 %) is varying between 12 % and 26 % depending on the analyzed scenario; this information is useful to understand the possible error undergone when using the simplified equations. Simplified Pay Back Time (S_PBT) and Simplified Levelized Cost Of Electricity (S_LCOE) have been expressed as follows.

$$S\_PBT(y) = \frac{CAPEX(€)}{Net\ yearly\ savings(€/y)} = \frac{CAPEX(€)}{Savings - OPEX(€/y)} \tag{43}$$

$$S\_LCOE\left(€/kWh\right) = \frac{CAPEX(€) + OPEX_{tot}(€)}{Total\ electrical\ production(kWh)} = \frac{CAPEX(€) + OPEX(€/y)\cdot N(y)}{Yearly\ production(kWh)\cdot N(y)} \tag{44}$$

3. Results and discussion

In this section results of the energy simulations and techno-economic analysis are presented and deliberated.

3.1 Energy simulation results

To supply the thermal demand for the plant, NG consumption (kWh) is obtained for each scenario. The results are demonstrated in Figure 7. The NG supplied to the systems from the grid is the most for the base case scenario as the system has to produce the thermal energy on its own. The second most case is the MGT case in which the MGT requires an extra amount of NG to produce extra electrical power. The solar case is the optimum scenario from the NG consumption point of view. In this case, the amount of NG would be reduced by about 50 % on average. In addition, the trend of the NG required in the plant is similar for the studied case. It indicates that during the summer season as the biogas produced in the plant is the lowest, the amount of NG requirement would increase in order to compensate for the reduction in the amount of biogas. For the trigeneration case, it can be observed that during winter and fall, the NG consumption is low similar the solar case, however, during summer when the biogas production is low, NG consumption of the trigeneration case reaches to the values for the base case, even higher than that of the MGT case.

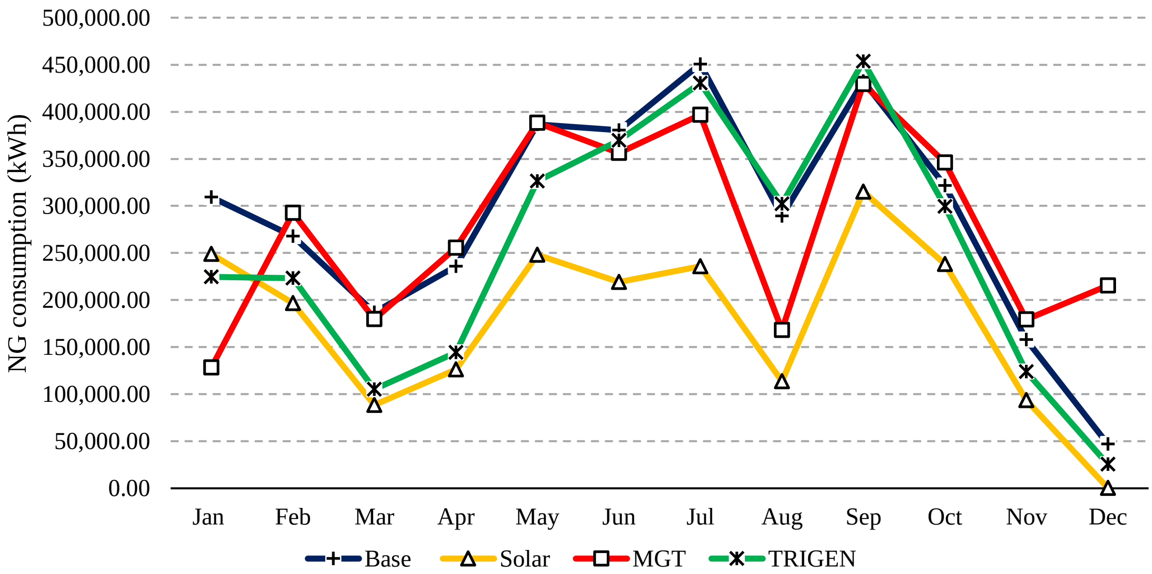

Figure 7. Monthly natural gas consumption for all case studies.

Results of efficiency for the proposed systems are illustrated in Figure 8. As the figure indicates, the overall efficiency for the trigeneration system is the highest while the base case has the lowest efficiency. The maximum efficiency of the trigeneration system can reach 89 % in August. The second most effective is related to the case of MGT in which extra power can be produced by means of micro gas turbines. It is also shown that the solar case efficiency was not so much different from that of the base case except for some months during the summer when the solar thermal energy utilization would be efficiently done.

