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Feasibility analysis of coupling an ORC to a mGT 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. Electric power is used to satisfy the plant internal need and the surplus is sold to the grid. 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. This study focuses on the potential of using an Organic Rankine Cycle as a possible 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 to have 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. Off-design behavior of all the components was also included in the simulation. The results of the investigation showed that a thermal energy recovery up to 77% could be achieved. From the economic point of view, the plant modification for introducing the ORC system has a payback period lower than 6 years and an interesting profitability index.

Keywords: Biogas; mGT; Organic Rankine Cycle; Feasability analysis

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1. Introduction

In the last years, an increasing interest is 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. The biogas produced in a digester is usually used in an internal combustion engines (ICEs) or a micro-gas turbines (mGTs) for cogeneration purposes [1]. 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. Since the revenues from electric energy sale are decreasing [2], an optimization of the waste heat use becoming more and more important. An example is reported in [3] where the coupling of a mGT and an absorption chiller aiming at reducing the turbine inlet air temperature was investigated. Another example is reported in [4, 5, 6] where the potential of exploiting the thermal energy excess for tri-generative purposes was investigated. In [7] the combination of an Organic Rankine Cycle (ORC) and a biogas fueled ICE was analyzed. Most of these studies were based on a steady-state approach and only few authors performed dynamic analysis of biogas-fueled systems [8, 9]. 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 [10]. A reference and a modified solution where an ORC is coupled with the mGT were simulated in AMESim in transient conditions. The coupling of the two plants were studied in details to take advantage of all the possible energy recoveries. The off design behavior of all the components and actual ambient conditions during a one-year-long period were considered in the simulation. The results of the investigation highlighted the interesting potential and the profitability of the proposed solution.

2. Case study

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 is used to this purpose. In addition, a regeneration heat exchanger ($10m^2$) is used to pre-heat the sludge by taking advantage of the sensible heat of the digestate removed from the plant. 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.

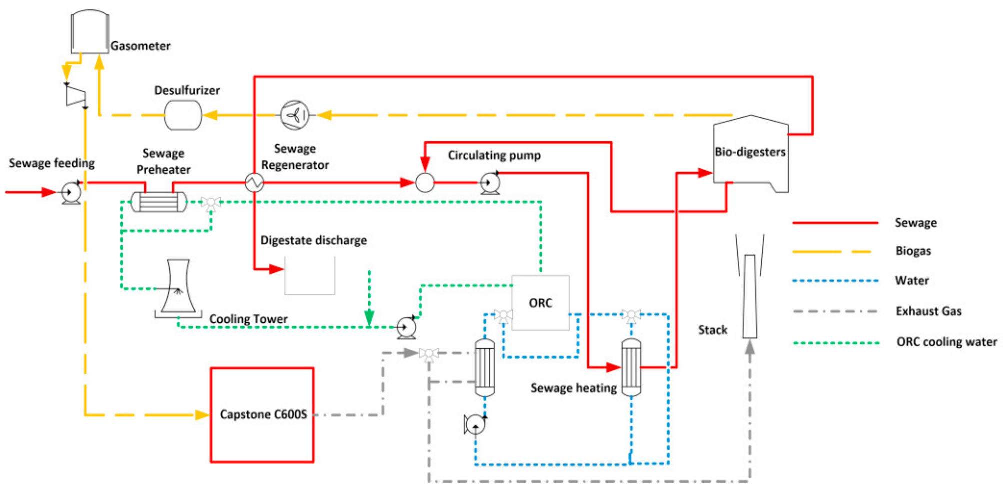

Fig.1 – Plant scheme in the improved scenarios.

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. Differently from the reference scenario, in this case the water loop exchanges heat with both the sludge and the evaporator of the ORC plant. The heat from the ORC condenser contributes to pre-heat the sewage from the wastewater treatment plant entering in the digester (Figure 1). A commercial ORC system from Infinity Turbine (IT50) was considered. This system uses a radial outflow turbine generator and produces 55 kWel with a thermal input of 550kWth. The heat is provided to the ORC evaporator by mean of the water loop at a constant temperature of 95°C. Simulations have been carried out in transient conditions with AMESim by considering one reference year. Hourly-discretized ambient temperature and radiation data were considered in the heat transfer model of the anaerobic digester for the estimation of the plant thermal load. The historical series of climate data for the town of Viareggio were retrieved from [12]. Sludge seasonal temperatures were also considered in this calculation and plant management provided the authors with the actual values. Air temperature was also used as an input for the estimation of mGT performance. All the heat exchangers were modelled by using the ε-NTU method and off-design performance of heat exchangers, mGT [13] and ORC [14] were considered starting from manufacturer data sheet (Figure 2). Biochemical reactions in the digester and biogas production come from previous studies [10, 15] and were not included in the simulation. Further details on plant modeling can be found in [6].

