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Alternative options for biogas-to-energy: A comparison of electricity and biomethane generation based on the real operation of a production site

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ABSTRACT

The production of biogas for energy generation through the anaerobic digestion is seen as an effective way to exploit local renewable resources as a substitute of fossil fuels. The two main applications that are currently adopted are the electricity production through biogas internal combustion engines, potentially combined with heat recovery, and the biogas upgrading to biomethane, to be supplied to the natural gas infrastructure. This research work contributes to the discussion by analyzing the performance of a real biogas plant in Italy, based on the anaerobic digestion of the organic fraction of municipal solid waste, that has shifted from power generation to biomethane generation. The performance of the two configurations is compared by means of the expected CO_2 emissions savings against the current average electricity in Italy and natural gas carbon intensities, including upstream emissions. The results show that, based on the assumptions of our analysis for the current context of Italy, 1 MWh of biogas from organic fraction of municipal solid waste can lead to 152 $kg_{CO2,eq}$ savings if upgraded to biomethane and injected into the grid, but only to 120 $kg_{CO2,eq}$ when used in engines running in full-electric mode. If the engines are also producing useful heat, emission savings increase, reaching a trade-off with biomethane if 31% of the annual heat production can be recovered. However, considering the expected 2030 electricity mix in Italy, biomethane production would still be the best solution to maximize emission savings. Performance data from real plants are an important resource to develop reliable and effective energy system models, that can support policy makers in defining local energy plans and decarbonization strategies.

1. Introduction

The fight against climate change caused by human activities, and in particular global warming, requires a radical and urgent rethinking of energy systems to protect the climate, ecosystems, biodiversity and human societies [1]. Energy efficiency and low-carbon solutions need to be deployed to replace the current reliance on fossil energy sources.

In accordance with the Paris Agreement in 2015, that aims to limit the increase of global temperature warming to less than 2 °C [2], the European Union has adopted a package of measures, known as the Green Deal, aimed at making the European continent the first carbon-neutral continent by 2050 compared to pre-industrial levels. Promoted by the Green Deal, the Fit-for-55 package aims to achieve the ambitious target of a 55% reduction in emissions by 2030 by adopting or revising a series of measures, including among the others the revision of the Emissions Trading Regulation and the Effort Sharing Regulation, the ReFuel EU Aviation and Maritime plan, the adoption of the amended Renewable Energy Directive (RED III) and the Carbon Border Adjustment Mechanism. Following the war between Ukraine and Russia, which led to a ban on Russian gas, in May 2022 Europe promoted another joint action for safer and more sustainable energy, called Repower EU, with the main objective of diversifying energy supply sources and reducing dependence on external gas suppliers.

Within this framework, different technologies can contribute to the substitution of fossil fuels across final energy uses. The main strategy is the direct end-use electrification coupled with low-carbon power generation, although some applications still require the use of fossil fuels, such as specific transport segments [3,4]. These applications may rely on synthetic gases [5], but also biogas and biomethane could represent an interesting solution. Given the need to reduce dependence on fossil natural gas, as well as the availability of a widespread transmission and distribution gas infrastructure, European policy is encouraging the production of biogas and its upgrading to biomethane. Furthermore, the production of biogas and biomethane from the anaerobic digestion of local biomasses (i.e. OFMSW, manure, sewage sludge, agriculture crops, ...) could play a key role in the transformation of the European

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Nomenclature

CHP	Combined heat and power
DH	District heating
ENTSO-E	European Network of Transmission System Operators for Electricity
ETS	Emissions Trading System
EU	European Union
GHG	Greenhouse gas
ISPRA	Italian Institute for Environmental Protection and Research
NGCC	Natural gas combined cycle
OFMSW	Organic fraction of municipal solid waste

energy system by reducing the dependency on fossil fuels and helping the EU to achieve its environmental targets.

Anaerobic digestion is a well-established technique to produce alternative energy by utilising the biogenic carbon present in biomass and organic waste that is increasingly produced in modern societies. In addition to energy purposes, the process of anaerobic digestion can also enable the utilisation of waste materials that would be critical or costly to dispose of. Furthermore, landfilling is discouraged by the Landfill Directive too (1999/31/EC), as it obliges the Member States to comply with restrictions and quantitative targets for the biodegradable waste sent to landfill. Specifically, the combined production of biogas and biomethane in Europe is expected to increase from 18 billion cubic metres in 2020 to 42 billion cubic metres in 2030 and 125 billion cubic metres in 2050 [6].

1.1. Literature review and scope

As a continent, Europe is currently the largest producer of biogas (around 18 Mtoe in 2018), mainly derived from crops and animal manure, with Germany being by far the largest market, followed by Denmark, France, Italy and the Netherlands [7]. In 2018, around 10% of the biogas produced in Europe was upgraded to biomethane, but by maximizing the total sustainable technical potential of biomethane it could reach a share of 40% of the total gas demand in 2040 [7]. The biomethane market in Europe has been growing rapidly in recent years: from 486 plants in 2018 to 1322 plants in 2023 [8].

The main reason for supporting energy production from biogas is related to the potential $CO_{2,eq}$ emissions savings compared to fossil-based alternatives, although this solution also offers additional benefits, including the exploitation of local resources and bio-waste, the decrease of pollutant emissions and the co-production of other materials such as compost for agronomic use to be spread on soil.

Biogas and biomethane emission savings have been estimated in the literature at country level (e.g. for Germany and the UK [9], Portugal [10] and Italy [11]), based on specific assumptions and available estimates of feedstock potentials.

The GHG emissions of the biogas supply chain depend on different parameters, such as the type of feedstock [12], the use of fertilizers for crop cultivation [13], the electricity consumption [11,13] ad well as fugitive emissions [4,14]. In particular, methane losses have an important impact on global warming, and it is important that the best available techniques are implemented to limit fugitive emissions as much as possible [15,16].

Several studies are available in the literature to assess the performance of CHP generation from biogas [17–19], which also consider different technologies [19,20].

More recently, literature studies have also addressed the upgrading of biogas to biomethane, to be injected into the gas grid [21,22] or to be directly used for transport applications [23].

Some scholars also suggest that biogas could also be used for purposes other than energy production, as for the recovery of high-value chemicals (such as nano calcium carbonate [24]): their simulations confirm the overall lower impact on global warming of this route compared to the energy generation.

Some studies have also addressed the influence of different parameters on the performance of biogas plants, and the differences across configurations, such as [25]. Most of these studies are based on simulations based on nominal design conditions, or in some cases on annual performance data. The availability of operation data from real plants with information on seasonal variability may lead to slightly different performance indicators.