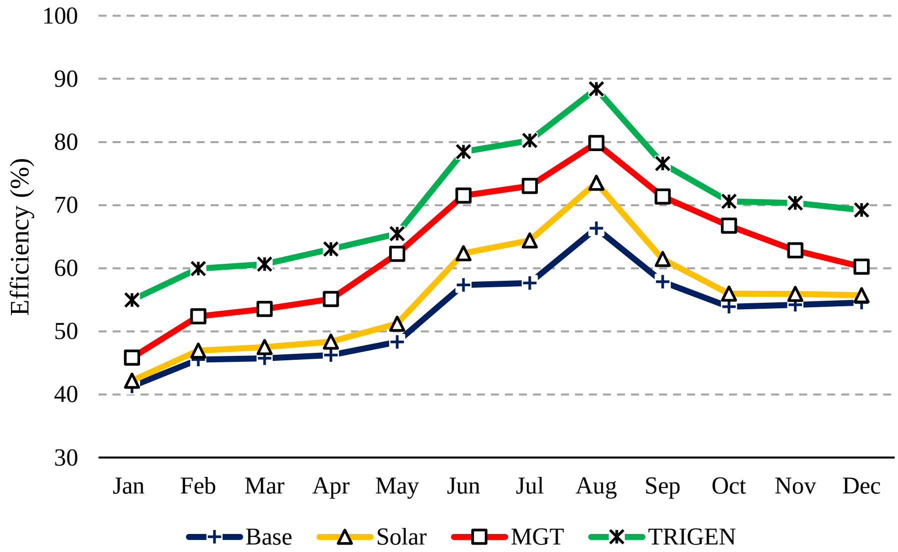

Figure 8. Monthly energy efficiency analysis for the defined case studies.

The total electrical power produced by the proposed systems is shown in Figure 9. Referring to this figure, the highest amount of electrical power is produced by the MGT case in which microturbines have the responsibility to produce extra power. For the trigeneration case, extra power would be produced by means of the expander while it is not comparable with that of the MGT case. It can be observed that about 275 kW could be produced in MGT case while in trigeneration case approximately 200 kW could be produced. One important point is that during summer season the MGT system would operate in partial load, as there is not so much need to produce extra thermal energy for the digester. As a result, the produced power via MGT would decrease and consequently, the overall electrical power would become lowest during summer. Electrical power in Solar case and base is identical as there is no an additional source of power production. The sole power production system is the SOFC units themselves.

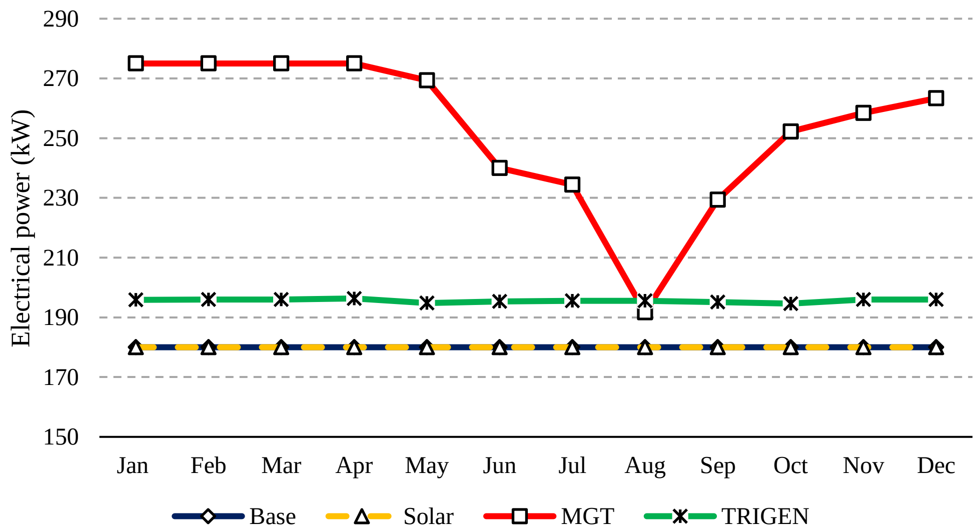

Figure 9. Monthly electrical power production for the four case studies.

In Figure 10 heating and cooling contributions of each auxiliary system are illustrated. Referring to this figure, as the base case is selected as the reference case, there is not any additional equipment in providing heating and cooling so SOFC exhaust gases and the boiler would provide the heating. However, for the solar case, solar collector can provide 20kW to 70kW heating depends on the time position. Clearly, during summer solar system could provide the most possible thermal energy rather than other seasons. In the case of a trigeneration system, uniform heating amount of about 90 kW could be produced. In addition, by implementing a trigeneration system, during summer about 22 kW cooling can be utilized. For MGT case, heating power produced by microturbines strongly depends on the heat load requirement of the whole plant. As it can be observed, during summer when SOFC and boiler can supply the demand, there would be not extreme need for other equipment so that microturbines would not run in full load, and as the trend shows during this period the heating by the MGT is lower.

