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Poly-generation capability of a biogas plant with upgrading system

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Abstract

Biomass, together with other renewable sources, is increasingly used to provide energy to minigrids and distributed generation systems. Particularly, biogas production seems an interesting solution as it can be used to produce electricity, heat and bio-methane (through an upgrading system). In addition, biogas can be relatively easily stored in gasometers to compensate for small request variations. On the other hand, the amounts of heat, electricity and bio-methane produced are strictly dependent one on the others. A poly-generation scenario was considered starting from an existing case study made up of a digester, a 600kW$_{el}$ micro gas turbine and an upgrading system for bio-methane production. An off-design system simulation was carried out to analyze the energy and mass fluxes between plant components as a function of the fraction of the biogas sent to the upgrader. The constraints and relations between heat, electricity and bio-methane production were extensively analyzed. Results show that this system can be a versatile poly-generation unit.

Keywords: Biogas; anaerobic digester, bio-methane; trigeneration; upgrading; microgas turbine

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1. Introduction

The interest towards smart grids has been increasing in the last years due to the possibility of increasing the efficiency of the electric system, the quality of services and saving operational costs [1]. In stand-alone systems the penetration

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of renewable energy can be important due to the high costs of connection to the national electric and gas grids [2]. However, a diesel engine is often involved in those systems to compensate the fluctuations and variability of renewable energy sources [3-5] but causing emission of pollutants. An alternative solution to diesel engines can be represented by bio-methane. Bio-methane is the product of the anaerobic digestion of organic wastes, such as manure, agricultural and farming wastes, sludge and municipal bio-waste [6,7]. The main advantage of anaerobic digestion systems is that they can be seen as poly-generation units providing electric energy, heat and cooling and also methane [8,9], partially covering the demand of the stand-alone system. Moreover, anaerobic digestion plants can be operated in co-digestion of sewage and food wastes [10-12], thus allowing the transformation of waste into useful energy, and biogas can be relatively easily stored in gasometers to regulate the power output. In this study, the potential of an anaerobic digestion plant as a poly-generation system was analyzed by considering the case study of the digester of the town of Viareggio [11-12]. The plant is now in an upgrading phase and, in the near future, it will produce electricity, heat and bio-methane. The study investigated the possibility of producing various output (electric energy, heat and bio-methane), and how these outputs are modified by the variation of the amount of bio-methane produced. The study considered the off-design behavior of the plant, estimated the net transfer of electricity, natural gas and heat between the plant and the electric and gas grids, showing the capacity of the plant to adapt the production to the request of the grid.

2. Case study

The biogas system is made up of an anaerobic digester, a biogas/methane boiler, a micro turbine and a biogas upgrading system, as shown in Fig.1 where the mass and energy fluxes between the components are highlighted in different colours. The biogas is produced from sludge collected from the waste water plant of the municipality of Viareggio, Italy [11,12]. An anaerobic digestion process is employed to this purpose. The digester operates in co-digestion of sewage and bio-wastes and produces biogas with about 65%$_{vol}$ methane percentage and 35%$_{vol}$ carbon dioxide. The boiler can operate with both methane and biogas, and produces heat to support, when necessary, the digester and the upgrading system operation. The upgrading system is a GM HPC based on the absorption of CO_2 in a hot solution of water and potassium carbonate and it produces methane from biogas (i.e. bio-methane) with a content of CO_2 lower than 1%$_{vol}$. The upgrading system requires electric energy and heat at the temperature of 120°C: however almost the 100 % of the heat requested can be recovered at a temperature of 70°C and used for anaerobic digester heating. The plant scheme is reported in Fig.2 (a). The bio-methane produced is sent to the grid. According to the supplier data, the upgrader specific consumption of electricity and heat can be considered constant with the biogas input variation. The employed micro gas turbine (mGT) is a Capstone C600s and it is composed by 3 modules of 200kW$_{el}$. The turbine is directly fuelled with biogas. An internal management strategy allows the use of the number of turbines which maximize the C600s overall efficiency. Nevertheless, the mGT operation is strongly sensitive from the off-design conditions, as shown by Fig.2 (b). According to Fig.1, the biogas can be employed for the upgrading, for the mGT, and for heat production in the boiler.

