Combined Heat and Power generation exploiting the biogas production from urban wastewaters treatment: the Genoa case study.

Davide Borelli[1], *Francesco* Devia[1], *Corrado* Schenone[1,*], *Federico* Silenzi[1] and *Luca* Tagliafico[1]

[1] Università degli Studi di Genova, DIME sez. TEC, Via all'Opera Pia 15a, Genova, 16145, Italy

Abstract. Wastewaters treatment with biological processes is widely applied as a reliable solution to water pollution in urban areas. This process produces sludges and process waters. Sludges can be furtherly threated in dedicated plants to produce biogas, that can then be used to produce heat in specific plants, but it is sometimes simply burned using flares. A possible alternative use of biogas is the coupling with a CHP generator which can be used to produce electrical energy and heat. In the present paper, it is investigated the possible exploitation of the sludges produced by a wastewater treatment plant for feeding a sludge treatment plant, both in Genoa (Italy), in order to produce biogas. This work is based on the analysis of available data (2009-2018) provided by the sludge treatment plant technical staff, which showed strong variations in sludge flow rates as a result of the variation of incoming wastewater load. Since the available data is not always correlated with wastewater incoming flows and biogas production, starting from data provided for similar plants operating in Italy, it was possible to estimate a theoretical biogas production which was considered as the reference trend.

1 Introduction

Renewable energies are fundamental to achieve global climate change management targets, as indicated by the Intergovernmental Panel on Climate Change (IPCC), International Energy Agency (IEA), and International Renewable Energy Agency (IRENA) reports [1]. Biogas can be accounted as a possible renewable fuel, substituting standard fossil fuels derivatives. Biogas is originated from the anaerobic digestion of organic materials, and it is thus naturally produced by a natural degradation process. This process can be effectively applied to stabilize the sludges produced by urban wastewater treatment facilities, in dedicated plants. While sometimes the biogas is simply burn in industrial flares, it can be successfully coupled with innovative technologies to achieve more than just thermal energy. For instance, MosayebNezhad et al. [2] studied the possibility of utilizing the biogas produced by a wastewater treatment plant to feed both Solid Oxides Fuel Cells (SOFC) and micro gas turbines to produce electrical power, while covering the digester reactors thermal demand. They found that using this configuration can bring interesting opportunities for cost-effective energy saving. Kluczek [3] proposed a dynamic energy LCA-based study to assess the energy intensity and the environmental impact of a Combined Heat and Power (CHP) system fed with biogas. Hamzehkolaei et al. [4] studied the possibility of exploiting the biogas produced by manure from livestock to replace fossil fuel in order to produce heat and electricity, using a small-scale CHP generator. The authors clearly showed that this technical solution is superior to conventional solutions, both from an economical and from an environmental point of view. More recently, Wang et al. [5] studied the possibility of feeding a SOFC CHP energy system with biogas, using a multiscale hierarchical model. The authors investigated the effects of different quantities (i.e the steam/carbon ratio, biogas composition, and the temperature gradient) on the system performances. Stürmer et al. [6] compared the biogas production from agricultural zones, comparing different technical parameters. The analysis focused on three countries (Switzerland, Germany, and Austria), considering the legal frameworks of each one. A recent study of Calbry-Muzyka et al. [7] focused on the necessity of high-efficiency solutions to remove impurities that are typically present in biogas streams. They carried out an experimental campaign, discussing both operational sampling issues as well as analytical methods ones. Moreover, they analysed the performance of the sorbent-based biogas cleaning system used. In the present framework, this paper describes the possibility of exploiting the biogas produced by an urban sludges treatment facility to feed a CHP generator, producing heat and electricity. The heat can be employed to rise the temperature of a natural gas stream before the expansion operations, in order to prevent temperature drops after the expansion devices. The temperature target is set to 5 [°C], to avoid formation of ice crystals as well as methane hydrates. The analysis is based on real measured data provided by the sludge treatment plant technical staff. The paper discusses about the best CHP operational profile and describes an environmental benefits analysis in terms of avoided carbon dioxide emissions.