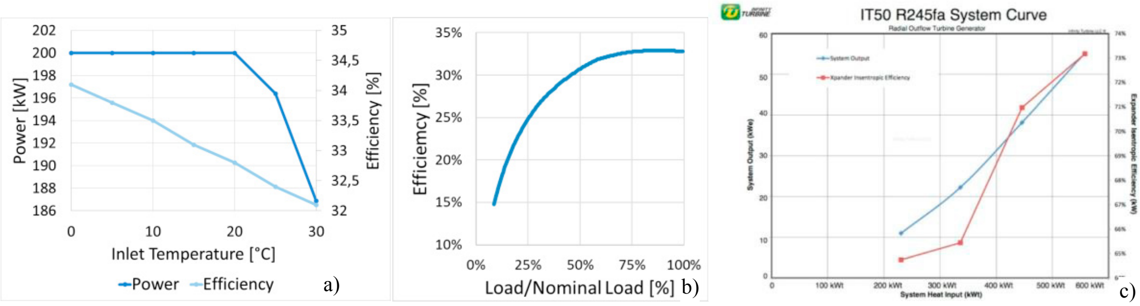

Fig. 2 – Off design performance of the mGT (a, b) and of the ORC system (c).

3. Results

3.1. Reference scenario

In the reference scenario, the temperature of the digesters is controlled and kept constant at 37°C by acting on a diverter, controlled by a PI, to vary the exhaust gas mass flow rate flowing in the heat exchanger. By changing the amount of diverted gas, the necessary heat flow is provided to the digesters. As shown in Figure 3 for a sample week, turbine power output and exhaust gasses mass flow rate and temperature are not constant due to ambient temperature variations. This effect was particularly apparent on the turbine energy production as shown in Figure 4. The lowest production is reached during the summer season when the mGT efficiency is at its lowest values.

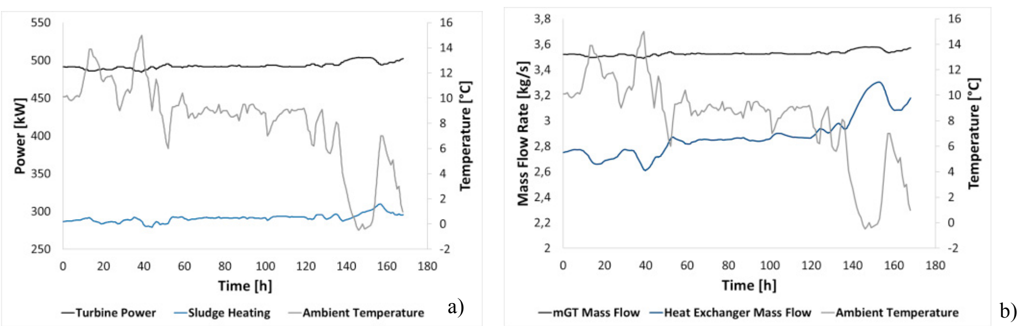

Fig. 3 – Simulation results in the second week of January: mGT power output (a) and exhaust gas temperature (b).

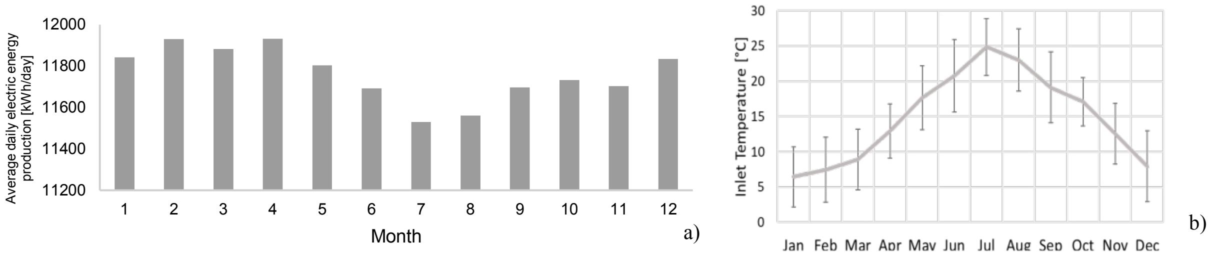

Fig. 4 - Average daily electric energy production (a) and ambient temperature (b).