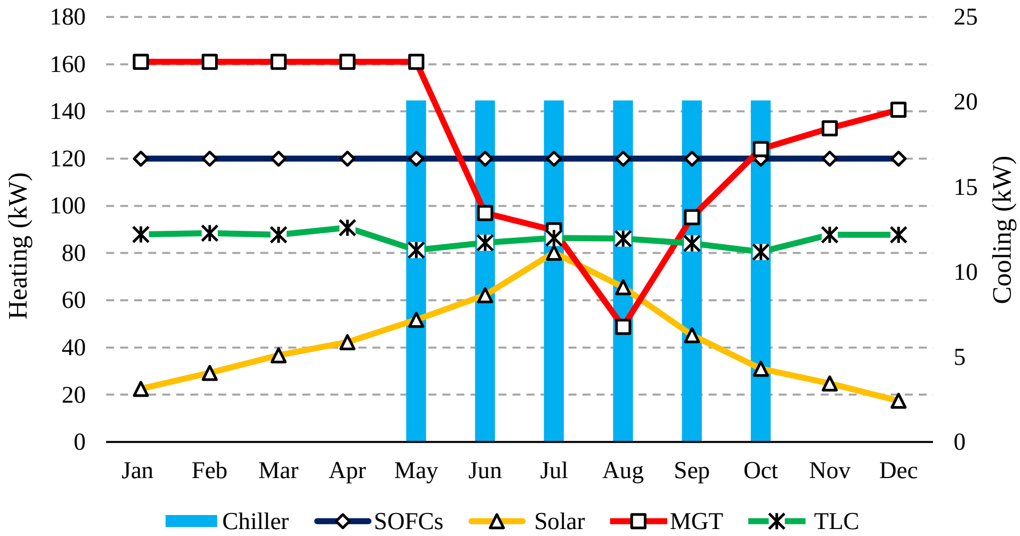

Figure 10. Heating and cooling rates produced by the different units in the proposed scenarios.

3.2. Techno-economic findings

Results of the performed techno-economic analysis are presented as follows.

3.2.1 Baseline case study results

This section is devoted to the analysis of the techno-economic model results. From the energy model, monthly electrical load profiles are available, and these data have been compared with SMAT Collegno electrical load of years 2016 and 2017 (Figure 11). The yearly coverage in the four scenarios (with 2017 data) is respectively 28 % for the Base and Solar Cases, 39.4 %

for the MGT case and 30.4 % for the Trigen Case. The use of the hybrid SOFC-MGT system is generating an increase in the electrical coverage of more than 10 %, and this will also affect positively the economic performance, as will be shown in the next paragraph. The Trigen Case increase is relatively low (around 2 %); however, extra-heat and extra-cooling are also available, and this will be accounted for in the economic analysis. Anyway, electricity is the key product for the plant and generates the highest saving (in €/kWh).

By using the economic model and input data described in section 2.6, investment (CAPEX), operating costs (OPEX) and savings for the four scenarios have been calculated. Results are shown in Figure 12, Figure 13 and Figure 14 for the Short-Term Cost scenario (which is related to cleaning unit investment and operative costs, SOFC modules investment, operation and lifetime).

Figure 12 shows the share of CAPEX items for the 4 different scenarios, for the Short-Term cost scenario. The SOFC module (5,656 €/kWe) is the highest share of investment in all the case studies (between 77 % and 85 % of total plant cost), followed by the cleaning unit (~ 6.5 %) and the anaerobic digestion section (~ 7 %). The MGT equipment (7.3 %), when present, is also comparable with cleaning unit and AD cost. Effect of the trigeneration section is indeed less impacting (5.2 %), while solar collectors account for around 9 %. On absolute values, as expected, higher costs are related to the three modified scenarios respect to the Base Case and the highest cost is related to the Solar Case where the investment cost of hybridization plays a decisive role. The costs share is, of course, changing when moving to the Long-Term Costs scenario, where SOFC share of the total cost is between 62 and 75 %.

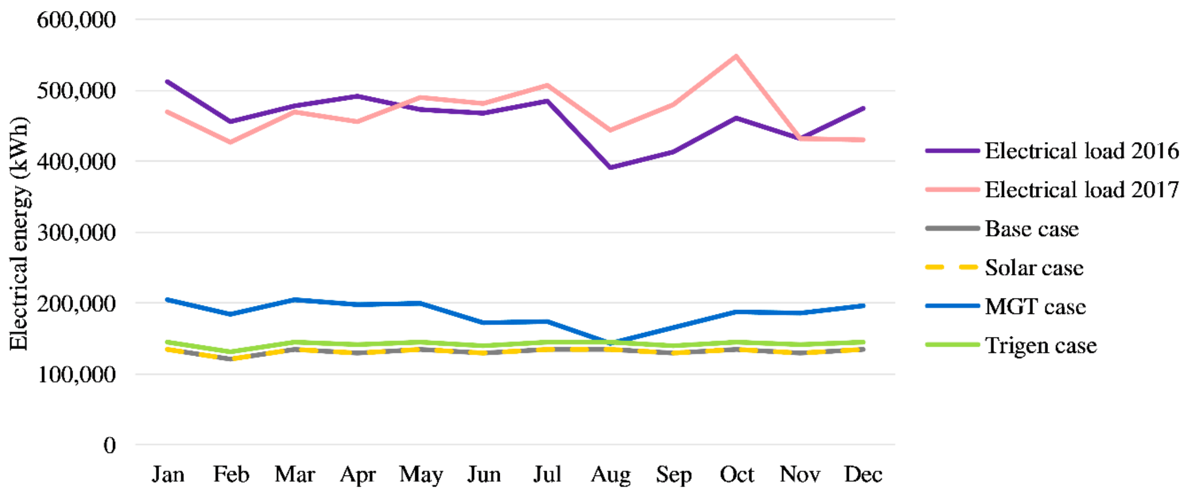

Figure 11. Electrical load coverage in the different analyzed scenarios.

