Potential energy recovery by integrating an ORC in a biogas plant

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Abstract

An increasing interest is devoted to biogas plants as they might play a key role in the reduction of current fossil fuel consumption for power production. The main component of the plant is the anaerobic digester where the organic fraction of waste products is converted in a gas with high concentration of methane and carbon dioxide. This biogas is converted in power and heat in a cogeneration unit that may consist in a micro gas turbine or an internal combustion engine. A portion of the heat is used to keep the digester at a constant temperature as requested by the anaerobic digestion, the reaming is generally dissipated. An Organic Rankine Cycle (ORC) can be adopted to increase thermal energy recovery and increase the power produced by the plant. This study focuses on the potential improvements of an anaerobic digestion plant when a commercial (ORC) is adopted as an additional thermal user to reduce the amount of dissipated heat and increase the power production. The study is based on an existing biogas plant operating in the town of Viareggio (Italy) which will be equipped with a 600kWe micro gas turbine. The integration of the two systems was studied in detail by investigating the plant modifications which are necessary to reach high values of thermal energy recovery. A reference and a modified solution were simulated in AMESim by considering a yearlong period with actual ambient conditions. Three different commercial size for ORC (30, 40 and 50 kW) were considered to determine the most suitable from the thermodynamic and economic point of view. A sensitivity analysis on the sludge regenerator, which recovers part of the heat from the digestate to preheat the sludge entering in the plant was carried out showing a strong increase in the ORC performance with the size of the sludge regenerator. The larger was the ORC size, the larger should be the sludge regenerator to increase system efficiency and avoid winter shutdown. The economic analysis showed that profitability index was maximum for the 30 kW ORC, due to the inefficiency of a larger size during winter, while the most remunerable solution was the 40 kW configuration, due to the larger amount of energy produced during the year.

Keywords: Biogas; mGT; Organic Rankine Cycle; Feasability analysis; Waste Heat Recovery

1. Introduction

In the last years, an increasing interest has been devoted to biogas plants for the key role that they can have in the reduction of fossil fuel usage and the mitigation of their environmental impact. Biogas is an interesting biofuel which is produced by the anaerobic digestion of organic wastes form different sources ([1], [2] and [3]) that is rapidly spreading in European Union [4]. Particular attention is devoted to the co-digestion of sewage from municipal wastewater treatment plant and municipal organic wastes as this procedure has the advantage of increasing the average methane concentration in the produced biogas up to 65% [5]. The biogas produced in the digester is usually converted in an internal combustion engine (ICE) or in a micro-gas turbines (mGT) for cogeneration purposes [6]. The power is used to satisfy the plant internal needs and the surplus is fed to the grid. As for the thermal energy, a portion of the heat is used to keep the digester at a constant temperature as requested by the anaerobic digestion, the reaming is generally dissipated. Due to the different efficiencies, the ratio between the thermal and electric power produced depends on the technology [7]. Since the revenues from electric energy sale are decreasing [8], an optimization of the waste heat use is becoming more and more important. An example is reported in [9] where the coupling of a mGT with an absorption chiller aiming at reducing the turbine inlet air temperature and increasing the electrical efficiency was investigated. Another example is reported in [10] where the potential of exploiting the thermal energy excess was investigated as a function of the digester feedstock and of the type of user. District heating and trigeneration [11] are another opportunity, but the high cost of the network and the limited hours of operation often make the investment unfeasible. Sludge drying [12] is another opportunity to use the heat surplus, and despite it does not provide any direct increase in the energy production, it contributes in the reduction of the transportation costs and emissions caused by digestate transportation for disposal. In [13] the combination of an Organic Rankine Cycle (ORC) and a biogas fueled ICE was analyzed. ORC demonstrated to be a viable option for the integration with anaerobic digestion plants, as it recovers part of the heat of the cogeneration unit and lead to a plant efficiency increase. ORC have been widely analyzed in the literature as Waste Heat Recovery (WHR) units [14] and several

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commercial applications have been installed worldwide [15] ranging from engines [16], gas turbines [17] and industrial processes [18]. Most of the studies on ORC applications in biogas plants were performed by focusing only on the ORC systems, assuming average operating conditions and neglecting part load operation, integration with anaerobic digestion plant and economic feasibility [19]. Yağlı et al. in [19] compared two ORC configurations to recover thermal energy from a biogas fueled engine that provides electricity and heat for an anaerobic digestion plant in Belgium. The study was carried out in design conditions and the authors defined the best configuration through a parametric optimization aiming at maximizing the second law efficiency. Dumont et al. in [20] designed and optimized a system with two ORC (one subcritical and the other trans-critical) to increase the performance of an anaerobic digestion plant with particular focus on the analysis of the expander type. The economic analysis was carried out by considering average conditions. Mudasar et al. in [21] optimized an ORC to recover flue gas from a biogas cogenerator and focused their attention on achieved environmental benefits. Sung et al. in [22] optimized an ORC by considering also the variable thermal load requested by the process. The authors took into account the off-design performance of the system by considering average monthly conditions. By analyzing the literature, it can be observed that most of the authors carried out analysis and optimization of anaerobic digestion plant in steady-state conditions or with average operating conditions. Only few authors performed off-design or dynamic analysis of biogas production systems [23,24] and none of them analyzed the coupling of these systems with an ORC in detail. Most of the authors concentrated their efforts on ORC efficiency, without considering any potential improvement related to a re-arrangement of the anaerobic digestion plant. It is also worth to notice that from a plant manager point of view the ORC is a commercial product, with fixed specifications, and that the only chance to increase the performance of the system is to operate a smart integration of the ORC in the plant. The current study is based on an existing biogas plant operating in the town of Viareggio (Italy) which will be equipped with a 600kWe micro gas turbine (mGT) [25]. In a preliminary study, the authors investigated with a simplified approach the suitability of coupling an ORC system in this plant with interesting results [26]. In this study, a reference and a modified solution, where an ORC is coupled with the mGT, were simulated by considering three different commercial sizes for the ORC. The coupling of the anaerobic digestion plant with the ORC was studied in detail to take advantage of all the potential energy recoveries. A numerical model of the system was developed in AMESim and the off-design behavior of all the components and the actual ambient conditions during a one-year-long period were considered in the simulation. Sludge line and digester were modeled in transient conditions to consider the phase shift between of the ambient temperature variation and the consequent thermal load variation , due to the inertia of the digesters. The results of the investigation show the potential improvements that a proper integration of a ORC unit can bring in a biogas plant.

