

EFFICIENCY AND ENVIRONMENTAL IMPACTS OF BIOGAS VS. BIOMETHANE IN COMBINED HEAT AND POWER APPLICATIONS

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ABSTRACT

The increasing demand for low-carbon energy carriers is increasingly driven by the urgent need to address climate change and reduce the environmental impact of conventional energy systems. In this context, biogas and biomethane are emerging as key renewable solutions within the global energy transition. This study investigates a biogas plant located in northern Italy equipped with an Ingenia-patented system designed to reduce ammoniacal nitrogen and CO₂, thereby improving biogas quality and enabling its upgrade to biomethane. A comparative energy and environmental analyses are carried out to evaluate the use of either biogas or biomethane as fuels in combined heat and power units having an electrical and thermal power output of 410 kW and 400 kW, respectively, focusing on primary energy requirements and greenhouse gas emissions comparison. Results show that biomethane, due to its higher lower heating value, requires less fuel consumption than biogas to produce the same useful energy output (both electrical and thermal), thereby improving overall system efficiency. Specifically, the lower primary energy demand of biomethane leads to annual savings of up to 1.35 GWh. Moreover, if biomethane production matches the volume of biogas needed to deliver the same useful energy, the excess biomethane, approximately 142,400 Sm³, can be injected into the gas grid, contributing to enhanced national energy self-sufficiency. From an environmental perspective, results show that biogas use achieves an annual emissions reduction of approximately 880 tCO₂ equivalent, while biomethane slightly improves the performance, reaching about 900 tCO₂ equivalent avoided per year. Overall, the study demonstrates that biomethane offers enhanced energy efficiency and climate benefits, confirming its role as a valuable option for integrated low-carbon energy systems.

Keywords: biogas, biomethane, combined heat and power, CO₂ emissions reduction, energy systems, renewable energy.

1 INTRODUCTION

In the context of growing global concern over climate change and the urgent need to reduce greenhouse gas emissions, bioenergy, particularly biogas, plays a strategic role in achieving decarbonisation targets. Unlike many renewable sources, biogas is a dispatchable energy resource, offering controllable and reliable power generation that can be integrated into existing energy systems to support grid stability and energy security. This flexibility makes biogas a valuable complement to intermittent renewables and a key enabler of a resilient low-carbon energy transition [1]. Moreover, biogas production contributes to environmental sustainability by valorising organic waste streams such as agricultural residues, livestock manure, food waste and sewage sludge [2]. Through controlled anaerobic digestion, it captures methane that would otherwise escape into the atmosphere, a gas with 28 times the global warming potential of CO₂ over 100 years [3].

In this regard, Cignini et al. demonstrated that biomethane can be used in conventional compressed natural gas (CNG) vehicles without affecting performance or emissions, showing up to 79% lower greenhouse gas (GHG) emissions compared to fossil natural gas [4]. Noussan analysed the potential of biomethane for decarbonising urban public transport in Turin, showing that its integration into the bus fleet could reduce CO₂ emissions by up to



71%, and up to 75% when combined with electric buses [5]. However, to the authors' knowledge, comparatively fewer studies have examined biogas upgrading to biomethane for combined heat and power (CHP) applications, particularly considering energy efficiency improvements, a detailed primary energy analysis, and the environmental benefits of near-zero CO₂ emissions.

This study addresses this gap by investigating a biogas plant in northern Italy equipped with an Ingenia-patented system that simultaneously reduces ammoniacal nitrogen and removes CO₂, upgrading biogas to high-quality biomethane. This approach provides two key advantages over conventional biogas utilisation: (i) Enhanced energy efficiency in the CHP unit, as biomethane's low CO₂ content and combustion properties similar to natural gas improve energy conversion; and (ii) Near-zero direct CO₂ emissions, with surplus biomethane potentially available for injection into the natural gas grid, supporting national energy self-sufficiency. By linking biogas upgrading to CHP performance and environmental gains, this work provides a novel perspective compared to existing literature, which largely focuses on transport applications. The analysis quantifies overall energy efficiency, potential annual primary energy savings and GHG emission reductions, using standard emission factors from Italian Legislative Decree 199/2021.