Techno-economic analyses in the literature also confirm that biomethane profitability still depends on incentives [26–28]. However, the inclusion of climate externalities in the energy price, for example through a carbon tax, could make the biomethane competitive in some applications, such as in the transport sector [27].

Therefore, energy production from biogas remains closely linked to economic incentives, as the sector is driven by policy. The choice of the best configuration (such as CHP vs. biogas upgrading) is strongly dictated by the existence of specific incentives. The case of Italy represents an interesting example: until 2018 (Min. Decr. 2 March 2018), biogas energy use was promoted for electricity production, while after that incentives were gradually shifted to biomethane generation as transportation fuel. The latest incentives for biomethane upgrading (Min. Decr. 15 September 2022) strongly support biomethane production, with the target of achieving 2.3 bcm by 2026.

1.2. Novelty and research question

Despite the growing importance of biogas and biomethane production, there is a lack of studies in the literature that provide a temporal profile of real plants operated both in CHP mode -with the combustion of biogas- and in biomethane upgrading mode. Only a few studies have analyzed and compared the emission savings related to the alternative energy use of biogas. Furthermore, the available studies are generally based on simulations and assumptions [29,30], or nominal conditions from manufacturers [31,32], rather than on measured performance of real plants. Data from real plants could provide additional insights on the variability of the operational data over time, providing more useful information compared to default nominal data or average annual indicators. The availability of performance data on a monthly basis is an important addition to compare the two configurations and to accurately assess the carbon emission impact in complex and interconnected energy systems, thanks to the possibility of incorporating the effect of the variability of the plant's performance. Dealing with uncertainty is an important issue in energy systems modeling [33,34], and additional information on the variability of input parameters allows for more robust results.

Moreover, the available literature does not clarify what parameters are the most important in determining the best option to convert available biogas into useful energy carriers. Thus, it is not clear under whose conditions the biogas upgrading to biomethane can outperform CHP generation in terms of $CO_{2,eq}$ emission savings. This is an important issue as these two routes are promoted in many countries worldwide through specific incentive schemes, and the production of biomethane is expected to increase more and more.

To fill this research gap, this paper analyzes monthly operation data from a real 3 MW plant to evaluate the $CO_{2,eq}$ emission savings per 1 MWh of biogas produced when directly used for CHP generation or alternatively upgraded to biomethane to be injected into the natural gas grid. Emission savings are evaluated in comparison to the average carbon intensity of electricity in Italy, heat and fossil natural gas.

The aim of this paper is thus to present a comparison of the performance of the two different configurations based on the real operation of a biogas plant, to highlight the main drivers and parameters that affect the results. The results of the study are based on the specific conditions of the case study, which can be used as a basis for estimating the potential performance of similar plants based on municipal solid waste and with a comparable plant size.

The analysis of performance indicators based on monthly values also allows to provide information on the statistical variability of the performance of the systems. This can be due to several reasons, including the variable characteristics of the feedstock used to produce biogas. The information about the expected uncertainty of the performance indicators for biogas and biomethane plants, obtained from an historical data analysis of a real system, can help to improve the robustness of the results of energy system models, leading to more effective and resilient policy decisions.

The two configurations are compared by quantifying the $CO_{2,eq}$ emissions per unit of available biogas, and analyzing over the available period to highlight the more likely performance as well as the range of variation. Emissions can also be allocated to the energy output by means of the conversion efficiency, based on the actual monitored performance of the plant that has been analyzed. More specifically, in the case of a CHP system, the allocation of the carbon emissions to the two outputs of the system -electricity and heat- is not trivial, as it can be performed with different methodologies and assumptions [35].

2. Materials and methods

The objective of the analysis is to evaluate the performance of a reference biogas plant that has operated in two different configurations, either for the generation of electricity and heat in CHP mode, or for the upgrading of biogas to biomethane. The main characteristics of the system and methodological assumptions are discussed in the following sections.

2.1. Reference plant

The reference plant for this case study is currently operated by a local multi-utility company, ACEA Pinerolese, and it is located in Pinerolo, a town of 35,000 inhabitants in Piedmont, Northern Italy. The plant exploits the organic fraction of municipal solid waste (OFMSW) through anaerobic digestion for the production of biogas. Currently, the plant manages 60,000 t/y of OFMSW, which are processed in two thermophilic anaerobic digesters, characterized by a total working volume of 5000 m^3 (excluding a third one that has been recently built and was not in operation during the time frame of the analysis). Besides, two additional biogas streams are generated from both a wastewater treatment plant serving roughly 150,000 equivalent inhabitants and a nearby landfill. Therefore, the biogas produced from different origins is sent to a gas-holder and temporally stored, before further valorization. In parallel, the co-produced digestate is sent to the composting plant for the stabilization process, in order to recover high quality compost.

Up to 2020, the entire biogas had been exploited to supply 3 combined heat and power (CHP) units (3 MW of output power in total) for the production of electricity and heat, exploting all the biogas streams (OFMSW, wastewater treatment plant and landfill), both partially sold externally once the on-site consumption was ensured. Due to a specific economic evaluation, heat recovery in the CHP units was only carried out via the cooling water, and not via the exhaust gases. In addition to the CHP units, two super-heated water boilers fueled with natural gas were installed as an integration and backup system.

Instead, the plant configuration was fundamentally changed in 2020, shifting from biogas combustion in the CHP units to biogas upgrading to produce biomethane with a nominal output flow up to 800 Sm^3/h, in line with the Italian strategy that envisages the production of transport biofuel, including liquid or gaseous fuels, such as biodiesel and biomethane from biomass. The biogas streams upgraded to biomethane are the ones coming from OFMSW and the wastewater treatment plant, however the latter represents less than 2% (v/v) of all the biogas produced on-site and its contribution is neglected. A multi stage membrane system has been in operation to produce biomethane of suitable quality to be injected into the natural gas grid; however, pretreatments, such as water scrubbing and activated carbons, are required to remove CO_2, H_2S and other impurities. The biogenic CO_2 separated through the upgrading unit is currently released into the atmosphere; however, the company is evaluating further vaporization activities.

The availability of data from several years of operation enables a comparison of monthly performance data in the two configurations, as described in more detail below. The comparison of the monthly plant performance can provide additional information on the variability and uncertainty compared to annual figures, which is an important aspect given the well-known variability of the feedstock and operation conditions of OFMSW anaerobic digestion plants.

2.2. Comparison of the two configurations

The actual organization of the two configurations is represented in Fig. 1.

In the configuration 1, operated until 2020, the three CHP units generate electricity to be supplied to the power grid and heat recovery by exploiting the cooling water of the engines. In this configuration, due to economic reasons, an heat recovery system to exploit the waste heat of the off gases has not been installed. A part of the heat is used in a nearby industrial plant, while another part is supplied to a local district heating network.