Nomenclature

M	Mass [kg]
t	Time [s]
ρ	Density [kg·m^{-3}]
V	Volume [m^{-3}]
$\dot{m}$	Mass Flow Rate [kg · s^{-1}]
E	Internal Energy [kJ]
c	Constant pressure specific heat [kJ·kg^{-1} · K^{-1}]
T	Temperature [°C]
h	Specific enthalpy [kJ · kg^{-1}]
$\dot{\varphi}$	Thermal losses [kW]
λ	Heat transfer coefficient [kW · m^{-2} ·K^{-1}]
A	Surface [m^{2}]
α	Absorbance
G	Incidence radiation [W · m^{-2}]
σ	Stefan-Boltzmann constant [kW · m^{-2} · K^{-4}]
ε	Emissivity
k	Thermal conductivity [kW · m^{-1} · K^{-1}]
ΔT	Temperature difference [°C]
s	Thickness [m]
$\dot{Q}$	Thermal power [kW]
NTU	Number of transfer units
U	Overall heat transfer coefficient [kW · m^{-2} ·K^{-1}]
C	Thermal Capacity [kJ · K^{-1}]
ϵ	Effectiveness
η	Efficiency
$\dot{W}$	Power Output [kW]
τ	Time interval [s]

Subscripts

$conv$	Convection
ext	External
int	Internal
rad	Radiative
$cond$	Conduction
w	Wall
a	Ambient
min	Minimum
max	Maximum
off	Off-Design
d	Nominal
mGT	Micro Gas Turbine
bio	Biogas
CH_4	Methane
ORC	Organic Rankine Cycle

y	Mass Fraction
LHV	Lower Heating Value [kJ · kg^{-1}]
NPV	Net Present Value [\$]
$Capex$	Capital expenditures [\$]
R	Revenues [\$]
$Opex$	Operative Expenditures [\$]
r	Discount Rate
$P.I.$	Profitability Index

2. Case study

2.1. Reference Scenario

The plant considered in this study is located in the city of Viareggio (Italy) and is used to treat the city wastewaters. Two anaerobic digesters with a total capacity of 4600 m3 process 10.8 t/h of a mixture of sewage and municipal organic waste with a 4:1 ratio. The digesters operate at a fixed temperature of 37°C and produce about 276.6 kg/h of biogas [10] with a methane concentration of 65%. The corresponding energy potential is about 1500 kW$_{th}$. Biogas is burned in a mGT and the exhaust gasses are used to heat the sludge from the wastewater treatment plant before entering in the digesters. A water loop insisting on a sludge recirculation loop (23:1) is used to this purpose. The amount of heat necessary to keep the digester at a constant temperature was regulated by controlling a diverter on gas turbine exhaust gasses. Electric power is fully used to satisfy internal plant consumptions. The mGT is a Capstone C600s [11] which is made up of 3 modules of 200 kWe each for a total output of 600 kWe. The three modules are operated to maximize the conversion efficiency according to the available amount of biogas. In nominal condition, the mGT produces 4.0 kg/s of exhaust gasses at a temperature of 280°C. The scheme of reference scenario is reported in Figure 1.

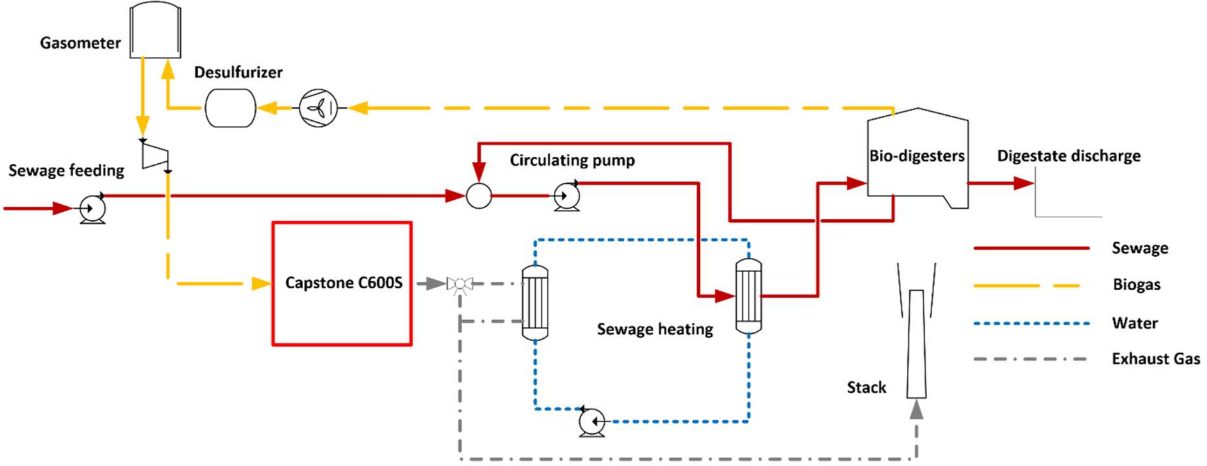

Fig. 1. Plant scheme in the reference scenario.

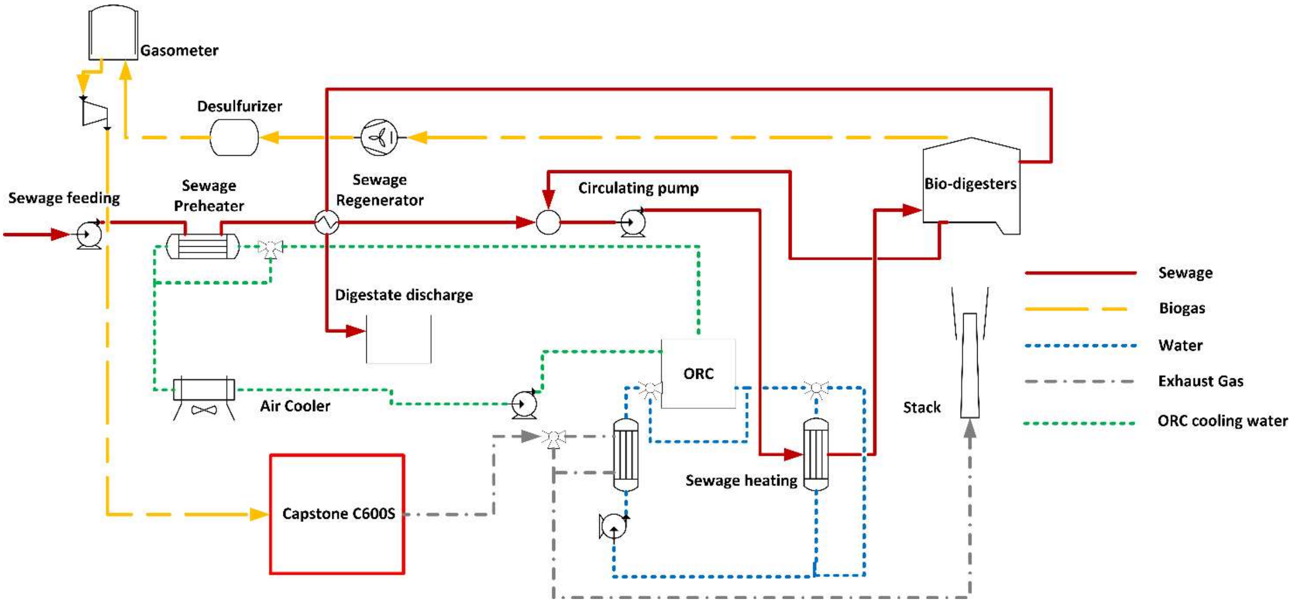

Fig.2. Plant scheme in the improved scenarios.

2.2. ORC improved scenario

In the reference scenario only a part of the heat contained in flue gas is used to heat up sludge and keep constant the digestion temperature. To improve the thermodynamic efficiency and the economic profits of the system, an improved plant configuration was investigated. In more detail, an Organic Rankine Cycle (ORC) was considered to further exploit the exhaust gasses thermal content. The integration of the ORC in the system should be carefully analyzed. Differently from other applications, in an anaerobic digestion plant the thermal energy is necessary to foster the digestion process itself and thus a full thermal energy recovery from the engine is not possible. In this study, two modifications to the plant were considered (Figure 2):

1) the use of part of heat rejected by the ORC condenser to increase sludge temperature in a preheater;
2) the use of a regeneration heat exchanger that recovers the heat from the digestate exiting the plant (at 37°C) to increase the temperature of the sludge.