The heat to the digesters was provided by both turbine exhaust gasses and sludge regenerator with a proportion between the two sources that changes with the season (Figure 5a). By increasing the regenerator size, the amount of heat recovered from the turbine exhaust gasses decreases. This is shown in Figure 5b where the percentage of recovered thermal energy is estimated for different regenerator heat exchanger sizes (0, 10 and 35 m^2). This means that in the reference scenario, where the sludge heating was the only useful thermal effect, the increase in the sludge regenerator area reduces the cogeneration efficiency. On the other hand, when an additional use of the exhaust gasses heat is considered, as in the improved scenario, the size of the regenerator has to be increased.

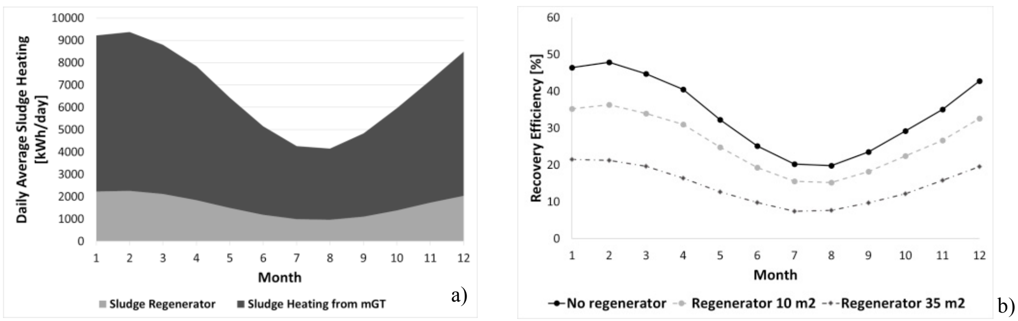

Fig. 5 – Sludge heating divided by source (a) and thermal recovery efficiency for different regeneration heat exchanger sizes (b).

3.2. Improved scenario

In the improved scenario, a commercial 55 kW ORC was considered as a bottoming cycle for the gas turbine. Since the ORC in nominal conditions requires about 550 kW_{th} at a minimum water temperature of 95°C, a regenerator of 35 m^2 was adopted. In this way, the heat extracted from the exhaust gasses to increase the sludge temperature is reduced and the ORC system can operate near to nominal conditions. To increase the amount of heat available for the ORC system, also the heat from the cooling circuit of the ORC was used to increase the sludge temperature. By considering one year of operation, the ORC provided 8.6% of the electric energy produced by the plant. The daily average electric energy output of the is almost constant over the year even though the single productions change significantly (Figure 6a). During summer, mGT power output decreases due to the highest air temperature, but this loss of efficiency leads to an increase in the heat available in the exhaust gasses that enhanced the power produced by the ORC. This effect is visible also in Figure 6b, where instantaneous turbine and ORC power output are reported together for a sample week. When the turbine power output increases due to a reduction of the ambient temperature, ORC power output decreases. The thermal energy available to the ORC plant is maximum during summer months when the heat content in the exhaust gasses is high and the turbine efficiency is low. As stated above, the heat necessary to keep the sludge at a constant temperature was provided by the heat exchanger in the ORC cooling circuit, by the sludge regenerator and by the exhaust gasses of the turbines. The different contributes are reported in Figure 7a. It is worth noting that with a regenerator area of 35 m^2 and with a heat exchanger area of 10 m^2, the turbine provided to the sludge less than 50% of the heat requested by the anaerobic digestion. Most of the heat content of the exhaust gasses is used to feed the ORC plant (Figure 7b). In comparison to the reference scenario, the adoption of the ORC led to an increase in the turbine recovery efficiency. Values from 74.6%to 77% are estimated (Figure 7c).

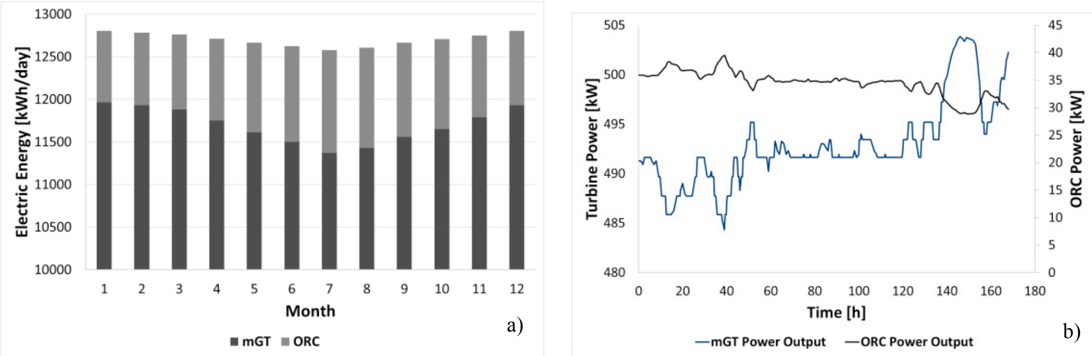

Fig. 6 – Average daily electric energy production (a) and detail of a sample week (b).