The paper is organised as follows: Section 2 describes the biogas plant and outlines the benefits of integrating the Ingenia-patented system; Section 3 presents the case study; Section 4 discusses the results and related comments; and Section 5 provides conclusions and future development perspectives.

2 PATENTED TECHNOLOGY AND BIOGAS PLANT DESCRIPTION

This section first introduces the Ingenia-patented biogas purification and upgrading technology in biomethane, highlighting its ability to remove CO₂ and reduce ammoniacal nitrogen to enhance biogas quality and enable efficient biomethane production. It then describes the northern Italy biogas plant used as a case study, outlining its configuration, feedstock and integration with the patented system.

2.1 Ingenia technology

The Ingenia technology consists of three main sections. The first is the alkaline hydrolysis section, where biomass is mixed with calcium or sodium hydroxide to raise the pH, while recycled water is added to dilute the feedstock and obtain sludge with the desired dry matter content. This section carries out a thermo-alkaline treatment aimed at breaking down the complex molecules present in the biomass into simpler, more bioavailable compounds. Since hydrolysis is an integral part of the anaerobic digestion process, its optimisation can significantly enhance both the quantity and quality of the biogas produced. Analyses conducted over a 2-year period on the pilot plant provided results from methanation tests performed on samples taken before and after hydrolysis, under both mesophilic (20°C to 40°C) and thermophilic (45°C to 70°C) conditions. Under mesophilic condition, the average specific biogas production (SBP) prior to hydrolysis is approximately 0.19 S m³/kgTVS, with a specific methane production (SMP) of around 0.10 S m³/kgTVS, corresponding to a methane content of about 55% in the biogas. Following the hydrolysis process, a significant increase in methane production is observed: SBP reaches approximately 0.51 S m³/kgTVS, while SMP rises to 0.29 S m³/kgTVS, corresponding to a 185% increase [6]. Under thermophilic conditions, the increase is less pronounced, as the pre-hydrolysis values are already higher, with an SBP of 0.29 S m³/kgTVS and an SMP of 0.18 S m³/kgTVS. After hydrolysis, the SBP reaches 0.45 S m³/kgTVS and SMP increases to 0.27 S m³/kgTVS,

corresponding to percentage increases of 59% and 54%, respectively [6]. This section also contributes to the reduction of the hydraulic retention time (HRT), which is the time required for the complete degradation of biomass, allowing for a smaller digester volume. In addition to boosting biogas yields, the hydrolysis section enables the efficient treatment of otherwise problematic feedstocks, such as poultry manure, the organic fraction of municipal solid waste (OFMSW), and civil, domestic, or industrial sludge. Moreover, this section enables the complete volatilization of ammoniacal nitrogen, enhancing its recovery in the subsequent stripping and scrubbing stages, the second section of the process, ultimately allowing the production of ammonium sulphate, which can be used as an agricultural fertilizer. As a result of the stripping section, the digesters are fed with sludge that is almost completely free of ammonia, which is toxic to methanogenic bacteria. This near-total removal of ammonia also ensures that the liquid digestate can be safely discharged into the municipal sewage system, complying with the emission limits specified in Annex 5, Part Three, Table 3 ('Discharge into the sewer') of Italian Legislative Decree No. 152/06 [7], following simple solid–liquid separation and, if necessary, a final polishing step in a small oxygenation tank. In the final stage, the CO₂ contained in the biogas is utilised to neutralize the previously alkalized biomass through an acid-base reaction. Depending on the alkaline agent used, this process leads to the formation of either calcium bicarbonate or sodium bicarbonate. Simultaneously, this CO₂ capture step upgrades the biogas to biomethane, as the carbon dioxide is effectively removed from the gas stream. Unlike conventional upgrading systems, such as membrane upgrading that release CO₂ directly into the atmosphere, this process prevents any gaseous CO₂ emissions. Furthermore, since the digestate is already stabilised and low in ammoniacal nitrogen, there is no need for energy-intensive downstream treatments such as composting, an aerobic process for stabilizing the solid fraction, or nitrification–denitrification, a biological process used to remove nitrogen from the liquid fraction. The biogas in this process is maintained at atmospheric pressure, eliminating the need for the significant electrical energy typically required for compression in membrane upgrading systems. Therefore, the electricity and heat demand can be met by a CHP system fuelled by the biogas produced. This highlights the system's high energy efficiency, consequently enhancing its overall environmental sustainability.