Differently from the reference scenario, in this case the heat transfer loop transfers heat with both the ORC evaporator and sludge. The thermal users were arranged in a sequential disposition, with the water entering the ORC first and then the sludge heating system. The ORC cooling system preheats the sludge and then enters in an air cooler to reject the rest of the heat.. The sewage flows through the preheater and then through the regenerator. Three commercial ORC system by Zuccato Energia, with a size of 30, 40 and 50 kW were considered. These systems use a radial turbine generator and have a nominal cycle thermal efficiency ranging between 8.5 and 10% [27]. The heat is provided to the ORC evaporator by means of the water loop at a constant temperature of 95°C, as reported by manufacturer.

3. Methodology

Simulations of the whole plant have been carried out by using AMESim and considering one reference year. AMESim is a multidomain one-dimensional software that allows the solution of complex energy systems in transient conditions. In this study the dynamic capability of the software was used to predict in a more accurate way the thermal load of the digesters as it was possible to take into account the time delay between ambient temperature variation and related load request varoiation. Due to the large inertia of the digesters (sludge residence time is about 20 days), only sludge line and digesters were simulated in transient conditions. Both mGT and ORC, which have time constants of few minutes, were modelled in steady-state conditions [28–30]. mGT was modelled as a functional dependence of ambient temperature and biogas availability while ORC was modelled as a function of heat transfer fluid mass flow rate and cooling water temperature. The creation of a hybrid model, combination of transient and steady-state models, is an approach which was adopted in the literature for other energy systems with two or more subsystems with largely different characteristic times [31]. The hybrid model allows one to obtain high results accuracies with a limited computational effort [31]. Hourly discretized ambient temperature and radiation (Figure 3) were considered in the heat transfer model of the anaerobic digester for the estimation of the plant thermal load. Ambient conditions were retrieved from [32].

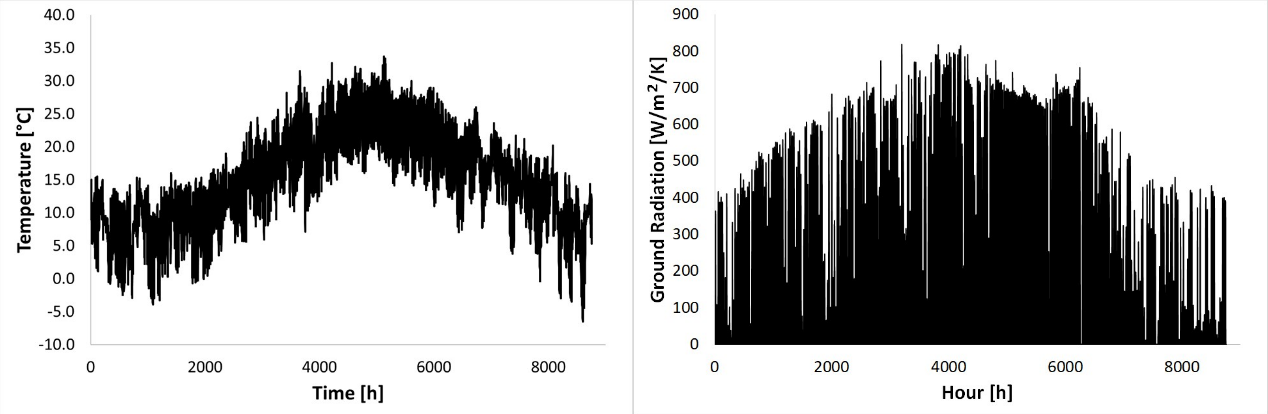

Fig. 3. Ground radiation (left) and ambient temperature right) for the locality of Viareggio.

3.1. Digesters and sludge line

The thermal-hydraulic library of AMESim was employed for the modeling of sludge line elements. . The two digesters were modeled as two zero-dimensional chambers exchanging heat with an external heat source. The internal sludge was consider perfectly mixed inside the digesters. Due to the high content of water in the sludge (>93%), thermophysical properties of water were considered for the sludge modeling. The continuity and energy conservation balance in transient conditions were applied by AMESim to each control volume, (Eq. 1 and 2) [33].

$$\frac{dM}{dt} = \frac{d(\rho V)}{dt} = \sum_{i=1}^{n} \dot{m}_i(t) \tag{1}$$

$$\frac{dE}{dt} = \rho \cdot V \cdot c \frac{dT(t)}{dt} = +\sum_{i=1}^{n} \dot{m}_i(t) \cdot h_i(t) \mp \dot{\varphi}(t) \tag{2}$$

where $\sum_{i=1}^{n} m_i(t)$ and $\sum_{i=1}^{n} m_i(t) \cdot h_i(t)$ are respectively the mass flow rate and the enthalpy flow rate entering or exiting the volumes, dU/dt is the internal energy variation and $\dot{\varphi}(t)$ is the heat transferred by convection and radiation with the ambient.. Density variations were accounted by the model but are not reported in these two equations due to the small sludge temperature variations during the process.

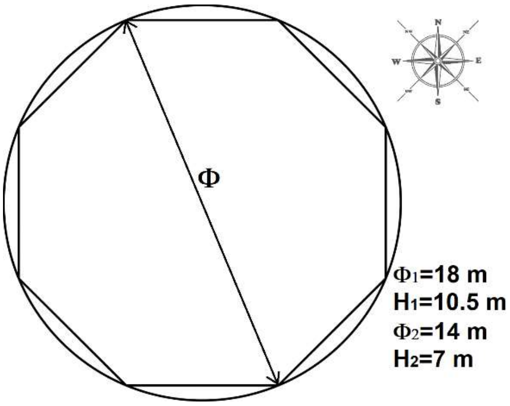

Fig. 4. Discretization of the lateral wall of the digesters to consider the effect of solar radiation and digesters size.

Heat transfer was simulated by considering the convection with the ambient temperature (Eq.3), radiation on external wall (Eq. 4), conduction through digester concrete walls (Eq. 5) and internal convection (Eq. 6) [33]. The lateral wall of the two digesters were discretized as eight plain walls to take into account of the variation of incidence angle of solar radiation during the day (Figure 4).

$$\dot{Q}_{conv,ext} = \lambda_{ext} \cdot A \cdot \left(T_{w,ext} - T_a\right) \tag{3}$$

$$\dot{Q}_{rad} = \alpha \cdot G \cdot A + \sigma \cdot \varepsilon \cdot A \cdot \left(T_a^4 - T_{w,ext}^4\right) \tag{4}$$

$$\dot{Q}_{cond} = \frac{k \cdot A \cdot \Delta T_w}{s} \tag{5}$$

$$\dot{Q}_{conv,int} = \lambda_{int} \cdot A \cdot (T_w - T_{int}) \tag{6}$$

where:

- λ is the heat transfer coefficient;
- A is the discretized wall surface;
- $T_{w,ext}$ is the external wall temperature;
- α is the concrete absorbance;
- G is the incident solar radiation;
- ε is the concrete emissivity;
- k is the concrete transmittance;
- ΔT_w is the temperature difference across the wall;
- s is the wall thickness;
- T_{int} is the digestion temperature.

Each wall of the digester (Figure 4) transferred the heat to the adjacent wall, to the roof and to the ground through conduction. For each wall the volume and the material of construction (concrete) were considered to take into account thermal inertia. The same equations reported above were employed for the roof of the digesters, whereas for the ground only internal convection and conduction were considered. Since biogas production and methane concentration were not continuously measured by plant management, and only the average production and composition were known, a variable profile from the literature [24] was assumed and adapted to the current test case. In particular, since the amount of biogas produced was larger than that produced in Viareggio, biogas volume flow rate was scaled down to obtain the same amount of yearly produced biogas. Regarding the composition, CH_4 concentration was increased to obtain a maximum concentration of 0.65%. Biogas production and composition are reported in Figure 5.