The configuration 2, that started its operation in 2022, has the main goal of upgrading biogas to biomethane, to be supplied to the natural gas grid to replace fossil gas in a decarbonization perspective. This change in configuration is in line with the new National incentives that have been described in the previous section. The economic incentives, which are the main driver in this change of configuration, also pushed the operator to maximize the biomethane output to the gas grid (due to the feed-in tariff), and thus avoid using a part of it to generate the heat and electricity required by the upgrading unit.

In both configurations, the available data on biogas production are limited to biogas output, and there is no consistent data over the monitored period on the actual energy consumption of the digesters. For this reason, the emissions associated to the digesters' operation are accounted for by considering literature data, as will be better explained in the following sections.

However, the additional energy consumed by the biomethane upgrading system is a fundamental part of the analysis. Available measured data from the reference plant provide the biomethane production, since heat and electricity consumption are obtained from other sources (i.e. from fossil gas CHP units). As explained above, this anomaly is caused by the formulation of the incentive, that pushes the operator to maximize biomethane supply to the grid. However, many plants instead use a part of the biogas to supply the required heat and electricity to the upgrading unit. To provide a meaningful comparison of the two configurations, we have estimated the adjusted biomethane production by calculating the share of biogas that would be required to run a CHP engine that sustains the upgrading process, i.e. without the need for external sources of heat and electricity. This is the case in many plants, especially when converting biogas power plants to upgrading plants, as engines are already in place and can be used to support the additional auxiliary energy consumption required by the upgrading system.

As a result, we have considered in our analysis the two adjusted configurations represented in Fig. 2. Furthermore, in addition to the modification already discussed for configuration 2, we have also adjusted configuration 1 to consider the heat recovery from the hot off-gases of the CHP units, which is a common practice in the industry. To account for the potential use of this additional available heat, the total heat recovery was estimated as the difference between a reference total CHP efficiency and the actual electric efficiency, since a decrease in electric efficiency is generally compensated by an increase of heat

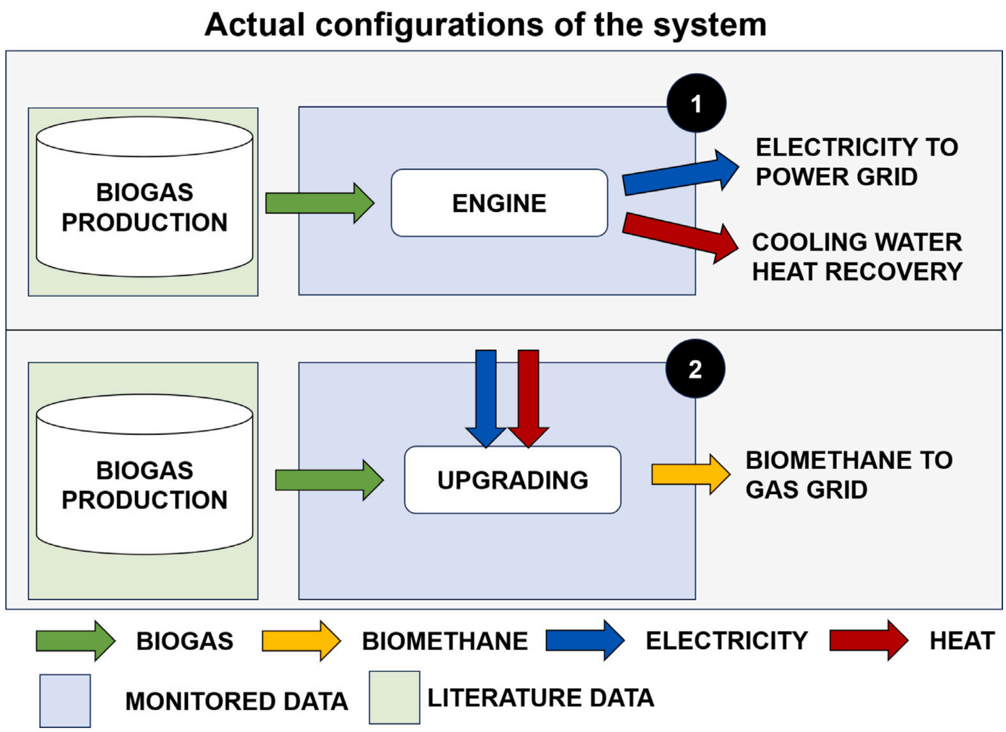

Fig. 1. Actual configurations of the system.

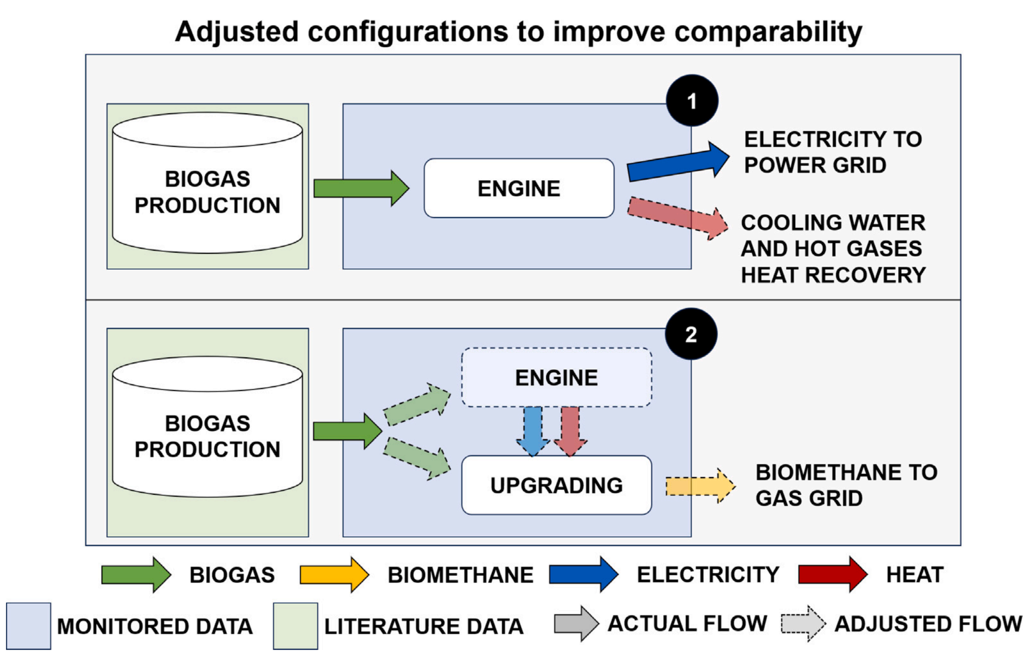

Fig. 2. Adjusted configurations of the system to improve comparability.

losses that can be recovered. A value of 80% was assumed as the reference value for the overall efficiency of CHP. This value is in line with the actual operation of CHP systems based on internal combustion engines, as demonstrated by the results of the operation of 120 CHP units of a comparable power analyzed in [35] (mean total efficiency 79.2%, median total efficiency 80.9%).