2.2 Biogas plant description

The analysed facility is a biogas cogeneration plant with a maximum installed capacity of ca. 500 kWe (Fig. 1). The plant processes approximately 60 tonnes per day of swine slurry, supplemented by around 10 tonnes of biomass consisting of 43% corn meal, 10% bran and 46% corn silage. Additionally, it receives an input of 4 tonnes per day of wheat silage. The Ingenia technology is currently applied only to the swine slurry stream, as this feedstock typically has the highest ammoniacal nitrogen content. By significantly reducing the ammonia load, the system produces a more manageable liquid digestate and delivers additional benefits to the anaerobic digestion process. Consequently, all analyses presented in this study have been conducted considering swine slurry as the sole input to the treatment system.

The daily biogas production is approximately 4,800 m³ per day, equivalent to 200 m³ per hour, which serves as the fuel supply for two cogeneration units. The system is designed to fully satisfy the constant thermal demand of the digesters, which amounts to 400 kW, while also covering a variable heat demand within the farm with a peak load of 34 kW. Additionally, the CHP unit produces approximately 410 kW of electric power, which is fed



Figure 1: Ingénia technology section in the existing biogas cogeneration plant.

into the national grid under the applicable feed-in-tariff scheme [8]. The total annual thermal energy produced to fully satisfy the heat demand of the digesters and the residential demand amounts to approximately 3.8 GWh, while the total electrical energy production is approximately 3.58 GWh.

3 CASE STUDY

This study evaluates the energy savings associated with the improved biogas quality observed at the plant described in Subsection 2.2, as well as the potential environmental benefits derived from the biogas upgrading process to biomethane. The methodology used to quantify these benefits is presented in Section 3. Specifically, Subsection 3.1 focuses on the analysis of the energy savings resulting from the use of biogas or biomethane in all considered scenarios, while Subsection 3.2 examines the reduction in CO₂ emissions by comparing the use of biogas and biomethane.

3.1 Energy analysis: biogas vs. biomethane scenarios

The energy analysis is performed considering the same electrical energy output, while accounting for the different biogas and biomethane flow rates required to fuel the CHP units, due to their different Lower Heating Values (LHV_s). To evaluate the primary energy input of the CHP system, the electrical energy output is related to the electrical efficiency according to:

$$E_p = \frac{E_e}{\eta_e} \quad (1)$$

where E_p denotes the primary energy input, while E_e represents the electrical energy output, and the parameter η_e corresponds to the electrical efficiency of the CHP unit. This analysis aims to assess the primary energy input in both scenarios, considering the same electrical energy output. The assessment uses electrical energy as the reference parameter, as the nominal capacity of the cogeneration unit is expressed in terms of electrical power, enabling a direct comparison of primary energy requirements for identical electrical production. The

comparison includes an average-efficiency case and a maximum-efficiency case to quantify the potential range of primary energy savings achievable by replacing biogas with biomethane. Typical efficiency values for CHP units fuelled by biogas and biomethane are reported in Table 1 [9].

Table 1: Typical efficiency values for CHP units fuelled by biogas and biomethane [9].