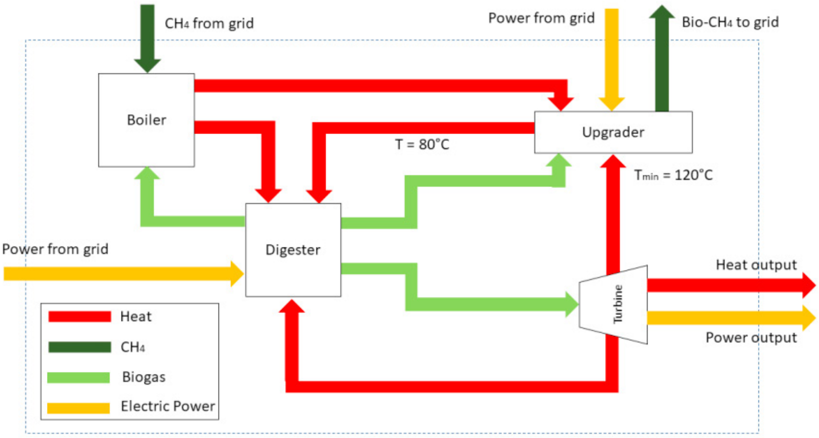
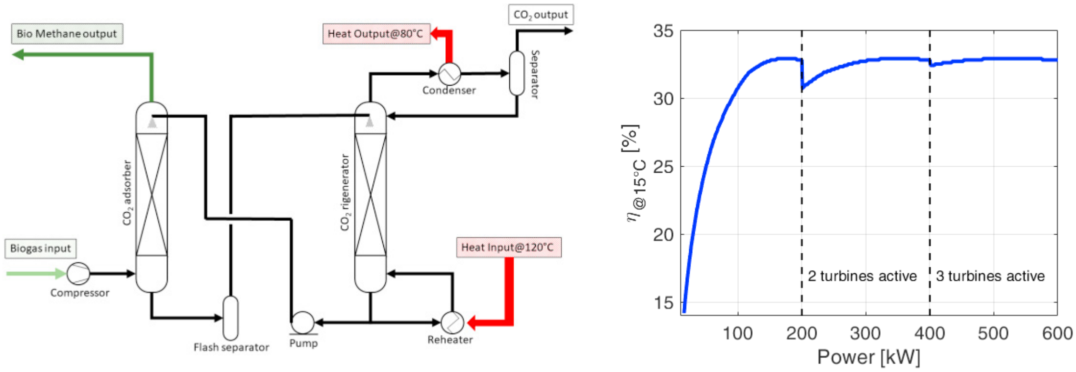


Fig. 1. Plant scheme and mass and energy fluxes involved.



(a) (b)

Fig.2: GM-HPC plant scheme (a) and the efficiency of the Capstone C600s with respect to the load conditions (b)

Turbine and upgrader waste heats are recovered to provide thermal energy to the anaerobic digester. Therefore, the biogas sent to the boiler is the minimum biogas amount necessary to sustain the digestion when no other sources are sufficient. Methane from the grid is also employed to this purpose only when strictly required (no biogas available). Electricity consumption is due to digester and upgrader auxiliary systems, and it is provided by the mGT or by the grid when needed. The plant produces three main products, which are the electric energy, heat and bio-methane. The net heat output is the surplus of heat produced by the turbine (up to a temperature of 60°C) which is not used by the digester or by the upgrader. Therefore, the amounts of heat, electricity and bio-methane produced are strictly dependent one on the others. An off-design system simulation was carried out to analyze the energy and mass fluxes between plant components as a function of the fraction of the biogas sent to the upgrader.