As for sludge seasonal temperature over the year, a continuous monitoring system was missing and only , the average summer and winter temperature values were available,. A sinusoidal trend was elaborated to provide continuity, making winter and summer averages equal to the data provided by plant management (Figure 6).

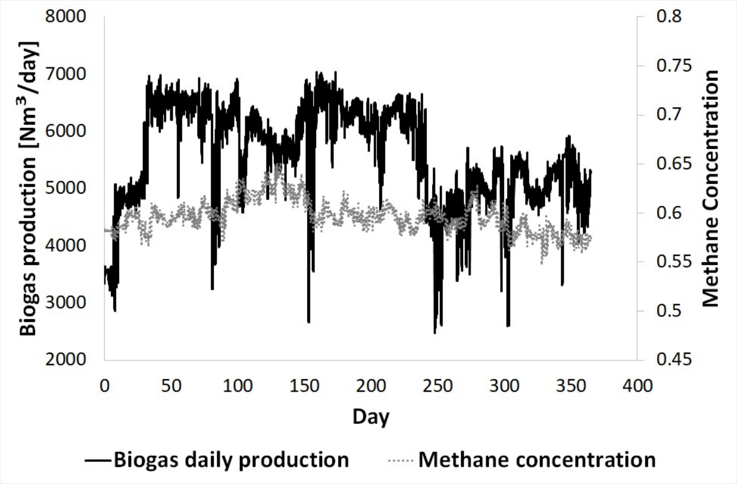

Fig. 5. Biogas production and methane concentration profiles.

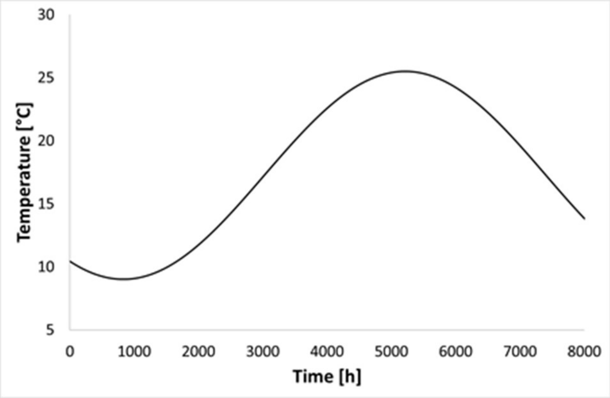

Fig. 6. Sludge temperature.

3.2. Heat Exchangers

The heat exchanger between exhaust gas and heat transfer fluid, as well as all the other heat exchangers in Figure 1, were modelled by using the ε-NTU method to take into account the off-design behavior of these components A proper routine was introduced in the solver to determine the off-design performance of these devices:

$$NTU = \frac{U \cdot A}{C_{min}} \tag{5}$$

$$\epsilon = f\left(NTU, \frac{C_{min}}{C_{max}}\right) = \frac{\dot{Q}}{\dot{Q}_{max}} \tag{6}$$

The surface and heat transfer coefficient in design conditions were estimated by considering the geometrical characteristic of the heat exchangers in Aspen Exchanger Design and Rating. This software, which was adopted in several study in the literature [34,35], is able to provide the actual geometry and the value of the heat transfer coefficient on both sides of the heat exchanger. The resulting surface and heat transfer coefficient were therefore employed in the heat exchanger routine introduced in the simulation environment. The off-design values for the heat transfer coefficients were calculated according to Eq. 7 [36]:

$$\lambda_{off} = \lambda_d \left(\frac{\dot{m}_{off}}{\dot{m}_d}\right)^n \tag{7}$$

where λ_{off} is the off-design heat transfer coefficient, λ_d is the design heat transfer coefficient, $\dot{m}_{off}$ is the off-design mass flow rate, $\dot{m}_d$ is the design mass flow rate and n is a coefficient equal to 0.6 for exhaust gas and 0.8 for water and sludge. Once the fluids volume was calculated by Aspen Exchanger Design and Rating, a proper value of capacity was considered in the numerical model.

3.3. Micro gas turbine (mGT)

The mGT, was a Capstone C600s microturbine. This device is made of three modules having a nominal power of 200 kW each. The caracteristic curves provided by the manufacturer [37] were used to evaluate the actual operational behavior according to ambient temperature and load. In more detail, these curves take into account the effect of the turbine part-load operation on thermodynamic efficiency (Figure 7, left), the influence of ambient conditions on efficiency and power (Figure 7, right) and the influence of both part-load and ambient temperature on exhaust gas mass flow rate and temperature. The turbines were fueled with all the amount of biogas that was produced by the anaerobic digestion plant.

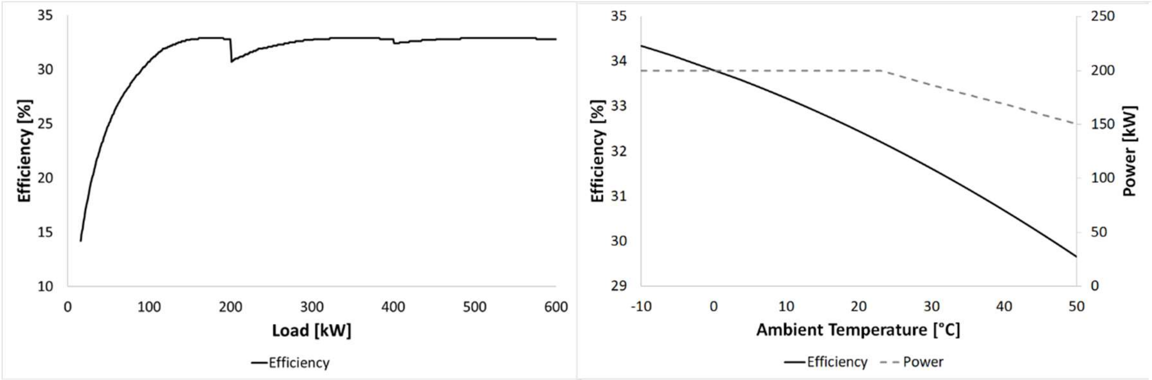

Fig. 7. Capstone C600s characteristic curves: part-load efficiency (left) and efficiency and power with ambient temperature (right).

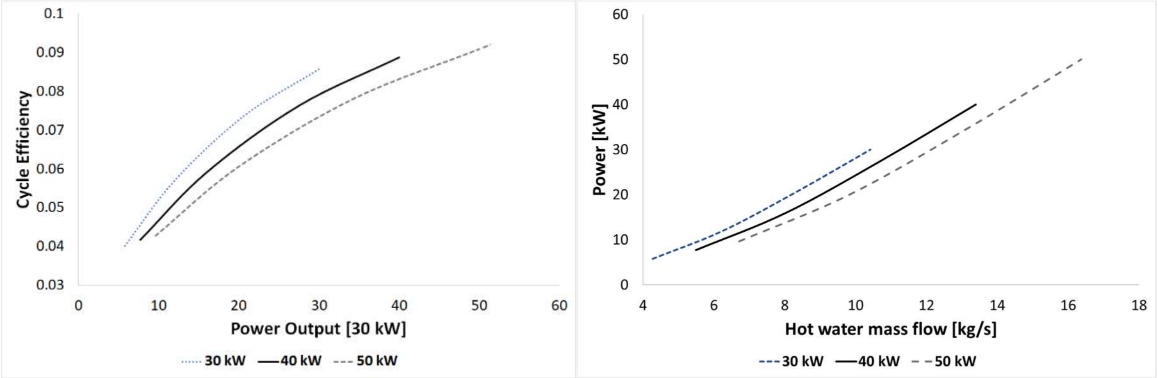

Fig. 8: ORC characteristic curves: Cycle efficiency as a function of output power (left) and output power as a function of water flowing in the ORC evaporator (right) for a water temperature of 95°C and a coolant temperature of 25°C.