The system boundaries under consideration are those represented by the light blue squares in Fig. 2, i.e. considering the biogas input flow and the electricity, heat and biomethane output flows.

The additional energy consumption for the production of the biogas in the anaerobic digestion plant is not being taken into account. Electricity and heat consumption data are not available for the entire period, and this would limit the effectiveness of the analysis. However, energy consumption for the anaerobic digestion process is an important aspect in terms of emissions. For this reason, we have considered these upstream emissions using available data from literature, as better described in the following section.

2.3. Analysis of the system performance

The comparison of the two configurations is based on the energy conversion performance as well as on the $CO_{2,eq}$ emission savings when using biogas to produce electricity (and heat) or biomethane to be supplied to the distribution grids.

The energy flows are obtained from the monthly recorded data for the two configurations. Available data span three years for the configuration 1 and two years for the configuration 2. The measured data that are used in this analysis are the following:

- Energy content of the biogas produced in the system (on a monthly basis, expressed in MWh);
- Electricity produced by the CHP engines, measured in medium voltage after the transformer (monthly basis, in MWh);
- Heat recovered by the engines and supplied to the local district heating network (monthly basis, in MWh);
- Biomethane produced by the upgrading system and injected into the distribution network (monthly basis, in MWh).

The energy conversion efficiency is calculated for both configurations as the ratio between the output energy flows and the input biogas flow. Monthly values are analyzed taking into account their statistical distribution, with a particular attention to the median values and the first and third quartiles, although the minimum and maximum values are also presented and discussed. The choice of focusing on the energy produced per unit of input biogas also allows to decouple the results from nominal input and output values, which are often not representative of the actual operation of the plant.

The evaluation of $CO_{2,eq}$ emissions savings are evaluated by comparing the estimated emissions of the biogas plant with the emissions intensity of the electricity in the power grid and the fossil natural gas. Furthermore, the heat recovery from the CHP unit is also evaluated, by comparing its supply to a local district heating network (with heat losses of 15%, in line with average values for Italy [35]) against an alternative option where heat is generated by a large fossil gas boiler with a 90% conversion efficiency (which is in line with the reference efficiency values used in the National regulation).

The $CO_{2,eq}$ emissions per unit of biogas produced in the anaerobic digestion process come from a detailed study by the Joint Research Center, the JEC WTT study [12]. The value of estimated $CO_{2,eq}$ emissions for the anaerobic digestion of MSW is equal to 14.1 kg per MWh of produced biogas. These upstream emissions, that lie outside the energy system under analysis, are nevertheless included in our calculation to provide a fair comparison with the alternatives that we are considering, i.e. the electricity and natural gas, as better described below.

The emission intensity for the electricity produced from biogas is evaluated against the average electricity intensity of power generation in Italy [36]. This analysis is performed on the basis of the latest available official data (i.e. for 2022, equal to 308.9 g_{CO2}/kWh), compared to the estimated 2030 data (based on the National targets of renewable penetration in the power sector, estimated equal to 120 g_{CO2}/kWh) and to the current national emission factor for NGCC plants in operation in Italy (391.6 g_{CO2}/kWh). This comparison highlights the potential impact of different electricity mixes.

The future emission factor for electricity in Italy is estimated by the authors based on the planned electricity mix in the latest National Renewable Energy Action Plan of Italy [37]. The 2030 objective aims at reaching 63.4% of power generation from RES, up from 37.1% in 2022. This very challenging improvement is linked to the plan of reaching a total installed capacity of 28 GW for wind (compared to 12 GW in 2022) and 79 GW for solar (compared to 25 GW in 2022). These targets are very challenging, but since they are the official target they are used as reference for a future situation in line with decarbonization scenarios.

In addition to the direct emissions related to electricity generation from different sources, the upstream emissions for electricity generation are available at country level from a report of the International Energy Agency [38]. The upstream emissions for electricity generation in Italy in 2022 are estimated to be 73.6 $g_{CO2,eq}$/kWh, while the values for NGCC are around 82 $g_{CO2,eq}$/kWh, and the values for Italy in the 2030 electricity mix are estimated by the authors at 24 $g_{CO2,eq}$/kWh (considering countries with similar emission intensities to the one to be reached by Italy).

Table 1
List of $CO_{2,eq}$ emission factors considered in the analysis.

$CO_{2,eq}$ emission factor (g/kWh)	Value	Reference
Emissions for the anaerobic digestion of OFMSW	14.1	[12]
Direct emissions - electricity mix (Italy, 2022)	308.9	[36]
Direct emissions - NGCC (Italy, 2022)	391.6	[36]
Direct emissions - electricity mix (Italy, 2030)	120	Based on [37]
Upstream emissions - electricity mix (Italy, 2022)	73.6	[38]
Upstream emissions - NGCC (Italy, 2022)	82	[38]
Upstream emissions - electricity mix (Italy, 2030)	24	Based on [38]
Direct emissions - natural gas	203.5	[39]
Upstream emissions - natural gas	32.4	[12]

The reference emission for the natural gas on the grid is set to 56.518 t_{CO2}/TJ, based on a recent publication of the average composition of natural gas in Italy [39]. The upstream emissions for natural gas are estimated at 32.4 $g_{CO2,eq}$/kWh at European level [12].

The $CO_{2,eq}$ emission factors described above are summarized in Table 1.

This work is focused on the effect of the real performance of the system under analysis. A detailed life cycle assessment (LCA) is beyond the scope of this work, as it would require several data that are not available to provide a meaningful and reliable result. For this reason, the comparison of both the system under analysis and the electricity and natural gas into the grid are considering direct emissions and upstream emissions, but without including the contribution of the materials required to build the energy systems and the infrastructure, nor any emission associated with their commissioning and decommissioning.

Losses in the distribution network were neglected for both the natural gas and electricity grid, as it is assumed that the energy would be consumed by users close to the production site. They were therefore not taken into account in the analysis.

The comparison also includes an evaluation of the share of heat that can be recovered on an annual basis. This is usually dependent on the type of heat demand (often associated to district heating networks for space heating) as well as the size of the CHP plant compared to the peak demand of the heat users. Thus, results are presented for variable annual utilization factors of the heat produced by the CHP system.