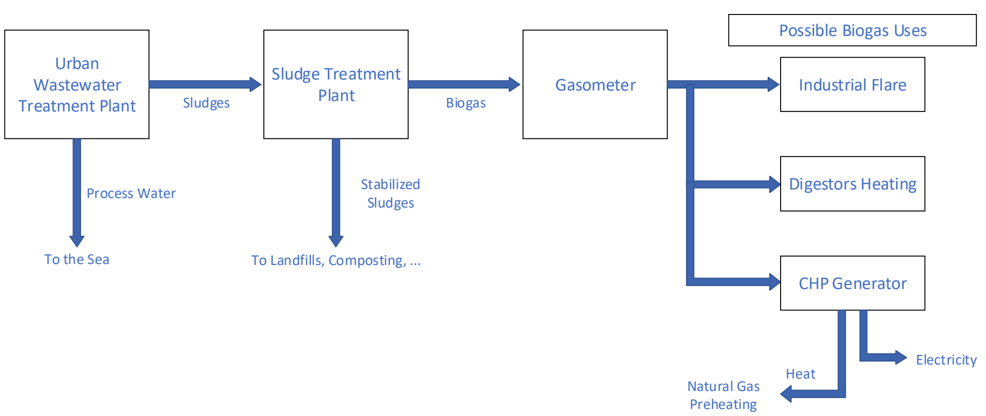

Figure 1: System Description Scheme

2 System Description

In this paragraph, a brief description of the facility, which is located in Genoa (Italy), is presented. Figure 1 illustrates the conceptual system layout. The starting point is an urban wastewater plant where the sewage waters are treated. This plant produces both water and sludge streams, which are disposed of separately. Process waters are discharged far from the coast directly in the sea, while the sludge stream is sent to a dedicated sludge treatment facility with a piping network. The sludge is processed into dedicated anaerobic digestors, producing stabilized sludge and biogas. The stabilization process is necessary to stop the decomposition processes of sludge biomass, allowing to safely dispose of the stabilized sludges in appropriate ways (i.e. landfills). The biogas is usually re-employed to produce heat, necessary to maintain the operativity of the anaerobic digestion process. Close to the sludge treatment facility there is a natural gas pressure reduction station: this process requires a gas preheating phase, which is maintained using part of the natural gas. A peculiarity of this pressure reduction station is the presence of a turboexpander in addition to classic Joule-Thomson valves. This technical choice, albeit more expensive, allows to produce electricity. In this paper, it is investigated the possibility of exploiting the biogas production from the sludge treatment plant to feed a dedicated Combined Heat and Power (CHP) generator to produce electricity and heat. This heat flux can be used to preheat the natural gas to be expanded, avoiding the necessity of burning part of the natural gas itself.

2.1 Biogas Production Scenarios and Analysis

In this paragraph it is presented the biogas production for the considered years. These data have been collected and provided by the technical staff of the sludge treatment plant. The biggest downside of those data is the lack of correlation and the presence of inconsistencies that are impactful on the data robustness. However, those measurements are to be considered a basis upon which is possible to draw hypotheses.

Table 1 reports the yearly biogas production, with the percentual variation with respect to 2009 production. The theoretical availability of biogas has been estimated using a minimum daily production value of 0.015 [Nm^3/day·pe], where [pe] means [population equivalent] which is the organic biodegradable load with a five-day biochemical oxygen demand (BOD5) of 60 [g] per day [8]. Considering that the sludge plant serves at least 250000 [pe], the biogas production is estimated to be 1368750 [Nm^3/y], a value very close to production recorded in 2009. To obtain a reference value it is necessary to make a comparison between the biogas production with respect to the national values.

Table 1: Biogas Production for Considered Years

Year	Nm^3/y	Variation
2009	1361305	-
2010	901289	-33.79%
2011	937595	-31.13%
2012	1032324	-24.17%
2013	779239	-42.76%
2014	595436	-56.26%
2015	860261	-36.81%
2016	753861	-44.62%
2017	570571	-58.09%
2018	308100	-77.37%
2019	32191	-97.64%

Adella et al. [9] analysed many Italian sludge treatment plants, dividing them into classes with typical values in terms of yearly biogas production. Results of this survey are listed in Table 2.