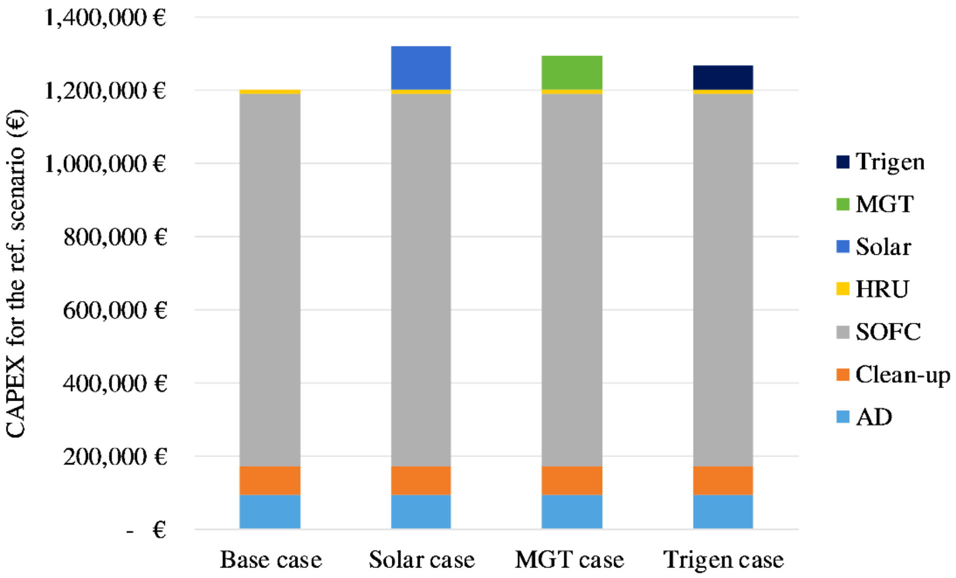

Figure 12. Investment cost (CAPEX) for the four analyzed scenarios.

Concerning the operating costs over the lifetime (OPEX), results for the Short-Term Cost Scenario are shown in Figure 13. In WWTPs, where the inlet biomass solid content is relatively low (~2 %), the need for thermal energy to reach the digester operating temperature is high compared to other biogas plants (based on agricultural or organic waste biomass) and this generates the need of extra-NG to be fed to the boiler for supplying the overall yearly thermal request (extra respect the CHP production). Furthermore, NG can be used to keep the CHP operation constant during the year, when biogas is reduced (see energy model chapter for further details). The NG bought from the grid is, as shown in Figure 13, the higher share in OPEX of the biogas section of the WWTP, followed by the stack substitution and the general maintenance of the plant BoP (called ‘other maintenance’ in the figure), the stack substitution (taken from (Roland Berger Strategy Consultants, 2015)) and the cleaning unit maintenance. The other OPEX items are almost negligible compared to the total cost volume (which is in the range of 100-130 k€/y). Among the four cases, Solar case results in the lowest OPEX because the total NG consumption is lower. OPEX costs are affected by the Long-Term Cost Scenario only for what concerns the OPEX of biogas clean-up and SOFC maintenance, while all the other cost items (like NG) remain constant.

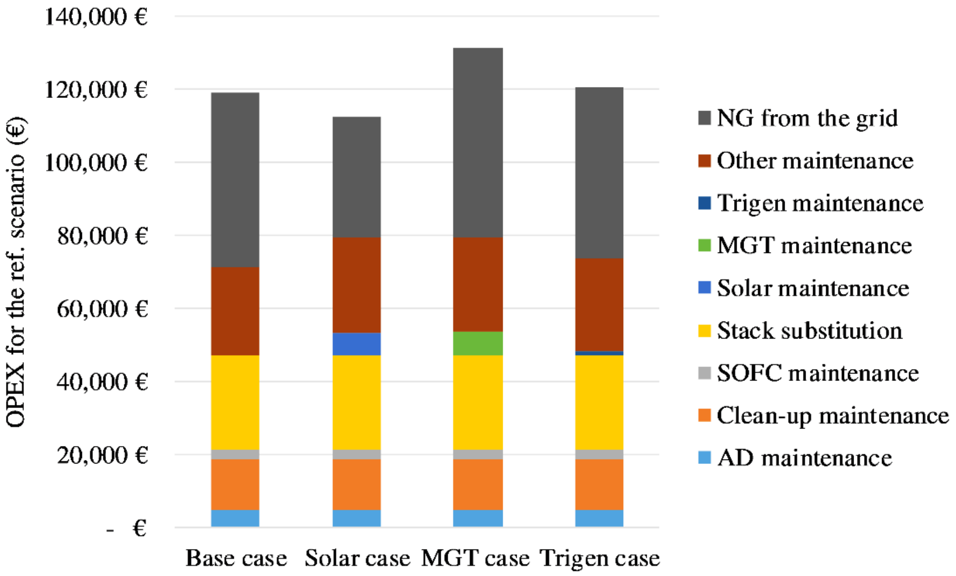

Figure 13. Operative cost (OPEX) for the four analyzed scenarios.

The amount of savings generated from the operation of the plant under the baseline scenario is shown in Figure 14. As previously commented, the highest share of saving is given by electricity self-consumption because this is the stream resulting in the highest monetary value. This amount is constant among Base and Solar Case while strongly increases in the hybrid MGT case. Trigen Case is an intermediate situation among the previous ones. Heating and cooling savings are also accounted for as discussed in the methodology section.