Fuel	η_e	η_{th}	η_{tot}
Biogas	37–42	39–48	80–85
Biomethane	38–43	42–53	85–92

3.2 CO₂ emission performance of biogas energy vs. national grid mix

This section examines the CO₂ emission performance of biogas-based energy production through a comparative analysis with the national average emission factors per kWh. The national benchmark values are sourced from the ISPRA database [10], which reports standardised emission factors for separate electricity and heat generation in Italy. Conversely, the emission factors specific to energy production from biogas and biomethane are drawn from the official data outlined in Italian Law No. 199/2021 [11], which defines the regulatory framework and sustainability criteria for renewable gas production. The emission factors used for the comparison are reported in Table 2. The resulting CO₂ emissions were calculated by multiplying these specific factors by the corresponding annual energy production values. Furthermore, the analysis includes the primary energy analysis. The corresponding energy savings are assumed to be injected into the natural gas grid, benefiting from the Italian government feed-in tariff.

Table 2: Emission factors for national mix, biogas, biomethane, and grid injection.

	Electricity production (gCO _{2-eq} /kWh _e)	Heat production (gCO _{2-eq} /kWh _{th})	Grid injection (gCO _{2-eq} /kWh _{biom})
National average	257.2 [10]	218.8 [10]	
Biogas	12.24 [11]		
Biomethane		−18.36 [12]	0.36 [12]

The emission factors for biogas and biomethane in Table 2 refer to electrical and thermal energy production from wet manure through a CHP unit under a ‘renewable configuration’. For biogas, the reported emission factor includes both the emissions from the treatment process and those from combustion, while also accounting for a negative contribution, the ‘manure credit’, representing the avoided emissions that would otherwise arise from conventional manure management practices, such as direct land application. For biomethane, the reported emission factor refers to the renewable configuration, as already defined for biogas. This value incorporates the same emission components considered in the biogas case, namely those associated with manure treatment and system operation, and additionally includes the emissions related to the upgrading process. In this analysis, a low loss upgrading technology is selected, with methane slip estimated at below 1%, consistent with the specific configuration under investigation. The emission factor, expressed in gCO_{2-eq}/kWh_{th}, refers to the category ‘other uses’, which includes energy production in industrial cogeneration plants, which can be also connected to district heating networks. The resulting negative value reflects the presence of net avoided greenhouse gas emissions. For the emission factor of biomethane

grid injection, the value was derived from data expressed in $\text{gCO}_{2\text{-eq}}/\text{MJ}$ of compressed biomethane for transport, as this category accounts for emissions from both the upgrading process and gas compression. Since compression is also required before injection into the gas grid, this value is considered representative of the environmental performance of biomethane under grid injection conditions.

4 RESULTS AND DISCUSSION

This section discusses the comparative performance of biogas and biomethane in CHP systems, focusing on primary energy analysis and $\text{CO}_{2\text{-eq}}$ emissions. Subsection 4.1 examines the primary energy requirements to deliver the same electrical and thermal outputs when using either biogas or biomethane as fuel. Subsection 4.2 evaluates the associated $\text{CO}_{2\text{-eq}}$ equivalent emissions for both configurations, benchmarking them against electricity and heat generation from the Italian national energy mix, based on ISPRA emission factors.

4.1 Primary energy input analysis

The results are presented in Fig. 2. The first scenario considers the average values from the ranges reported in Table 1, resulting in an electrical efficiency of 39.5% for the biogas-fuelled system and 40.5% for the biomethane-fuelled system. The second scenario is based on the extreme values of the same ranges, representing the maximum achievable primary energy.