3. Results

3.1. Monthly performance of the actual configurations

The available data on CHP configuration spans three years (see Fig. 3).

During this period, the monthly biogas production varied in the range 2.7–4.1 GWh, with a median value of 3.4 GWh. The medium-voltage electricity output of the system had a median monthly generation of 1.2 GWh, with ranges from a minimum of 1.0 GWh to a maximum of 1.4 GWh. The highest variation is seen in heat recovery, ranging from a minimum of 149 MWh to a maximum of 621 MWh, mainly due to the seasonal variation in heat demand from users. However, as already mentioned in the previous sections, the system was equipped to recover only a part of the available heat from the CHP engines, due to economic reasons.

In 2020–2021, the plant was converted for the production of biomethane, and monitored data on two full years of operation are available (see Fig. 4). In this period, the input monthly gas reached a median value of 3.8 GWh, in a range of 3.0–4.1 GWh, which is comparable to the CHP configuration. However, in some specific months the plant had some operation problems related to the settings of the upgrading system, leading to a lower biomethane output for a total of three months of the two analyzed years. Biomethane output

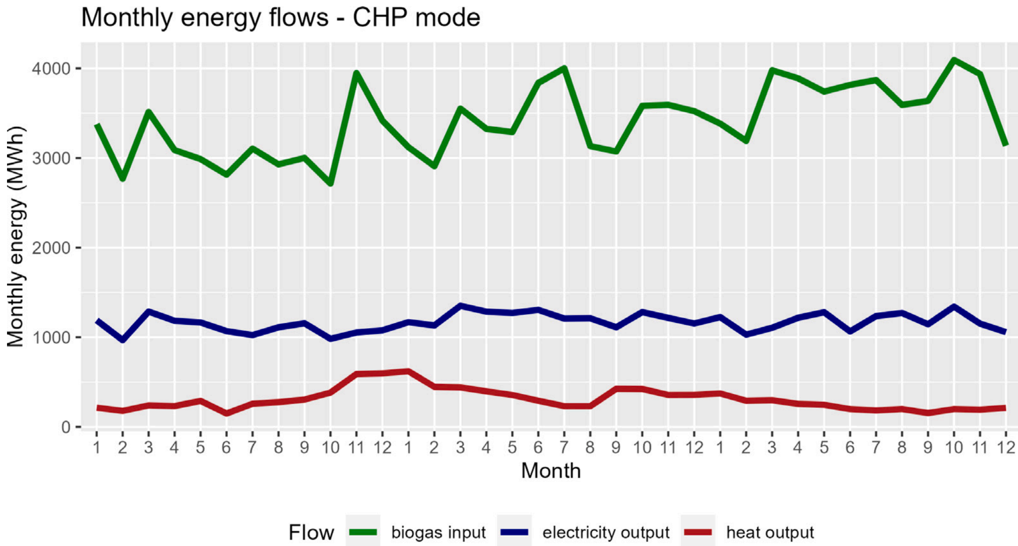

Fig. 3. Actual energy flows for the reference plant, CHP mode, three years of operation.

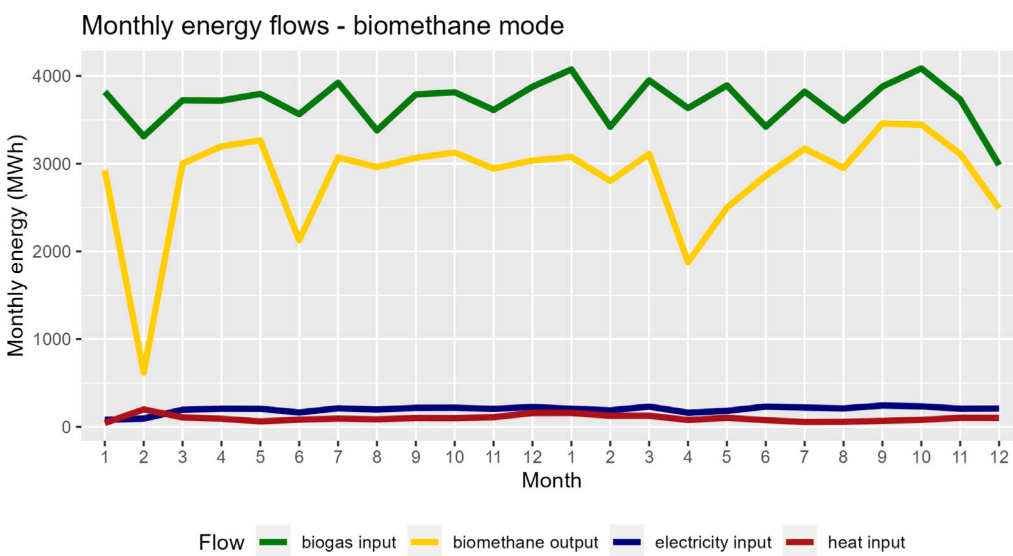

Fig. 4. Actual energy flows for the reference plant, biomethane mode, two years of operation.

was in these months as low as 0.6 GWh, but in general the performance has been much higher, with a median value of 3.0 GWh, and first and third quartiles of 2.9 and 3.1 GWh (and a maximum of 3.5 GWh). This tendency confirms that these months with lower biomethane generation were rather an exception, but they also show that some unexpected operation may happen, especially in the first years of operation of a newly-converted plant.

3.2. Comparison of the two actual configurations

Fig. 5 shows a comparison of the monthly gross energy production per unit of biogas during the operation of the plant over five years in the two different configurations. When operating in CHP mode, median values over each year of operation range from 0.321 to 0.368, and a general median value of 0.351. The heat recovered and supplied to local users has been much lower, with a median value of 0.080 MWh per MWh of input biogas (and annual median values from 0.061 to 0.113). Conversely, when upgrading biogas to biomethane, the monthly conversion efficiency from biogas input to gross biomethane output showed a median value of 0.817 (with median values of 0.808 and 0.832 for the two years of operation).

As discussed in the previous section, biomethane upgrading performance has seen very low conversion values in some specific months, due to some specific operational issues with the upgrading process, that have now been solved.

The results presented in Fig. 5 were limited to the gross energy output of the plant. However, as discussed in the methodology section, some additional calculations are needed to obtain results that can be further generalized to describe the performance of biogas plants.

3.3. Comparison of the two adjusted configurations

The upgrading of biogas to biomethane requires an additional consumption of heat and electricity. Taking this additional energy consumption into account leads to the adjusted biomethane production represented in Fig. 6, whose median efficiency is 70.4%, which is 14% lower than the gross production presented before (and annual median values are 13%–15% lower).