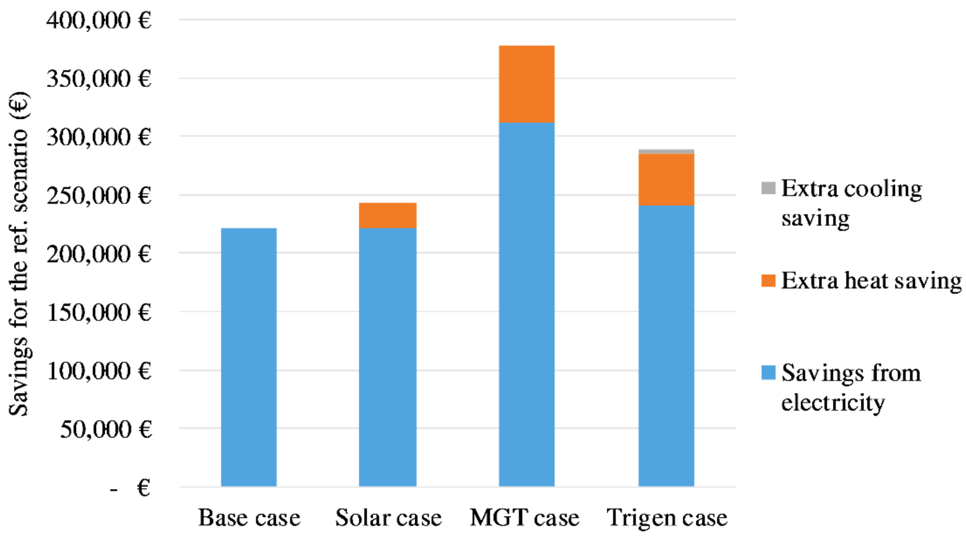

Figure 14. Savings (from electricity, heating and cooling) for the four analyzed scenarios.

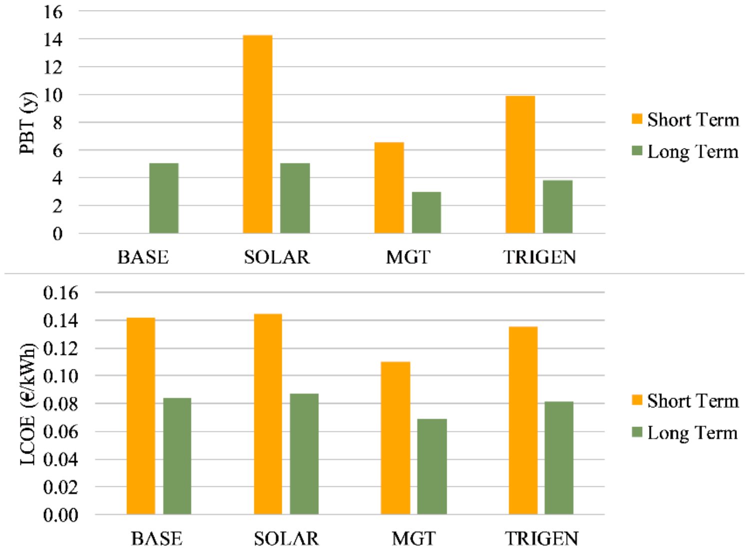

Figure 15. Short and Long term cost scenarios comparison. Effect on PBT and LCOE.

Economic performance indicators (PBT and LCOE) are then calculated, for the Baseline Scenario, starting from the presented data. Results for both Short-Term and Long-Term Cost Scenarios and for 4 Cases are presented in Figure 15. As a general instruction to the following graphs, when PBT is not plotted is because it is higher than the plant lifetime (assumed as 15 years). This situation is happening, for example, in the Base Case Short-Term case study, where also LCOE is very high, equal to 0.1418 €/kWh, higher than electricity price. The other case studies (Solar, MGT and Trigen) are – even if with long PBT – able to generate an investment recovery during the plant lifetime. Among the three cases, MGT Case is the one showing the lowest PBT (6.58 y in Short-Term) and LCOE (0.1100 €/kWh), followed by the Trigen and the Solar Case. Moving from Short- to Long-Term Costs, a general benefit can be seen in the whole analysis. Having lower investment and operating costs generate a positive effect on the analysis and almost all the cases become interesting from an economic point of view, with PBT ranging from 2.95 (MGT) to 5.03 (Solar) and LCOE between 0.0688 (MGT) and 0.0866 (Solar) €/kWh. The reason for having a switch on the worst case between Short-Term and Long-Term cost scenarios is the share of the solar collectors in the overall plant CAPEX. In the Short-Term case, solar influence is low and higher electrical production produces more benefits than Base Case in terms of economics while moving to the Long-Term, the effect of solar collectors on CAPEX share is heavier and this results in a decrease of the economic evaluator.

The Long-Term scenarios seem indeed to be economically acceptable without the help of any external subsidy, while the Short-Term is feasible for some configurations only (MGT) and remains quite challenging for the Base Case. An existing Ministerial Decree on electricity production from biogas is existing (Ministero dello Sviluppo Economico, 2016). However, the price paid for the electricity from sewage WWTP biogas (11 c€/kWh) is lower than the price paid by SMAT (14.1 €/kWh) and thus the most economic use of the electricity is self-consumption.