3. Biogas system model

According to the Fig.1, steady-state mass and energy conservation equations were used to model the case study system. Heat exchangers are designed in nominal conditions and ε-NTU method was adopted both for design and off-design calculations. The digester heat requirement was estimated by evaluating the heat losses due to the heat transfer mechanism by conduction and convection between the sludge inside the digester and the external air and the heat requested to warm up the sludge up to the digestion temperature (37°C, mesophilic digestion). Off-design conditions for the mGT and the boiler were considered. A steady state simulation was carried out by means of a Visual Basic software, which was developed to solve the described system

The biogas mass flow management is represented by a parameter *F*, which is the ratio between the biogas mass flow rate sent to the upgrading process to the total biogas produced by the digester, as shown by Eq.1.

$$F = m_{biogas}^{upgrading} / m_{biogas}^{tot} \tag{1}$$

It is clear, that *1-F* is the biogas mass flow fraction which is processed by the turbine or by the boiler . The F factor influences the heat flow inside the system and the net outputs. Several rules are employed to implement the plant control strategy and the systems constraints. Firstly, the mGT can operate up to a maximum F value after which the performance decrease considerably and the turbine is shut down. In addition, as the heat recovered from the turbine is also dependent on F according to Fig.2 (b), when F is high, the boiler must provide the necessary heat to the digester and to the upgrader. In order to investigate the net outputs of the system, the *F* value was varied between the 0 and 100%.

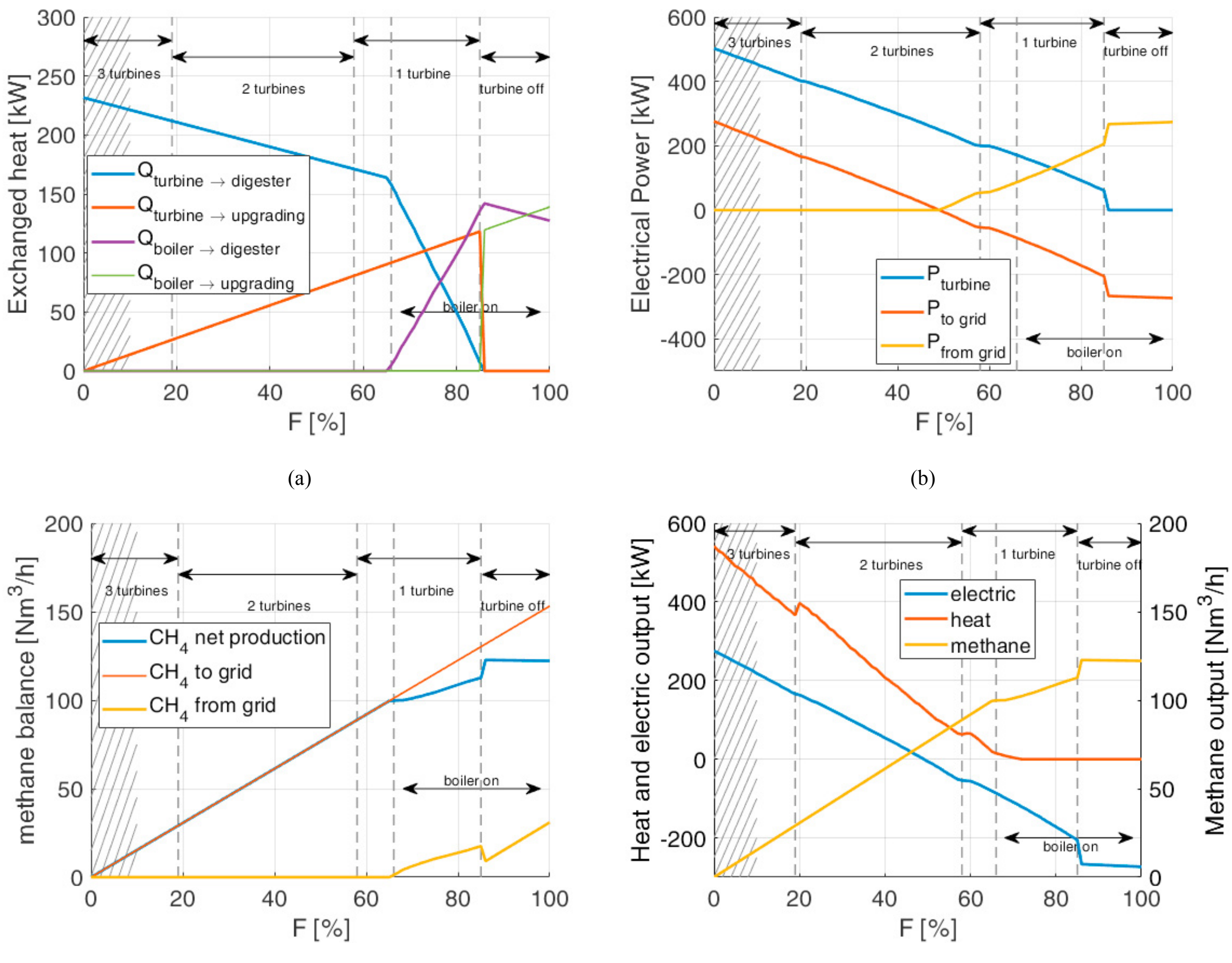
Process temperature are taken as constraints input, such as the anaerobic digestion temperature $T_{dig,set}$, and the minimum upgrader heat temperature inlet $T_{up,in}$.. Particularly, the simulation is made by adopting daily average values for air temperature (T_{air}), sludge temperature (T_{sludge}), biogas and sludge input flow rates (V_{biogas} and m_{sludge}, respectively). These values are reported in Tab.1.