3.4. ORC module

Similarly, ORC module was modeled as a function of the heat transfer fluid mass flow rate (water as from manufacturer brochure), and of the cooling water temperature. The ORC electrical output and the absorbed thermal energy were the main model outputs. Since operating maps were not directly available from the manufacturer, they were reproduced by adapting those from a similar cycle [38] still considering the constraint on design efficiency stated by the manufacturer. In particular, , these maps had the same function trends in terms of power and cycle efficiency but had a different nominal power and efficiency for each module. The cycle efficiency as a function of the power output and the power output as a function of the hot water mass flow rate are reported in Figure 8 for the three ORCs.

3.5. Heat transfer fluid circuits and control

In the reference scenario a constant mass flow rate of water was considered for the heat transfer fluid circuit. Therefore, the sludge temperature control was obtained by bypassing the flue gas heat exchanger. Bypass was numerically modeled as a variable opening valve located on the flue gas line and controlled by the digestion temperature. A simple PI controller was adopted to keep the sludge temperature at 37°C.

In the modified scenario, the heat transfer fluid circuit was modeled by considering the ORC and sludge heating unit in a serial arrangement. After being heated up by mGT exhaust gas, water flowed in the ORC evaporator and then in the sludge heating heat exchanger. Water mass flow rate was controlled through a simple PI to keep constantly at 95°C the temperature at the ORC evaporator inlet. The operation of with a constant heat transfer fluid temperature prevents a significative drop of the ORC output [39].Similarly, to provide the right amount of heat to the digesters, a heat exchanger bypass was considered. The bypass diverted part of the water mass flow rate to keep the digestion temperature at 37°C. Exhaust gas was diverted when the heat transfer fluid temperature exceeded the design temperature of 95°C. When the thermal power provided by the mGT was not enough to operate the ORC above the technical minimum the ORC was turned off.

For the ORC cooling, a closed water loop was considered Part of the condensing heat was transferred to the sludge, thus reducing the amount of thermal power requested from the mGT for sludge heating. That thermal energy which was not transferred to sludge in the preheater was dissipated in an air cooler.

3.6. Efficiency evaluation

The monthly and annual electric efficiency of the system in the reference scenario was calculated as:

$$\eta = \frac{\int_0^\tau \dot{W}_{mGT} \cdot dt}{\int_0^\tau \dot{m}_{bio} \cdot y_{CH_4} \cdot LHV \cdot dt} \tag{8}$$

where $\dot{W}_{mGT}$ is the mGT power output, m_{bio} is the biogas mass flow rate, y_{CH_4} is the mass fraction of CH_4 in biogas and LHV is the lower heating value of CH_4. Conversely, in the improved scenario, the electric efficiency of the system was calculated as:

$$\eta = \frac{\int_0^\tau (\dot{W}_{mGT} + \dot{W}_{ORC}) \cdot dt}{\int_0^\tau \dot{m}_{bio} \cdot y_{CH_4} \cdot LHV \cdot dt} \tag{9}$$

where $\dot{W}_{ORC}$ is the output power of the ORC module.

3.7. Economic Analysis

The economic analysis took into account the revenues from electric energy production (supposing self-consumption), the cost of the ORC and of extra devices required (CaPex) in comparison to the reference scenario and the operative costs (OpEx) of the ORC solution with respect to the reference. The procedure reported in [40] was assumed for the evaluation of heat exchangers cost. For the ORC, since the difference in size between the considered modules was very small (largest difference was 20 kW), a specific cost of 4350 $/kW was assumed from [34] where a similar ORC size was considered. The cost of the three considered systems, including heat transfer fluid and cooling circuit heat exchangers, is reported in Table 1, assuming a 20 m^2 preheater. It is worth to notice that the cost of the sludge regenerator is not included since its size was varied in the analysis.

	Module power		
	30 kW	**40 kW**	**50 kW**
Cooling and heat transfer loop cost [$]	182400	188500	194348
ORC Module Cost [$]	130500	174000	217500

Table 1: ORC module costs.

Maintenance cost was considered equal to 2.5% of equipment purchasing cost. Electric energy was supposed to be completely consumed in the wastewater treatment plant, thus leading to an avoided cost. Once CaPex, OpEx and revenues were known, Net Present Value (NPV) was estimated as:

$$NPV = -CaPex + \sum_{i=1}^{n} \frac{R_i - OpEx_i}{(1+r)^i} \tag{10}$$

where R_i are the revenues at the ith year and r is the discount rate supposed equal to 5%. The profitability index was also considered as an investment indicator:

$$P.I.=\frac{NPV+CaPex}{CaPex} \tag{11}$$

This indicator gives an idea of the investment profitability and risk as it is a ratio between cash flows and investment cost. The higher is the PI, the lower is the investment risk and the higher is the investment profit.

4. Results

In the reference scenario, the temperature of the digesters is controlled and kept constant at 37°C by acting on the diverter to vary the exhaust gas mass flow rate in the heat exchanger (Figure 9). By changing the amount of diverted gas, the necessary heat flow is provided to the digesters to keep its temperature constant (Figure 10). It is worth to notice that, due to the large inertia of the digesters, there was a delay of about 8 hours between ambient temperature variation and thermal power requirement variation. It is important to highlight that in the reference scenario, during all the year, exhaust gas mass flow rate is always much larger than the mass flow rate flowing in the sludge heat exchanger, even without regenerator. This means that the exhaust gas diverter always discard to the stack a part of the thermal energy and the plant is always self-sustained from the thermal energy point of view. As shown in Figure 11 and 12 for a sample week in March, turbine power output and exhaust gas mass flow rate and temperature are not constant due to both ambient temperature variations and biogas production variations (Figure 11). The effect of biogas production variation is particularly apparent on turbine monthly energy production as shown in Figure 12. Daily average power production during the year (Figure 12) was influenced more by biogas production rather than by ambient temperature. The effect of the ambient temperature on mGT was instead particularly clear on average monthly turbine efficiency, which reached its minimum values during summer period (Figure 12).

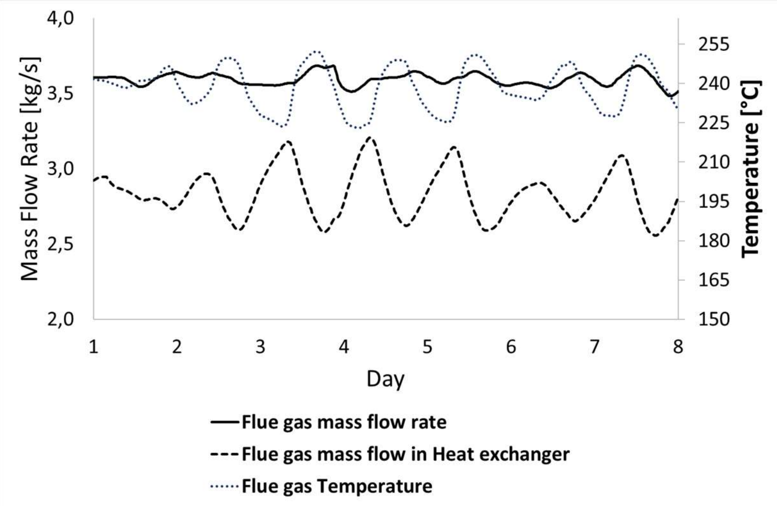

Fig. 9: mGT exhaust gas mass flow rate and temperature and mass flow rate through the heat exchanger in a asample week of March.