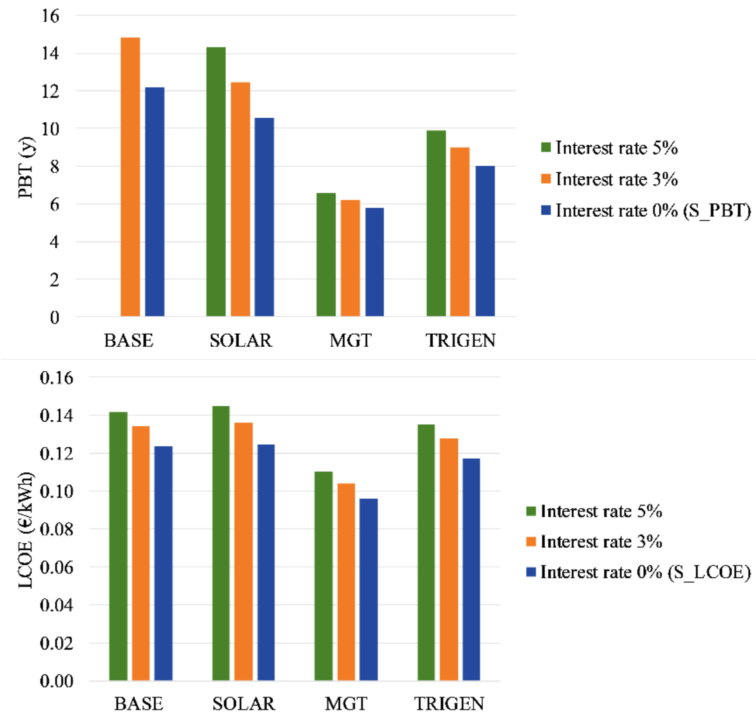

Figure 16. Interest rate effect (0 %-3 %-5 %) on PBT and LCOE. Interest rate equal to 0 % is the same as the simplified values.

The second analysis performed on the Baseline Scenario is on the effect of the interest rate on the economic performance evaluators. The results are then useful to understand the values of the next EU Scenario, where the interest rate was fixed to zero in order to analyze a more simplified scenario. As shown in Figure 16, the effect of the interest rate effect is low. When moving from an interest rate of 5 % to 0 % (simplified scenario), the PBT is reduced by 12-26 % in all the four Cases and LCOE by 13-14 %. A lower impact of the interest rate can be found on the LCOE, and this is motivated by the different formulations of the two parameters.

3.2.2 EU area: results from the economic analysis

Starting from the Baseline SMAT Collegno analysis, the model has then been extended to the whole EU area, taking advantage of available energy prices from the Eurostat database, as discussed in section 2.6.

Results are shown in Figure 17 and they refer to the Base Case Scenario (only biogas and SOFC, without hybridization). The graph shows the direct correlation between investment performance and the difference between electricity and NG price for each country (i.e., the spark spread). This is even more visible in extreme situations like those in Finland and Sweden, where the spark spread is very low and the S_PBT is thus never reached during the plant lifetime. Otherwise, for countries like Denmark, Germany and Italy – where the spread is higher, the investment is profitable, even with Short-Term costs.

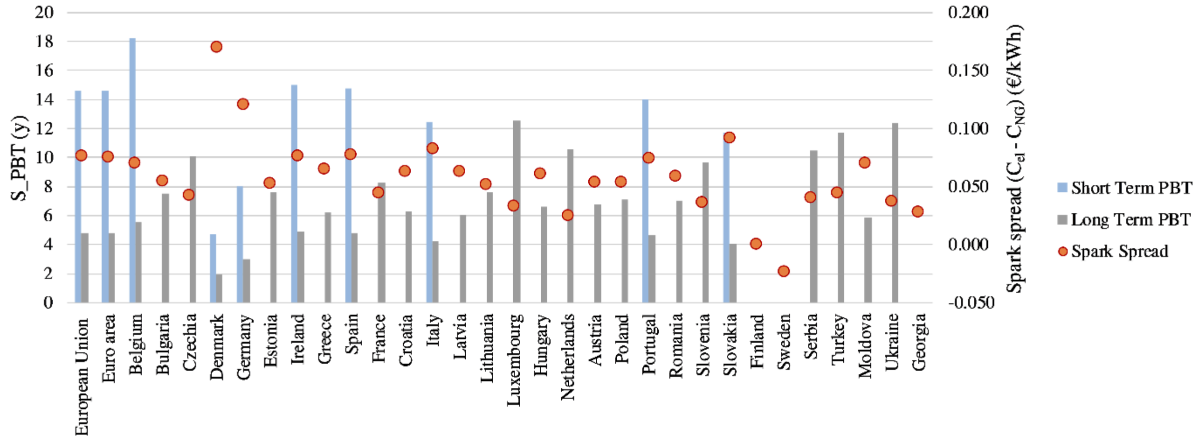

Figure 17. EU analysis: Base Case results and correlation among S_PBT and spark spread values. Light blue bars refer to the Short-Term costs, light grey bars to the Long-Term costs and orange points to the spark spread in each country.

The relation between the economic performance and both electricity and NG prices is due to the need, in many WWTPs, of both electricity and NG to supply the required thermal load. In the case of optimized plants with reduced, or even zero, thermal load (achievable for example with the use of a sludge pre-thickening system as demonstrated in Ref. (Giarola et al., 2018)), the economic performance will depend only on the electricity price and results will vary consequently.