Using a linear extrapolation is possible to give an estimate of the biogas production class equal to 1000000 [Nm^3], obtaining 5.62 [Nm^3/pe], which corresponds to a specific daily production of 0.0153 [Nm^3/day·pe].

3 Energy production of the biogas-powered CHP generator

The energy conversion efficiency values are given by the technical specifications of the CHP generator, and they do not vary by switching the engine feeding between natural gas or biogas. The lower heating value (LHV) of biogas depends on the methane concentration which is usually equal to 60÷65% in volume. Considering a reference LHV value for methane equal to 35.253 [MJ/Nm^3] (or 9.79 [kWh/Nm^3]), the biogas LHV is estimated to be 22.2 [MJ/Nm^3] (or 6.15 [kWh/Nm^3]) on average.

The analysis is carried out considering two different scenarios, which account for different biogas availability.

The first scenario proposed assumes an optimal situation, i.e. the sludge treatment plant working at full capacity with a specific production of 0.015 [Nm^3/pe·d] (with a biogas production equal to 1300000 [Nm^3/y]).

It is possible to consider that the biogas production can be exploited to both feed the CHP generator and to heat the sludge treatment reactors, feeding a gas boiler. This heating process is mandatory to maintain the efficiency of the sludge anaerobic digestion. If the boiler is considered, the amount of biogas available for the CHP generator must be decurted of the appropriate share.

Table 2: National Sludge Treatment Plants Survery – 2016 [9]

Classes - Biogas production per year	**Total population equivalent per class**		**Total biogas production per class**		**Specific biogas production per class**
	N.	**%**	**Nm^3**	**%**	**Nm^3/pe**
≤200000 Nm^3	791483	10.13	910205	3.68	1.15
>200000 Nm^3 ≤500000 Nm^3	2174550	27.83	4055142	16.38	1.86
> 500000 Nm^3	4848211	62.04	19792296	79.94	4.08
Total	**7814244**	100	**24757643**	100	3.17

https://doi.org/10.1051/e3sconf/202131208002

Table 3: Total available biogas to CHP when boiler is considered

Biogas production	Biogas to Boiler	Natural gas to Boiler	Equivalent Biogas to Boiler	Total Biogas	Available biogas to CHP
Nm^3/y	Nm^3/y	Nm^3/y	Nm^3/y	Nm^3/y	Nm^3/y
1300000	217806	87274	138929	356735	943265

Table 4: CHP electrical and thermal power calculation

Biogas LHV	kWh/Nm^3	6.15
Electric efficiency	-	0.39
Thermal efficiency	-	0.48
Only CHP fed with biogas		
Biogas production	Nm^3/y	1300000
Electric Power	MWh/y	3118.0
Thermal Power	MWh/y	3837.6
CHP and BOILER fed with biogas		
Biogas production	Nm^3/y	943265.1
Electric Power	MWh/y	2262.4
Thermal Power	MWh/y	2784.5

3.1 Optimal Scenario Analysis

Like mentioned before, for the optimal scenario, the availability of biogas is set to the theoretical value of 1300000 [Nm^3/y]. Table 3 shows the necessary calculations: the natural gas required to feed the boiler is considered equal to the yearly amount measured by the sludge facility technical office during the 2009 year.

It is now possible to calculate the theoretical thermal and electrical productions: calculation results are reported in Table 4.

At this point, in Table 5 it is possible to analyse the CHP generator electric performances, to assess the effective percentage of utilisation with respect to nominal value (which is equal to 529 [kW]). For this purpose, it is hypothesized to run the generator for 7000 and 5000 [hours/year].

The results show that, overall, the generator is well suited for the proposed application, except for the first case proposed, which resolves in an under-sizing of the device.