Table 1. Boundary conditions used in the simulation.

T_{sludge}	T_a	$T_{up,in}$	$T_{dig,set}$	m_{sludge}	V_{bio}	CH_4 / CO_2 bio
[°C]	[°C]	[°C]	[°C]	[t/h]	[Nm^3/h]	[$\%_{vol}$ / $\%_{vol}$]
16.3	14.5 °C	120 °C	37 °C	8.3	235	65 / 35

4. Results and discussion

The results are presented as the main electrical power Fig.3(a), bio-methane flow rate Fig.3(b), and heat Fig.3(c) that are produced by the plant, together with their net output Fig.3(d).

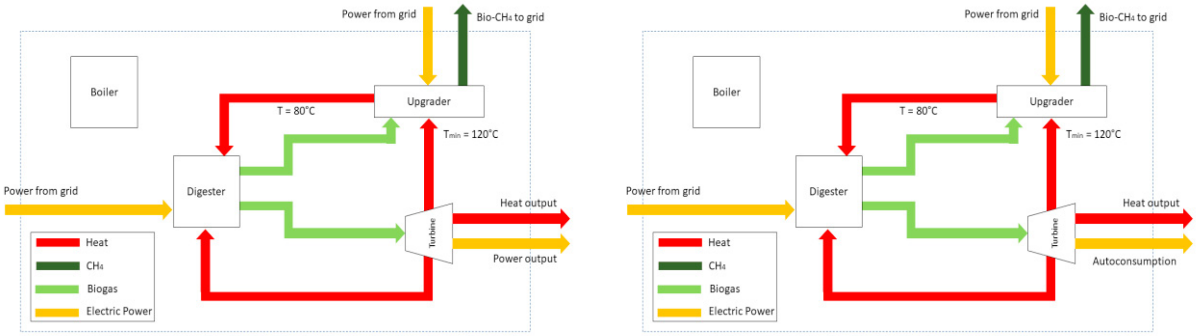


(a) (b)