It is important to remind that all the EU analysis is based on simplified economic parameters (S_PBT and S_LCOE) and thus results are generally underestimated (real values with interest rate would be around 15-20 % higher, according to the results shown in 3.2.1).

Moving from the Base Case Scenario to the whole 4 scenarios analysis, Figure 18 and Figure 19 show S_PBT and S_LCOE with Short- and Long-Term costs for the different EU countries. For the S_PBT, a target value of 6 years is set as a goal (black line in Figure 18), while for the S_LCOE the values are plotted against the price of electricity; when electricity price is higher than production cost (S_LCOE), the investment is convenient and there is a net saving between production and self-consumption.

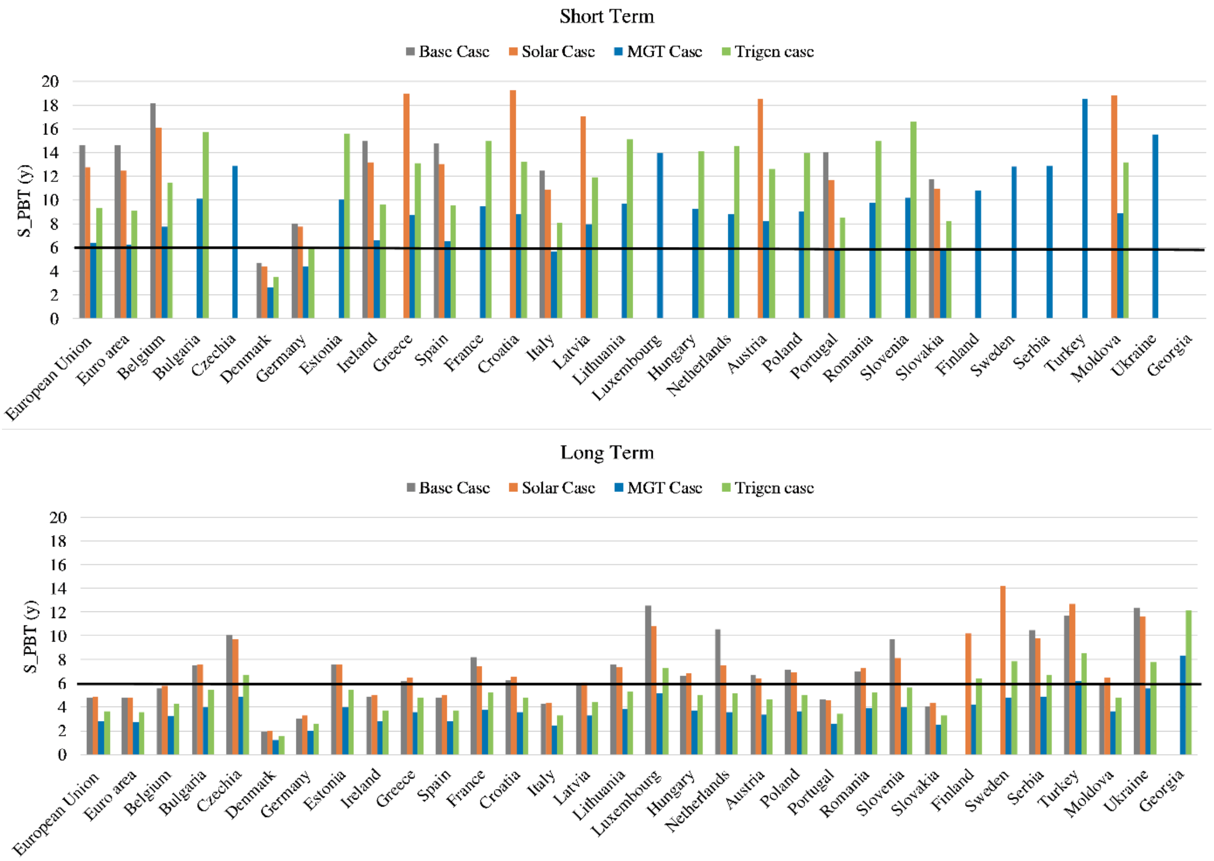

Figure 18. EU analysis: Short and Long term scenarios effect on PBT for the four scenarios.

In Figure 18, in the Short-Term Costs analysis, countries with PBT lower than or equal to 6 years, in one of the 4 cases, are only Denmark (in all cases), Germany, Italy, Portugal and Slovakia (only in MGT case). The other countries show higher S_PBT, which are usually closer to the plant lifetime (15 years), which is not acceptable from an economic point of view. Looking at the Long-Term cost analysis, all the countries become economically interesting (S_PBT < 6 years) in at least the MGT case but usually also in the other proposed configurations.

The Long-Term scenario could be considered as a future scenario where the cost of the technology will be reduced (thanks to the mass production), or a current scenario where an incentive on the investment is given for high efficiency and zero emissions fuel cell systems. In both cases, biogas-fed SOFC systems will become economically interesting and comparable with traditional technologies.

Figure 19. EU analysis: Short and Long term effect on LCOE (vs. country electricity price).

The same concept can be observed for what concerning the S_LCOE: the Short-Term cost analysis (upper graph of Figure 19) is showing a not-too-bad and not-too-good scenario, where the production cost (S_LCOE) is comparable with the country electricity price: this is the reason why, as confirmed by the previous figure, the PBT is comparable with the plant lifetime. On the other side, moving to the Long-Term cost analysis, as already demonstrated in the S_PBT analysis, the production price (S_LCOE) is always (except in specific countries like Finland and Sweden) higher than the electricity price, and this is generating a net income for every kWh produced.