Table 5: CHP generator electrical performance analysis

	Biogas Availability	Electric Power	CHP Operating Hours per Year	Theoretical CHP Power	% of CHP nominal Electric Power
	Nm^3/y	MWh/y	h/y	kW	%
CHP ONLY	1300000	3118.0	5000	624	118
			7000	416	84
CHP+BOILER	943265	2262.5	5000	452	86
			7000	302	61

3.2 Coupling the CHP generator to the Natural Gas Pressure Reduction Station

At this point it is possible to select the best CHP generator operating mode to maximize the energy production and the generator working conditions. The thermal requirements for the gas pressure reduction station are given by the facility technical staff, and they are estimated to be equal to 3800.0 [MWh_t/y], while the electrical production from the turboexpander is 3000.0 [MWh_e/y].

Considering the results previously showed in Table 4 and in Table 5 a solid choice would be using the biogas to feed only the CHP generator (operated for 7000 [h/year]), exploiting all the resulting thermal power to preheat the natural gas before the expansion. In this way the CHP generator is working close to the nominal power. It is then possible to calculate the required amount of natural gas necessary to maintain the sludge reactor heating system, considering the remaining share of thermal power still available from the CHP generator. Results of this calculation are listed in Table 6. The natural gas required yearly is reduced by roughly 3800 [Nm^3/y]. On one hand this value may be deemed low, but it must be considered that the thermal energy necessary for the digestors is obtained from combustion, thus degrading chemical energy to thermal energy. Moreover, a reduced natural gas consumption leads to a higher amount available to be sold to the final users. Considering the price of natural gas for Italy in 2021 [10], this results in approximately 3300 [€/y].

Table 6: Digestor Heating System Methane Requirements

Digestor Total Thermal Power	CHP Available Thermal Power	Digestor Required Net Thermal Power	Digestor Required Net natural gas	Digestor natural gas Savings	Economic Gains
MWh/y	MWh/y	MWh/y	Nm^3/y	Nm^3/y	€/y
854.4	37.6	816.8	83433.3	3 840.7	3372.7

Table 7: Avoided Carbon Dioxide Emissions

Environmental Benefits – Avoided CO_2 Emissions		
Emission Factor	307.7	gCO_2/kWh_e
100% of Biogas used for CHP Generator		
total Electrical Power	6118.0	MWh_e/y
total CO_2	1882.5	ton/y
Biogas Used for Feeding Digestor Boiler and CHP Generator		
total Electrical Power	5262.5	MWh_e/y
total CO_2	1619.2	ton/y

4 Environmental Benefits

For a more complete analysis, it is useful to quantify the environmental benefits (in terms of avoided emissions of carbon dioxide) bound to the proposed technical solutions. The pertinent emission factor is 307.7 [gCO_2/kWh_e] [11]. This value is referred to the large-scale electrical production for Italy in 2019, and it can be used to give an estimation of the avoided atmospheric emissions, deriving from both the electricity generated by the turboexpander as well as by the CHP generator. Table 7 summarizes the results obtained.

According to the Environmental Protection Agency, on average, a car can be considered to emit 4.6 [ton CO_2/y] [12], meaning that the avoided carbon dioxide emissions, for the proposed scenarios, are equal to those of about 400 or 350 cars, respectively.

5 Results and Conclusions

In the present paper it was investigated the possibility to exploit the biogas production from an urban wastewater treatment plant to feed a CHP generator, to produce electrical energy and thermal power. The thermal power can be used to preheat a stream of high pressure (24 [bar]) natural gas before expanding it (down to 5 [bar]) in a dedicated turboexpander. The preheating phase is necessary to avoid low temperatures after the expansion and the formation of ice and/or gas hydrates.

A set of measured data (2009-2019) was made available by the sludge plant technical staff, but since the reported data for certain periods were inconsistent, the analysis of biogas production was based on both a statistical comparison as well as on literature data, showing that the results are in good agreement with 2009 measurements. Then, it is possible to calculate the biogas available for feeding the CHP generator, since a share of this gas can be used to substitute the natural gas that is used to regulate the temperature of the sludge digestion reactors. At this point two scenarios are analysed and studied, to find the energy production (thermal and electrical) from the CHP, as well as to find the operating conditions when different functioning time are hypothesized.

The next step was to select the working conditions that suited the most, finding that operating the CHP generator for 7000 [h/year], using all the biogas available to feed it, allows to generate enough thermal power (3837.6 [MWh/y]) to satisfy entirely the pressure reduction station preheating requirements (3800 [MWh/y]). The surplus can be used to heat the sludge digestion reactors, saving up to 3800 [Nm^3/y] of natural gas, equal to roughly 3300 [€/y].