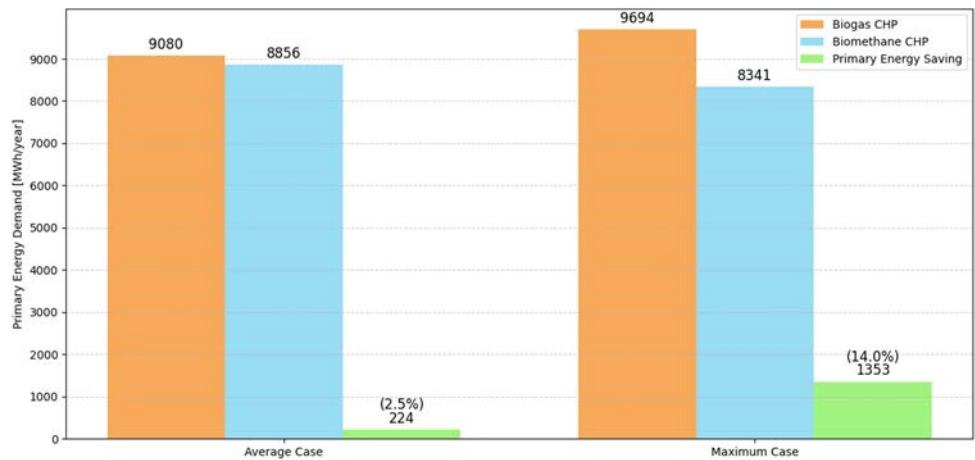


Figure 2: Primary energy input and saving for biogas- and biomethane-fuelled CHP.

Fig. 2 compares the primary energy inputs of biogas- and biomethane-fuelled CHP systems under two scenarios: average case and maximum case. In the average case, biomethane reduces primary energy input from 9,080 MWh/year to 8,856 MWh/year, yielding a 2.5% saving (ca. 224 MWh/year). In the maximum case, the demand decreases from 9,694 MWh/year to 8,341 MWh/year, corresponding to a 14.0% saving (ca. 1,353 MWh/year). The figure highlights how the higher efficiency of biomethane CHP translates into measurable primary energy savings, which increase under more favourable performance conditions.



4.2 CO₂-eq emissions of biogas and biomethane CHP vs. Italian energy mix

As shown in Fig. 3, operating a CHP system with biogas achieves a substantial reduction in CO₂-equivalent emissions, up to 95%, compared to generating the same amount of electricity using the Italian grid mix. In quantitative terms, annual emissions decrease from approximately 922 tCO₂-eq to about 44 tCO₂-eq. The biogas CHP system achieves a substantial reduction in emissions thanks to the manure credit, which partially offsets the emissions from digestion and combustion. This configuration delivers a strong climate benefit, cutting overall emissions by 95% compared to the national grid mix.

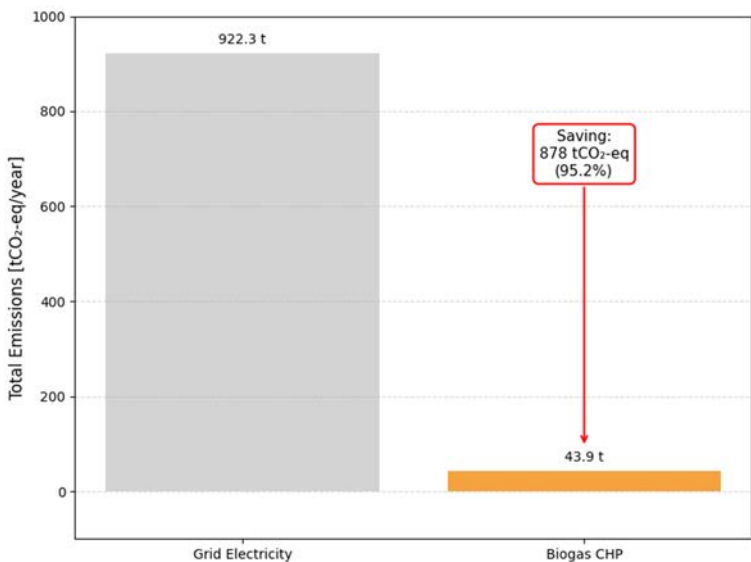


Figure 3: Emission reduction potential of biogas CHP compared to the Italian grid electricity mix.