Finally, the economic analysis has pointed out the countries and the areas where the biogas-fed SOFC system could generate the highest financial benefits because of the positive energy price conditions and these are Germany, Denmark, Slovakia, and Italy (in the current cost scenario without incentives). In the case of a further reduction in SOFC manufacturing cost (because of production volume, technology learning, and dedicated incentives,) almost all the EU area will become an interesting market for the SOFC modules. The most critical countries, on the other side, have been identified as Sweden and Finland.

4. Conclusions

There is the potential to use the thermal energy from the exhaust gas of a biogas-fed SOFC system to meet a part of the energy demand of wastewater treatment plants. Four scenarios are investigated by looking at the integration of solar collectors, microturbines, trilateral Rankin cycle, and absorption chiller with the SOFC in order to increase the overall plant efficiency. Along with supplying the electrical demand of the plant and thermal demand of the digester, a focus on the reduction of natural gas consumption for the proposed systems is performed. In addition, a comprehensive techno-economic investigation is performed. The following conclusions can be drawn from the results:

- The trigeneration system attains the highest thermal efficiency among the proposed scenarios.
- The natural gas consumption is comparatively low for the solar integrated system
- The electrical demand supplied by the MGT case is promising
- MGT Case is also effective from the economic point of view since it is found to be the most interesting case in terms of PBT and LCOE compared to other system configurations.
- Hybridization of the system with solar collectors or trigeneration could play a fundamental role for the end-user self-sufficiency rate and from the environmental point of view but is not currently suggested from the economic point of view since the investment cost is increased in a comparable way to the savings and thus the economic evaluators are almost constant.
- SOFC short and long term cost trajectories suggested by EU funded studies (Roland Berger Strategy Consultants, 2015) have a huge impact on the economic performance. If, thanks to dedicated incentives on the investment or to mass production volumes, SOFC CAPEX would decrease at around 2,300 €/kW, the economic competitiveness of biogas-fed SOFC systems, in different hybrid configurations, would be reached in most of the EU countries. Short term cost reduction, leading to an investment cost of around 5,600 €/kW, would generate anyway interesting niche markets in specific EU countries where the energy prices are favorable for CHP installations.
- The analysis of the whole EU area has indeed pointed out a direct and proportional link between the spark spread in the selected country and the economic performance of the investment. The more the electricity is expensive compared to the NG, the more

a high-efficiency cogeneration system is interesting for an industrial plant. In this scenario, most favorable markets for SOFC installation – in a short-term view – are Germany, Denmark, Slovakia, and Italy. The area could also be enlarged is long term cost trajectories will be reached or specific incentives on investment (for high-efficiency CHP system) will be issued.

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Appendix A

The tables below summarize the CAPEX, OPEX and savings for the short-term scenario. Results are here shown for the baseline configuration, with data (energy prices) related to the SMAT Collegno WWTP.

Table A1. CAPEX of the biogas-SOFC plant, in the 4 scenarios.

CAPEX (€)								
	AD	**Cleaning**	**SOFC**	**HRU**	**Solar**	**MGT**	**Trigen**	**Total CAPEX**
Base case	91,816 €	78,945 €	1,018,138 €	10,760 €	- €	- €	- €	**1,199,659 €**
Solar case	91,816 €	78,945 €	1,018,138 €	10,760 €	118,417 €	- €	- €	**1,318,076 €**
MGT case	91,816 €	78,945 €	1,018,138 €	10,760 €	- €	95,000 €	- €	**1,294,659 €**
Trigen case	91,816 €	78,945 €	1,018,138 €	10,760 €	- €	- €	66,491 €	**1,266,149 €**

Table A2. OPEX of the biogas-SOFC plant, in the 4 scenarios.

OPEX (€/y)										
	AD maintenance	**Cleaning maintenance**	**SOFC maintenance**	**Stack substitution**	**Solar maintenance**	**MGT maintenance**	**Trigen maintenance**	**Other maintenance**	**NG from the grid**	**Total OPEX**
Base case	4,591 €	13,831 €	3,000 €	25,632 €	- €	- €	- €	23,993 €	47,952 €	**118,999 €**
Solar case	4,591 €	13,831 €	3,000 €	25,632 €	5,921 €	- €	- €	26,362 €	33,021 €	**112,357 €**
MGT case	4,591 €	13,831 €	3,000 €	25,632 €	- €	6,402 €	- €	25,893 €	51,845 €	**131,194 €**
Trigen case	4,591 €	13,831 €	3,000 €	25,632 €	- €	- €	1,169 €	25,323 €	47,067 €	**120,613 €**

Table A3. Savings of the biogas-SOFC plant, in the 4 scenarios.

SAVINGS (€/y)				
	Savings from electricity	**Extra heat saving**	**Extra cooling saving**	**Total savings**
Base case	221,604 €	- €	- €	221,604 €
Solar case	221,604 €	21,941 €	- €	243,544 €
MGT case	311,577 €	65,814 €	- €	377,391 €
Trigen case	240,762 €	44,402 €	3,561 €	288,724 €