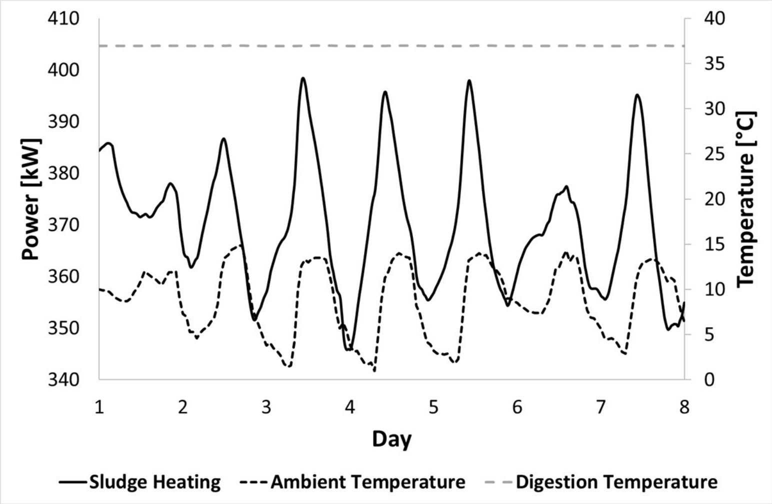

Fig. 10: Thermal power transferred to sludge, ambient temperature and digester temperature in a sample week of March.

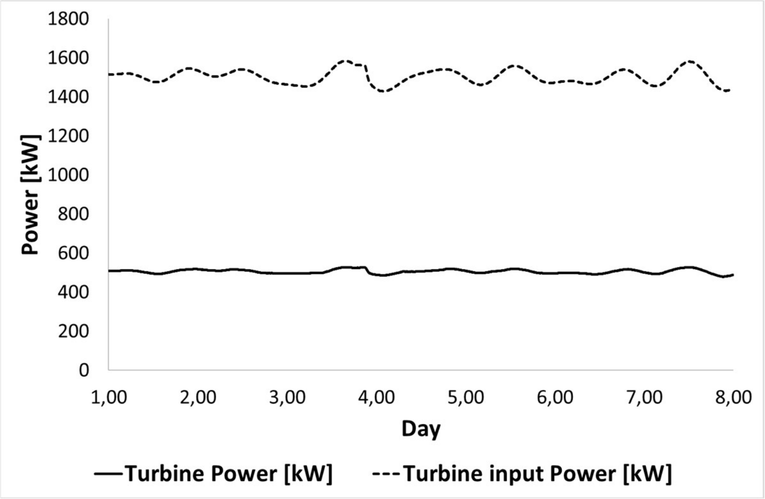

Fig. 11: mGT input thermal power and electric output power.

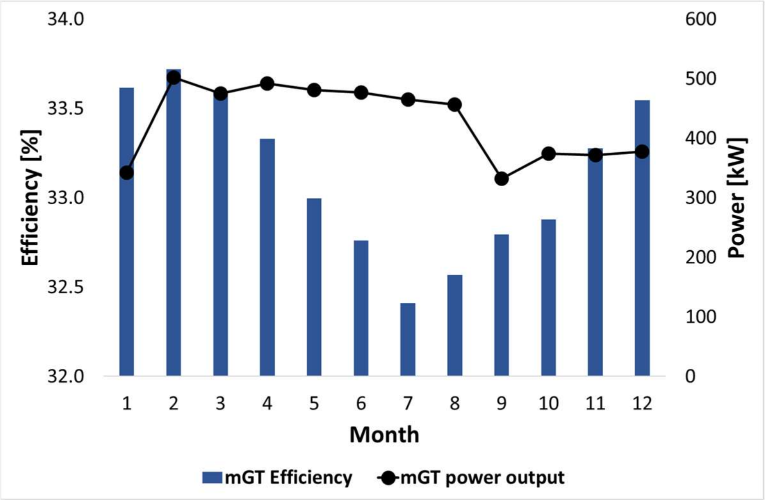

Fig. 12: mGT monthly electric efficiency and daily average power per month.

4.1. Effect of sludge regenerator

In improved configuration, ORC module should increase the system efficiency by exploiting the part of turbine exhaust gas which in the reference case was discharged in the atmosphere. Differently from other waste heat recovery systems in which the bottoming cycle should exploit as much heat as possible, consistently with the thermodynamic and economic constraints, in the case of anaerobic digestion, the waste heat recovery system shares the heat source with sludge heating. In addition, sludge heating shall take the priority over the waste heat recovery system to guarantee the correct digestion temperature and biogas production. For a better operation of the waste heat recovery system, the amount of heat requested by digesters should be reduced.

The introduction of the sludge regenerator to increase sludge temperature at plant inlet and of a preheater, which uses part of the heat rejected by the ORC condenser, may reduce the amount of heat requested by anaerobic digestion. The electric output of the three ORCs in the same week of Figure 9 are reported in Figure 13 by considering a 20 m^2 counter current shell and tube heat exchanger on the cooling circuit for a sludge preheating and a sludge regenerator of 25 m^2.

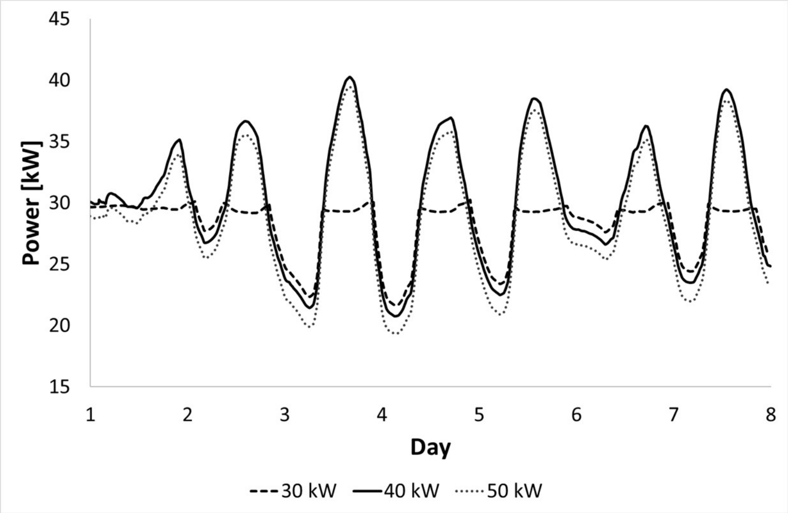

Fig. 13 ORC modules power output for a sample week of March.