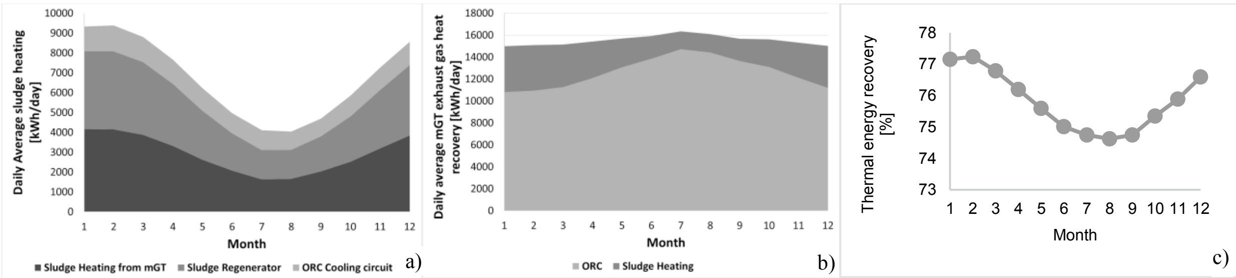

Fig. 7 – Sludge heating combination (a), mGT exhaust gasses utilization (b) and thermal energy recovery coefficient (c).

As for the profitability of the system, the costs of the improved solution are reported in Table 1. For the ORC, a cost of 4350 $/kW was assumed [16]. Heat exchangers and water loop costs were evaluated according to the procedure reported in [17], which provides both total direct and indirect costs. The 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. Two values for electric energy cost (0.27 and 15 $/kWh) and discount rate (5 and 7%) were considered. The trends of the cash flow are reported in Figure 8. NPV and PBP values are reported in Table 2 for each combination of electric energy cost and discount rate. In the most favorable scenario, the improved solution provided an NPV of about 812 k$ and a payback period below 6 years.

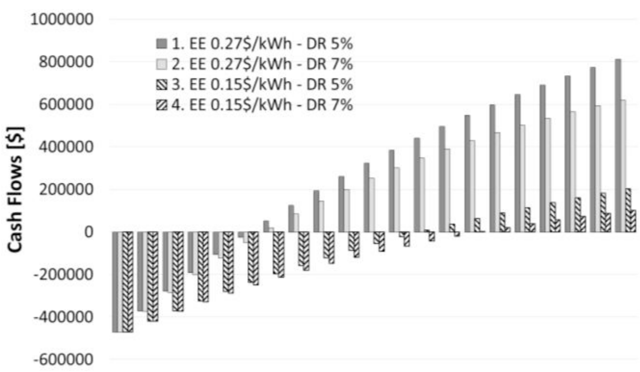

Fig. 8 – Cash flow of the improved solution.

Item	Cost [$]
ORC module	239500
Heat Exchangers and water Loop	230000
Total Capital Cost	469500

Table 1. Cost of the improvement

Case	PBP [y]	NPV [$]
1. EE 0.27$/kWh - DR 5%	6	812700
2. EE 0.27$/kWh - DR 7%	6	620360
3. EE 0.15$/kWh - DR 5%	12	202084
4. EE 0.15$/kWh - DR 7%	14	101181

Table 2. Economic parameters for different scenarios

4. Conclusion

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. mGT electric output is used to partially cover the needs of the plant whereas the thermal output is used to keep the digesters at the required temperature. 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 thermal energy recovery. The reference and modified solution were simulated in transient condition with AMESim over one year of operation by considering the local radiation and temperature conditions. The off design performance of heat exchangers, mGT and ORC were also considered by taking account manufactures data sheet. The main outcomes of the research were:

- The use of a regeneration unit to pre-heat the sludge entering in the digester 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 the recovery of mGT waste heat increases up to 77%
- From the economic point of view, the investment is profitable with a payback period lower than 6 years. The profitability is strongly influenced by the economic scenario.

Acknowledgements

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