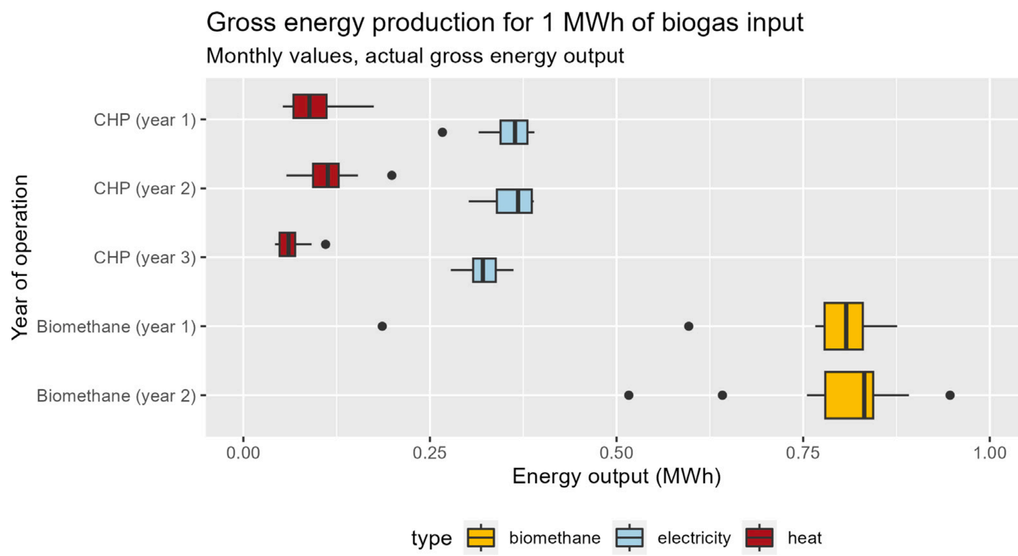

Fig. 5. Actual configurations: comparison of the distributions of gross electricity, heat and biomethane output per MWh of biogas input.

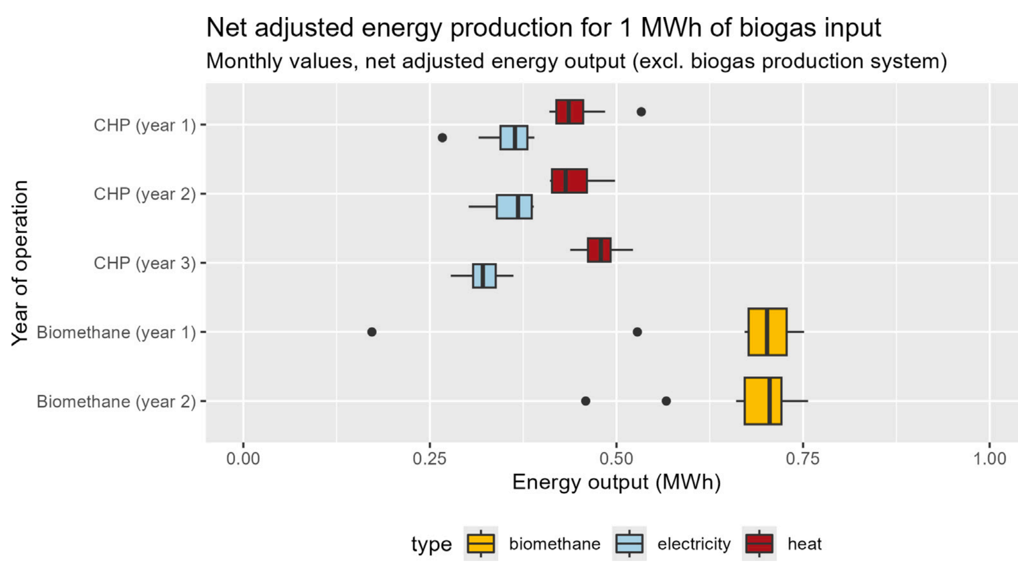

Fig. 6. Adjusted configurations: comparison of the distributions of monthly electricity, heat and biomethane output per MWh of biogas input. The dots represent the outliers in the distributions.

Also, when using biogas to supply the CHP system, the amount of heat that could be recovered is higher than the actual amount that is currently recovered, since the recovery system does not include the energy recovery from the hot gases. Thus, heat production values shown in Fig. 6 are much higher than those of Fig. 5. Furthermore, it is important to remember that, although biomethane and electricity can be supplied to the distribution networks and are likely consumed by other users all over the year, heat demand is significantly affected by seasonality, and in some months the useful heat demand could thus be lower than the heat generation in the plant.

A synthesis of the distribution of the adjusted conversion ratios for the plant is presented in Table 2. Looking only at the conversion efficiency, since both electricity and biomethane are generally used throughout the year, the crucial aspect for the comparison of the two configurations is the amount of heat that can be used over the year. The first and third quartiles of the distributions show differences that are below 8% compared to the median values, which means that the performance of the system is comparable to the median values in most months (as already noticeable in Fig. 6), although with some variability.

Table 2
Distribution of monthly adjusted conversion ratios from total biogas input to electricity, heat and biomethane output flows.

Config.	Output	Conversion efficiency				
		Median	1st quartile	3rd quartile	Min	Max
1	Electricity	0.351	0.322	0.379	0.267	0.390
1	Heat	0.449	0.421	0.478	0.410	0.533
2	Biomethane	0.704	0.675	0.724	0.172	0.789

The median electric efficiency of the CHP configuration is 35.1%, with a variability of −8.3% for the lower quartile and +8.0% for the higher quartile, while the thermal efficiency ranges from −2.8% to +6.5% in the inter-quartile range, against a median value of 44.9%. The relative variability is lower for the biomethane configuration, with quartile differences of −4.1% and + 2.8% respectively compared to a median efficiency of 70.4%. These median values and uncertainty intervals can be of use to characterize the performance of biogas plants, leading to a better accuracy than when using nominal performance indicators.