Obviously, power output is influenced by the heat availability at the mGT output and by ambient temperature, which influences both the condensation and the digesters heat request. In this week, the smallest module is operated near nominal condition (30 kW) for most of the time and off-design is limited to those conditions in which the input thermal power was insufficient. The other two sizes of ORC modules were never able to reach their nominal conditions (with the exception of one spike for the 40kW module between day 3 and 4). By varying the regenerator size, it was possible to increase the power output of the largest modules, as reported in Figure 14 where the influence of the regenerator on power output of 40 kW module is reported

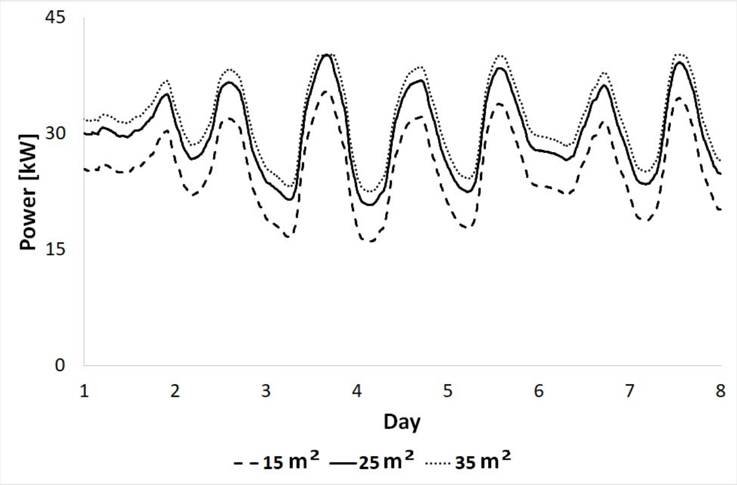

Fig. 14: Power output of the 40 kW ORC module different sizes of the regenerator in a sample week of March.

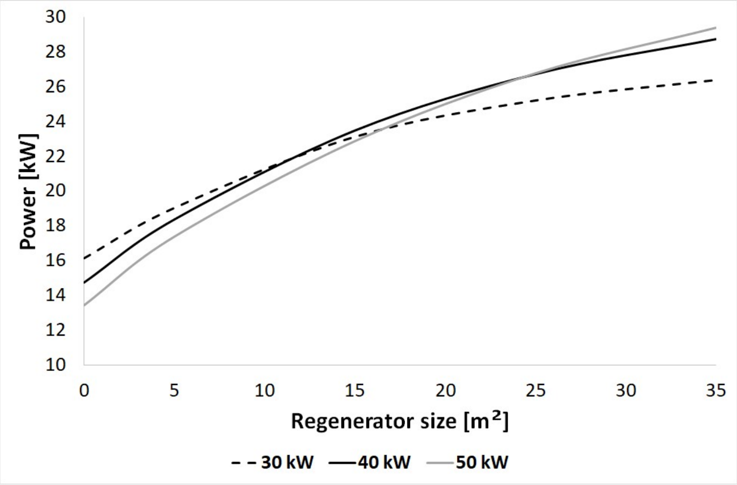

Fig. 15: Average annual power for the three modules as a function of the regenerator size.

Average annual power output of the three modules showed a strong dependence on the regenerator size (Figure 15). All modules operate in off-design conditions in the case of null or small regenerator size. Particularly, the largest sizes (40 and 50 kW) were strongly penalized in the case of small regenerators. For these two modules, operating without regenerator led to frequent stops and very low efficiencies (annual average power below module technical minima). The average power output resulted maximum for the 50 kW module with a regenerator area of 35 m^2, despite the 40 kW module produces just one kilowatt less. With a 50 kW module, a sludge regenerator area of 35 m^2 and a preheater of 20 m^2 annual system efficiency increases of about 2.3%. Sludge regenerator has therefore a key role in the integration of ORC and influences the produced energy and the utilization factor of the ORC modules.

4.2. Effect of sludge preheater

The effect of the preheater on the produced power in a sample week of operation. is highlighted in Figure 16. The preheater has a benefic effect on the power output that depends on ORC operating conditions. The greater is the power output of the ORC the greater is the power increase achieved with a preheater as the heat rejected at the ORC condenser increases.

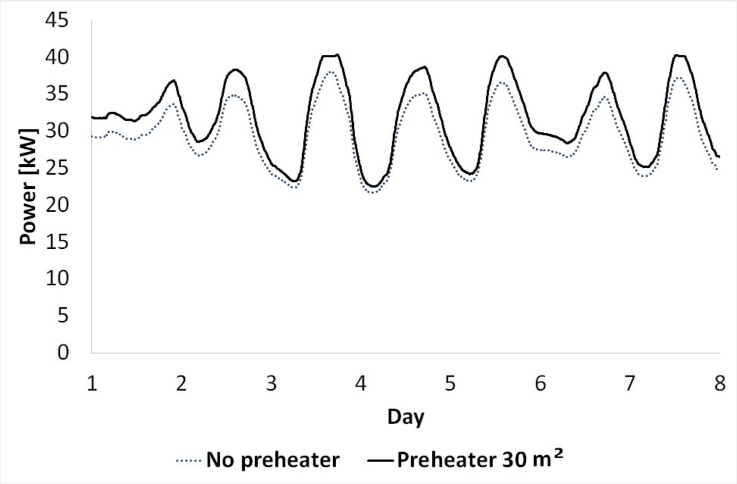

Fig. 16. Effect of the preheater on the 40 kW ORC power output in a sample week of March.

The effect of the preheater on the average power obtained during the year, was summarized in Figure 17. This heat exchanger contributes less than the regenerator to the efficiency improvement of the system (maximum average gain was between 1.7 for the 30 kW module and 2.3 kW for the 50 kW module). This reduced gain is due to the low difference between the temperature of the cooling water (which depends mostly on ambient conditions) and that of sludges entering in the plant. For preheaters larger than 20 m^2, the power increase is negligible. For this reason, in the following efficiency and economic evaluations a preheater of 20 m^2 was considered.

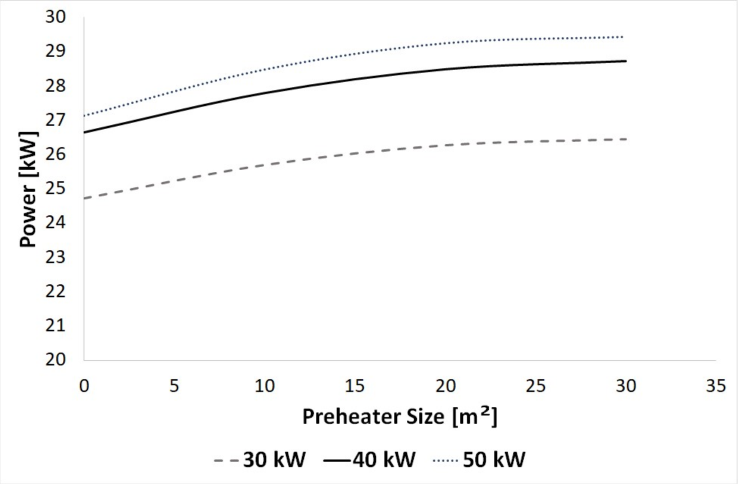

Fig. 17: Average annual power as a function of the preheater size, with a fixed

By considering a sludge regenerator of 35 m^2 and a preheater of 20 m^2, the monthly efficiency for the three ORC systems is reported in Figure 18.

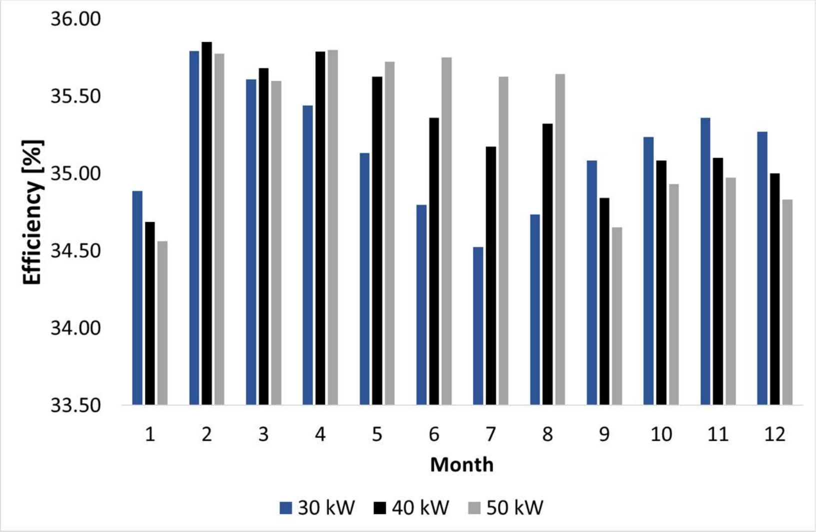

Fig. 18: Overall electric efficiency with the three ORC modules with a regenerator area of 35 m^2 and with a preheater area of 20 m^2.