Fig. 4 compares the annual CO₂-eq emissions associated with thermal energy production from a biomethane-fuelled CHP unit and those from conventional heat production using the Italian gas grid, based on the emission factors provided in the UNI/TS standard [12]. Despite producing the same amount of thermal energy, the biomethane CHP case achieves net negative emissions amounting to -69.9 tCO₂-eq/year, resulting in a total saving of 902 tCO₂-eq/year, which corresponds to a 108.4% reduction compared to the conventional reference. The biomethane CHP unit achieves net negative emissions thanks to the manure credit, which offsets the emissions from the digestion and combustion processes. Indeed, this significant reduction strongly depends on the biomethane production pathway. In addition to the previous assessment, the total energy savings evaluated in Subsection 4.1 can also be considered. This energy corresponds to the amount of biomethane that could potentially be injected into the national gas grid, equal to 23,600 Sm³ in the average case and approximately 142,400 Sm³ in the maximum energy saving case. The corresponding total CO₂ emissions are calculated by multiplying the saved biomethane energy by the CO₂ emission factor reported in Table 2. For the maximum energy saving scenario, the total emissions are

approximately 0.4 tCO₂, so the total emissions could range from −69.9 t to −69.5 t in the case of maximum energy saving with injection into the grid, considering the small positive contribution of CO₂ emissions associated with biomethane injection into the grid.

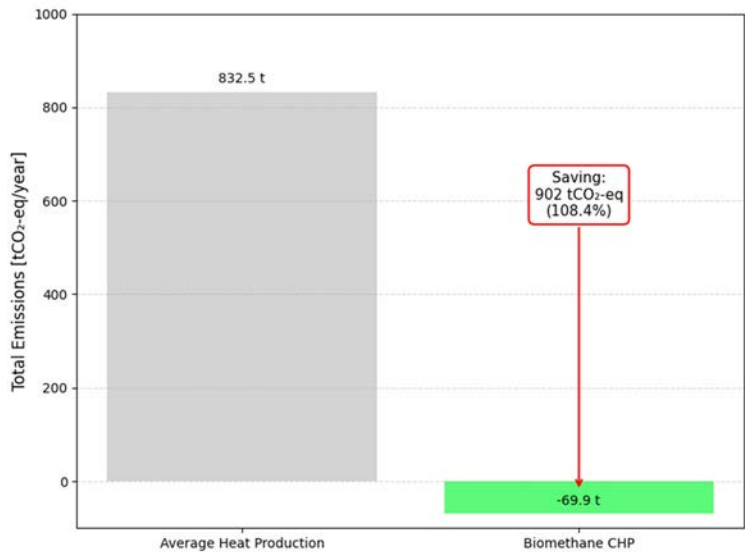


Figure 4: Emission reduction potential of biomethane-fuelled CHP compared to the average heat generation in Italy.

5 CONCLUSIONS

This study evaluated the energy and environmental performance of a 500 kW_e biogas-fuelled CHP unit equipped with the Ingenia-patented system, with a focus on the benefits of upgrading biogas to biomethane. The analysis compared the two configurations in terms of primary energy input and CO₂-eq emissions for the same combined heat and power output.

The results show that replacing biogas with biomethane in the CHP system can achieve primary energy savings of up to 14% (approximately 1.35 GWh/year), which may potentially be injected into the national gas grid. From an environmental perspective, both biogas and biomethane enable significant reductions in GHG emissions compared to the Italian electricity and heat production mix. Biogas achieves a reduction of about 95%, while biomethane reaches net negative emissions of up to −69.9 tCO₂-eq/year, corresponding to a 108% reduction. Considering the maximum energy-saving scenario with grid injection, total emissions range between −69.9 t and −69.5 tCO₂-eq/year, accounting for the small positive contribution of emissions associated with biomethane injection.

These findings underline the crucial role of biogas and, in particular, biomethane as key enablers of the low-carbon energy transition. However, the overall environmental performance of biomethane is highly dependent on the upgrading technology adopted: conventional systems typically vent the separated CO₂ to the atmosphere, which can carry along higher amounts of entrained methane. In contrast, the upgrading configuration adopted in Ingenia-technology avoids direct CO₂ emissions to the atmosphere.

Future developments will involve the process a new feedstock mix, no longer composed exclusively of manure. This will enable a detailed evaluation of how the modified substrate

composition affects the quality of the produced biogas, the achievable increase in methane yield, and the resulting environmental performance in terms of CO₂-eq emissions.

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