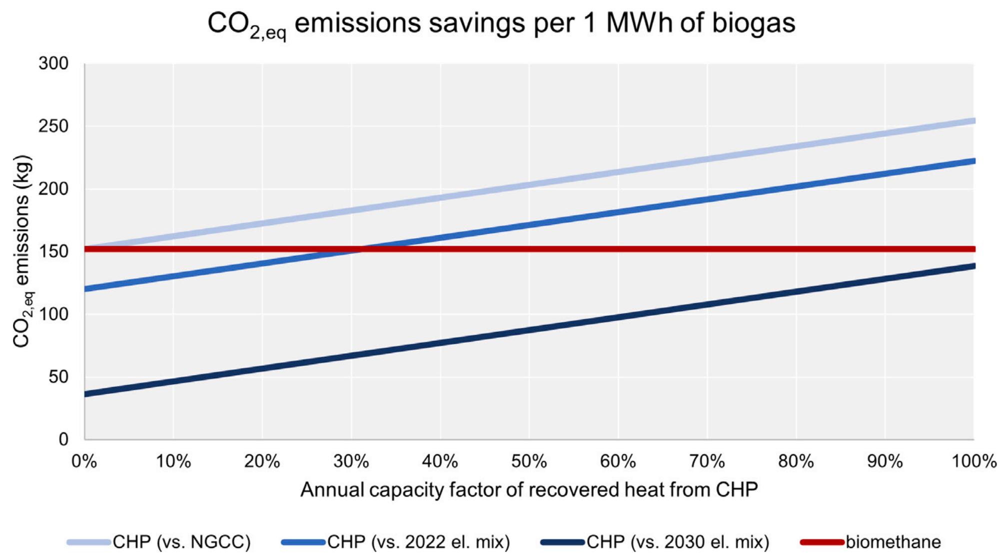

Fig. 7. Comparison of emission savings estimates for electricity and biomethane supplied to the distribution networks, with different electricity generation alternatives and annual heat demand load factors.

However, as already noted, some specific problems on the upgrading system have caused in some months a very low performance for the biomethane configuration. This issue has been related to the set-up of the plant, and it should not affect the future operation of the system.

3.4. Effects on emission savings

However, in addition to the energy conversion efficiency, potential CO_2 emission savings that can be achieved should also be taken into account when comparing the two solutions, as GHG emissions are the main target of EU and national strategies to decarbonize the energy system.

A comparison of emission savings that can be obtained by electricity generation and biomethane generation are compared in Fig. 7. The main variables that are included into the chart, and that affect the comparison, are the alternative generation option for electricity (i.e. the national electricity mix or the comparison with NGCC, which is the marginal technology for most of the hours in the Italian electricity wholesale market) and the amount of heat that can be exploited as useful heat (supplied to a local DH network). The results of Fig. 7 are based on median conversion values for electricity, heat and biomethane, considering the biogas generation from OFMSW in the case study under analysis.

The results show that the supply of biomethane to the distribution grid can lead to 151.9 $kg_{CO2,eq}$ savings per MWh of input biogas. Biomethane generation generally leads to higher emission savings than electricity-only generation from biogas when considering the average electricity mixes in Italy in 2022 and 2030. The emission savings of electricity generation from biogas, without heat recovery, range from 36.4 $kg_{CO2,eq}/MWh_{biogas}$ for the 2030 estimated electricity mix to 152.1 $kg_{CO2,eq}/MWh_{biogas}$ when compared to power generation from large NGCC plants. Considering the current national electricity mix, power generation from biogas leads to 120.2 $kg_{CO2,eq}/MWh_{biogas}$ savings, but it can become more climate friendly than biomethane generation if at least 31% of the annual heat can be recovered. Conversely, with respect to the expected 2030 electricity mix, biomethane production would always remain the best solution to maximize emission savings. It is important to remember that these results are applicable to Italy, as other countries with different electricity mixes will have variable results for the comparison of electricity from biogas and biomethane upgrading.

However, the comparison leads to a different outcome when considering the comparison with NGCC plants, which are the most common marginal technology for power generation in Italy, instead of the average electricity mix. The results of this analysis show that when considering the substitution of electricity generation from NGCC, biogas would lead to higher emission savings when used in a CHP unit rather than for its upgrade to biogas. Emission savings are in line with biomethane production when operating in full-electric mode, but a heat recovery of 30%would lead to 20% higher emission savings compared to biomethane, and this would increase up to 68% with a 100% heat recovery.

The emission savings presented in the previous chart have been evaluated in the Italian context, considering the current and future electricity mixes of the national grid. These results can also be generalized by expressing them with respect to the $CO_{2,eq}$ emissions intensity of the electricity. Fig. 8 shows the dependence of $CO_{2,eq}$ emissions savings per MWh of biogas with respect to the direct electricity emissions intensity of the grid (upstream emissions for electricity have been scaled accordingly).

Results show that countries with electricity mixes higher than 390 g/kWh would always obtain higher savings when using biogas for power generation instead of upgrading it to biomethane, irrespective of the amount of heat that is recovered. For electricity mixes between and 370 g/kWh the convenience of power generation from biogas against upgrading to biomethane depends on the share of heat that is recovered, while for electricity mixes lower than 130 g/kWh biomethane always appears to be the best option in terms of emission savings. It is also interesting to note that for a fully decarbonized electricity mix power generation from biogas would result in higher emissions, due to the contribution of upgrading.

4. Discussion

The results of this case study are based on the operation of an OFMSW anaerobic digestion plant that has been operated both for CHP production and for biomethane upgrading. The comparison of the performance of these two configurations, based on specific indicators on their energy efficiency and impact on global warming from greenhouse gas emissions, can serve as a basis for policy decisions dealing with similar plants. However, the performance indicators that have been presented and discussed can lead to different values for plants running on different feedstocks, of different sizes and with different upgrading technologies and other technical parameters. Although Primary Energy Savings (PES) indicator is a key parameter for the performance of CHP systems, this aspect is not the main core of this work and, together

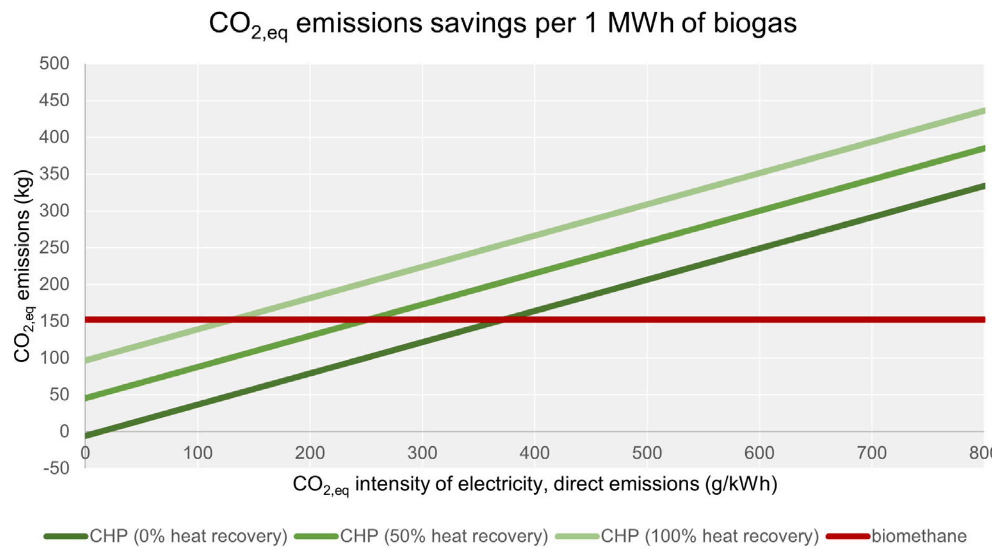

Fig. 8. Comparison of emission savings estimates for electricity and biomethane supplied to the distribution networks, with different electricity carbon intensity levels.

with the performance of different upgrading plants, will be addressed in future works dealing the assessment of the variability related to these parameters.