4.3. Economic analysis

The three solutions showed a highly different behavior during the year. The highest performance during winter was achieved with the smallest ORC module, while during summer it was reached with the largest one. The reason of this behavior was due to the low availability of heat during winter (due to the larger amount of heat required by digesters) which forced the largest modules to work in extremely low part-load condition or to be switched off. Conversely, during summer, due to the lower amount of heat necessary to the digesters, the largest ORC produces higher power output than the smaller one. This increases the efficiency of the system and compensates to the mGT efficiency loss caused by higher ambient temperatures. To define the best configuration of the system and assess the best size of both ORC module and sludge regenerator (fixed preheater area of 20 m^2), the profitability index for a 20 years operation was estimated by considering a 0.20 $/kWh as electricity price (self-consumption) and reported in Figure 19.

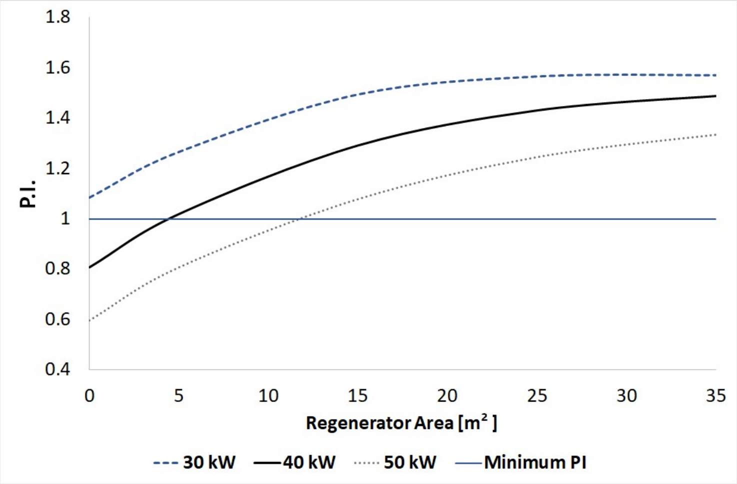

Fig. 19: Profitability index for the three modules as a function of the regenerator area for an electricity price of 0.2 $/kWh.

Due to the high purchasing and maintenance cost, the 50 kW module was the one which showed the lowest profitability index among the considered solutions, for almost any regenerator size. The 40 kW module was always better than that of 50 kW, but with a limited gain as still the module operate in part-load for most of the time,. The PI of the 30 kW solution showed the best results: the ORC system operated most of the time near nominal condition, thus exploiting the potential of the module. With this last module, the slope of the curve became quickly flat: the average power output is only slightly dependent on the regenerator size, since this module works near design conditions even without the regenerator. On the other hand, the investment cost increases with regenerator size. Therefore, this module is the solution that maximizes investment profitability and reduces investment risk.

Risk reduction does not lead to the maximization of the revenues. From the analysis of the NPV for a configuration with sludge regenerator of 35 m^2 and a preheater of 20 m^2, the 30 kW unit maximizes the investment return for an electricity cost of 0.20 $/kWh (Figure 20). By increasing electricity cost to 0.27 $/kWh, the 40 kW unit becomes more advantageous, due to the highest efficiency and power output of this module. The 50 kW system is the less profitable solution even in the case of high electricity prices.

Cash flow analysis shows that revenues may achieve 213 k$ with a 30 kW ORC and 0.20 $/kWh as electric energy price. The revenues may increase up to 450 k$ with the 40 kW module and 0.27 $/kWh as electric energy price. The payback period (PBP) is between 7 and 9 years for the three modules with 0.27 $/kWh and between 11 and 13 years for the three modules with 0.20 $/kWh.

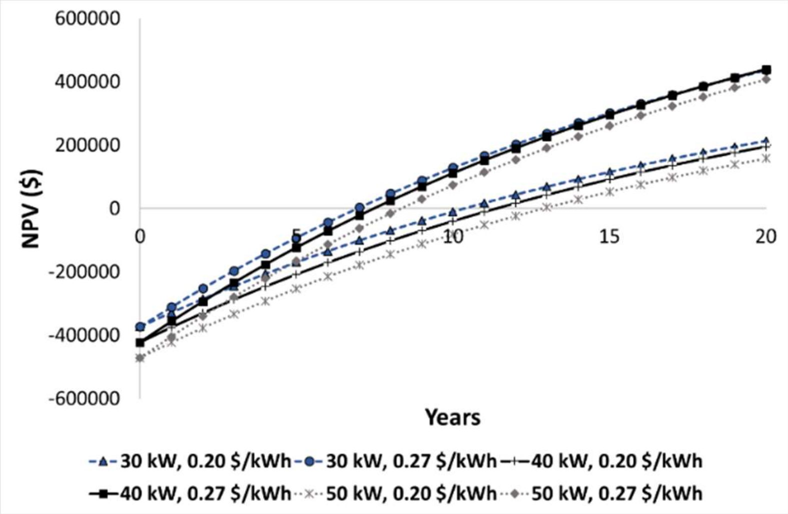

Fig. 20. NPV for the ORC modules for two different prices of electric energy (sludge regenerator area = 35 m^2).

Conclusions

An improvement of the anaerobic digestion plant of the town of Viareggio has been investigated. The plant is currently thought to operate with a 600 kWe mGT fueled with the biogas produced by the digesters. The mGT electric output is used to partially cover the needs of the plant. The thermal output is used to keep the digesters at the required temperature and heat surplus is currently dissipated. The opportunity of coupling the plant with a small ORC system has been investigated. The integration of the two plants was conceived to optimize the system efficiency and the investment profit. The reference and modified solutions were simulated in a hybrid transient and steady-state modelwith AMESim over one year of operation. Local ambient conditions and three different commercial ORC with the size of 30, 40 and 50 kW were considered in the simulation. Transient performance of sludge line, heat transfer fluid and ORC cooling circuit were also taken into account. Conversely, mGT and ORC, which are characterized by a low characteristic time, were modelled by considering off-design maps from manufactures data sheet with a steady-state approach. The main outcomes of the research were:

- If properly integrated, an ORC may increase the energy performance of in an anaerobic digestion plant
- The introduction of a sludge regeneration unit and of a preheater exploiting the heat rejected by the ORC plays a key role in the exploitation of the mGT waste heat.
- The ORC system produces around 8.6% of the electric energy produced by the mGT and compensates for the variation of mGT production during the year due to ambient condition variation.
- By using an ORC, system efficiency increases of about 2.3 % in the best case (50 kW and sludge regenerator size of 35 m^2 and preheater size of 20 m^2).
- From the economic point of view, the 30 kW system maximizes the profitability index, due to an almost constant operation near nominal conditions along the year. In this case the investment is profitable even without sludge regenerator, but a preheater is always required. 40 and 50 kW modules always require a sludge regenerator to be profitable.
- Sludge regenerator increased the profitability of the investment independently on the power of the ORC.
- System revenues are maximum for 40 kW module that, even if it operated near nominal conditions only in summer, provided a good compromise between system cost and generated energy along the year.

Acknowledgements

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