Lastly, it was calculated the associated environmental benefit, in the form of avoided carbon dioxide emissions, thanks to the electrical production of both the turboexpander and the CHP generator. This calculation was performed for the scenarios considered. The avoided CO_2 emissions were calculated to be equal to 1882 [ton/y] if only the CHP is fed with biogas, and about 1600 [ton/y] if the biogas is used also for the digestor heating. Results show that the technical solutions proposed can be fruitful, allowing for reduction in natural gas consumption, economical gains, and reduced emissions.

References

[1] J. Lu and X. Gao, “Biogas: Potential, challenges, and perspectives in a changing China,” *Biomass and Bioenergy*, vol. 150, p. 106127, Jul. 2021, doi: 10.1016/j.biombioe.2021.106127.

[2] M. MosayebNezhad, A. S. Mehr, M. Gandiglio, A. Lanzini, and M. Santarelli, “Techno-economic assessment of biogas-fed CHP hybrid systems in a real wastewater treatment plant,” *Appl. Therm. Eng.*, vol. 129, pp. 1263–1280, Jan. 2018, doi: 10.1016/j.applthermaleng.2017.10.115.

[3] A. Kluczek, “Dynamic energy LCA-based assessment approach to evaluate energy intensity and related impact for the biogas CHP plant as the basis of the environmental view of sustainability,” in *Procedia Manufacturing*, 2018, vol. 21, pp. 297–304, doi: 10.1016/j.promfg.2018.02.124.

[4] F. Teymoori Hamzehkolaei and N. Amjady, “A techno-economic assessment for replacement of conventional fossil fuel based technologies in animal farms with biogas fueled CHP units,” *Renew. Energy*, vol. 118, pp. 602–614, Apr. 2018, doi: 10.1016/j.renene.2017.11.054.

[5] Y. Wang, L. Wehrle, A. Banerjee, Y. Shi, and O. Deutschmann, “Analysis of a biogas-fed SOFC CHP system based on multi-scale hierarchical modeling,” *Renew. Energy*, vol. 163, pp. 78–87, Jan. 2021, doi: 10.1016/j.renene.2020.08.091.

[6] B. Stürmer, D. Leiers, V. Anspach, E. Brügging, D. Scharfy, and T. Wissel, “Agricultural biogas production: A regional comparison of technical parameters,” *Renew. Energy*, vol. 164, pp. 171–182, Feb. 2021, doi: 10.1016/j.renene.2020.09.074.

[7] A. Calbry-Muzyka *et al.*, “Sampling, on-line and off-line measurement of organic silicon compounds at an industrial biogas-fed 175-kWe SOFC plant,” *Renew. Energy*, vol. 177, pp. 61–71, Nov. 2021, doi: 10.1016/j.renene.2021.05.047.

[8] F. Reale, R. Stolica, M. Gaeta, M. Ferri, M. Sarnataro, and V. Vitale, “Analisi e stima quantitativa della potenzialità di produzione energetica da biomassa digeribile a livello regionale . Studio e sviluppo di un modello per unità energetiche Parte 1 - Metodologia,” p. 129, 2009.

[9] L. Adella, G. Aragona, I. Lupica, L. Muto, V. Iaboni, and Pasquale De Stefanis, “Rapporto sul recupero energetico da rifiuti in Italia,” p. 331, 2019.

[10] “Natural gas price statistics - Statistics Explained.” [Online]. Available: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Natural_gas_price_statistics. [Accessed: 03-Jun-2021].

[11] A. Caputo, *Fattori di emissione atmosferica di gas serra nel settore elettrico nazionale e nei principali Paesi Europei*. 2019.

[12] “Greenhouse Gas Emissions from a Typical Passenger Vehicle | Green Vehicle Guide | US EPA.” [Online]. Available: https://www.epa.gov/greenvehicles/greenhouse-gas-emissions-typical-passenger-vehicle. [Accessed: 03-Jun-2021].