This paper has focused on the biomethane injection into the existing natural gas grid, as a reference solution that is being considered and used by different plants. However, biomethane could also be supplied as liquefied biomethane or pressurized at high pressure. This is particularly common when it is supplied to transportation users, such as trucks or ships that may use LNG, or light-duty vehicles and buses that use CNG. These options are particularly suitable for the Italian context, as fossil gas is already being used in many applications in transport, well above the average penetration levels in the EU. In these cases, additional electricity consumption is required for liquefaction or compression, but the analysis should also consider the alternative technology that biomethane is substituting.

This paper evaluated the energy efficiency and emissions of these two configurations, to limit the analysis to the technical and environmental dimensions. An economic analysis would also be important, as economic revenues are of course the main reason for choosing a solution over another. However, both biogas CHP plants and upgrading to biomethane have been and are currently subject to significant incentive schemes, which are now the main aspect that guarantees the economic sustainability of these plants. This may have also an indirect impact on the costs of these plants, due to the alteration of the market conditions and competitiveness with other technologies. For this reason, we preferred to avoid an economic analysis that would have been too much related to the specific incentive schemes, and we focused instead on the technical performance of the system.

The comparison of the emission savings of electricity generation from biogas against biogas upgrading to biomethane have been evaluated in the context of Italy, which is the site of the plant. However, as discussed when presenting the results, in countries with higher levels of electricity carbon intensity the best way to save emissions could be to use the available biogas for electricity production. Upgrading to biomethane should instead be preferred for countries that already have a lower carbon intensity of electricity, which means that other renewable or low-carbon sources are already in use in the power generation sector. The evaluation should also consider the trend of electricity carbon intensity, which is quickly decreasing in many countries.

The choice of a solution over another should also be evaluated in a broader framework, as in addition to emission savings also other priorities should be incorporated in energy planning. Examples may include energy security and grid balancing, and biomethane could be potentially used in the existing fossil gas storage systems to partially compensate for seasonal variations of other electricity sources. Furthermore, the results also depend on the alternative electricity generation that is substituted by biogas plants: the results of Fig. 7 clearly show the effect of considering average or marginal carbon intensities of electricity. Future research could also evaluate the possibility of operating the same plant in different configurations depending on specific external conditions, such as the carbon intensity of the power grid at a specific time.

While the results that are presented in this work are valid for the case study under analysis and potentially for similar plants, the choice of the actual configuration can also be very site-specific, as additional aspects may play an important role. These include the distance from the electricity and gas networks, that may push the operators towards a specific option. The electricity network is often the most developed, although the increasing diffusion of distributed electricity generation plants may in some cases lead to limitations in connecting additional capacity to the distribution grid. Finally, in some regions, biomethane injection into the grid in summer could also represent a problem if the gas distribution grid is facing a very low demand from the users.

The analysis presented in this work has been focused on the single plant, but of course the choice of the configuration is also related to the number of plants in a region and the planned utilization of the energy carriers that are produced. A further conversion of the produced biomethane in electricity in high-efficiency NGCC plants could seem worse than the direct electricity generation from biogas, although such a choice may provide a larger flexibility in the operation of the plant. On the other hand, the biomethane needed to supply a large NGCC plant would require the operation of many distributed biogas plants, and additional analyses are needed to assess the availability of feedstock and the actual pros and cons of such a solution.

The results of this study are also subject to some limitations and assumptions. While we rely on many months of operation, the results are limited to a single plant, which means that it is not possible to assess the influence of some potential parameters of interest (such as the size of the plant, the biomethane upgrading technology and its distribution strategy). A future research work may compare the performance of different plants to address this specific aspect. The analysis is not currently considering real data for the estimation of the energy consumption for the anaerobic digestion plant (due to a lack of data), that could vary from a site to another, also depending on the type of waste that is treated and the technologies that are used. However, its effects on emissions has been incorporated into the analysis by considering average emissions for biogas production available in the literature.

5. Conclusions

This works presents an analysis of the performance of a real biogas plant by considering its energy efficiency and potential $CO_{2,eq}$ emission savings. The plant is evaluated in two different configurations that have been in operation in the last years: the CHP generation from available biogas, and the biogas upgrading to biomethane.

The analysis is based on measured monthly values for input and output energy flows over a total of five years of operation. These results can be of use for researchers that need to incorporate the variability and uncertainty of the performance of biogas plants. The indicators have been adjusted to be representative for biogas plants in general, by means of an evaluation against different levels of electricity mixes and annual capacity factors for the heat recovered from CHP.

The results show that the possibility of recovering heat from CHP is a crucial aspect that drives the comparison of the two plant configurations. Our estimates show that the emissions savings that can be obtained from 1 MWh of biogas produced from OFMSW reach 151.9 kg_{CO2} when biomethane is injected into the grid. The performance of electricity production strongly depends on the amount of heat that can be exploited. With the current Italian electricity mix as a comparison, producing electricity from biogas leads to higher emission savings compared to its upgrading to biomethane, as long as at least 31% of the annual heat production can be used. However, considering the expected decrease of the Italian electricity mix following the current decarbonization targets, biomethane upgrading would become the best option in terms of emission savings, irrespective on the amount of heat that can be recovered and used.

In the current regulatory framework, many biogas plants are being converted to biomethane upgrading plants in Italy, mostly due to the economic incentives that are in place. The results of this study confirm the potential benefits in terms of emission savings, especially compared to a power grid in which the share of renewable generation is expected to significantly increase. Future research work should thus analyze further operational data of additional biogas plants to confirm the positive benefits that are being anticipated in terms of emission savings.

CRediT authorship contribution statement

Viviana Negro: Writing – review & editing, Writing – original draft, Methodology, Data curation, Conceptualization. **Michel Noussan:** Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Formal analysis, Data curation, Conceptualization. **David Chiaramonti:** Writing – review & editing, Supervision, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

The authors do not have permission to share data.

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