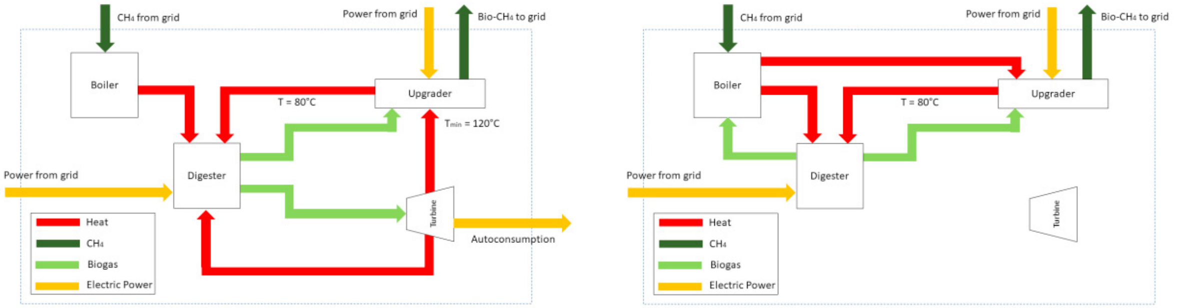
(c) (d)

Fig.3: Heat and mass flows calculated by the simulation

Fig.3 also reports the number of active turbines and the boiler activity, which are deduced from Fig.2 (b). Despite the upgrader production is not strictly dependent from the load condition, the model cannot be considered reliable when the biogas fraction is below 10%, due to the lack of data. Therefore, no reliable information for $F < 10\%$ are provided (hatched region). In Fig.3, four operation patterns are detected according to *F* range as shown in Fig.4.



(a) F < 50% (b) 50% < F < 66%



(c) 66% < F < 86% (d) F > 86%

Fig.4: Workflow of the plant in different F range

When F is below 50% the output balance is positive for each single term (i.e. biomethane, heat and electricity). Above 50%, the turbine efficiency decreases according to Fig.2 (b), and the electricity production is not sufficient to cover internal consumption (see Fig.3 (b)). Until F = 66%, the boiler operation is not necessary. However, when 66% < F < 86% the turbine waste heat cannot sustain the digestion process, and the net heat system output is zero as shown by Fig.3 (a,d). Above F = 85%, not enough biogas input is provided to the turbine, which cannot operate. As shown by Fig.3 (c), the methane consumption is significantly decreased due to the larger availability of biogas available (turbine is switched off) and to the higher thermal efficiency of the boiler in heat production. Fig.3 (a) also shows that the digester heat is provided by the boiler in this phase.

When F is lower than 50 % the plant is tri-generative and provides heat, electricity and bio-methane, Fig.4 (a). On the other hand, the heat and electric production is inversely proportional to the methane production. As shown by the schemes in Fig.4 (b,c,d), when F is around 50% the electric power produced is totally self-consumed. A further increase of F imply that electric energy from the grid is required. Heat and methane production results sustainable with 50% < F < 86%, but after F = 86% the plant can produce only biomethane, and the turbine is shut down. Therefore, the 1-F biogas fraction is used in the boiler for providing heat to the processes. The system results flexible in heat and electricity production, or biogas upgrading. However, due to internal constraints, the contemporary production of a high amount bio-methane and high electrical power is not possible. On the other hand, the system can be seen as an interesting solution to switch the production from one source to another according to the necessity of the grid.

5. Conclusions

A biogas plant, coupled with a biogas upgrader and a micro gas turbine is considered within this research. The plant produces biogas which is used into a micro gas turbine and into a biogas upgrading system. The net outputs of the system are the bio-methane from the biogas upgrader, electricity from mGT and heat from mGT and boiler. The internal mass and energy flows, together with the net system output, are investigated by varying the biogas fraction that is used in the upgrading process. A steady-state analysis was carried out by considering the plant operation in off-design conditions through a Visual Basic routine.

Results show an interesting poly-generation capability of the system in terms of electric power, heat and bio-methane. Contemporary generation of electricity, heat and bio-methane can be only achieved when less than 50% of the biogas produced is used in the upgrading process. For higher values, only heat and methane production can be sustained. Above 86% of the total biogas sent to the upgrading system, only bio-methane can be generated but electric energy from the grid is required. No electricity or bio-methane can be produced at maximum rate at the same time. The system can be seen as an interesting solution to switch the production from electric energy to bio-methane (absorbing energy) according to the necessity of the grid.

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